



Beyond the Artifact: CONSTRUCTABILITY, COMPLEXITY & CONSTRAINTS

PROCEEDINGS OF THE 2023
BUILDING TECHNOLOGY EDUCATORS' SOCIETY CONFERENCE
THE COSANTI FOUNDATION + KENNESAW STATE UNIVERSITY



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BTES

**BUILDING
TECHNOLOGY
EDUCATORS'
SOCIETY**

Edited by

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Liz Martin-Malikian
The Cosanti Foundation

BEYOND THE ARTIFACT: CONSTRUCTABILITY, COMPLEXITY & CONSTRAINTS

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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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BEYOND THE ARTIFACT: CONSTRUCTABILITY, COMPLEXITY & CONSTRAINTS

ABOUT THE THEME

Buildings for me represent opportunities of agency, transformation, and storytelling. They are not just artifacts. There is this big tradition of buildings-as-artifacts - constructed artifacts 34but for me they are these incredible sites of negotiation.”

David Adjaye

Interpreting architecture as artifact is a matter of reading a building and its environment. To best comprehend the language of buildings, designers often consider form and material grammar in terms of assemblies, details, and systems. How a building reads depends on how all these elements are composed with the intent of being realized as a built object. Today, we are witnessing a reformulation of the grammar of materials leading to a more eco-sustainable syntax of construction and building structure through experimentation and innovation. Rather than seeing architecture from the 'outside as object' or built artifact, we need to instead understand the built realm as a form of production 'from within' to create a site of negotiation.

This conference will explore this intention to demystify architecture by reconsidering how we critique a discipline whose role in the built world lies mainly in the reception of its built products, and not in their material production. In using the term 'material production,' Adjaye means more than just detailing a building. He is discussing the realignment of the profession concerning the democratization of knowledge, acknowledging architects as active protagonists rather than the consumers that we have arguably become as a profession.

The four topics described below represent opportunities of agency, transformation, and storytelling as a point of departure for this conference:

-Constructability. The awareness for the method of construction of buildings, their systems, materials, and assembly.

-Complexity. The theories that seek to clarify the relationship between people and places. These include, among others, historical, archival, ethnographical, experimental, simulational, survey, mapping, statistical, and qualitative analysis methods.

-Constraints. The range of techniques on gathering, assessing, interpreting, and comparatively evaluating relevant information for inquiry, education, and methodologies.

-Open Artifact. The process of 'making' through abstraction and autonomy as a speculative mode of architectural production.

THE VENUE

Located in the Paradise Valley (Arizona) the 2-locations: Cosanti and Arcosanti were the gallery and studio of Italian-American architect Paolo Soleri until his death in 2013. They are now an Arizona Historic Site open to the public marked by terraced landscaping, experimental earth-formed concrete structures, and sculptural wind-bells. They were built by hand by more than 8000 students and volunteers who came from all over the world to participate in The Cosanti Foundation's signature multi-week workshop program.

This gathering of minds engaged architecture in its role as a cultural agent and examine the way buildings establish and organize dynamic relationships not only between site, program, and material but also architecture and ecology.

Giovanni Loreto
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CONFERENCE PAPERS





CONSTRUCTABILITY

The awareness for the method of construction of buildings, their systems, materials, and assembly

Linking Sustainability and Housing Affordability to Neighborhood Design Compatibility

Michael L. Garrison

The University of Texas at Austin, Austin, Texas

ABSTRACT: While economic and social policy models have failed to move the public demand to build more affordable housing in Austin, Texas, urgent environmental, sustainability and climate change realities may finally demonstrate how it is in everyone's self-interest to build more affordable urban Zero Net Energy (ZNE) housing now. Residents of Austin's older urban neighborhoods have been reluctant to accept zoning changes that would allow large numbers of urban middle density housing units, fearing the higher densities would not be compatible with the character of their existing single-family detached (SFD) scaled neighborhoods. SOLEIL Homes presents a ZNE middle density housing model combining affordability and sustainability to add a new standard for neighborhood compatibility. The SOLEIL model allows existing neighborhood residents to visualize a modest middle density increase (31.1 units per acre), ZNE energy efficiency, and affordability to maintain diversity and compatibility with the character of Austin's SFD scaled urban neighborhoods. The SOLEIL factory-built modular housing model lowers construction costs by 20% and the middle density allows more housing units to share – and thus lower – raw land costs, addressing the primary cause of rising home prices. Through its green building design, evaporative cooling rain gardens and enhanced energy conservation features, SOLEIL achieves a low Energy Use Intensity (EUI) ZNE Ready rate of 7.9 kBtu/ft²-year, and with the addition of a 5.14 KW per unit Community Solar PV system, the SOLEIL units achieve a Zero Net Energy home classification. A rainwater harvesting design reduces water use to less than 30 gallons per capita day. SOLEIL units achieve neighborhood design compatibility and energy efficiency at a sales price affordable to residents with an income of less than 80% of Austin's annual median family income (MFI). By extending ZNE sustainable housing to include the affordable and moderate housing markets, enough urban units could be built by the end of this decade to meet Austin's affordable housing demand and help forge a pathway to reduce the city's carbon footprint CO₂e/year by 50% by 2030.

KEYWORDS: Climate Change Mitigation, Housing Affordability, Middle Density, ZNE

INTRODUCTION

The 2015 United Nations Paris climate agreement set a target of limiting the global average temperature increase to less than 3.6° Fahrenheit (2° Celsius) above pre-industrial levels by 2050 to avoid the worst impacts of climate change. (1) In response, the City of Austin, Texas (COA) adopted a new Climate Equity Plan in 2021 that sets a target to become a net-zero community wide CO₂e/year emissions by 2040. Austin's pathway to achieve this goal links affordable housing, and zero net energy (ZNE) housing at an increased density that is compatible with the design character of Austin's existing urban neighborhoods. In Austin the electricity and natural gas used to power residential buildings and the transportation fuels used to power vehicles traveling between home and work account for 83% of Austin's Community Greenhouse Gas Emissions (10.8 million metric tons of CO₂e/year in 2022). (2) Austin's Climate Equity Plan requires a 50% reduction in the city's community greenhouse gas emissions by the end of this decade. To achieve a change of this magnitude will require significant revisions to COA policies on how and where housing is built. Specifically, Austin must reduce the operational energy use of all its existing housing stock by 25% and add another 100,000 new ZNE housing units to meet demand and for 80% of these new housing units to be built within Austin's urban neighborhoods to reduce transportation carbon emissions. Since two-thirds of the city's housing market is for moderate and affordable units, it is imperative that affordable middle density ZNE housing models compatible with the scale of Austin's urban neighborhoods be constructed in large numbers to achieve Austin's climate change mitigation goals.

1. COMPATIBILITY: NEIGHBORHOOD SCALED MIDDLE DENSITY HOUSING TRANSITION ZONING.

A sample 19,279 ft² site in Central East Austin's Blackland Neighborhood, comprised of three adjoining lots zoned single family (SF-3) is used as a case study analysis to develop the SOLEIL Homes model. (3) Located in a historically black urban neighborhood now experiencing gentrification, the site is in a proposed half-block housing density transition zone bordering neighborhood streets lined with single-family detached houses to the south and denser four-story Vertical Mixed Use zoned housing along a core transit corridor to the north. The housing density transition zone would allow housing densities up to 31.1-dwelling units per acre, a maximum height of 34-feet, a maximum building area to site area ratio of one to one, a maximum building

coverage area to site area ratio of 50% and a maximum impervious surface site coverage of 60%. When the site impervious coverage ratio exceeds the current SF-3 allowable of 45% (4) a green stormwater infrastructure (GSI) system is required to assure that storm water flow will not exceed the flow currently existing from the site. To address concerns about the design compatibility building scale of middle density in their single family detached (SFD) scaled neighborhood, SOLEIL provided a physical model that allows residents to visualize a middle density scaled housing design project.



Figure 1: SOLEIL 14-unit middle density housing model proposed for a ½ block housing density transition zone. Source: (Garrison 2021)

The SOLEIL model design limits building heights along neighborhood local streets to two-stories in height and breaks up the massing of the project using deep balconies and front porches that sit back 15-feet from the street. The elevated front lawns and xeriscape landscaping provide privacy for street-facing row homes without building privacy fencing. Rather than attempt a fake historical reproduction of the Swiss farmhouses or the bungalow style of Blackland’s earlier times, SOLEIL homes achieve design compatibility by using domestic gable roof forms similar in size to the older houses in the neighborhood, and with their 14-foot-wide front porches they are aesthetically compatible with the scale and character of the existing Blackland neighborhood. Based on the physical model, the neighborhood association found the proposed middle density to be in keeping with the character of their neighborhood. The middle density overlay zoning allowed 14-SOLEIL housing units, averaging 1,200-square-foot in size, to be built on the 19,279-square-foot site zoned for the three SF-3 lots. The SOLEIL Housing model was then used as an economic, sustainability and design compatibility comparison to the three three-story SFD units and the two two-story Accessory Dwelling Units that were built on the site under SF-3 zoning in 2022-2023. The Travis County Central Tax Appraisal District in 2020 (5) assessed the property value for the three SF-3lots at \$425,000 for each lot. When raw land prices are this expensive, it pushes the sales price of a home built on the site up to the luxury class level. A developer typically would like to keep the raw land costs below 20-25% (6) of the home sales price. For example, one SFD house built on one of the lots in 2022 is a 3-bedroom, 2-bath, 2,245-square-foot, 3-story home with a market sales price of \$1,100,000. (7) The raw land cost (\$425,000) represents 39% of the home sales price. The \$1.1 million house is too expensive for existing neighborhood residents and twice the square footage of typical Blackland houses. Neighbors labeled the house a “McMansion” and opposed its development.

As an economic alternative, the raw land cost for the 14-unit SOLEIL homes is \$91,300 per unit. This allows the developer to build smaller 1,200-square-foot housing units with an affordable (8) market sales price of \$367,116 each. Their raw land costs are 25% of the home sales price. Additionally, because middle density only adds a modest increase of energy and water efficient housing units, utility infrastructure demands can be met without drastically increasing the utility infrastructure capacity of existing urban single-family detached scaled neighborhoods.

2. AFFORDABILITY: PREFABRICATED MODULAR FACTORY-BUILT HOUSING CONSTRUCTION

Factory-built modular construction can reduce costs by approximately 20% through benefits that include bulk purchasing of building materials, better controlled indoor work conditions, more experienced factory

workmanship, assembly line efficiency, automation, and reduced construction times. Local building code compliant prefabrication is a process in which a modular home is constructed off-site, under controlled indoor plant conditions and then shipped to a site where modules are assembled to form a multifamily housing project. The construction process uses a selected unit or module, such as a rectangle or other subcomponent, which is used repeatedly in an assembly line construction process. The modules are constructed in a factory, trucked to the site where they are unloaded using a crane and then placed on a concrete perimeter beam foundation and stacked together to form row houses. The modules arrive at the site with fully finished interiors, MEP systems, windows, doors, cabinets, kitchens, bathrooms, and interior finishes. The row houses are put together by connecting the stacked modules to stairway modules, and the entire project is assembled on site in just a few days.



Figure 2: Prefabricated factory-built row housing modules shipped to the site and stacked together. Source: (Garrison 2021)

The SOLEIL module costs were based on 2022 prices quoted by Oak Creek Modular Homes in Fort Worth, Texas. (9) While the SOLEIL design is different than the standard Oak Creek modular home design, the company will build custom modules when the number of modules is significant enough to justify the set-up costs. SOLEIL meets this requirement building 28-14'W x 40'L x 11'H home modules, 14- 4'W x 40'L x 11'H stairway modules and 10- 14'W x 40'L x 8'H @45° sloped roof modules. An Oak Creek standard modular home similar in size to a SOLEIL row house costs \$126,562 (July 2022 dollars). Because the SOLEIL project includes more expensive materials, finish upgrades, electrical and appliance upgrades, the SOLEIL units are slightly more expensive at \$138,895 per modular unit delivered and assembled on site. On-site construction costs another \$60,321 per unit for site prep and finish out work including site grading, perimeter concrete pier foundations, under floor bladder cisterns, exterior rainscreen FRP siding, galvalume roofing, rain garden courtyards, pervious paving, living fencing, a community garden roof deck located above the SOLEIL flats, a roof deck shading pergola to support PV panels, utility infrastructure systems, exterior lighting, and xeriscape landscaping. Quality materials and finishes are used to assure SOLEIL will meet highest quality for standard construction (moderate income market) at an "all in" base cost of \$199,216 + \$11,600 in energy efficiency upgrades \$210,816 (\$175/square-foot).

3. SUSTAINABILITY: MICROCLIMATE SITE DESIGN, ENHANCED ENERGY CONSERVATION AND ZNE SOLAR PV POWER

Enhanced energy conservation features are incorporated into the SOLEIL Homes design to meet the requirements of a U.S. Department of Energy (DOE) ZNE READY home certification. These features include: 1) a microclimatic site design featuring evaporate cooling, shading, and solar induced stack ventilation; 2) specifying Austin Energy Green Building (AEGB) program multi-family five-star green building features (10)

Seasonal Energy Efficiency Rating (SEER) of 14 or above. A 2023 AEGB certified home has an average annual electrical use of approximately 9,600 kWh/year which equates to an EUI of 17.56 kBtu/ sqft -year. To achieve a 5-star AEGB rating Austin home builders must add additional green building measures and energy conservation features that reduce the home's annual electrical use by a minimum of 55% below code to 5,400 kWh/year which equates to an EUI of 9.88 kBtu/ sqft -year. Reducing a home's annual electrical use by 55% below the benchmark code home is the minimum rating to qualify for a DOE ZERH certification. (18) The AEGB 5-star and the ZERH features include, R-19 wall insulation, bridging wall board insulation, R-49 ceiling insulation, window U-value less than .26 and a SHGC of .25 or less, improved hot water heating efficiency and a minimum HVAC SEER of 15 or above as well as energy-star rated lighting and appliances.

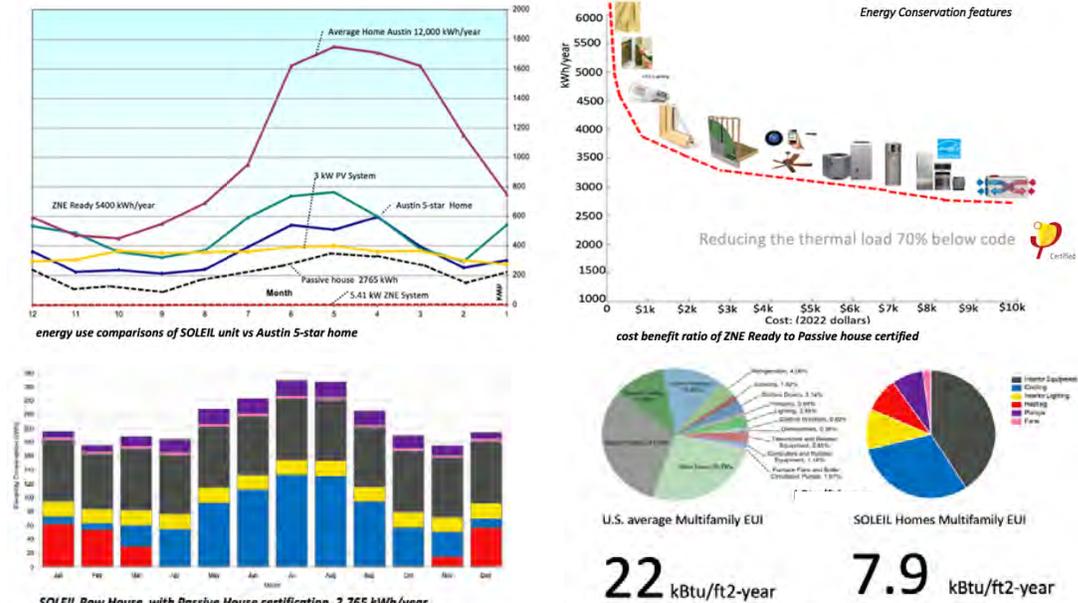


Figure 4: Zero Net Energy Ready classification using enhanced energy conservation features. Source: (Garrison 2021)

Before SOLEIL Homes are sized for a roof-top solar photovoltaic (PV) power system to become ZNE homes, they should consider even more energy conservation measures to lower the housing project per unit power load to reduce the number of required PV panels to make the power system more economical. (19) Therefore, SOLEIL adopted Passive House super insulation standards to reduce total annual electrical use by 77% below the 2015 IECC code Austin benchmark home. The SOLEIL Homes built to the Passive House standards reduced the annual electrical load to 2,765 kWh/year which is an EUI of 7.9 kBtu/sqft-year (For a 2-bedroom, 1- and ½-bath, 1,200 sqft SOLEIL attached row house unit). PHI and PHIUS certified measures include, R-23 wall insulation, R-57 ceiling insulation, window U-value .17 or less and a SHGC of .2 or less, low e-3 heat mirror windows, responsive exterior window shading, heat-pump water heating, a minimum HVAC SEER of 16 or more, LEED lighting, high energy-star rated fixtures and appliances, well-sealed exterior building envelope with .22 air changes per hour along with an Energy Recovery Ventilator (ERV) to assure adequate amounts of interior fresh air and a smart energy management system thermostat.



Figure 5: ZNE U.S. DOE classification with the addition of a community solar power system. Source: (Garrison 2022)

Austin low-rise residential and multifamily building permits require IECC Manual J HVAC sizing calculations. (20) When these calculations are applied to a SOLEIL row house (Passive House standards), the peak HVAC load is calculated at 1,800 Btu/hour (or 1 ton of HVAC per 800 ft2 of floor area). Each SOLEIL housing unit has its own 19- SEER air source heat pump heating and cooling system and heat pump domestic hot water

system. During hot summer conditions, the air source heat pump will supply cool forced air to dehumidify and cool air to maintain interior comfort at 75°F. The cooling load and the heating load were calculated using peak design high and low outdoor temperatures of a 110°F outdoor summer high temperature and a 10°F outdoor winter low temperature. The simulation estimated a peak thermal load of 17,899 Btu/hour summer and 10,800 Btu/hour winter. Given the summer dominant cooling load, a 1.5-ton, 19-SEER air source heat pump for cooling and heating is specified for each SOLEIL housing unit.

3.3 Zero Net Energy PV community solar power systems

To achieve a zero-net-energy operational power performance, the SOLEIL housing units' photovoltaic panels were added to the project. SunWatts Mono Sol XL solar PV Monocrystalline C-Si panels with 20% efficiency, 450 watts, (23.5 sqft/panel) were added in two locations: On the Poquito St. row house south-facing roofs, 48-PV panels are fixed mounted at a tilt angle of 45 degrees and at an azimuth angle of 190-degrees. And across the central north-south courtyard an additional 112-PV Sunwatts panels are mounted on the roof pergola above the SOLEIL flats. They are fixed mounted at a tilt angle of 3-degrees and a 190-degree azimuth angle. In combination the panels provide a 72kW PV power system. (21)



rooftop PV panels mounted on shading pergola above the Soleil flats garden roof deck.

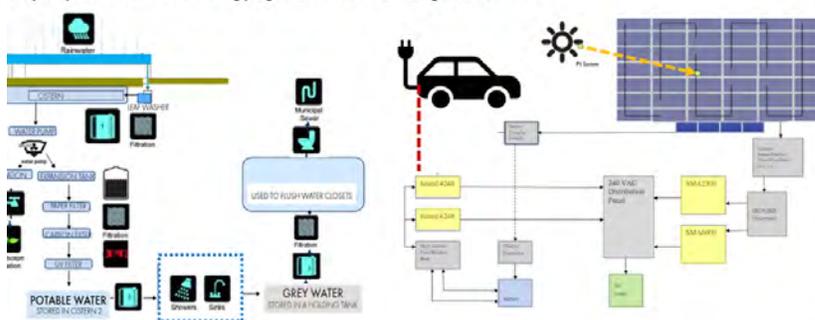


Figure 6: SOLEIL 72 kW (5.14kW per unit) AE Community Solar PV power system with water and power storm resilience. Source: (Garrison, 2021)

The SOLEIL Homes (Passive House Standards) is estimated to require only 61PV panels to become a ZNE housing project. Because the SOLEIL Community Solar design provides 160 PV panels, they will provide more electricity than the housing project needs. During a typical summer day excess PV power is sent back into the electrical grid where it can be used by other customers. At night the housing units pull power from the electrical grid. If the housing units use less energy than they produce, under a Community Solar lease agreement Austin Energy would pay the SOLEIL residents at a rate of \$0.03 per kWh for their excess power. On an annual basis if the housing project supplies more power to the electrical grid than it uses it is considered a zero net energy project. (22) The estimated cost of SOLEIL's PV panels is \$0.81/Watt-dc x 72 kW PV system equals \$58,320 and after the maximum AE PV rebate of \$35,000 equals \$23,320 cost plus installation and inverter costs to the owner. This up-front solar PV cost is too expensive for affordable home buyers, but Austin Energy offers a Community Solar program for affordable multifamily housing without any out-of-pocket expenses to the residents. SOLEIL is planned to use the Community Solar Program option and therefore no costs for the solar system are not included in the ZNE housing construction budget.

4. LINKING COMPATIBILITY, AFFORDABILITY, AND SUSTAINABILITY TO CLIMATE CHANGE MITIGATION

An Austin housing market survey identified two first-home buyer groups as the primary market for new middle density homes in urban East Austin (23) including, 1) younger tech-savvy environmentally conscious singles and couples looking for housing close to downtown and its urban amenities and, 2) younger black home buyers who would like to live in an older historically black East Austin neighborhood. While the market survey found location was most important to both homebuyer groups, equally important was value. These first-time homebuyers are willing to pay a little more for energy and water-efficient housing. How much more? Additional costs for green building features should not exceed the amount of savings generated from lower utility bills

within a timeframe ranging from 5-10 years. For each SOLEIL certified green building home energy conservation features add approximately \$1,420 (\$1.18/sqft) but lowers annual electrical use by more than 13% with a 2.8-LCC (Life Cycle Cost) year payback. The AE 5-star or ZERH certified features add an additional \$3,744 (\$3.12/sqft) but reduce the annual electrical load by 55% with a 4.2-LCC year payback. Passive house standards add \$6,436 (\$5.36/sqft) but reduce the thermal load by an estimated 77% with a 6.8-LCC year payback. The total green building and energy conservation upgrades add \$11,600 to the sales price of a SOLEIL housing unit but pay for themselves in energy savings in less than ten years. The sales price of a SOLEIL housing unit is equal to, the raw land costs (\$91,300) + construction costs (\$199,216) + enhanced energy efficiency upgrade costs (\$11,600) + soft costs including, marketing, sales, overhead, fees, etc. (\$15,000), COA zoning and permit fees exempted for affordable housing + developer's fee and investor equity return (\$50,000 per unit) equals a sales price of \$367,116 per unit (\$306/ft²). At a sales price of \$367,116 every SOLEIL unit qualifies as COA affordable housing for homebuyer couples who make less than 80% of Austin's annual MFI. Although the SOLEIL units would be initially affordable, if only a few projects like SOLEIL are built, investors will quickly buy the units and then flip the units (reselling them) to other buyers at much higher prices. If the demand for middle density urban housing remains high and the inventory remains low, achieving affordable urban housing in Austin will remain a challenge. However, if large numbers of affordable middle density ZNE housing units were built in every Austin urban neighborhood, using ½ block middle density housing transition zoning, market supply could rapidly increase to meet market demand, and affordable home prices would likely stabilize. When affordable housing units are developed in partnership with a non-profit neighborhood community design corporation (CDC) using land trusts, lower income residents can receive assistance in reducing the financial impacts of rising property taxes and HOA assessments and facilitate large numbers of units to be built.

CONCLUSION

Because two-thirds of Austin's housing market is for moderate income buyers (below 135% of Austin annual MFI) and lower income buyers (below 80% of Austin annual MFI), and if Austin residents can reach a consensus on enacting housing transition zoning in Austin's urban neighborhoods to allow large numbers of ZNE middle density housing to be built to meet market demands, then significant climate change mitigation can be achieved to meet Austin's goal of becoming a net-zero greenhouse gas emissions community by 2040.

The Austin Energy fuel mix used to generate electrical power impacts the conversion rate of kWh used to measure the carbon fuel emissions emitted to generate electrical power. In 2021 AE's electrical power generation fuel mix (coal, hydro, gas, wind, solar, nuclear) was 68% from non-carbon fuels and by 2030 it is scheduled to be 93% non-carbon. In 2021 the AE fuel mix customer carbon rate was .739 pounds CO₂e/kWh. By applying the AE fuel mix rate to an average Austin Home's annual electrical use (12,000 kWh/year X .739 metric tons of CO₂e/kWh) divided by 2,204.6 lbs./metric ton equals 4.6 metric tons CO₂e/year-unit. A SOLEIL row house (passive house standards) contributes only .92 metric tons CO₂e/year and a SOLEIL ZNE row house with zero-net operational energy consumption use would eliminate 4.6 metric tons of CO₂e/year. Embodied energy (EEH) use should be added to the household operational use along with household waste and household transportation emissions too define the total household carbon footprint. The embodied material carbon emissions (MCE) are the (upstream) carbon emissions contribution for mining, manufacturing, transportation, and construction of the building materials used to build a home. By applying the volume and weight of each material and its embodied energy content provided by a Carbon Calculator website, (24) the initial embodied energy of each SOLEIL housing unit was estimated at 17.9 metric tons CO₂e, which is a 40% reduction below the average U.S. townhouse embodied energy contribution (E.I.A.) estimated at 29.9 metric tons of CO₂e. SOLEIL Homes are built using an extensive amount of wood-based building materials, recycled and reclaimed materials and low embodied energy building materials and finishes. The estimated SOLEIL row house 17.9 metric tons CO₂e embodied energy emissions equate to a rate of 31.8 lbs. of CO₂e/ft², which is well below AE's recommended maximum embodied carbon emissions rate for buildings of 100 lbs. of CO₂e/ft². The EEH emissions spread over a 30-year LCC time frame and ongoing maintenance and material replacement embodied energy costs were estimated to add approximately 1.2 metric tons CO₂e/year.

Waste management in Austin represents 3% (327,000 metric tons) of Austin's community carbon dioxide equivalent footprint annually. The City of Austin Resource Recovery Plan is committed to a zero-waste goal to reduce the amount of trash sent to landfills by 90% by the year 2040. The diversion rate at the end of fiscal year 2021 was 41.96%. This diversion through recycling and reductions in per capita and construction solid waste levels reduced Austin's waste management carbon footprint by 137,209 metric tons of CO₂e/year.

Where Austin residents live and how they get around has an important impact on carbon emissions. In Austin, per capita vehicle miles traveled (VMT) per day has been steadily increasing for decades, mirroring suburban population growth. In 2010, Austin's average per capita transportation related CO₂e emissions was 4.8 metric tons CO₂e/year. Seventy-four percent of Austin's transportation-related emissions came from single-

occupancy private cars and trucks mostly commuting to and from work. Suburban residents living in lower-density sprawling developments have a greater dependency on carbon-intensive automobiles to access their daily needs in contrast to their Austin's urban neighbors. The SOLEIL Homes project is in an older urban neighborhood just 150 feet from an urban transit stop and within walking distance to neighborhood retail, restaurants, and other urban amenities. The urban location and the SOLEIL Homes shared electric zip-car program are projected to reduce SOLEIL Homes per capita transportation emissions to 2.4 metric tons CO₂e/year. If 100,000 new SOLEIL-like ZNE units were built within Austin's urban neighborhoods by 2030 (when at that time all new buildings must be ZNE), Austin could reduce transportation emissions down to 3.6 Mmt CO₂e/year by 2030 and 2.4 Mmt CO₂e/year by 2040.

Adding 100,000 new ZNE affordable housing units by 2030 would not only meet Austin's affordable housing demand, but it would also save 580,000 metric tons of carbon emissions per year over Austin's current average benchmark home. This would be in addition to the savings achieved by reducing all of Austin's existing 467,291 residential units and 50,451 commercial buildings energy use annually by 25%, an estimated savings of (1,250,000) + ZNE homes (580,000) equals 1,830,000 metric tons CO₂e/year. And by adding waste management (137,209) + transportation (2,400,000) equals a total reduction in carbon dioxide equivalent emissions of 4,037,209 metric tons of CO₂e/year. To achieve Austin's goal of reducing its 2021 community carbon footprint of 10.8 million metric tons of CO₂e/year by 50% by 2030, Austin will need to reduce its industrial, refrigerants and natural gas carbon footprint by 25% (650,000 metric tons CO₂e/year). Austin must then add carbon sequestration programs that will sequester carbon emissions of 712,791 metric tons CO₂e/year. Austin's goal of being a net-zero carbon emissions community by 2040 is optimistic but by linking affordability, sustainability, and neighborhood compatibility together in new housing policies on how and where housing is built demonstrates how neighborhood compatible, affordable ZNE middle density housing is the most scalable pathway to reduce Austin's carbon footprint by 50% by 2030.

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Learning Via Making, a Hands-On Approach

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ABSTRACT: *This paper showcases research and coursework conducted by the author in a higher education environment where hands-on approaches are used as the base for what is also known as experiential learning. The pedagogy is contextualized within the evolution of hands-on learning in academia, as well as the impact of new technology and advances in material sciences on learning through making. The goal is to understand how hands-on explorations in the use of concrete can constitute self-directed processes of conceptual and technical inquiry that can augment the students' self-critique to determine next steps in the design process, while acquiring a comprehensive understanding of the building tectonics.*

Three methodologies are identified under experiential learning: design build, digital fabrication and scale prototyping. Through the use of course curriculum, the author presents case studies of each of these methodologies, as well as hybrid versions of their application. In all cases, knowledge production was advanced by making and testing as a framework for architectural discourse, enabling critical thinking in search of optimal solutions through hands-on explorations. Students gained new knowledge and skills by actively working on a specific problem or challenge while exploring broader and deeper realms of the course proposal through the prescribed material. When courses were combined with a project-based learning methodology, it enabled students to learn by actively engaging in real-world projects. Ultimately, knowledge production was advanced through engagement with industry leaders and demonstrated either in a design based on physical explorations and/or presentation of the proposal for a real client or audience.

Making is a unique resource able to critically inform the design process and provide real-time feedback. Therefore, it is expected that hands-on courses will expose students to the exploration of materials within conceptual and technical frameworks to legitimate design decisions. The presented courses demonstrate that these pedagogical models ultimately nurture students with an assertive and solid foundation that can propel them as creative thinkers in the architectural field. However, more research needs to be conducted on understanding the learning curve of students that experience the hands-on methodology over other types of learning and their impact on their post-academic work.

KEYWORDS: hands-on pedagogy, design-build, digital fabrication, scale prototyping, concrete

INTRODUCTION

John Dewey, a prominent American scholar, and a progressive educational reformer was one of the pioneers in the hands-on approach to education. He argued that this approach enabled the sense of reality acquired through first-hand contact with actualities. When referring to the importance of experimentation in children's education, he states,

"[a]s to discipline, they get more training of attention, more power of interpretation, of drawing inferences, of acute observation and continuous reflection than if they were put to working out arbitrary problems simply for the sake of discipline" (Dewey, 1900).

Given the practical nature of the field, the pedagogy of many courses in architecture schools has traditionally included hands-on approaches. There are increased learning opportunities when hands-on exercises are strategically included in an architectural curriculum (Erdman, 2006). The very idea of designing through making is essential to grow and develop our practical knowledge through experience (Harrison, 1978).

Hands-on learning is a process that uses manipulation to deepen the understanding of the material possibilities and limitations while allowing an adequate response to specific needs. Hands-on courses constitute an excellent opportunity to explore and showcase innovation in materiality, including new applications of traditional materials as well as novel construction methods. Students can embrace emerging technologies and materials developing their "ethos of making" by critically experimenting with "the tectonic relationship of technology with technique and materials" (Wrightsmann, 2006).

Over the last years, the author has been engaged in applied research in concrete in tandem with teaching a series of courses addressing experiential learning in the form of hand-on approach. Concrete is the most common man-made material on earth. Given its phase change from fluid to solid, concrete relies on formwork to adopt its final shape. The inextricable interdependence between concrete and formwork provides a fertile ground for exploration of the material itself, its formwork and casting methods. The casting process requires extensive hands-on experimentation and testing to understand the precise point of inflection between flexible fluidity and obstinate solidity (Mori, 2010).

The goal of this study is to validate learning through making as a comprehensive teaching methodology that provides students with a robust understanding of building tectonics. It also aims to demonstrate how the exposure of students to direct experimentation with materials within conceptual and technical frameworks could legitimate design decisions while increasing the knowledge production in the classroom.

1. HISTORIC OVERVIEW OF HANDS-ON LEARNING IN ARCHITECTURE EDUCATION

Architecture, like engineering, is a practical discipline where design, making, and serving humankind is its fundamental purpose (Feisel & Rosa, 2005). Making things is a rational activity that has the potential of changing the world by bringing into existence objects and entities that did not exist before (Harrison, 1978). Both professions, before becoming part of academia, were rooted in apprenticeship methods where design, analysis, and manufacturing of creations took place – in other words, they were disciplines rooted in the notion of learning by doing (Feisel & Rosa, 2005). However, the academic system did not emerge to substitute the apprenticeship system. In the case of architecture education, the initial goal was to incorporate theoretical discussions about art and architecture and to develop the drawings as a medium to conceive buildings beforehand (Celani, 2012). During the Renaissance, drawings became a truthful depiction of the three-dimensional world, introducing a fundamental change in perception; consequently, architects gained a much higher status given their role as drawing makers (Hill, 2005). Making drawings became as important as making buildings; the two acts fused into an inextricable relationship. It was not until the early twentieth century, that the framework of a workshop-based academy was implemented in the inception of the Bauhaus in Weimar in 1919. Bauhaus's founder Walter Gropius, was the youngest of the Deutsche Werkbund's leaders. He envisioned reconciling art and an industrialized society, a problem that William Morris had foreshadowed in the 1880s in reaction to the artistic confusion of his day. Gropius wanted to combine the Academy with the Weimar Arts and Crafts School to create a "consulting art center for industry and the trades" (Dorner, 1975). Therefore, the Bauhaus was founded as an institution in flux promoting new methods of instruction in the visual arts while challenging existing academic practices (James-Chakraborty, 2006). Conception and materialization of objects were no longer considered two differentiated tasks. As the first proclamation of the Weimar Bauhaus states, "There is no essential difference between the artist and the craftsman" (Bayer, 1975). In October 1920, the Council of Masters approved a reform to increase the workshop training to six hours a day. The technical drawing was also introduced by Walter Gropius who taught theory and Adolf Meyer who introduced the practical side of the subject. The objective was to integrate the theoretical background of teaching with practical workshop training. This "bipolar" teaching model enabled students to receive a comprehensive education where apprentices had two mentors: a Master of Forms and a Master of Craft (Droste, 2006). Pottery, textile, metal, furniture, stain glass, mural-painting, wood carving, stone sculpture, bookbinding, and graphic printing were some of the workshops offered. However, despite Gropius's intention to place architecture as the central discipline of the Bauhaus curriculum, a workshop for architecture was never offered. Instead, Gropius gave students practical hands-on learning experiences on an experimental building site and apprenticeships in his office (Miller, 2006). Gropius's explanation of the culminating phase of the Bauhaus curriculum was described in his essay "Idee und Aufbau des Statliches Bauhauses Weimar" in which he establishes that journeymen are drawn into formal and manual collaboration in actual building projects so that, through practical experience, they would become acquainted with all of the building trades (Dearstyne, 1986). Gropius intended to merge art and technology into a new discipline coupled with the possibilities provided by the industrial production to deliver objects that were functional, aesthetic, and able to comply with industry standards (Garmazio, Kohler & Oesterle, 2010). Although Gropius was a strong advocate of handwork, he was very aware of the advantages of machine production and embraced the idea of having factories at the disposal of the creative artist to develop new forms; he envisioned art and technology as a new unity (Dearstyne, 1986). Despite the Bauhaus's strong influence on architectural education, after World War II many professional schools were incorporated into larger universities and gradually changed the curriculum to include more scientific content, losing part of their traditional hands-on educational methods. As science and technology rapidly advanced, architectural education reduced its practical instruction into the "science laboratory" to conduct tests of physical concepts in architectural applications such as wind, acoustics, and light studies. In the 2000s, the advancement in digital technologies resulted in the introduction of computers in architectural schools' model shop in. Digital fabrication labs enabled systematization, use of control variables, elaboration of conjectures, and documentation of processes of experimental work that characterizes the scientific approach in education (Celani, 2012).

1.1 Material Explorations and the Hands-on Approach

Although architecture and material are intrinsically intertwined, in general materials receive superficial attention in architectural design. Form, structure, and geometry have dominated architectural discourse, leaving materiality unattended (Borden, 2018). Through a methodology of research and experimentation, material explorations can advance the projects, which can, in turn, benefit from informed decisions based on the capabilities and limitations of different construction materials, the applied construction methods, and their performance. Moreover, materiality has become a field of study that opens up an enormous range of possibilities for buildings and ultimately, the user. Technical innovations emerge from accepted procedures of science-based engineering and creative thought (Fernandez, 2005). In academia, design studios typically focus on the spatial quality and configuration of the projects, while oftentimes material selection is not necessarily a part of the studio agenda. Yet, building materials, their inherent properties, and assemblies are key in defining buildings' space as well as the identity of buildings themselves. Hence, materiality should be

an integral part of the design process from the early stages of education. This has a particular impact on students as the act of manipulating materials subconsciously develops the ability to interpret the possibilities and limitations of materials and assemblies during the design process (Oakley, 2007).

Material is the medium of architecture; its intrinsic qualities and limitations, manufacturing processes, and formal capabilities determine the approach to design and form (Borden, 2010). Consequently, material is essential to form. Therefore, the production of objects and their associative qualities are intertwined with the material, its tools, and processes of production (Borden, 2018). Materials impose constraints not only on what is intended to build but on the understanding of construction as a finished product (Harrison, 1978).

Meanwhile, buildings and their constituent elements are in constant evolution. Advances and discoveries in material and fabrication technologies can have a strong influence on the way buildings are made (Rowe, 1987). Therefore, architecture is susceptible to changes in the very material and dimensional aspects that fundamentally determine its constitution. Using contemporary materials in the best possible ways involves a technical understanding as well as design invention (Fernandez, 2006). In their book, *Morpho-Ecologies*, Hensel & Menges introduce the term *material system* as an integral concept that describes the complex reciprocity between materiality, form, structure, and space, including the related processes of production and assembly, and the performative effects derived from the interaction with environmental conditions. Architecture is characterized by prioritizing form generation over inherent material logic. As a result, means of materialization, production, and construction are executed as top-down engineered material solutions after the building shape is defined. Usually, the materialization of these designs pays little to no attention to functionality and performance (Hensel & Menges, 2008). *Digital morphogenesis* refers to the processes of form generation resulting in geometries detached from material and construction logic. *Natural morphogenesis*, on the other hand, is a process of growth and evolutionary development that generates systems capable of obtaining complex articulation, specific gestalt, and performative capacity through the interaction of system-intrinsic material characteristics and external environmental forces and factors. Therefore, materialization and design are inextricably related to natural morphogenesis, where form generation and materialization processes are part of one undifferentiated process that enables morphological complexity and performative capacity (Menges & Ahlquist, 2011). This is especially pertinent in the design and construction of buildings using digital technology where material and morphological characteristics are derived through iterative feedback loops by continually processing the material system's interaction with statics, thermodynamics, acoustics, light, winds, and others (Hensel, 2010). While the predominant approach in architectural schools consists of using digital technology for formal explorations without consideration of construction, the notion of *material systems* emerges as a generative driver in the design process (Hensel & Menges, 2008).

2. HANDS-ON COURSES USING CONCRETE

Concrete has a reputation as a not sustainable material. Cement production accounts for an estimated 1.2 percent of U.S. greenhouse gas (GHG) emissions and 7 percent of global carbon emissions (Fransen, 2021). While, it is the cement the component that has a high carbon footprint, it only accounts for about 10% of the concrete mix. Besides steel used for reinforcing, the other components of concrete –water, sand and coarse aggregates- are fairly low in carbon emissions. Today, there are a number of approaches to reduce the carbon footprint of concrete and reduce the usage of cement including adding inter-ground limestone to Portland cement, improving aggregate gradations, incorporating supplementary cementing materials, using recycled concrete aggregate, injecting CO₂, employing water-reducing admixtures, and other methods. However, the quality that distinguishes concrete from other construction materials from a sustainable point of view, is its inherent durability and resiliency. Concrete outperforms all other common construction materials with a much longer lifespan and can be employed as both part of the structure and the envelope of buildings. It requires no maintenance and, if properly insulated coupled with its inherent thermal mass it works as a very efficient thermal envelope and ultimately, an outstanding overall life cycle performance. Ranging from speculative and conceptual exercises to project-based learning, these hands-on laboratories ultimately tested the effectiveness of the pedagogical model experiential learning in delivering feasible solutions to architectural proposals using concrete.

2.1 Design Build

Design-build is a pedagogical alternative to desk-oriented and media-based design processes typically adopted by design schools, in which students engage in both the design and construction of projects (Canizaro, 2012). Design-build education has its origins in the late nineteenth century and its goal still prevails as conjoining design with the act of building as a single process (Verderber, 2014). Students actively participate in practical exercises aimed to develop their sensibilities about all aspects of materials and how they are used in the built environment (Erdman, 2006). The primary goal of a hands-on curriculum is not only the acquisition of knowledge about material and construction but also learning delivery methods and budgeting, increasing exposure to other cultures and history of specific regions, and engaging in community service among other opportunities (Erdman, 2006). There is a long list of schools across the country that have embraced some kind of design-build project and a shorter list of schools that have consistently taught these kinds of courses

for long periods of time. The curricula usually deliver full-scale projects that can range from simple structures such as pavilions to more complex ones such as single-family houses. Usually, the students are challenged to expand their design skills by experimenting with real construction tasks putting together different materials and assemblies, and using the appropriate tools. During this process, the outcomes evolve through the act of making rather than as a result of the execution of a design strategy (Sheil, 2005). Students learn by building. In short, design-build education is a design activity that enriches the students' decision-making through direct engagement and ultimately exposes students to a broader range of architectural practices (Canizaro, 2012). If we put into perspective the challenges that most students will face after graduating, there is no doubt that the experience gained in a design-build project serves as an introduction to the design hurdles and inquiries present in the professional realm.

2.1.1 Surface_It, with Pieces (Elective Seminar)

These hands-on labs consist of two fabrication seminars offered in the fall of 2011 and 2012. Students were asked to design and produce a set of repeatable concrete units to generate a man-made topography (hardscape) capable of modifying physical interaction with the ground.

The design exercise started by exploring pattern options and tessellations, based on the repetition of a specific geometry, which resulted in the design of one or more pieces. The pieces were developed with consideration of the limitations of the material in terms of strength, weight, and size, among others in order to be handled by a single person. Students built the corresponding molds and cast concrete to produce pavers (Fig. 1).

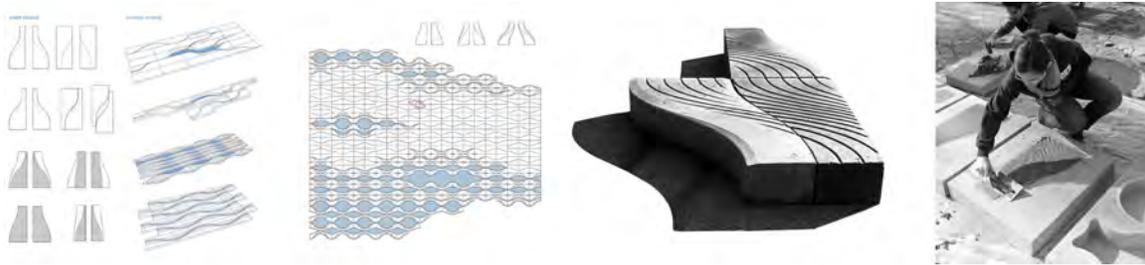


Figure 1. Surface_It,with Pieces F22. Concrete pavers designed and manufactured by students. (Photographs by author)

In these seminars, students gained practical knowledge about the act of construction, assemblage and mass production, as well as the use of digital and analog tools, the basics of mold making, and other fabrication techniques while testing their abilities to design a prototype to create walkable surfaces. Concrete colors and surface treatments such as textures and exposed aggregates were also subject of study.

One of the limitations factors of this course was the lack of funding. Students had to purchase their own materials. Most of the molds relied on the use of urethane rubber which although it allows multiple castings, it was very expensive and limited the size and quantity of molds produced. In some cases students had to produced single cast molds which were time-consuming to make and only yielding one cast. However, they provided tangible outcomes allowing students to assess the capabilities of small molds for concrete production.

2.1.2. Furnish_It, with Pieces (Elective Seminar)

Funded by Anova, a local urban furniture company, the projected-based seminar was offered for five consecutive semesters, in the fall 2013, 2014, 2015, as well as spring 2017, and 2018. This new pedagogic agenda challenged students to research specific materials – including concrete, metal, recycled plastic lumber, and lamboo (laminated bamboo) – to design and implement methods of construction to build usable urban furniture. Different concrete types and formwork techniques were employed based on the geometry and size of the pieces. Standard concrete and Glass Fiber Reinforced Concrete (GFRC) mixes with different types of fiberglass reinforcing were tested. While prototyping the furniture, students were asked to take careful consideration of human scale and ergonomics.

The fabrication courses served as valuable learning experiences for the students while increasing the school's capacity to effectively manage, promote, and implement the use of digital and analog fabrication tools to deliver design-build projects. Students received feedback on the design and technical intricacies of their projects from designers and manufacturing experts from the company. Such interaction greatly benefited the students' understanding of the fabrication process as well as the outcome of the final product. The furniture produced during the first two semesters were installed in a vacant plot turned into a naturescaping in the Old North St. Louis neighborhood, providing its residents useful and much needed outdoor furniture. All the projects consisted of assembled pieces challenging students to design, coordinate and execute feasible connections. Having a sponsor involved and end users for the final product not only made possible more ambitious projects but also created a sense of accountability on students that empowered and incentivized the production process (Fig. 2).

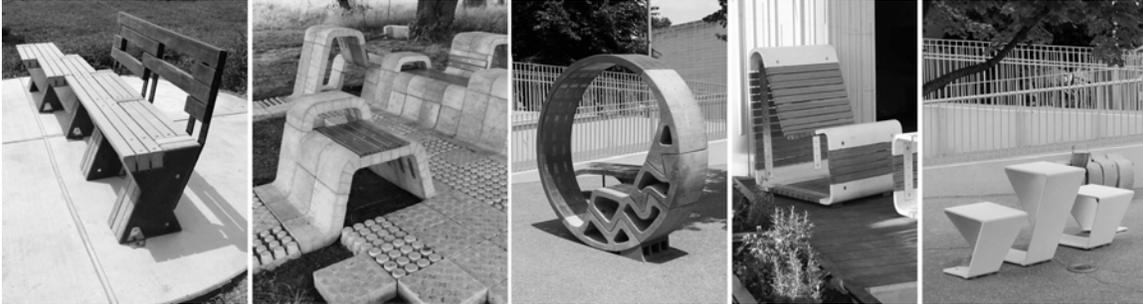


Figure 2. *Furnish_It,with Pieces*. Urban furniture designed and manufactured by students. (Photographs by author).

2.1.3. CRETE House, Solar Decathlon 2017 (Design Option Studios)

This initial hands-on, small-scale teaching experience was followed by the author's participation as the Faculty Project Design Leader in Washington University's Solar Decathlon 2017 competition team. For this project, the school collaborated with several precast partners. This was a two-and-a-half-year commitment culminating in the construction of the CRETE House, a model for advanced building technology, resiliency, and livability (Fig. 3). CRETE house achieved second place in the Architecture Contest (Moyano Fernandez, 2020).



Figure 3. *CRETE House* in Denver, CO. Solar Decathlon 2017 (Photographs by Richard Nodle).

The nature of the competition called for the project to be conceived and materialized in a non-conventional construction method. The house was designed as a demonstration of integrated advanced building technology to show how precast concrete homes can be a compelling alternative to traditional wood light-frame construction, providing a strong (tornado resistant), resilient, durable, and maintenance-free envelopes. Thin shell exterior walls were manufactured using Ultra-High-Performance-Concrete (UHPC), a fairly new material with exceptional mechanical properties and an innovative alternative for building envelopes. Students participated in the entire process, including the early stages of research and design, design development, documentation, and construction. Students also actively interacted with industry partners and manufacturers involved during the design, fabrication and assembly processes gaining invaluable experience. The grooving on the surface of the exterior UHPC wythe was done by students using formliners that were reutilized in different orientations for multiple casts as master molds to achieve a non-repetitive appearance. Students spent an entire semester designing and producing molds made in MDF using a combination of hand-made and CNC equipment and then cast formliners out of urethane rubber. (Fig. 4).



Figure 4. *CRETE House*. Formliners fabrication process led by students (Photographs by author).

The students that participated in the project later reported very positive feedback highlighting how their learning experience eventually marked their trajectories as professionals. In particular, the dual degree students pursuing MArch and MCM (Master of Construction Management) were able to take full advantage of the project by participating in the different design phases through studios and supporting electives, as well as by taking key roles in critical tasks during the construction phase.

2.1 Digital Fabrication

With the emergence of digital fabrication technologies, architecture and the construction industry in general greatly expanded their options in terms of the materialization of building assemblies. The introduction of computer-aided-design (CAD), and computer-aided-manufacturing (CAM) established a robust digital platform nurturing designers with new sets of tools while enabling an expansion of their creativity and sophistication – and sometimes, the performance– of building components. CNC and 3D printing are examples of technologies that helped advance the construction of innovative assembly methods. These tools also have the capability of materializing sophisticated geometries, providing designers with a broad spectrum of morphological possibilities, embracing the mass production of differentiated building elements. As the Industrial Revolution embraced repetition and mass production, the Digital Age is giving way to singularity and mass customization. Yet, the departure from the economics associated with orthogonal geometry tectonics requires more precision from the interface between architectural form and the computer-driven fabrication processes (Weinstock, 2011). The traditional design process started with the definition of the form by the architect followed by the definition of the structure and material in collaboration with engineers (Celani, 2012). The rise of digital fabrication technologies in architecture not only expanded the designer’s options when it came to building design and construction but also pushed design and construction into a new direction. As a result, this marked a cultural evolution in the design and construction of buildings, where expanded collaborative relationships between architects, engineers, and oftentimes professionals from other disciplines are rapidly becoming the norm. The traditional sequential development of form, structure, and material was challenged by the cultural shift. In the words of Rivka and Robert Oxman (2010), a new order called The New Structuralism rose. Innovative materials, production methods, and technologies directly inform architectural construction (Barkow, 2010). Architects can integrate fabrication as a generative paradigm into the design process (Garmazio, Kohler & Oesterle, 2010). The New Structuralism sequential process was redefined as material, structure, and form (Oxman & Oxman, 2010). Leading architecture schools rapidly adopted digital technologies in the late 1990s. The physical manifestation of this was the introduction of dedicated space for digital fabrication laboratories (Celani, 2012). The implementation of digitally fabricated projects in schools was present both in full-scale and scaled-down options. Today, the prevalence of digital fabrication in most architectural schools has opened up a broad spectrum of possibilities in building technology and design that is reluctantly being adopted by the construction industry. While digital fabrication tools can offer appealing construction methods, these methods usually rely on a labor-intensive process to set up the equipment, assemble the components, and finish the piece. Consequently, there is still a wide gap between the assemblage process required by digital technologies and the methodologies effectively adopted by the building industry.

2.2.1. Precast Concrete Enclosures (Elective Seminar)

This design-build elective, was offered in the spring of 2021, 2022 and 2023. The seminar was based on the design and fabrication of full-scale (1:1) precast concrete building envelopes. Due to the size and weight of the panels, the materialization of full-scale prototypes required collaboration with industry partners as it provided access to resources not generally available at higher education institutions. With this in mind, a partnership was established with Gate Precast company and supported by a PCI Foundation grant. The pedagogy of this seminar exposed students to different precast methodologies and best industry practices through the design-build agenda. Therefore, the fabrication of concrete building enclosures highly benefitted from the partnership through the novel applications of concrete and associated products, the understanding of precast manufacturing practices as well as construction systems. During the process of making full-scale formwork, students were engaged in direct experimentation, learning about the properties of the materials, the act of construction, assemblage, and mass production. Important topics such as panel size, thickness, structural integrity, reinforcing, connections, and resistance to the weight and pressure of fresh concrete, among others, enable students to learn from the precast manufacturers’ expertise. Students’ proposals were assessed by engineers and plant personnel from Gate Precast in person and online; their feedback was critical to advancing their design to a feasible outcome. Students were able to experience the entire design-build pedagogical model including research, design, experimentation, documentation, and materialization of full-scale molds and concrete panels. Full-scale formworks were materialized at school using both analog methods and digital fabrication tools. Digital fabrication tools have the capability of materializing sophisticated, non-conventional geometries providing students with a broad spectrum of morphological possibilities as part of building envelopes. The molds were transported to the manufacturing facility in Ashland City, TN for concrete casting. A field trip to the plant allowed students to witness the casting and actively participate in the demolding of the panels.

Gate’s plant personnel were very impressed with the quality and complexity of the molds the students made. Architects and contractors from all over the country visit the plant regularly and find the panels produced by this course very helpful to understand the design capabilities subjacent in precast concrete envelopes. Students learned about the fundamentals and intricacies of the precast process and carefully observed and documented the entire process through photographs and videos. The experience gained in fabrication courses

like this one serves as an introduction to the design inquiries, possibilities and challenges that students will soon face in the professional realm, equipping them with a one of a kind experience (Fig. 5).

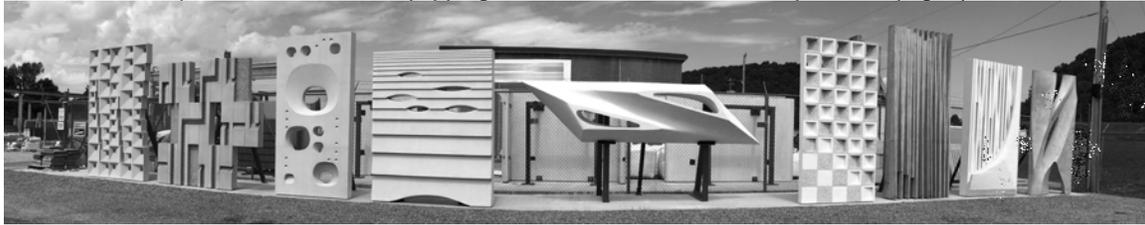


Figure 5. *Precast Concrete Enclosures*. SP21 & SP22 Full-scale panels designed and made by students on display at Gate Precast plant in Ashland City, TN. (Photograph by Daniel Thomson).

2.2 Scale Prototyping

Prototyping is essentially the production of something new as compared with previous models. The strength of the prototype as a working methodology is that it supersedes representational strategies (drawings and scale models) with an artifact that predicts with a high level of accuracy the architectural effect and its performance. The built prototype is an actual constructed object serving as an effective means to close the gap between representation and actual building (Barkow, 2010). Size is usually a limiting factor when it comes to the production and storage of prototypes. Prototyping can be implemented at full scale or a range of smaller scales allowing faster and more economical approaches to fabricating and testing samples.

Designing by making takes observation to a greater intellectual involvement with the developing product. During the creative process, the model outperforms drawings (Porter & Neale, 2000). The act of making reinforces the understanding of three-dimensional space where the physical models offer a continuum in the perceptual and design generative process (Lee, 2015). The reason why architectural physical models are so important in the design of buildings is that they are considered the most effective way to understand spatial quality and they bring into play various other faculties of judgment including binocular vision, allowing a wider field of view and a precise depth perception (Prizeman, 2005). Three-dimensional scaled models have served for a long time a very common design and representation tool in architectural offices as well as in architecture schools. Physical models vary in scale and scope. Models either at 1:1 or scaled prototypes, can operate as functional models carrying behavioral aspects of the intended assemblies. The construction of an artifact demands understanding and interpretation and is a vehicle for thought (Harrison, 1978). They are excellent instruments for form-finding, topological coherency, performance capacity analysis function, manufacturing, and assembly method investigations (Hensel & Menges, 2006).

2.3.1. Resilient Concrete Undergraduate Option Studio SP22

Current construction practices for single-family residential buildings in the US use predominantly wood frame, ninety percent of homes built in 2019 were wood-framed, according to the National Association of Home Builders. Despite its benefits, wood structures face several challenges such as combustibility, susceptibility to degradation by humidity, mold, and insect infestation, and its inherent vulnerability to withstand debris impact in case of extreme weather events, such as tornadoes, regardless of the cladding system selected. Alternatively, concrete construction can provide buildings with robust structures and envelopes with a longer lifespan compared to other traditional methods. During this studio, students were asked to use concrete as the primary constituent material in the design of a small resilient house located in a rural area within a tornado alley zone in the mid-west. With a focus on the design of the building envelope, and considering the bearing and resilient capacity of concrete, this studio challenged students to envision ways to design strong concrete shells able to withstand extreme storm forces. Concrete construction offers strong and durable building envelopes that are maintenance-free. Special emphasis was placed on learning through making while seeking the simultaneous use of intuitive explorations with feasible outcomes of concrete design principles. Hands-on sessions were dedicated to exploring different techniques of formwork making and concrete cast to acquaint students with concrete, in particular, how materiality determines the way buildings are made and perform. The overarching inquiry of the studio was how material and concrete tectonics can define a working conceptual framework to generate buildings. The studio was structured in three correlated assignments. In the first phase, students investigated how different configurations of a building envelope could protect the interior space from severe weather conditions allowing the controlled passage of light and air. This assignment required envisioning a building envelope for a single space. Using a virtual cube of 12' x 12' x 12' as a point of departure, they were asked to designate two sides of the volume as part of the exterior envelope. This enclosure had to include at least one opening to allow light and air into the space with careful consideration of its size, purpose, orientation, and experience from inside-out and outside-in. This process provided the basis of a design framework to be further developed as a strategy for the conceptual understanding of a building envelope and the basis for the casting methodology for the next assignment (Fig. 6).

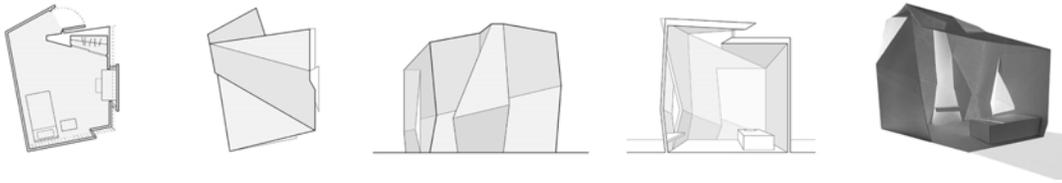


Figure 6. *Resilient Concrete Studio* SP22, Assignment 1, Exterior envelope study. 1"=1'-0" scale prototype. Student: Maya Yildirim

During the second phase students were asked to materialize the anatomy of the envelope developed in the previous assignment in concrete. Students were introduced to Sequential Casting Concrete System (SCCS), a casting technique developed by the author (Moyano Fernandez, 2021). This hands-on approach, allowed students to investigate and design within the possibilities and limitations of this casting methodology while incorporating highly creative and digitally fabricated geometries, details, and textures (Fig. 7).

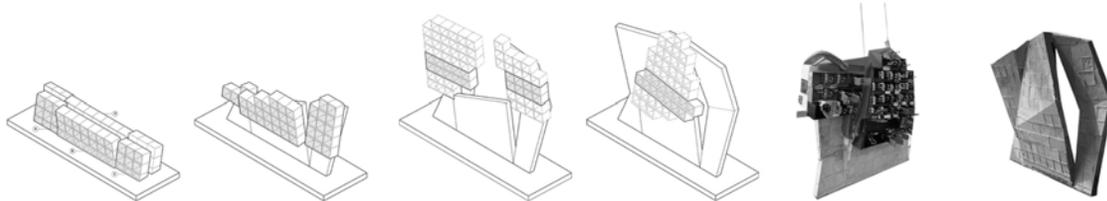


Figure 7. *Resilient Concrete Studio* SP22, Assignment 2, Sequential Casting Concrete System. 1"=1'-0" scale prototype. Student: Maya Yildirim

Through experimentation with actual concrete mixes and molds, students were able to elucidate the essence of the material, its properties, and its architectural applications. SCCS was used as a generative driver that integrates materiality as a medium for form-finding in performative concrete envelopes. As a first step, they adapted the design by developing a series of small and reusable molds to cast the concrete in sequential steps. Students worked on scaled prototypes at 1"=1'-0" scale in concrete. The methodology called for in-depth research through direct experimentation, challenging students to rethink the materialization of traditional enclosure solutions and testing ideas through an iterative process. Making scaled prototypes in concrete is a vehicle for students to explore the use, characteristics, and potential of building materials, their assembly, tectonics, and, ultimately, spatial configurations (Canizaro, 2012). The third and last phase was dedicated to the design of a 1,200 sq. ft. house in a rural site. The conceptual ideas developed in the previous two phases provided the design framework for the house. Therefore, the programmatic components were expected to be integrated with the emergent tectonic logic into a single robust massing to safely protect its dwellers from severe weather conditions (Fig. 8).

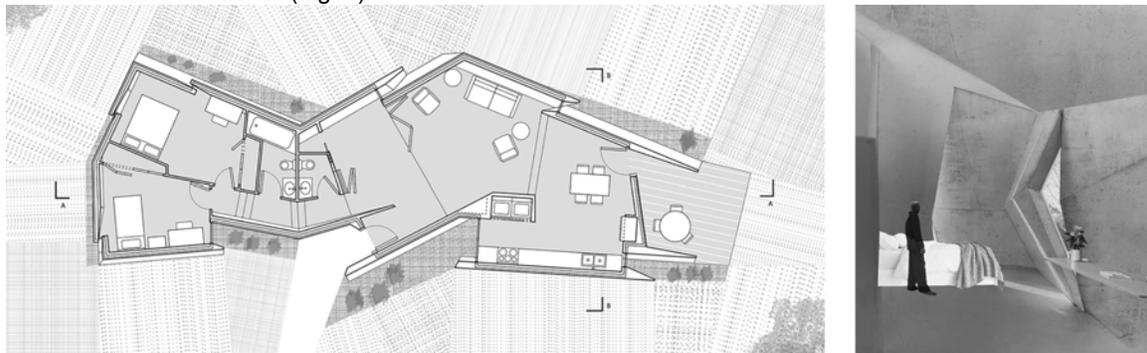


Figure 8. *Resilient Concrete Studio* SP22, Assignment 3, Design a resilient concrete home. Floor plan and interior view. Student: Maya Yildirim

The sequence of exercises was intended to prompt students to research, make, and design simultaneously. The studio pedagogic based on material experimentation allowed students to make informed and responsive design decisions grounded in the logic of the material and methods of construction. By the end of the semester, students were able to critically engage a conceptual idea through the design process by experimenting with a specific concrete formwork technique to inform the tectonics possibilities of the concrete (Fig. 9).



Figure 9. Students casting prototypes using SCCS method developed by the author. (Photographs by author).

CONCLUSION

The realization of ideas into built form is a necessary step during which some qualities are gained and others are lost. As immaterial and intangible ideas develop, the question of how things are made generates a period of opportunity (Sheil, 2005). Hands-on learning highly benefits students to develop an intrinsic understanding of how things are made. Yet, in most architecture schools across the US, the hands-on approach as a pedagogical model tends to be limited to specific studios and seminars where the curriculum relates to materials and methods of construction, not as a holistic approach to architectural education.

Due to the rapidly ever-evolving material science and computer technologies that support both the design and construction of buildings, it is key for educators to provide students with fundamental principles of building technology that remain present regardless of time as core concepts of building tectonics. When the conceptual framework of a project is rooted in the act of building rather than theoretical notions of divergent topics, architectural design becomes deeper, richer, and physical, in other words, real (Oakley, 2007). The constitutive material of any built form determines its morphological potential and limitations while serving as the media with which designers can operate. The invention and use of new materials and the re-interpretation of traditional ones have been at the root of architectural evolution (Borden, 2018). Hands-on education constitutes a pedagogical method that uses materialization as the way to allow the imagination of the designer and the act of execution to be the vehicle of inquiry and invention. The exercise of design via a hands-on approach provides students with a set of technical skills, a fundamental tectonic foundation particularly important in buildings design and construction. By working at full-scale, the appreciation of the size and the limits of material manipulation became decisive aids to furthering architecture beyond the mere discussion of form and intellectual process (Prizeman, 2005).

Interestingly, this was evident in both full-scale and scaled prototypes courses presented. Although full-scale approaches gave students a very realistic exposure to the constraints and possibilities of the real building components, its execution was usually more challenging primarily because of the size, weight, time, material resources, and budget demands. Scaled prototype experimentation in concrete provided students a very similar experience than full-scale counterparts and allowed the execution of entire assemblies without the constraints and limitations of larger full-scale pieces. Students making concrete prototypes at 1"=1'-0" scale were able to test their initial envelope concepts with a specific casting methodology achieving a high level of accuracy and control. Making is a resource that critically informed the design process and provided real-time feedback. Mistakes and/or miscalculations were addressed and corrected in further testing, while self-directing the steps in the design process.

In sum, hands-on courses exposed students to the tactile exploration of materials within conceptual and technical frameworks while legitimated design decisions as they gained a deeper understanding of building tectonics. The act of learning via making became the guiding principle of the design process. Ultimately, the hands-on model nurtured students with an assertive and solid foundation that could propel them as leaders in the architectural field. Although there is substantial evidence that architectural schools can greatly benefit from experiential learning, for experiential learning to become the predominant pedagogic model in architecture education, a comprehensive evaluation would be required. Further assessment should be done on students taking hands-on courses to determine the short-term effect on the impact of this pedagogy on their academic leaning as well as the long-term effect of experiential learning on their post-academic careers.

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Energy Retrofit Evaluation of a Naturally Ventilated Historic Building in a Hot and Humid Climate

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ABSTRACT: *Successful energy retrofits of historic buildings are those that take into consideration energy savings, thermal comfort, and the conservation of cherished heritage values. This study proposes passive energy efficiency measures that abide by historic preservation standards and evaluates their impact on a wood-frame heritage residential building in a hot and humid environment. It also assesses the efficacy of natural ventilation in those conditions. The approach is structured according to the following steps: (a) the building performance assessment through onsite monitoring; (b) the numerical studies by energy simulations; (c) the selection of adequate passive energy efficiency measures; (d) the investigation of potential energy savings of the chosen energy efficiency measures; (e) the investigation of the efficacy of natural ventilation. The achieved results reveal that high energy savings can be attained through the selected solutions, with some measures better than others. However, natural ventilation proved to be ineffective without being paired with the package of energy measures. The findings of this research are replicable to numerous similar historic buildings in hot and humid conditions.*

KEYWORDS: Historic buildings, Energy retrofit, Building simulation, Natural ventilation, Passive energy efficiency measures

INTRODUCTION

Based on literature reviews on databases like Scopus (Elsevier 2022), Web of Science -former Web of Knowledge- (Web of Science 2022), Google Scholar (Google Scholar 2022), and ResearchGate (ResearchGate 2022), research investigating cooling and dehumidification of indoor environments has grown considerably in the past decade, reaching hundreds of highly ranked publications. Additionally, countless historic buildings have been retrofitted with energy savings and occupants' comfort as the main motivations. In many cases, the building envelope conditions were very dire, and mechanical systems were non-existent or causing damage to the building's materials and features (Martinez-Molina and Dupont 2020). The severity of ASHRAE climate zones 1A, 2A, 2B, 3A, and 3B exacerbates the situation by increasing the difficulties in controlling the indoor hygrothermal conditions (air temperature and relative humidity) of these structures. Moreover, before the installation of air conditioning became regulated in historic buildings, cooling systems were selected with only occupant comfort in mind, conclusively overlooking the sustainable conservation of the historic building and its cultural values. A detailed literature review by Lidelöw et al. (2019) examined the connection between energy efficiency and the historic preservation of heritage buildings. Their outcomes expose that research in this field mainly focuses on the energy aspect while hardly dealing with the valued architectural and cultural values. Nevertheless, a successful retrofit of a historic structure can only be performed by balancing the goals of energy efficiency with those of historic conservation. As shown in Preservation Brief 3 of the National Park Service (Hensley and Aguilar 2011), planning must holistically consider the building envelope, its systems and components, site, and environment, as well as a systematic assessment of all the procedures to be implemented.

Natural ventilation is also considered crucial to the overall historic building's performance. While natural ventilation contributes to reaching enhanced thermal environments, the effectiveness of using wind-driven flow depends on multiple factors. For example, investigations on the use of natural ventilation in residential buildings in Thailand (a hot and humid climate) demonstrate that an indoor air velocity of as little as 0.04 m/s is sufficient to increase occupants' thermal comfort (Aflaki et al. 2015). A study conducted by Bay et al. (2022) in Texas also concluded that natural ventilation can achieve the acceptable range for user comfort in a number of summer days. However, natural ventilation solutions are not sufficient to maintain comfortable indoor conditions throughout the cooling period, and mechanical cooling systems are necessary to reach not only thermal comfort but also required conservation standard levels (Ahmed, Kumar, and Mottet 2021). Hot and humid climate zones experience extremely high temperatures and humidity values at times during the year, even at night, making natural ventilation ineffective. However, in these areas, a thorough and methodical

evaluation of natural ventilation opportunities and optimization remains important to decrease the use of mechanical cooling systems. This saving in operation time of the mechanical cooling system will reduce the above-mentioned conservation issues that could be resulting from the forced indoor conditions that are created. Past publications have revealed a research gap regarding naturally ventilated historic buildings in hot and humid climates which this research aims to address through a case study under the adverse environmental circumstances of the Cfa-Humid Subtropical Climate (Institute for Veterinary Public Health 2011).

Passive retrofit measures alone can achieve great energy savings in historic buildings retrofits. However, relevant research revealed that retrofit strategies usually applied to new buildings are not always appropriate for heritage structures due to the requirement to keep their historic value unaltered. For example, almost all publications in the literature do not mention the use of exterior insulation due to its harmful impact on historic facades. However, applying insulation on the interior of the historic external walls is recommended when adequate (Webb 2017). New approaches must therefore be comprehensively assessed before implementing them to prevent permanent damage to valuable architectural features, materials, and the building's surroundings. Numerous strategies and passive energy approaches (Martinez-Molina and Alamaniotis 2020) nevertheless can considerably increase the energy savings of a building without invasive and intrusive interventions (Bay, Martinez-Molina, and Dupont 2022). The goal of this research is to analyze the impact of commonly used passive energy efficiency measures that could be adopted for wood-frame historic buildings in a hot and humid climate in addition to the efficacy of natural ventilation in these particular conditions.

1. METHODOLOGY

As known, the energy refurbishment of historic buildings offers ample prospects for enhancing occupants' comfort, reducing global greenhouse gas emissions, and extending the life of heritage assets. By means of a case study, this research would accentuate the necessity of suitable retrofit measures that can achieve great energy savings without compromising cultural and historical values.

The suggested approach can be structured according to the following steps:

- The building's current energy performance evaluation through onsite monitoring.
- Numerical energy simulation of the building with a calibration of the model using the measured data.
- Proposal of potential energy efficiency solutions tailored to the building's needs and that abide by historic preservation principles.
- Evaluation of the energy savings yielded by the selected measures.
- Evaluation of the impact of natural ventilation.

1.1 The case study: The Kelso House

The Kelso House, a 1907 wood-frame residence, was selected for the purposes of this study. It is located in San Antonio, Texas, and is listed on the National Register of Historic Places as a contributing structure in the Monte Vista National Historic District (National Archives Catalog 1998). The area has a Cfa-Humid Subtropical Climate according to the Köppen-Geiger climate classification (Kottek et al. 2006) and an average annual temperature of 70°F with summer temperatures reaching 100°F (US Department of Commerce 2022). The property is owned by the Power of Preservation Foundation (PoP), which completed an exterior restoration of the structure while opening it as a learning laboratory for trades education. The foundation aims to rehabilitate the currently deteriorated interior and improve the energy performance of the Kelso House without compromising its heritage values.

The structure was constructed in the simplified Neoclassical style with Craftsman and Queen Anne influences (Ahlquist et al. 2021). Neoclassical features include elaborate Doric columns, wood-trimmed entablature and frieze, dentils, and curved cornice. Queen Anne influences include asymmetrical facades, a two-story porch wrapping the primary south and east facades, a front-facing gable roof, and textured cladding. The irregular and asymmetrical plan arrangement, unenclosed eave overhangs with exposed roof rafters, and divided-light windows reflect Craftsman influence. In addition to its architectural significance, the Kelso House is also renowned for being designed by famous architect Atlee B. Ayres and for having the prominent civic leader and Judge Winchester Kelso as its owner (Huddleston 2022).



Figure 1: The exterior of the Kelso House (left) and the interior (right) in its current state. Source: (Huddleston 2022)

1.2 The onsite monitoring

Temperature (°F) and relative humidity (%) conditions of the Kelso House were monitored to evaluate the environmental conditions and explore any specific thermal issues in the building. The monitoring campaign was performed from the 1st of May to the 30th of September of 2022, as cooling is the main concern of this study taking place in a hot and humid climate. Figure 2 shows the deliberate positioning of 13 indoor and 2 outdoor data loggers throughout the building. Data was logged in 15 minutes intervals and averaged hourly to ensure a thorough acquisition of the thermal conditions.

The obtained data, displayed in Figure 3, showed that indoor temperatures were very elevated during the monitoring period. In fact, a maximum of 107°F was recorded in July and temperatures surpassed 100°F in June and August as well. Great temperature differences were also observed. For instance, while the maximum temperature in June was 104°F, the minimum temperature was 72°F, exceeding a 30°F difference. It can also be noted that the indoor temperatures were higher than the outdoor temperatures throughout the entire study period due to the high air infiltration and absence of mechanical ventilation and air conditioning. Finally, the indoor and outdoor relative humidity values were linearly correlated, with the outdoor relative humidity remaining higher than the indoor value during the five months.



Figure 2: Arrangement of the indoor data loggers (orange) and outdoor data loggers (blue) on the first and second levels of the building. An additional indoor logger is located on the attic level. Source: Drawings by (UTSA School of Architecture 2019) and edits by (Authors 2022)

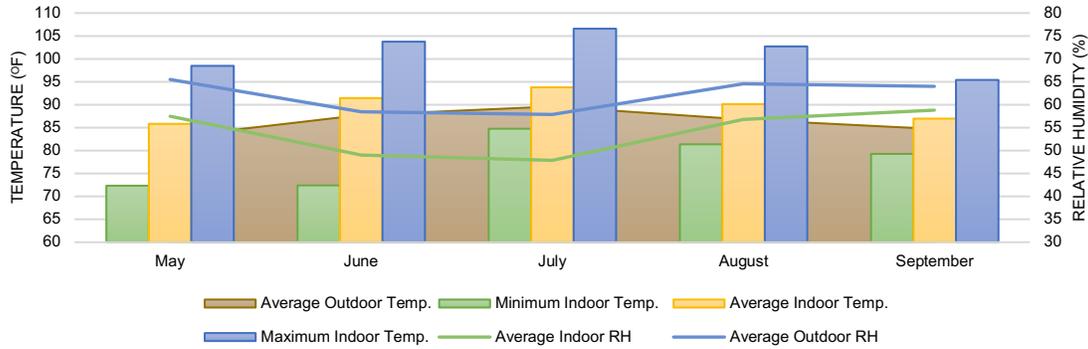


Figure 3: Indoor minimum, average and maximum temperatures, outdoor average temperatures, and indoor and outdoor relative humidity throughout the period of study. Source: (Authors 2022)

1.3 Numerical simulation of the building and calibration of the model

The energy simulation of a building is an effective tool to estimate and quantify the energy savings of different solutions for energy retrofits. In order to simulate dependable energy performances, a detailed energy model of the Kelso House was developed using DesignBuilder. The geometrical and thermal characteristics of the building were defined. Table 1 presents the most significant envelope properties in the as-in-state calibrated model. The building is very leaky due to the wood-frame construction with low thermal mass as well as the deteriorated state of the envelope on the interior. According to Cho et al. (2022), the airtightness performance of historic buildings ranges between 0.8 ACH to 10 ACH (air changes per hour). Moreover, Tiberio and Branchi (2013) classify that detached houses have a low airtightness level when values exceed 10 ACH. Accordingly, the air infiltration rate in the model was fixed at 10 ACH.

After assigning the input data to the model and running the simulation for the selected study period, the temperatures evaluated by the energy simulations were compared to the measured temperatures. To assess the ability of the model in forecasting the actual building performances, the two main uncertainty indices recommended by ASHRAE Guideline 14 (2014), mean bias error (NMBE) and coefficient of variation of the root mean square error CV(RMSE), were used. Models are typically considered to be calibrated if NMBE and CV(RMSE) do not exceed $\pm 10\%$ and 30% respectively for hourly calibration (Pachano and Bandera 2021). Two representative summer days, July 15th and August 19th, were chosen to validate the model. NMBE values were 0.9% and -0.4% for the two days respectively and CV(RMSE) values were 11.3% and 2.5%. These comparisons reveal a convergence completely satisfactory according to the literature indications. Figure 4 and Figure 5 show the results of the comparison between the measured and simulated indoor temperatures for the two days.

Table 1: Envelope properties in the as-in-state calibrated model. Source: (Authors 2022)

Component	Characteristics	Thermal transmittance (Btu/h.ft ² .F)
Exterior walls	Wood-frame with wood shingle cladding	0.235
Roof	Pitched roof clad with composite asphalt shingles	0.259
Floor	Wood joists and hardwood	0.311
Windows	Single-glazed wooden windows	0.93

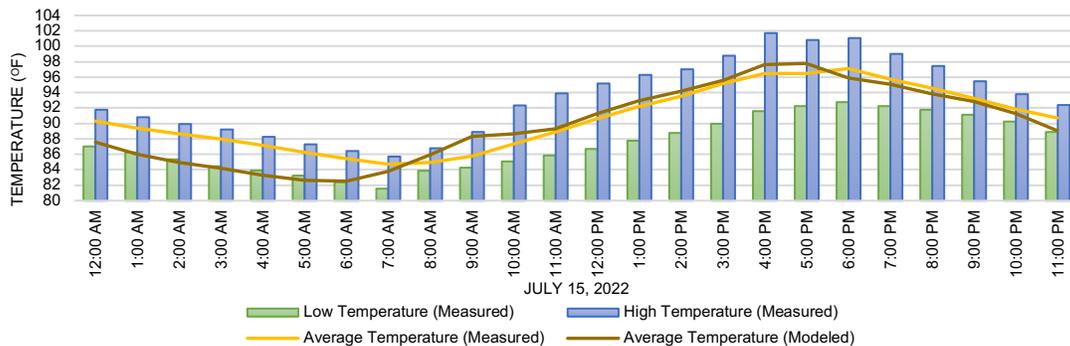


Figure 4: Hourly indoor temperatures (°F) measured onsite compared to those simulated in DesignBuilder on July 15th. Source: (Authors 2022)

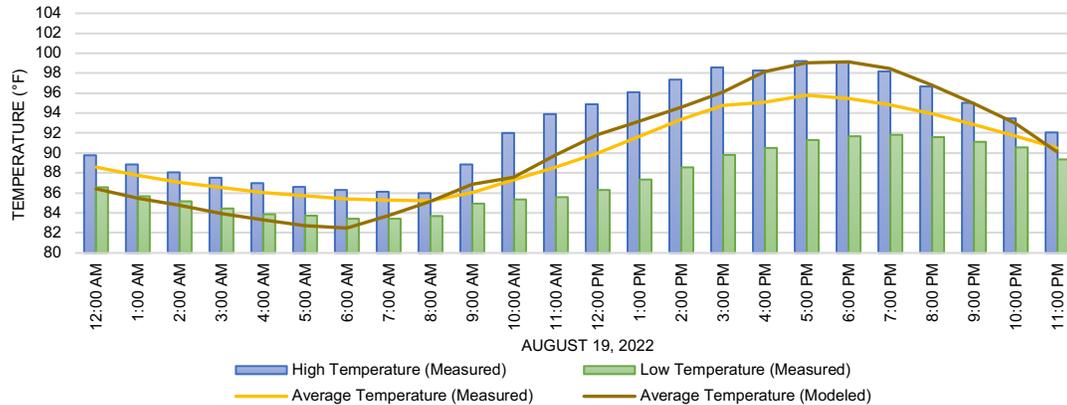


Figure 5: Hourly indoor temperatures (°F) measured onsite compared to those simulated in DesignBuilder on August 19th, 2022. Source: (Authors 2022)

1.4 Selection of the passive energy efficiency measures

The compromise between energy performance and the requirements of historic preservation is necessary and thus reduces the selectable energy efficiency measures greatly (Ascione et al. 2015). In fact, the energy retrofit is restricted by certain conservation principles and guidelines that ensure the protection of valuable historic materials and features. In the United States, the rehabilitation of historic buildings is guided by the Secretary of the Interior’s standards for rehabilitation (U.S. Department of the Interior National Park Service 1995; U.S. Department of the Interior and National Park Service 1997). According to these standards, the basic principles that need to be taken into account are the following:

- Retention of the materials, features, finishes, and construction techniques that are important to defining the building’s historic character;
- Minimal intervention;
- Protection of archeological resources;
- Compatibility of new materials and features used to replace deteriorated materials or features;
- The distinction of any additions;
- Reversibility of the interventions.

For the presented case study, the following set of passive energy efficiency solutions was selected following the abovementioned requirements:

Addition of insulation on the interior of the exterior walls. This process does not impact any historic materials since most walls are already unfinished in the existing state of the building. Moreover, since the wood-frame envelope has low thermal inertia, the addition of insulation can yield great energy savings.

Addition of attic and crawlspace insulation to reduce heat transfer through these surfaces. The installation is simple and has a minimal impact on historic materials in both cases.

- Reducing air infiltration by weatherstripping openings and sealing cracks in the walls, crawlspace, attic, and surrounds of doors and windows.
- Installation of tight-fitting storm windows and doors to increase the thermal performance of the openings without losing any historic fabric.

Furthermore, the building was considered to remain naturally ventilated and the inherent energy concept was retained by avoiding any change in the spatial relationships, placement, and size of the openings and ceiling height, as well as preserving all existing shading devices.

2. RESULTS AND DISCUSSION

Analyses of energy savings that were achieved by the considered energy retrofit measures, in addition to the efficacy of natural ventilation are presented in this section. Since the building’s interior finishes and the envelope are currently in a deteriorated condition, there was no benefit in considering the as-in state as the control model to attain significant results. Therefore, the characteristics of the control model were determined considering that the building was restored to a habitable condition without the addition of any energy efficiency technologies. The materials’ characteristics were acquired from Ahlquist et al. (2021) and onsite surveys, while the thermal transmittance (U-value) of the historic windows was obtained from Myers (1982). Table 2 summarizes the characteristics of the control model. The features of the five retrofit measures applied to the building were acquired from ASHRAE Guideline 34 (2016); The United States Department of Energy (2022); Myers (1982); Tiberio and Branchi (2013); Cho et al. (2022); Hensley and Aguilar (2011) and are displayed in Table 3.

Table 2: Characteristics of the control building energy model. Source: (Authors 2022)

Component	Characteristics
Exterior walls	Wood-frame construction with wood shingle cladding. U-value = 0.267 Btu/h.ft ² .F
Roof	Pitched roof with composite asphalt shingles. U-value = 0.259 Btu/h.ft ² .F
Floor	Wood joists and hardwood. U-value = 0.366 Btu/h.ft ² .F
Windows	Single-glazed wooden windows. U-value = 0.93 Btu/h.ft ² .F
Occupancy	5 people
Infiltration	10 ACH

Table 3: Summary of the five retrofit measures applied to the building. Source: (Authors 2022)

Retrofit measure	Content
Wall insulation	R-19 fiberglass batt insulation, applied to the interior of the exterior walls. U-value of the new wall assembly = 0.047 Btu/h.ft ² .F
Attic insulation	R-38 fiberglass batt insulation. U-value of the new attic assembly = 0.026 Btu/h.ft ² .F
Crawlspace insulation	Rigid foam insulation. U-value of the new floor assembly = 0.045 Btu/h.ft ² .F
Air infiltration reduction	Weatherstripping with holes and cracks filling. Infiltration 10ACH → 3ACH
Storm doors and windows	U-value of the new assembly = 0.46 Btu/h.ft ² .F

2.1 Analysis of the retrofit measures' efficiency based on cooling loads reductions

Simulations were performed in DesignBuilder to test and compare the cooling loads in cases when no passive retrofit measures were applied (control model), when each retrofit measure was applied solely, and when all measures were applied simultaneously. According to Dalugoda (2020), cooling load is the amount of energy removal necessary to sustain the indoor environment at a desired temperature and relative humidity. Therefore, the lower the cooling load, the better the energy performance of the house. The total cooling load is the sum of sensible and latent loads. The results of the simulations are presented in Table 4 and Figure 1. Among the applied measures, wall insulation afforded the best savings in sensible cooling (21.9%) while the reduction of air infiltration yielded the most reduction in total cooling (23.8%). Attic and crawlspace insulation also proved to be very effective, yielding respectively 10.7% and 12.4% savings in sensible cooling loads and 17.5% and 9.4% in total cooling loads. However, storm windows and door installation was the least effective of the selected passive technologies. The sensible cooling energy was reduced by 3.0% and the total cooling energy by 3.6%. When all five retrofit measures were applied simultaneously, the savings in sensible cooling loads were equal to 63.6% and those in total cooling loads were equal to 61.8%. Following this analysis, wall insulation, attic insulation, crawlspace insulation, and air infiltration reduction are the measures to be prioritized in the retrofit of the case study, while the addition of storm windows and doors can be overlooked.

Table 4: Comparison of cooling loads under different energy retrofit measures. Source: (Authors 2022)

Retrofit measure	Cooling load (Btu/ft ²)		Energy savings (%)	
	Sensible cooling	Total cooling	Sensible cooling	Total cooling
None	-33,846.4	-44,818.9	-	-
Wall insulation	-26,419.3	-36,990.3	21.9	17.5
Attic insulation	-30,223.5	-40,613.0	10.7	9.4
Crawlspace insulation	-27,952.8	-38,424.5	17.4	14.3
Air infiltration reduction	-28,392.9	-34,174.2	16.1	23.8
Storm doors and windows	-32,837.8	-43,205.2	3.0	3.6

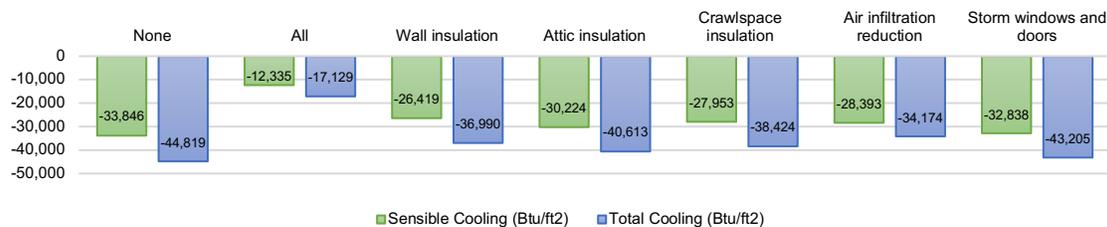


Figure 6: Cooling loads analysis during the study period. Source: (Authors 2022)

2.2 Analysis of natural ventilation's efficiency

The impact of natural ventilation was analyzed by producing two sets of simulations. In the first set, no retrofit measures were applied to the building and the cooling loads were compared in cases where natural ventilation was off and when it was on. Conversely, in the second set of simulations, all retrofit measures were employed. The results of these simulations are displayed in Figure 6. In the first case, natural ventilation contributed to a 0.92% reduction in sensible cooling while increasing the total cooling by 1.39%. In the case where all retrofit measures were in effect, sensible cooling loads were reduced by 13.71% when natural ventilation was in operation and total cooling loads decreased by 6.24%. The results indicate that natural ventilation is not an

effective strategy for wood-frame buildings in a hot and humid climate unless it is paired with other passive retrofit measures such as those used in this study. In that case, it contributes to additional energy savings.

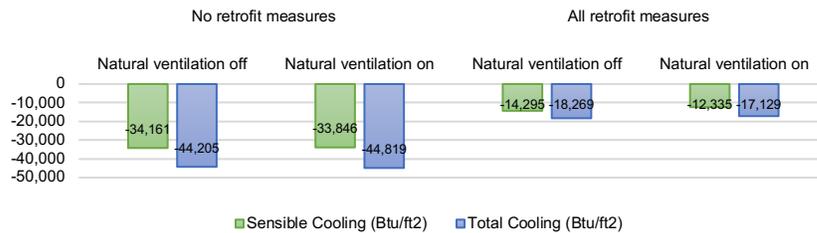


Figure 7: Natural ventilation analysis during the study period. Source: (Authors 2022)

CONCLUSION

This paper investigated the relationship between energy retrofits and conservation requirements in a residential historic wood-frame building in San Antonio, Texas, situated in a hot and humid climate. A set of passive cooling strategies, in addition to using natural ventilation, have been analyzed to control and mitigate indoor air temperature and relative humidity and to reduce the cooling energy load. A set of passive retrofit measures was thoroughly selected and field monitoring and building energy modelling were used to evaluate the impact of these measures in addition to the efficacy of natural ventilation in this case.

The results revealed that the internal insulation of the exterior walls and the reduction of air infiltration were the best strategies to increase energy efficiency. In this particular case study, the addition of insulation to historic walls was possible since the walls are unfinished, which resulted in greater energy savings without compromising any historic materials. The addition of attic and crawlspace insulation was also very effective. However, the addition of storm windows and doors did not yield great energy savings. Moreover, natural ventilation proved to be ineffective without being paired with the other retrofit measures, but its efficacy increased when all the considered strategies were employed.

Some current methodologies promote a combination of building energy retrofits, historic preservation, and occupant satisfaction by optimizing passive systems. Building energy simulation is a crucial tool for determining which interventions affect a heritage building's thermal environment and for figuring out potential energy performance upgrades. While upgrading a building's energy efficiency is an essential approach for delivering indoor thermal comfort, the cultural and heritage significance of the building must be considered to achieve heritage-sensitive management. Lastly, this approach reinforces the sustainability aspect, creating a more resilient historic building stock facing potential future rising temperatures and humidity levels due to climate change. The methodology of this investigation is replicable and the results are adaptable to countless historic buildings in hot and humid climates throughout the world.

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Catenary Timber: The 2022 Barry Onouye Studio

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ABSTRACT: The annual Barry Onouye Studio in the Department of Architecture at the University of Washington investigates the intersection of architecture and structural design through hands-on exploration. In Spring 2022, the studio focused on the rising importance of structural timber as part of a larger transition to lower embodied-carbon buildings. This studio utilized a pre-determined donation of sustainably-sourced timber from local foresters as the sole material of construction. Students were challenged to collectively design and build a free-standing timber pavilion that demonstrated the structural design potential of dimension lumber, and expand the existing formal and assembled logics of timber.

The studio was offered to first-year graduate Master of Architecture students, as an 'exploration' studio. Initial assignments fostered an appreciation for timber as a grown, natural, organic material. By researching the specific forester locations, wood species, forest climate, and distances of forest-to-mill-to-UW, students began to understand wood as both a standardized building product and natural artifact of our surrounding environment. Students then focused on the specific 2x3, 2x4, and 2x6 geometry of the donated stock (60, 8'-pieces of each), and identify guiding values of their design process. These values included the need to make the most of the material we had (minimize waste both during construction and at the end of life), while creating something exciting and interesting for our UW community. They identified three priorities: 1) Make Structurally Efficient Use of Material, 2) Create a Unique Spatial Experience, and 3) Design for Disassembly.

Through a series of case study assignments and charettes, the studio arrived at a design rooted in process more than form. In the north lawn of Gould Hall at the UW, two elevated bridges span over a sunken courtyard. This courtyard would be the site of our installation, and the bridges would become the generator of our form. Students fabricated a set of 'timber chains' – standard sized segments of wood doweled together at each end to form a flexible chain. These chains were then hung from the elevated bridges to 'find' an efficient structural shape. This shape was then marked, and 'vouissoir' blocks of wood were cut to fit between the links. Once brought to the ground, the efficient, hanging form could be re-configured as compression arch. These arches were pinned to a platform base and stabilized by a diagonal lattice in between.

At the end of life, the dowel-connected arches could be easily disassembled. The standardized pieces were then re-purposed into furniture and other small-scale artifacts, and the pavilion was distributed and dispersed throughout the community.

In the end, this studio was successful in its attempt to both challenge the existing logics of timber construction, and deeply consider the material consequences of architectural design – from acquisition through dispersal.

KEYWORDS: timber, wood, structure, structural design, studio, catenary, interdisciplinary.

INTRODUCTION

Since its beginning in 2012, the Barry Onouye Studio at the University of Washington has encouraged architecture students to consider the creative potential of structural design, and the important relationship between architects and structural engineers in the realization of buildings. With this as a premise, this studio aims to:

1. Encourage design thinking that equally considers both architectural and structural opportunities
2. Explore possibilities that challenge the conventional separation of disciplines, and suggest new areas of innovation
3. Foster mutual understanding and appreciation between architects and engineers

Past studios have welcomed visiting professors to the University of Washington (like John Ochsendorf, 2017, Mark West, 2018, Sigrid Adriaenssens, 2019) and explored a variety of topics, like wood shells, fabric-formed concrete, and hanging nets. Returning to in-person instruction meant the Spring 2022 studio could resume the hands-on exploration of pre-pandemic studios, and connect to a pressing issue in the built environment: the rise of timber as a primary structural material. The studio was offered to graduate students in the Master of Architecture program, as an Exploration studio (for first-year students in the 2-year program, and second-year students in the 3-year program). These students had all taken structures courses, as well as Foundation and Integration studios.

1. STUDIO PARTNERS

The Onouye Studio has always relied on a large network of collaborators and partners. These individuals or organizations provide design expertise, material donation, and important contextual/ cultural insight in to the design work. While the studio prioritizes structure, it still embraces the full complexity of architecture as a situated, culturally-produced artifact.

1.1 Structural Engineering Collaborators

With an interest in wood design, the studio partnered early with the structural engineering firm Fast+Epp. Originally based out of Vancouver, BC, Fast+Epp has become a global leader in the design of timber structures. Notable structures include the Grandview Heights Aquatic Center (Surrey, BC, 2016) with a timber tension-roof, hung in a catenary shape, and the Richmond Olympic Oval (Richmond, BC, 2010) with hybrid timber trusses. The Seattle-office of Fast+Epp were involved in the early stages of the studio and served as important critics along the way.

1.2 Foresters

The emphasis on timber in the studio was, in part, based on the large role that forestry and timber practices play in the Pacific Northwest. The large expanses of timber wilderness in Washington State fueled early, resource extraction economies in the 19th and early 20th centuries. In more recent times, second- and third-growth timber (of smaller diameter) continues to make the region one of the top producers of wood products in the country. The current arrangement of foresters, timber harvesters, and lumber mills are key parts of the state's future – both in the management of forest lands and in the economy of the state.

Through a previous relationship with the Sustainable Forestry Initiative, the studio instructor contacted the Washington Implementation Committee about a material donation. With an intention to showcase the structural potential of timber, several companies agree to donate and deliver a stock of dimension lumber from their mill. Rather than secure the donation after the design was complete, the studio chose a different approach. Without knowing what design would take place, the instructor and the lumber mills decided on a donation consisting of the quantities and sizes of different lumber species (Table 1).

Table 1: Donated Lumber for Design.

Quantity	Dimensional Size	Species	Lumber Provider
60	2x3	Douglas Fir	Hampton Family Forests
60	2x4	Mix (Doug Fir, White Fir)	Yakama Forest Product
60	2x6	Douglas Fir	Sierra Pacific Industries

Each of these foresters provided lumber that was a product of their forest lands, forest management practices, mill size and capacity, as well as their overall approach, or philosophy, to harvesting timber. Their approach was evident in the material that each provided, and served as the starting point for the studio exploration.



Figure 1: Donated lumber. Source: (Tyler Sprague 2022)

2. SITE

2.1 Gould Hall Lawn

Our studio installation would take place on the north lawn of Gould Hall. This lawn space is adjacent to the primary building for the College of Built Environment. As Gould Hall navigates a significant slope, the rectangular lawn is also a level (story) below a nearby sidewalk and below two bridges that connect to the second level of Gould Hall. (Figure 2). This site is highly visible to both the occupants of Gould Hall on the first floor, and to the people entering the building via the two bridges.



Figure 2: Gould Hall, north lawn. Source: (Tyler Sprague 2022)

3. STUDIO PROCESS

The instructor divided the 10-week studio in to a series of assignments intended to first introduce students to the studio topic and prepare students to embark on collective design work. These assignments presented the underlying premise of the studio – that locally grown timber is a carbon-friendly, renewable resource that can be used to generate new formal geometries.

3.1 Material thinking

The first assignment asked the students to work individually, and do a thoughtful study of the donated material. It began:

This lumber represents a connection to the forest lands of Washington State, the people who work and manage the forest lands, the processes of their production and a latent architectural potential. Each board was once a tree growing in a forest. Each board is a specific species of wood. Each board experienced a carbon-sequestering life time before being harvested, processed and arriving at our university. This exercise is intended to help gain an intimacy with wood, prior to the design & construction process – through both qualitative and quantitative means.

Students read responses gathered from the local foresters on the specific location the trees were grown, species harvested, age of tree, and general forest management tactics. Students then selected two specific boards to examine specific dimensions, grain pattern, knot location, stamped markings, tool markings, etc. As a deliverable, students produced a graphic collage of their exploration and a one-page reflection.

Student responses highlighted the natural quality of the wood, even as it came in standardized, dimensioned shapes.



Figure 3: Material Thinking, Stephanie Cote. Source: (Stephanie Cote 2022)

3.2 Precedent review

For the next assignment, students researched other timber pavilion structures. The assignment asked students to focus on the material, structural form and assembly process of each timber structure. Working in pairs, the student groups looked at work by Kengo Kuma, Shigaru Ban, Rural Studio, Toyo Ito, and others, examining how the structures utilized the unique qualities of wood. The logics of assembly connected to labor, fabrication, and ultimately the forest that grew the wood. The idea that the site (or location of a project) could physically generate a structure was a powerful idea that remained with the studio throughout. While some precedents were permanent structures, others were temporary pavilions – begging the question, what happens at the end? Disassembly? Land-fill? These precedents rooted the idea of re-use as a core studio value, inspiring the students to design for a second life.

The studio also undertook the simple assembly of a DaVinci bridge – a simple, reciprocal structure with compression-only connections. Through a sequence of assembling longitudinal and lateral beams, a spanning structure can be easily constructed. This exercise introduced students to the hands-on work of assembling a load-resisting structure and the impact that a vaulted form can have on space.

3.3 Conceptual design work

With these assignments complete, the studio began the design process – progressing quickly through conceptual design (many individual ideas quickly presented) to several options (developed by small groups).

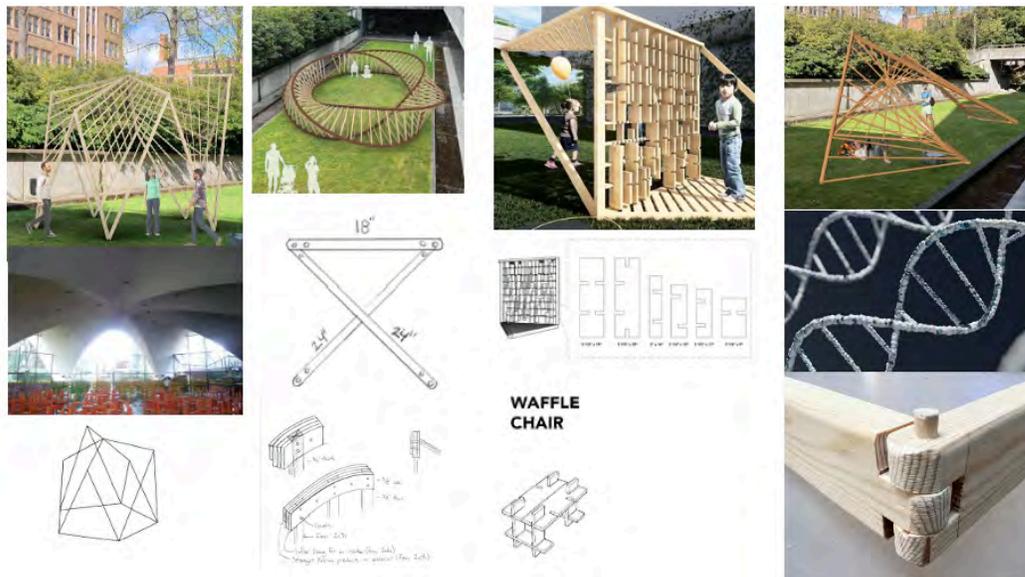


Figure 4: Studio Mid Review of student work, Summary. Source: (Studio Collective, Tyler Sprague 2022)

Along the way, the studio defined core values that guided the decision-making:

- Wood is a local, regional, grown material
- Wood represents a relationship to the land (native tribes, foresters)
- Wood is not a uniform material (with grain, knots, etc) and not all wood is the same
- Wood is flexible in thin sections, but can be made stiff through geometry
- Structure can respond to support conditions, constraints
- Dis-assembly and re-use are vital, and must be considered from the beginning

These values were then operationalized through three strategies: 1) Make Structurally Efficient Use of Material, 2) Create a Unique Spatial Experience, and 3) Design for Disassembly.

3.4 Final design approach

After considering many options, the studio converged onto a single design approach. This approach was a synthesis of design ideas, rather than a selection of a specific option, rooted in shared values for the project. The approach was rooted around the idea of a timber chain, consisting of predetermined 'links' of wood connected by round dowels. These chains could be assembled, and then hung from the elevated bridges on either side of our site. The hanging chain would develop a materially-efficient form as a pure tension structure, such that when inverted, would become a compression arch. In order to capture the geometry, the spaces between the rotated links could be filled with an angled 'voussoir' – which would work as a compression block.

The pavilion could then consist of a series of different-sized arches – made only from the donated 2x4s - rising from a common platform. The platform would be made of only 2x6s, with tension tie between the ends of the arch. The arches could then be connected by thin, flexible strips cut from the 2x3 boards, and fastened to the arches.

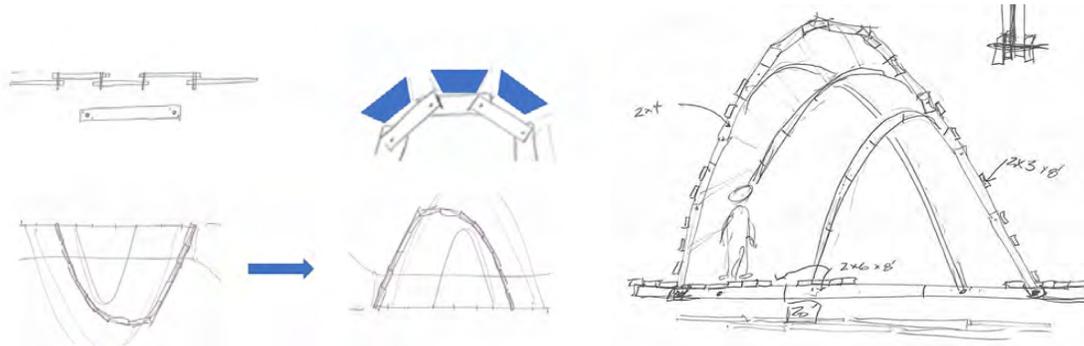


Figure 5: Final Design, diagram of hanging chain inverted to be compression arch. Source: (Tyler Sprague, 2022)

With only doweled connections in the arch, and minimal processing needed, the material of this pavilion could be disassembled, and re-made into furniture as a second life.

3.5 Working groups

With the project direction decided, students took on different tasks in several groups of 3-4 students. Groups were focused on BASE (layout and detail), ARCH (hang links, solidify), LATTICE (cut strips, fasten), MODEL (model ideas physically and digitally as rapidly as possible) and FURNITURE (propose possible). With such inter-connection between groups, check-ins at the start of studio were essential.

Student self-selected and utilized different design skills in their individual work. The BASE group was charged with defining the on-site condition, and the direct contact with the grass below. Utilizing the sectional orientation of the 2x6 members, the group defined paired members (on end) to by-pass and receive the arches with a single, wooden pin. On top of these arch 'ties', the group specified 2x6 laid flat as decking, or walking surface, elevated above the ground. This platform was doweled to the arch ties below, being mindful to not create too great of span or overhang.

The ARCH group defined the height and size of the different arches, and developed a strategy for erection. With the links and 'voussoirs', each arch was two-boards wide. Once hung from the bridges, the arches were marked with pencil and corresponding 'voussoirs' were cut and doweled in place (on the ground). Each arch was then separated into two halves, wrapped with a rope to keep all the pieces in place, and doweled into the base. The two halves were then lifted up and re-joined at the peak of the arch.

The LATTICE group determined size and pattern of the connecting lattice work. This began with the ripping of 2x3 boards into 3 widths (roughly 3/8" thick), and determining a fastening system to connect to the arches. The 8' strips defined the maximum distance between arches, but also required a diagonal pattern to assist in the bracing of the arches against each other. This lattice was essential in creating shell, or membrane behavior, across the structure as a whole, while also defining the interior space and exterior pattern/ texture.

The MODEL group ran parallel to the other groups, providing design feedback as each fabrication and installation process developed. This group worked with both physical and digital models, allowing the groups to visualize the synthesis of all the different components and make high-level design choices together. Physical models gave a tactile sense of the structural behavior – instructing the group on the importance of the shape of each arch (not too steep or shallow) and connecting the arches together (for stability as a whole). Digital models provided rapid feedback on larger spatial possibilities, where the relationship between arches and the pattern of lattice could be quickly altered and evaluated.

The FURNITURE group worked to rapidly prototype furniture options, based on the dimensions and materials used in the pavilion design. With the goal of losing the least amount of material, the group prioritized use of un-cut pieces taken directly from the arches or lattice design. Students developed a variety of chairs, end tables, and stools, designing at an accessible, human scale.



Figure 6: Hanging Chain to Standing Arch, Assembly. Source: (Tyler Sprague, Stephanie Cote 2022)

Form Finding - Stabilizing the Arch

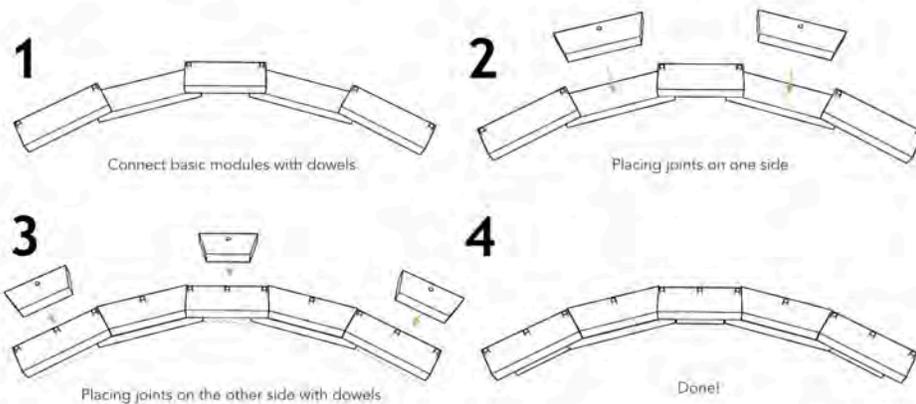


Figure 7: Stabilizing the Arch, Source: (TJ Gassaway, 2022)

4. FINAL INSTALLATION

Over the last week of the quarter, final installation took place on Gould Lawn. The pavilion attracted significant attention from students, and became a popular place to study, or rest. The pavilion remained until mid August, when students dismantled the structure and stored the material. Over the next few months, different students gradually assembled different pieces of furniture. As intended, the pavilion then dispersed among the population, taking a second life in people's homes. In the end, this studio was successful in its attempt to both challenge the existing logics of timber construction, and deeply consider the material consequences of architectural design – from acquisition through dispersal.



Figure 7: Final Installation. Source: (Sprague 2022)



Figure 8: Final Furniture. Source: (Tyler Sprague 2022)

5. EVALUATION

5.1 Final Review

At the end of the quarter, a final critical review of the project was held – with members of the architectural, engineering, academic and forestry communities. Representatives of all foresters who donated lumber were on hand to observe and critique the results. The reviewers broadly praised the transparent connection between material sourcing and structural form – providing evidence of the material transformation that good design leads to. The foresters also remarked about the community of students, instructors, and critics that came together to create such a transformation. This community, for them, mirrored the community of people that produced the initial dimensional lumber. People like arborists, timber harvesters, equipment operators, truck drivers, administrators, and managers. This project made evident the community-led transition from tree to product to architecture. Criticisms of the project largely resided at the level of detail, specifically the connection of the lattice to the arches. The rapid pace at the end led to a structurally stable solution, be left something to be desired aesthetically.

5.2 Student Evaluations

After the quarter, students completed a course evaluation with useful feedback on their experience of the studio, with 7 out of 12 students completing the evaluation. The overall “course as a whole” was rated 4.8 out of 5. When asked about various aspects of the course, students ranked “Feedback from my peers was valuable” first, reflecting the group nature of the course. This was followed by “Instructor encouraged me to acquire new skill and approaches”, reflecting the experimental nature of the design and construction process. Unsurprisingly, the statement “Instructor encouraged me to think independently was ranked last.

In the next category of responses, there was a consensus on the top skill the course helped develop: “Develop your ability to work in fluid or ambiguous situations.” This response reveals the occasional anxiety among students that “everything would work out.” Most students were used to a much more established design process, with lower stakes on the output. The physical structures - experimental yet absolutely must not fall over - at times felt like a high bar to clear in a 10-week, collaborative studio.

Students also responded with written comments, asking if the course was mentally stimulating, what contributed most to learning, aspects that detracted from learning, and suggestions for the future. Comments were positive, with the exception of the speed we were required to work towards the end of the quarter.

6 CONCLUSION

This studio advanced a distinct perspective in its approach to timber – producing a collaborative, site-specific, hand-made installation, with minimal material waste and a potential second life. The structural form was both efficient and spatially compelling, and three large lessons emerged:

- Students adopting common priorities for the project, early on, made collaboration between easier. Overall, the studio was successful in following the priorities established for the design: 1) Make Structurally Efficient Use of Material, 2) Create a Unique Spatial Experience, and 3) Design for Disassembly. Early, consensus-building group work (accomplished around mid review) paid off
- Clearly defined roles allowed everyone to contribute to the project in a distinct and definable way. This was important for assessment (grading) but also stressed the dual nature of group work: gaining the advantage of everyone working together, while maintaining individual accountability.
- Remaining flexible – with clear communication between groups – and the baseline assertion that the design will change, was very important. As groups uncovered different aspects of their work, the design would change, requiring each group to contribute and adapt. Check-ins before each studio session, with the whole class, was very important.

Future work could extend both the group-structured process and the efficient form-finding used in timber. A comparison to a conventionally framed space (perhaps by the ratio of interior volume to structural material) would validate the assertion that it is a truly a more- efficient structure.

The design values embedded in this studio are needed within many areas of the architecture, engineering and construction industry. As the industry advances to a less carbon-intensive means of producing buildings, potential direction – like those demonstrated here – must be considered.

ACKNOWLEDGEMENTS

The author would like to thank all the students involved in this studio: Stephanie Cote, Rimin Dai, Indra Erdenebat, Angel Garcia Guillen, TJ Gassaway, Justin Guo, Alex Holbrook, Siqi Hu, Zihao Huang, Kellie Kou, Justin Ly, Annie Torgersen. The author would also like to thank Fast+Epp for their continued guidance, Hampton Family Forests, Yakama Forest Products and Sierra Pacific Industries for their material donation and consultation, the Department of Architecture of University of Washington, the College of Built Environments of the University of Washington

Reflecting on the Intent of Undergraduate Design Research Coursework

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ABSTRACT: This paper discusses two research-focused Advanced Architecture Systems seminars in which the instructor's personal research agenda was the impetus for the courses. With comparable student enrollment (year-level, total number, and construction experience), a common foundation to the research was established with consistent background knowledge given to the two upper-level elective courses. By mapping a shift of quantitative vs qualitative investigations, along with a subtle change in the timing of student buy-in, the author draws correlations to the substantial difference in the objectivity and sustained rigor adopted by the students in their final independent research.

KEYWORDS: pedagogy, undergraduate research, research methods, design as scholarship.

INTRODUCTION

In the last two decades, students who engage in Undergraduate Research Opportunities (URO's) have demonstrated an increase in overall academic engagement and success at the graduate level (Russell 2007). As an instructor who has focused on introductory courses in the areas of design, technology, and techniques; when appointed to instruct an Undergraduate Research-focused Course (URC), I found myself asking, "At such an early stage of engaging the concept of design research, what role does the foundational levels (*remembering, understanding, and applying*) of Bloom's Taxonomy play?"

This paper discusses two Advanced Architecture Systems electives in which my scholarship in fabric-lined tensile formwork for cast-in-place concrete was the focus. Positioned as Scholarship of Integration, my research draws together structural concepts explored by Frei Otto, flat-sheet fabrication studies by Mark West at CAST, and decades of professional experience in the construction industry (Boyer 1997; Roland 1970; West 2016). When centering my work in these two URC's, I debated if I should expect the students to remember all background knowledge of my interests, to understand my nuanced point of view, and for them to apply new concepts furthering my research? Or, are these URC's an opportunity to use the content (my research) as a means to establish a strong foundation to research practices (Weimer 2013)? At face value, this question sets the direct advancement of the instructor's research agenda against focused effort towards establishing research methods.

The two URCs discussed in this paper saddle a moment in my teaching when I expanded my methods of investigation beyond familiar qualitative deliverables (that too easily fetishized the object) to assignment briefs that nurtured student's interest in communication of quantifiable investigations. In the first attempt at instructing a URC, I focused on qualitative methods and a more studio-like, "research through architectural inquiry" (Frayling 1993). In the second attempt, I aimed to strengthen the students' understanding (and therefore appreciation) of Frayling's "research for architecture" with various approaches to quantifiable design research. With comparable facilities, enrollment, and student experiences, the two courses act as case studies into the impact of the agenda and methods within a URC. Reflecting upon the objectivity and sustained rigor adopted by the students in their final independent research, correlation can be made between the impact of qualitative vs quantitative investigations and the focus of the agenda on the depth of the student learning.

1. METHODS

This study establishes commonality between the two courses (*Course A* and *Course B*) by documenting their student demographics, facilities, funding, and the background knowledge seeded at the introduction. The assignments in each course are identified as either those with qualitative deliverables (open and supporting unencumbered design exploration) versus assignments that demand objective quantitative documentation as the deliverable product. In addition, the semester schedule for each class makes note of when student buy-in occurs and their role in the ownership of course content. Conclusions are drawn for a comparative assessment of the objectivity and sustained rigor exhibited in the evolution of students' initial directed work into their later independent research, along with student evaluations.

2. FRAMEWORK

2.1 Facilities & Funding

Both courses were assigned to equivalent rooms for instruction. Although these rooms were dedicated solely to these courses—allowing supplies to be stored—they did not have plumbing or work benches for construction level activities. No equipment or funding were provided for the students either semester.

2.2 Existing knowledge

In both courses, existing knowledge regarding tensile structures was established through the same three readings: History of Fabric Formwork in Mark West's Fabric Formwork Book, Selected projects from Conrad Roland's Frei Otto: Tension Structures, and Fabric-Lined Tensile Formwork for Cast-in-Place Concrete Walls, an article I published in Technology|Architecture + Design.

Student Enrollment_

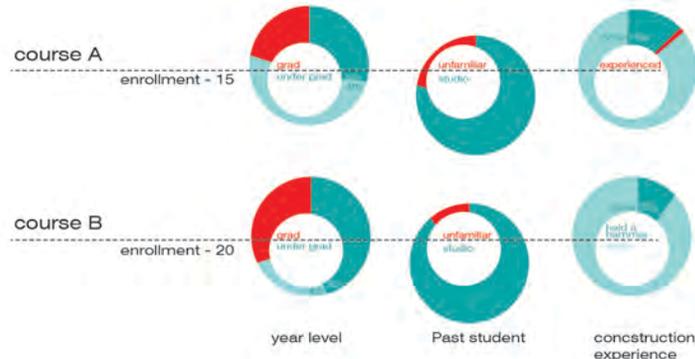


Figure 1: Diagram highlighting similarities between student participants and their construction experience. (Author 2023)

2.3 Credit and Schedule

Although both courses were listed as 3 credit advanced architectural systems courses, *Course A* was held for 1.5 hr on Tuesday and Thursday afternoons, while *Course B* was held only on Wednesdays for a single three-hour session.

2.4 Method of Investigation

Although the principal research is cast-in-place concrete, in both courses a frame was required as a stand in for a physical site. Students were asked to use the frames to deploy fabric formwork systems and cast concrete forms.



Figure 2: Frame systems utilized as a stand-in for physical site conditions. (Author 2023)

Course A semester schedule_

A_ wk 01-03_ INTRODUCTION (quantitative + assessment)

Existing Knowledge was presented through lectures, readings, and hands-on modeling demonstrations. Students were asked to demonstrate their understanding of the existing knowledge by diagramming the structural systems for several of Frei Otto's built work, constructing variations of tensegrity structures, and taking a short quiz. Once the students demonstrated an awareness of the concepts, this Introduction phase ended with a group effort to construct the frames for their future projects.

A_ wk 04-06_ TEAM EXPLORATION (Qualitative)

In pairs, the students were charged with exploring their ideas on how tensegrity systems might influence the tensile assembly presented in my research. Using their frames, the students wove unique tensile systems as formwork for casting concrete. One cast was required to be submitted. Class time was spent conducting individual team design critiques.

A_ wk 07-10_ INDEPENDENT EXPLORATION (Qualitative)

Having matured an idea in teams, the students were given four weeks to either refine their previous work independently or begin a new direction. One cast was required to be submitted. Class time was spent conducting individual team design critiques.

A_ wk 11-14_ PRESENTATION (open)

The final four weeks were given to documenting and diagramming the logic of their assembly system used in the final casting. A poster presenting how ideas in the existing knowledge (West, Otto, Tensegrity, and the Fabric-lined system) influenced their design decisions.

Course B semester schedule_

B_ wk 00_ PRE-COURSE

Students were asked to complete a survey and consume the assigned reading prior to the first day of class.

B_ wk 01,02_ BASELINE (Quantitative documentation + assessment)

Drawing from the pre-course survey, students were divided into two groups--each with an equal cross-section of students with construction experience. On the first day of class, the 'Shadow' group watched me deploy the assembly system to be tested. During this same class, the other 'Blind' group began attempting to construct the same assembly system from written instructions. Both Shadow's live discussions, and the Blind cohort's written instructions, outlined five phases for the construction of a tensile assembly system. The students had two weeks to attempt the formwork a minimum of three times. With each attempt, they documented their times and noted specific troubles for each phase. All data was verified by a second student and collected in a class-wide excel file.

B_ wk 03_ DATA VISUALIZATION (Quantitative documentation + assessment)

Students were tasked with visually analyzing of all the data collected (time and notes) to assess where common problems might have occurred. The only constraint to the visualizations was that the data had to remain a direct import from Excel to Illustrator. First attempts were printed and discussed for their ability to communicate anomalies and/or consistency in the data before submitting a final digital copy.

B_ wk 04-06_ REVISIONS (Quantitative documentation + assessment)

Taking note of issues highlighted in the data, students were asked to individually proposed revisions to the original five phases to improve how to communicate the deployment of the tensile system. Each student developed an instruction manual which was printed, reviewed in-class, and revised.

B_ wk 07_ DEMONSTRATION (Quantitative documentation + assessment)

As a group, we deployed the tensile assembly system and cast one test together. During the process we discuss various methods and techniques of mixing, pouring, and cleaning-up the concrete along with the potential architectural impact of the system.

B_ wk 08-10_ TEAM RESEARCH (Quantitative documentation + assessment)

Following a class-wide brainstorming session in which students identified multiple areas of interest, students self-selected a research agenda and groups were formed. A one-page research agenda was written and reviewed before the group moved forward. Over three weeks, the students were prompted to assess initial tests for their effectiveness and attempted again to correct errors, establish consistency, or to greater focus the research. A single research document was submitted by each group which documented the initial agenda, the first experiment, findings, revision to the agenda, second experiment, and findings.

B_wk 11-14_ INDEPENDENT RESEARCH (open)

Students were asked to draw upon personal interests to develop a research agenda. No specific requirements were given for the final research document.

2.5 Student Work Product

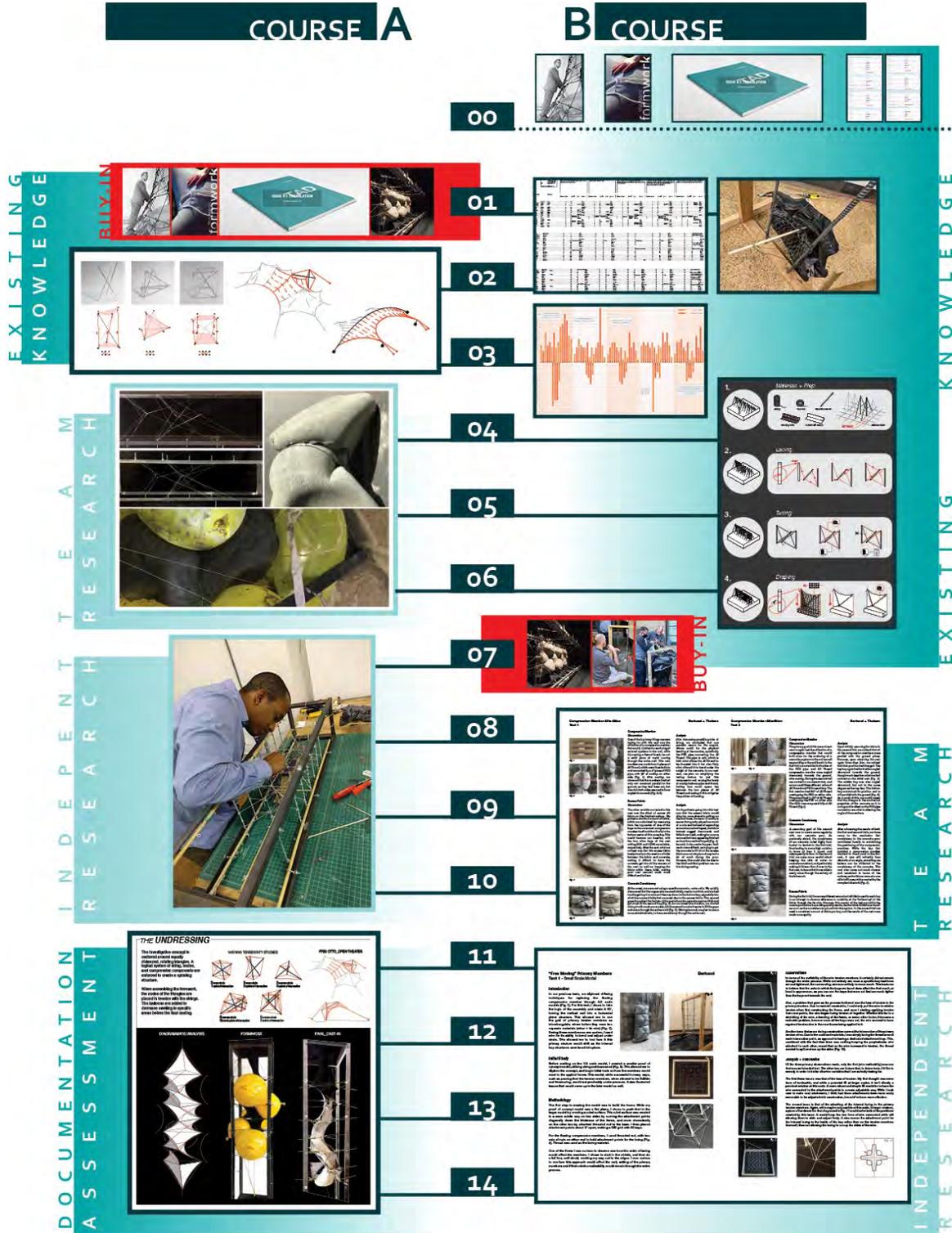


Figure 3: Assignment sequence with Buy-in lecture noted. (Author 2023)

2.6 Student Evaluations

Three questions have been selected from the two courses' student evaluations. Please note: Between the instruction of these two courses, the university elected to comically flip the scale from (1 High – 5 low) to (5 high – 0 low).

Course A

Assignments were pertinent to topics presented in class_	1.0	(1 high - 5 low)
Assignments were well spaced throughout the course_	1.33	(1 high - 5 low)
The demands made upon my talents were exciting and challenging_	1.33	(1 high - 5 low)

Course B

Assignments were pertinent to topics presented in class_	5	(5 high – 0 low)
Assignments were well spaced throughout the course_	4.67	(5 high – 0 low)
The demands made upon my talents were exciting and challenging_	5	(5 high – 0 low)

3. ASSESSMENT

3.1 Deliverables

Similar in outline, these two courses each dedicated time to establishing Existing Knowledge followed by two phases of research: first as a team then independently. A significant difference between the curricula can be found in the deliverables for the exercises within the Existing Knowledge phase. *Course A* drew from my studio experience with the first week dedicated to introductions to my research and group discussions regarding the readings. Once the conceptual idea was clear, we then spent time together bonding as a group while constructing frames for their projects. *Course A*'s three weeks of Existing knowledge phase ended with the submittal several aggregated items (a series of structural diagrams of several Frei Otto tensile structures and initial structural concept models that explored principles of tensegrity) along with a quiz on the history of fabric formwork. Little weight was given to the grading of these items, as they were seen as loose contextual experiences to inform their future research through architectural inquiry.

In comparison, prior to the first day of *Course B*, the students were required to complete the assigned readings and take a survey regarding their construction experience. With this survey already completed, attempts to construct the tensile cushion formwork began immediately. Unlike *Course A*, where the assembly system was merely a starting point for them to explore, *Course B*'s Baseline demanded rigor in the examination of their personal learning process. The "product" of their efforts was the data they produced documenting their time and struggles. From the initial assignment forward, *Course B* focused on the student's ability to communicate the data collected. Not only did the second assignment, Data Visualization, explicitly do this, this assignment also demonstrated the usefulness of collecting data as the students were asked to find similarities between their struggles and revise the instructions they were given. The Revision assignment reinforced their ability to communicate the logic of the assembly system and take emotional ownership of the concepts involved. Unlike *Course A*, where the students only diagrammed Frei Otto's work, both the Data Visualization and Revision assignments gave the students opportunity to strengthen and find success with graphic skills in the clear communication of the complex information that they had accumulated. A live Demonstration was held the final week of the Existing Knowledge phase where I constructed and cast an example wall. It was only then, 7 weeks into the semester, that the finish "object" is brought into focus. And even when it is, the focus of the discussion was on how to demonstrate mastery of the process with accuracy and speed.

3.2 Student Buy-in

Not an assignment, but in both semesters lectures and discussions were held inviting the students to dream about the possibilities of the research agenda's potential. *Course A* initiated this the first week with passionate talks about how the work of Frei Otto, Mark West, and concepts like tensegrity have personally inspired the author's personal research. Beautiful imagery was used to seed their imagination while open ended questions helped fever speculation on the possibilities that might grow from their work. In effect, the student's energy was direct, from the first week, towards exploring new frontiers. This place "research through architectural inquiry" as the agenda for the course almost immediately.

Course B withheld this moment of buy-in until the 7th week of the semester. In the build up to these discussions, the assignments nurtured the student's creativity in, and they were rewarded with praise for, the skills with which they communicated the quantifiable data they collected. When the "buy-in" finally happened in the 7th week of *Course B*, a rigorous process supporting "research for architecture" had been set for the semester (Fraybil). The students' creativity was focused on strengthening a recursive research agenda and communicate their findings.

3.3 Student Work

Although students in both courses worked diligently throughout their respective semesters, the Independent Research assignments in *Course A* demonstrated an distinct lack of sustained rigor in their investigation. Whether during in-class design critique or in the transition between their Team Research and selecting a final Independent Research Agenda, the students routinely discarded their previous work when the artifact created did not live up to their preconceived design intentions (loss of objectivity). In comparison, the work in *Course B*'s final Independent Research explicitly walks through the primary research developed in the Team Research Agenda, their new proposal, results, as well as conclusions outlining future research areas.

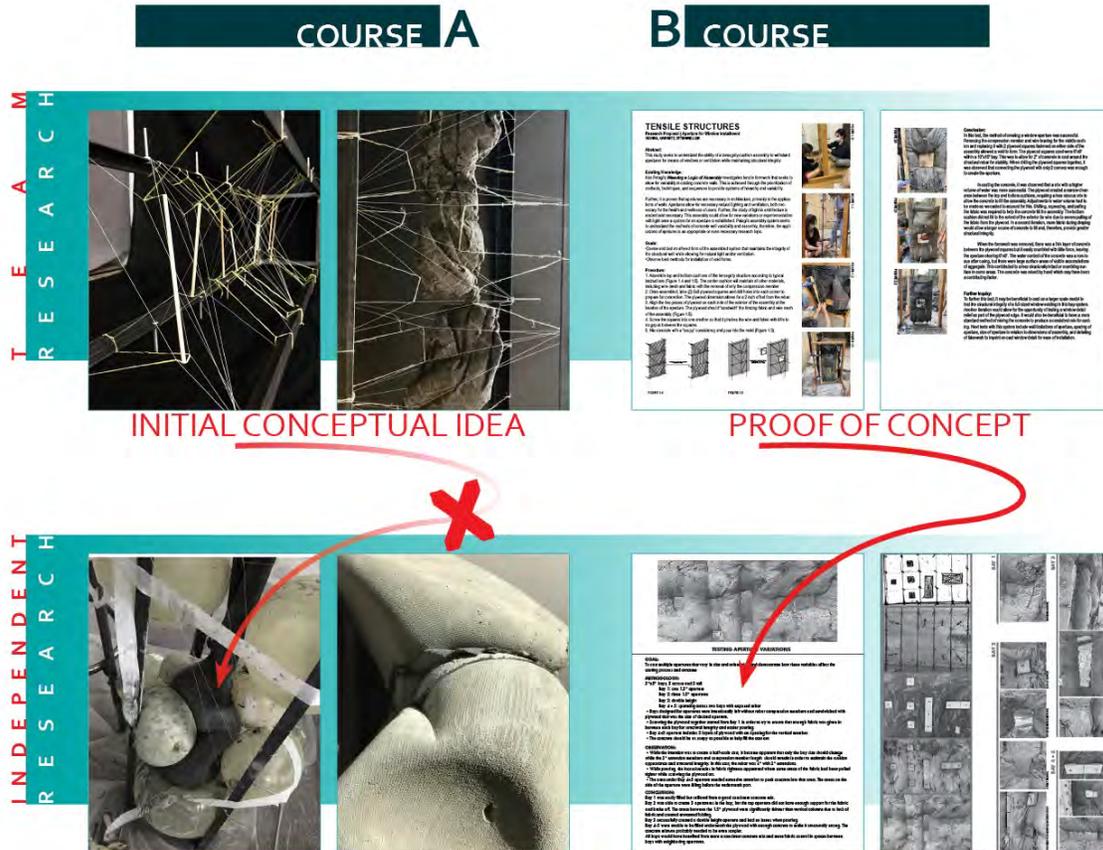


Figure 3: Selected student work depicting the continuation of student agendas through the semester. (Author 2023)

CONCLUSIONS

As a professional transitioning to academia, like many others, understanding the methodologies relevant to scholarship within architectural design has remained a hurdle (Buday 2017). But more so, the effort to break away from a mindset in which all design efforts must conclude in a refined, completed product. This remnant of my professional experience has had a direct influence on my pedagogy, the deliverables assigned, and how they are assessed. Within the design studio, I approach the concept of rigor in one's design process through pragmatism and plurality (James 1907; Jenck 2013). The first by assessing qualitative investigations against an ever-increasing body of experiences and the latter, the systematic competing of multiple, opportunistic paths. I mention this to stress that I feel a critical design process, Farley's "research through architectural inquiry" holds a place in design as scholarship. When considering URO specifically, I have found the specific questions regarding the agenda and the method employed in the research need to be thoughtfully considered. For an undergraduate class, should the agenda focus on the progression of the specific scholarship or is the content best used to establish fundamental research skills (Weimer 2013)? Regarding the methods employed, although both qualitative and quantitative investigations are fruitful in design as scholarship, is one approach more effective at developing a foundational knowledge of research methods?

Reflecting on the consensus with which students in *Course B* independently approached their final research projects with continued systematic rigor, I believe spending the first 7 weeks focusing on how we conduct research, may superficially take class time away for the research agenda, but had impact on the depth with which the students independently pushed their work. When introducing research that would fall into Frayling's

notion of “research for architecture” to undergraduate students, reinforcing a scientific quantifiable investigations early as with *Course B*, appears to allow the recursive nature of research for architecture compared to familiar and loosely defined qualitative methods.

With the second course conceptually shifting the students focus from presenting the object to presenting the data, I was surprised to find the students evaluations maintain an equally high level in both courses when considering the “demands made upon my talents were exciting and challenging” and “Assignments were well spaced throughout the course”. Each of which I would have expected to have been more positive in the familiar studio-like environment of *Course A* than the highly structured, quantifiably focused *Course B* curriculum. Which leads me to conclude, when developing curriculum for courses focused on UGO’s around an instructor’s agenda, time spent early in the semester nurturing the communication methods with which you plan on documenting your later research (rather than convincing the students of your research’s potential) is effective in establishing rigor in how they examine what they themselves find inspiring.

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Remote Control: Attuned Interventions in Mass Timber for Inuit Housing

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ABSTRACT: *This paper investigates the cultural and ecological resilience offered within prefabricated mass timber housing solutions for a small, remote Inuit village at the northernmost tip of the Canadian province of Quebec. Just below the Arctic Circle, the harbor is open for less than one month a year, with no roads connecting Ivujivik to other northern Quebec communities. Timing and prefabrication of design solutions are essential to providing building infrastructure to this remote part of the planet. Additionally, this underserved community is overcrowded and lacks the necessary means of constructing suitable dwellings to withstand the long, cold winters. A brief history of this society and a rationale for why mass timber and pre-fabrication are appropriate for this remote location, followed by several lessons learned during an exploration into ecology, environmental awareness, health and well-being, and cultural sustainability towards the ultimate design project of prefabricated mass timber eco-housing for the Arctic. The studio process was threefold; 1) explore local resources of Inuit and other indigenous populations, 2) research qualitative and quantitative understanding of low-carbon and renewable materials for sustainable architectural design futures, and 3) speculate on prefabrication possibilities of mass timber in contemporary design for architectural interventions within remote locations. This paper will present several design benefits of employing pre-fabrication for construction in remote areas – from reducing waste and time of on-site labor through construction processes to durability, while also relating to the phenomenological and cultural resonance that aims to reconnect indigenous peoples to more symbiotic and biogenic building practices through regenerative and durable materials.*

KEYWORDS: Ecological Resilience, Prefabrication, Mass Timber, Culture, Environmental Awareness.

INTRODUCTION

Ivujivik, like much of Upper Canada, is cut off from the rest of the world. It is an island, not in a geographic sense, but through its remoteness, placing it at an extreme distance from major population centers of North America. This separation isolates its community from much of the inhabited world. No roads link this community to the larger cities of Montreal and the extensive North American hard infrastructure of highway and rail networks, nor is this community connected by road to any neighboring communities. It is a distant, isolated, and unique region of the world.

It is estimated that this area was the initial landing spot of the ancient Thule tribe and the entry point from Baffin Island into the province of Quebec. It was a seasonal village and only formally established as a permanent settlement by creating a post for the Hudson Bay Company in 1947. Nomadic ancestors of these First Nations Inuit (Nunavummiut), 'Eskimo' in the United States, have seasonally populated this area for thousands of years. Historically, these peoples erected temporary structures and camps from naturally occurring materials readily available as they followed animal migration patterns, fishing near the sea, or gathering, farming, and trading during the summer months.

“A fundamental difference between our culture and Eskimo culture, which can be felt even today in certain situations, is that we have irrevocably separated ourselves from the world that animals occupy. We have turned all animals and elements of the natural world into objects. We manipulate them to serve the complicated ends of our destiny. Eskimos do not grasp this separation easily and have difficulty imagining themselves entirely removed from the world of animals. For many of them, to make this separation is analogous to cutting oneself off from light or water. It is hard to imagine how to do it.” (López 1986)

The spring 2021 design studio was initially interested in exploring the pre-fabrication of housing modules and the benefits of using carbon-negative and renewable building materials for architectural ideation. During the research phase of the semester, which included interviews with people and experts from the community, the studio grappled with the humanitarian disaster of housing in Canada's Aboriginal region. Most of Canada's 60,000 Inuit live in small, typically underprivileged communities of less than 1,000 people. It is estimated that 53% of families in Nunavik live in overcrowded homes, coupled with the prevalence of deleterious health effects such as chronic lung disease, tuberculosis at 250 times, and suicide at four times the national average, caused for deeper investigations (Pepin et al. 2018). What is the relevance and importance of architectural design for these underserved communities, and how can material choices positively affect these underserved communities that were once self-reliant and migratory to the now sedentary and governmentally funded?

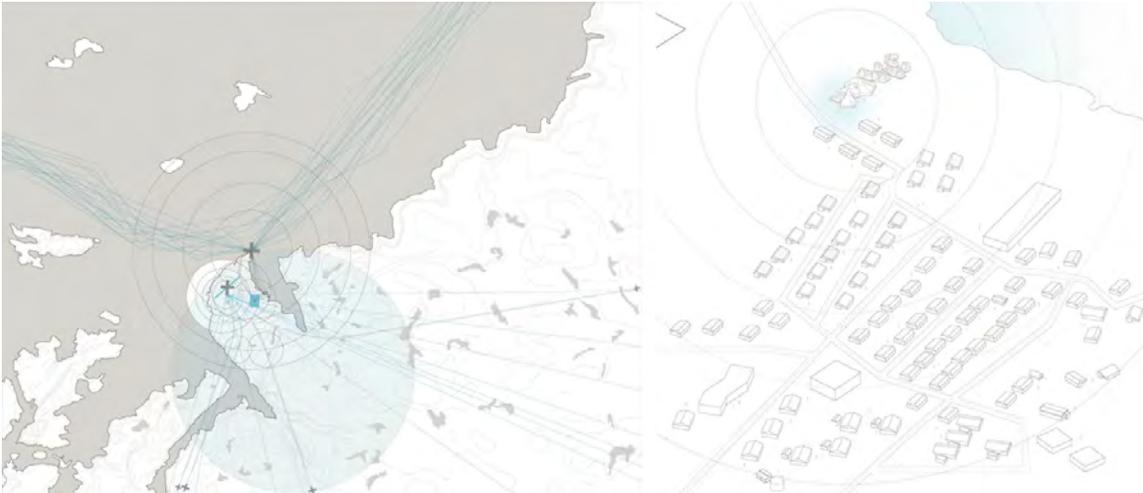


Figure 1: Mapping regional connectivity; nautical, aerial, and land-based migration patterns (left) and community connections and social spaces within Ivujivik (right). Source: Juliet Hollister, 2021

1. PROXIMITIES AND CULTURAL CONNECTIVITY

1.1 Remoteness as motivator for design innovation / necessity

Ivujivik translates to *'the place where ice accumulates because of strong currents'*, where median temperatures range from -11°F (-24°C) in January to 52°F (11°C) in July. Ivujivik is the northernmost village of Quebec. Like almost all the communities within Nunavik, the small community is located along the coast. Surrounded by cliffs that plunge deep into the turbulent waters of Digges Sound, the strong tidal currents of the immense Hudson Bay and narrow Hudson Strait collide and churn, causing shards of ice to form. This town is 1,000 kilometers north of the 56th parallel. This numerical line of demarcation is important, as it is the liminal boundary where the landscape changes from a treeless Arctic tundra covered in lichen, mosses, and dispersed peat bogs to the boreal forest and taiga, which covers much of lower Canada. The Arctic is home to polar bears, foxes, hares, and the indigenous Inuit people. This remote landscape is serviced daily by plane service Air Inuit, which brings in milk, dairy, bread, and staples to this community of less than 500 inhabitants. This area is under federal jurisdiction within Canada, yet several responsibilities are directed to the provincial government of Quebec to provide services for the Inuit population. One of the primary needs of these people is housing. With harsh climatic and important cultural considerations, design solutions require careful study of technological, environmental and social challenges latent within the landscape.

Materials other than stone, water, and any organic material that is brought to the area by the coastal currents are limited, and building materials suitable for such a harsh climate must be coordinated and shipped to this location during the brief 20 days that its port and harbor are ice-free. This greatly influences architectural projects as they must be planned well in advance - designed, constructed, and onboarded onto ships in late spring to make this narrow window. Upon arrival, workers install these prefabricated units onto above-ground foundations, which are pinned to the rocky surface. The permanently frozen ground is often colder than the air, creating structural settlement issues and thermal transmittance that may thaw the ground or invade the interior space. The lack of tools, materials, experienced labor, and building infrastructure invites prefabricated architectural solutions that can be deployed during the summer months to satisfy the local community's needs and a lack of housing. Transitions in growing younger populations must await a seasonal influx of housing that has to be planned well in advance, and the control is not local but remote.

There can be issues when working with prefabricated housing units. Tools, labor, and materials are employed outside a community, and only the finished product is brought to the community. Issues arise when these units are poorly constructed of non-durable materials that cannot be easily mended, painted, or sealed due to the lack of access to building materials or trades. Building with more durable, solid materials, such as mass timber, can not only provide a healthier interior environment, especially in nail laminated timber eliminates the harsh glues associated with other composite wood products, but also reduce the need to repair less durable drywall or foam panels. With limited access to these sheet materials, it may take several months to source, and many such deliveries are limited to the summer. Solidly constructed, easily repairable, and durable materials such as mass timber and structurally insulated panels are highly practical solutions for building infrastructure.

1.2 Boreal forests and renewable resources

The construction industry has been turning towards renewable resources since the invention of mass timber and readily available manufacturers of this new technique. The ability to utilize younger, faster-growing trees such as pine, fir, spruce, and even some grasses in glue-laminated bamboo has created an ability for architects to design large panel prefabricated walls, roofs, and primary structures using mass timber. With similar material properties to heavy timber, mass timber is fire-resistant and comparable to concrete and steel for structural strength. Additionally, by growing building materials, timber can also serve as a carbon sink by storing carbon within its cells, providing a reprieve from typical carbon-intensive building materials. When insulated and protected from the elements, wood can last generations. Additionally, mass timber offers the potential to be recycled if the connections and assemblies are designed for future convertibility.

Canada is home to 9% of the world's forests, covering over 347 hectares and 38% of the country's land mass. With over 90% of these forests on publicly owned land, the government has implemented silviculture practices for sustainable management of these areas. Sustainable harvesting seeks to maintain residual forest structures dispersed evenly throughout and grouped into islands of intact pieces of forest that are left to maintain diversity and protect wildlife habitat. (Pitt, 2009). Sustainably harvesting certifications such as FSC "must be paired with legal protection of intact forests if biodiversity and ecological services are to be maintained over time." (Grant, 2012) Sustainable forestry practices aim to promote new growth to preserve renewable resources while conserving invaluable ecological zones of biodiverse areas.

1.3 Multitude of benefits of mass timber

Pairing local, natural, and renewable resources for housing is important for multiple reasons. First, the cultural significance of using bio-based, organic, and locally sourced materials has a veritable connection to the locale and indigenous culture of the Inuit people. Through the study of historic indigenous structures, many employed wood, bone, or other naturally occurring materials which washed onshore as primary structural components of their dwellings. In the summers, these materials would be lightweight and allow for transport to more remote areas that offered superior hunting, fresh water, and security. In the winter, animal skins, oil for heating, and other resources would be used to create warm and comfortable interior environments for the long, dark winters. Utilizing wood within contemporary housing allows for a veritable connection to the natural world while using a material with a lower thermal diffusivity than stone or earth. Second, timber is a renewable resource that can be sustainably harvested and is readily available within the province of Quebec. The major Quebec ports that service Iqviq are Montreal and Quebec City. These cities have several mass timber processing plants that can provide regionally sourced materials to the remote community by boat. Lastly, cross-laminated timber (CLT) and nail-laminated timber (NLT), and dowel-laminated timber (DLT) are structurally stable, thermally massive, and easily assembled for modular housing applications. The benefits of using mass timber for housing offer a robust yet lightweight material that can withstand the environmental impacts of the Canadian Arctic while creating a livable space that better connects these people to their land.

While industrialization has dramatically impacted the construction industry since the late 19th century, timber has only played a "subordinate role." (Huß, 2019, 9) The 2015 International Building Code (IBC) approved using CLT in exterior/interior walls, floors, and roofs for Type IV Construction and as a structural system if manufactured to the Standard for Performance Rated Cross-Laminated Timber (ANSI/APA PRG-320:2012). This has triggered several advances in the design and construction of mass timber buildings. While this has been published extensively recently, it is important to state that mass timber has lower embodied carbon and produces lower greenhouse gas emissions during manufacturing than alternate assemblies. Advancements in life-cost analysis and the "shift from a prescriptive approach to sustainable design toward systematic, performance-based considerations" allows users to make informed decisions about what products designers specify and use. (Dangel, 2017, 62)

Pre-fabrication for construction in remote areas has several sustainable design benefits, as discussed above. In addition, the prefabricated mass timber panels also reduce waste and time of on-site labor for construction. The ability to decrease time in these harsh weather conditions almost precludes other means of building while also ensuring tight-fitting envelopes and highly resilient connections.

1.4 Wood and thermal diffusivity

Wood is distinctive as a natural material that can accumulate energy by heat transfer, as an isolating material, and one that can equilibrate different temperatures more slowly than other materials. The R-Value of softwood is 1.41 per inch (2.54 cm). Therefore, a 3-ply CLT panel used for exterior wall and structure can already have an R-Value between 6.35 and 9.87 (see Table 1 below). The required envelope design for thermal resistance (RSI/R-Value) found in the Housing Construction Guide to Good Practices published in 2017 is high and requires careful planning to ensure tight envelopes. This is assisted by increased control of prefabrication, where air tightness and continuity of insulation can be closely monitored and tested before deployment. With the addition of thermal resistance associated with mass timber, it is possible to use natural fiber, such as

recycled denim insulation, while limiting rigid insulation to satisfy the recommended thermal resistance values for this Arctic climate.

Table 1: Thermal Resistance Factors for Arctic Climate Zone

Recommended Values		
	R-Value	RSI
Roof	51.0	9.00
Wall (above grade)	29.0	5.11
Wall (foundation)	17.0	2.99
Floor	29.5	5.20

Insulative Design Values*		
	R-Value	Inch
Denim Batt	21.0	5.5"
	30.0	8.0"
Compressed Straw	21.0	10"
	41.0	17.5"
Rigid CLT Wall Panel	7.5	1.0"
	6.35	4.5"
	8.46	6"
	9.87	7.5"

*Numbers above do not consider windows, doors, and mechanical service penetrations.

Students were given these insulative values to design their prefabricated panels to satisfy the thermal resistive requirements.

Source: (Société d'habitation du Québec, 2017)

2. CLIMATE AND CULTURAL CONNECTIVITY

2.1. Colonialization and cultural resilience

As an embodiment of culture, architectural artifacts can connect us to our heritage. Inserting architectural forms that ignore the indigenous culture or the vernacular rooted in climate specificity, local materials, and the place is a form of colonialization. Architecture has long been used to establish dominance over native populations by directly embodying power structures and distant cultures they represent. The Canadian government during the 19th and 20th centuries used formal settlements to fix indigenous populations of northern Canada to lay claim to extensive lands to the north. However, this hampered indigenous histories of migration to follow the caribou herds while relying on fishing and whaling to sustain their livelihood. Climate change, overfishing, and the European whaling industry that began in the mid-1800s have decimated the once extensive local food supply and caused local populations to rely on more contemporary means of living. This lifestyle shift requires the importation of food, clothing, and even buildings to survive.

It could be argued that any architecture designed and constructed without the input of local people and culture would continue to reinforce colonialization structures already in place. This topic could be an entire paper unto itself. While the studio researched the local community and indigenous vernacular structures to attempt to reconsider building practices that can reconnect the Inuit people with their natural surroundings through architecture rooted in phenomenology and culture. The studio itself was speculative, using technical with ecological and environmental knowledge within a single, sixteen-week semester. Ultimately, the best remedy would be working with the Inuit population directly as the client to get their input for the designs of their homes. The current housing stock is both inadequate in number and isolates occupants from the environment while not allowing for easy manipulation or mending of the structures once deployed. Employing a more reflexive model of educating both the designer of the culture and utilizing more resilient architectural materials can foster more emphasis on self-reliance while dismantling the existent power structures that have been in place since first contact.

As outlined within Lola Shepperd and Mason White's book "Many Norths," understanding this expansive territory is multivalent. Architectural and social solutions go beyond solar geometry, building science and understanding geographic conditions as we attempt to comprehend the complexity and vastness of Canada's Nordic region. Shepperd and White expounded on Louis-Edmond Hamelin's "Many Norths" to present ten different factors for defining regions from the economic, northern extent of roadways, boreal zone limited by mean July temperatures not reaching 10°C, permafrost and 10,000 Heating Degree Days Line – all which Ivujivik is beyond. Its northness is unquestioned. How can architectural design create thermal comfort within a treeless, permanently frozen ground with nearly sunless winters and nightless summers? How can architects reconsider foundations and connections to the ground within the Canadian Shield encircling Hudson Bay, which is the largest area of exposed Precambrian rock in the world?

3. STUDENT OUTCOMES

3.1 Studio Methodology and Delivery

This studio was offered during the spring 2021 semester amid the Covid-19 pandemic and therefore was entirely virtual. The studio prompt of 'Remote Control' was born from the idea of remoteness and attempted to recreate connectedness through a virtual, synchronous studio format using platforms such as Zoom for audio and video connections and Miro as a virtual studio 'pin-up' space to record the ongoing and iterative student work. With two semesters of virtual studios previously completed, the format was embraced by inviting several experts to present virtually to the studio to present their ongoing work and expertise in environmental design, mass timber fabrication and implementation, cultural connectivity, and Arctic design via remote interviews and presentations. Since travel was cost-prohibitive and disallowed due to the ongoing Covid-19 pandemic, experts from the University of Montreal, Arctic Design Lab, and Canadian architects who deal with the climate complexities and native communities regularly via Zoom. Climate specialists and mass timber engineers joined virtually for design reviews and discussions essential to the studio's success.

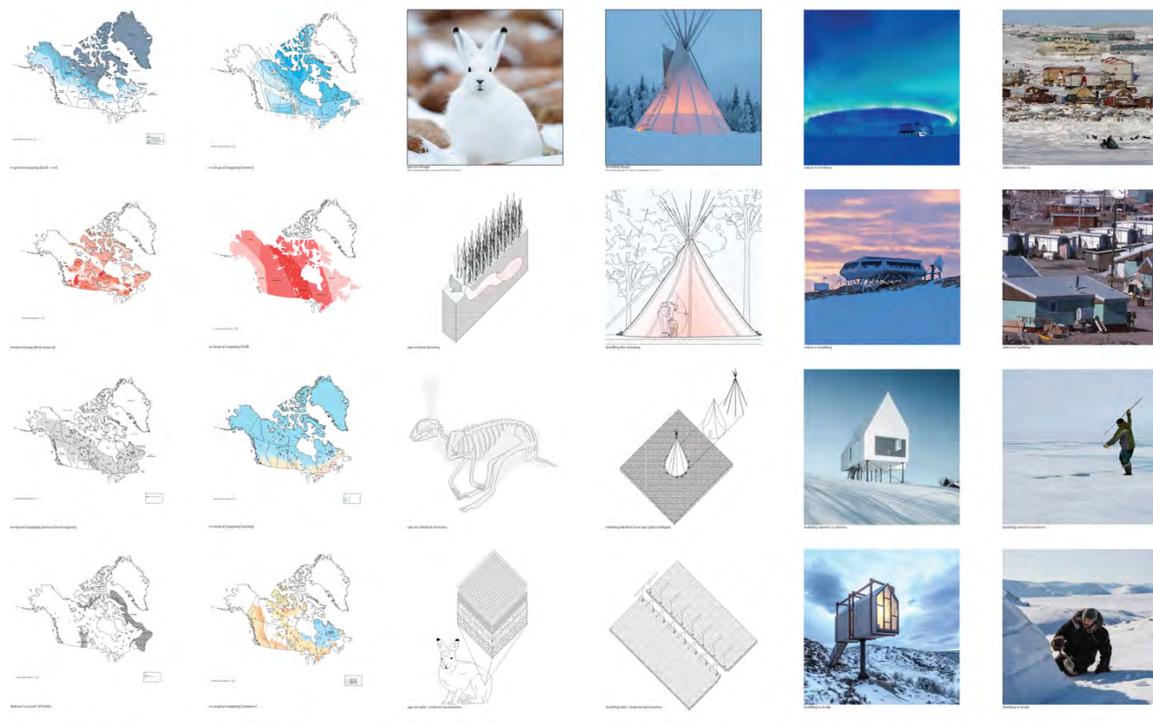


Figure 2: DNA Matrix drawing describing the territory, climate issues, thresholds of biological and vernacular architectural systems, and current cultural situations within the region. Source: (Colton Grieger, 2021)

The specificity of choosing a remote location such as Iqviqvik premeditates some design decisions, such as prefabrication and climate-based design strategies that deal directly with the severity of the site. The realities of the place were presented as the precursor for design decisions.

3.2 Natural processes and learning from the environment

Students began researching existing climate and weather patterns within the area. Solar angles, wind direction, speed, the relative dryness of the frozen air, and dry bulb temperatures throughout the year. This empirically rich study was coupled with each student choosing an indigenous population and investigating their vernacular structures. Questions such as how they mitigate climate, source materials, construct dwellings, and deal with seasonal fluctuations through their architectures were addressed. Not all indigenous precedents were located within the Arctic region. However, specific discussions of place, space, and connections to the land were interrogated and compared to determine why one form of architecture prevailed or became repeated. Students were also asked to find exemplary images of contemporary buildings that embodied the region to address preconceived notions of image and place-making. The final aspect explored within the semester's initial research phase was for each student to pick an animal from the Arctic region of Canada to study. These studies explored skeletal structures, thermal resistance through skins, furs, and fat tissue, and how each animal burrowed, hibernated, or migrated throughout the year. Each of these studies was shared with the class and offered a toolkit of vernacular and biomimetic structures rooted in place.

3.3 Program plus

During the second phase, as students grappled with the environmental and site contexts such as the sloping permafrost, existing rural community, and the sea, the architectural program was introduced. Accompanied by a series of readings, film screenings, and lectures from outside experts, students developed 'wildcard' spaces that introduced a specific need or amenity that was either lacking or required attention. For example, some students determined that a community meat locker and kitchen would be beneficial, others a community library or café, and others still thought an indigenous heritage center or greenhouse would be most appropriate. This offered a diverse array of architectural solutions that were tied to the people and designed with the larger community in mind. By introducing a community component, students were required to investigate existing conditions, map the rural community, and determine what could be beneficial to the larger community and the individual success of their project. Also, having a larger spatial component within the program allowed for the investigation of why, how, and where to differentiate the small housing modules with a larger communal space within the envelope.

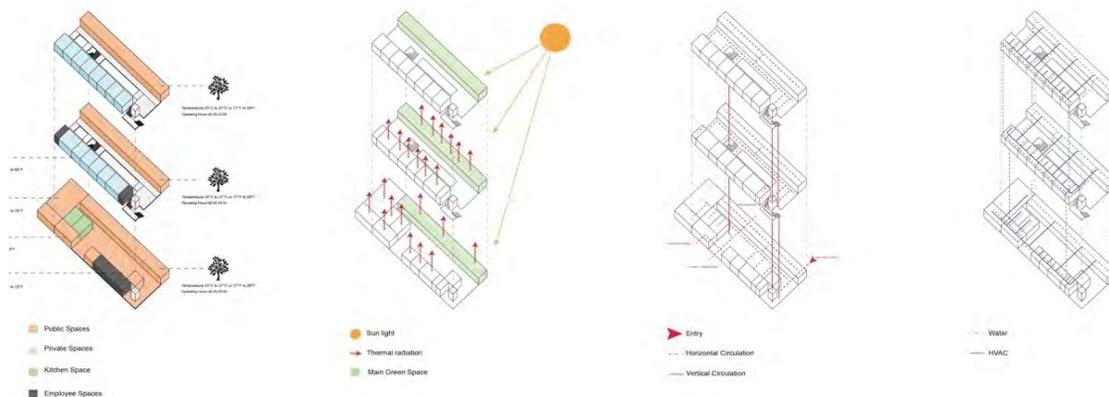


Figure 3: Systems diagrams investigating open and closed systems that exchange with the larger environment. Source: (Timothy Tipparch, 2021)

3.4 Biophilic design and health

With the massive housing shortage in the northern territories of Canada, finding a more sustainably derived solution can benefit the material and resource issues and create comforting interior environments for their occupants. The visual warmth of a wooden interior, coupled with adequately sized and thermally broken windows to provide views and light during the day, can allow for a more comfortable space. Solving the current overcrowding issue and truly designing spaces that are enjoyable to live in during the long, dark winter months.

The realities of limited daylight hours, a total of only five hours during the winter, coupled with nearly twenty during the summer months, students investigated territorial climates and weather patterns of freeze and thaw and geographic conditions, followed by an extensive understanding of how animals and people have adapted and mediated their environments to survive. A deep and thorough investigation to better understand the realities of this remote location also coincided with documentation through reading and film of the area a people who live there. Givens in our more temperate climates, such as sun angles, diurnal temperature swings, and the relative notion of hot summers and seasonality and even when and where the sun rises and sets created interesting considerations throughout the semester set in this extreme environment. The importance of airtight thresholds between interior conditions and innovative solutions towards pre-fabrication and constructability were important modes of operation for the studio. As we continue to consider the real effects of climate change on future architectural solutions, students participating in courses such as this will be better prepared to tackle such questions.

3.5 Building technology and design

Purely technical rationale, solving only issues of acclimatizing the interior space without considering connecting the people to the land ignored the indigenous culture and history of colonization embedded within the architecture. Throughout the semester, students grappled with fanciful design ideations and the harsh reality of climate, culture, and construction, ultimately balancing the imaginative with the pragmatic. Many students desired to engage the sky, stars, and distinct landscape features throughout the year with minimal envelope penetrations to the all-important insulative envelope. This differs somewhat from more traditional architecture studios that employ fully glazed floor-to-ceiling façade solutions for more nuanced and purposeful

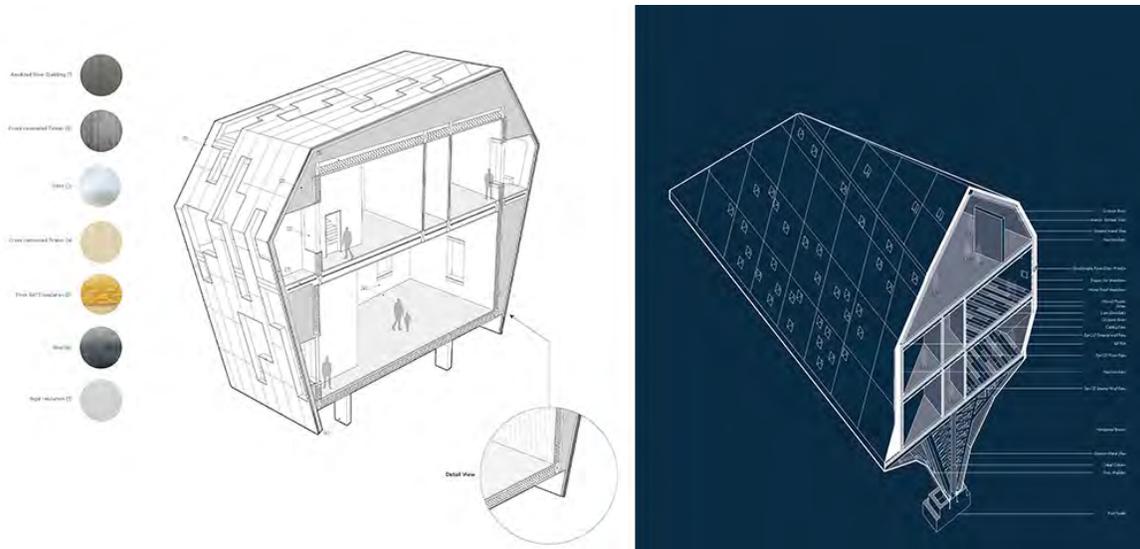


Figure 5: Digital 'bay model section' translating the insulative properties of whale blubber into the thickened 'poche' of the architectural envelope and the specifying of materials for the assembly. Source: David Nelson (left), Colton Greiger (right).

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The Virtual Facade Mockup for Architectural Education

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ABSTRACT: Creating high performance facades is increasingly an architect's environmental responsibility. Teaching these complexities are challenging in the evolving academic environment of limited time and resources. Virtualization projects of construction details offer a method of providing deep substitute learning experiences. These cannot be in place of hands-on real world lab experiences. We evaluate the coordination of both these methods across two courses in our architecture program in this paper to discover opportunities to exploit both. Evaluation of both techniques reveals that hands-on and virtual explorations are not exclusive; rather, they ultimately complement each other by indicating an increasing need for both to exist. Programs with less focus on digital modeling may face difficulties implementing virtual modeling techniques described in this paper and its instruction-based scenarios.

KEYWORDS: Façade, education

INTRODUCTION

In architectural programs with limited hands-on construction experiences available for students, virtual facade mockups may offer a method of creating deeper learning experiences of building construction. Balancing these virtual projects with opportunities for simpler hands-on experiences can give programs more flexibility, especially for programs with budgetary constraints and those evolving to remote and asynchronous learning models. For institutions with less or no resource constraints, virtualization offers new modes of experimentation for the student to better understand how performance and design are related. Found in necessity, this paper reveals an admission: the 'technology' of the architectural discipline is constantly placed into a laboratory of experimentation, where the material and experiential modes of environmental construction are reevaluated, reexamined, and revolutionized. The pressure-cooker of new technologies found in academia are reciprocated back and forth with professional desires to achieve the cutting edge of design performance. This paper explores one of these moments, reexamining the potential crossover of virtualization and hands-on mockup construction.

1. THE VIRTUAL FACADE MOCKUP FOR ARCHITECTURAL EDUCATION

1.1 The usefulness of mockups

Mockups are generally the place where architectural ideas meet reality. They are extremely useful for understanding construction details, and working through those details with collaborators. In education they can serve an even more important role in helping students better understand the details involved in constructability, aesthetics, performance, and embodied carbon reduction. While constructing physical mockups might be considered the "gold standard" they come with a heavy cost in time, effort, and flexibility. Virtual mockups allow much of the same level of exploration and understanding with the advantages of speed, flexibility, and autonomy (a student can build remotely and asynchronously)(Figure 1). The virtual mockup, as artifact, has other advantages, allowing the study of a facade detail to be scaled to a specific section of the total facade, providing a more manageable way for students to focus on specific details (Figure 2) and not becoming overwhelmed with the full facade.

From a theoretical viewpoint, some might assume the discipline of architecture is focused on the making of buildings, and that such a projection is the long and short of it. However, there resides an obvious precarity in such an assumption, and begs even further, a clarifying question: Do architects make buildings, or do they merely assemble instructions for how to build a building, as manufacturers of lines on paper? Put another way: Is the architectural artifact the building or the set of instructions? In a more protracted view, how do digital technologies and virtual experience extend the role of the architectural artifact, especially as it regards the conceptualization and production of architectural components, like flashing, bricks, expansion joints, electrical quads or insulation? The relevance of these new 'digital' developments, specifically as they relate to a

pedagogic interface, is intertwined with the 'use value' applied across space and time - the 'how' of which students measure the efficacy of the architectural artifact.



Virtual Mockup

Real World Mockup

Figure 1: Virtual vs Real Mockup. Source: (Author 2023)

Still the final element of the instruction process is the translation of the virtual artifact into the physical artifact through construction. The physical artifact as an instructional tool takes particular significance in transforming the virtual facade mockup experience into an understanding of the real-world implications of virtual design decisions with consideration of mass, flexibility, fragility, and gravity. Particularly for applied research, hands-on discovery is crucial in transitioning an otherwise nebulous concept into one that has mass and shape. Much of the construction of the physical artifact is centered around a tactile understanding of that virtual experience where additional decision-making and critical thinking occur, clarifying that the drawings and other artifacts we create as architects are a vehicle for fabrication and do not exist wholly in a virtual space. The process of translation from the abstract to the real is the core of the architectural student's full design experience, and educating students on the production of the physical artifact can be understood as being the arbitrator or negotiator between the freedom, experimentation, and expressiveness in a virtual space, with the constraints of physical design, from specifications to structural concerns.

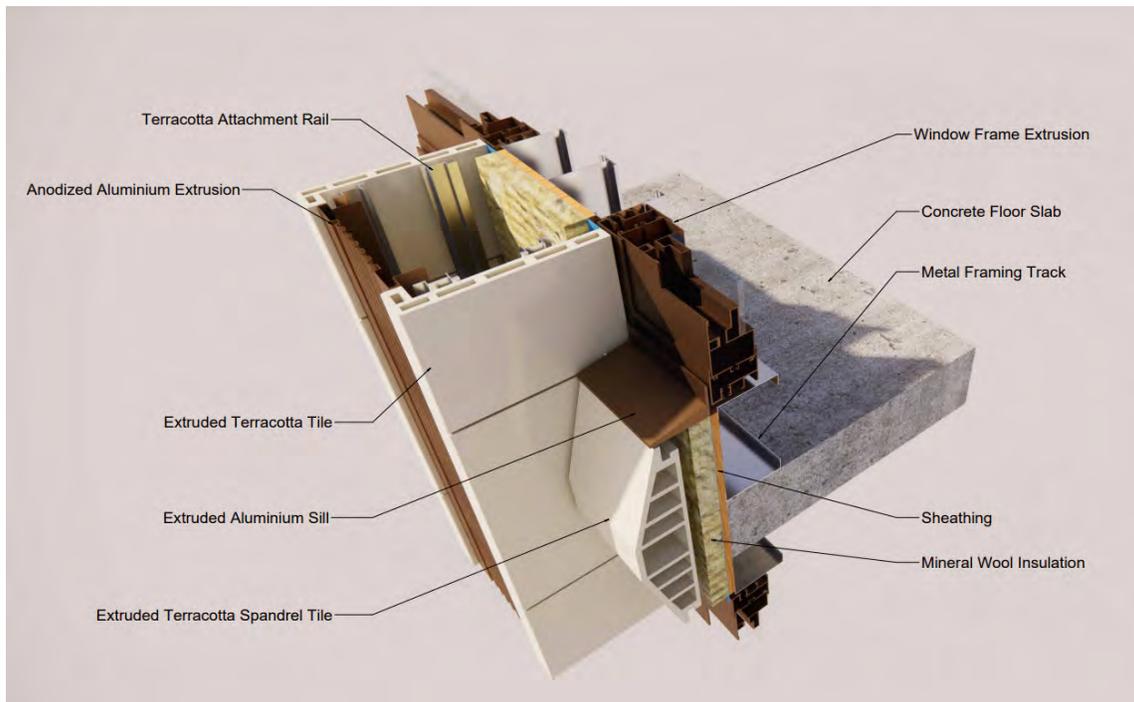


Figure 2: Virtual Mockup Detail. Source: (Author 2023)

1.2 Balancing virtual with real world

If we are to provide design experiences that are more weighted to the virtual, can we provide physical mockup experiences to the student in ways that inform without burdening the process? Is the creation of common types of facades in a lab a strong enough experience to meet this important requirement? We are currently evaluating the use of a reusable mock up platform that allows students to quickly explore process-based design and constructability concepts.

Representation and virtualization are important distinctions for what architects do: create drawings for the construction of buildings and create virtualizations of building artifacts. This space of creation also admits the construction of negotiated space - where different actants perform different roles for a singular goal: the built environment (Ruges, et al, 2022). For example a window placed in a planometric view is a representation, but when that same window is created in a BIM environment it becomes part of a digital model. When viewed in model space the window component reveals details of its construction: trim, sash, glass, etc. The visualization is only limited by the details embedded in the component. Indeed, the applications of these digital visualizations are robust, and provide more nuanced and more experiential play/introspection/modification throughout the design process. If architecture is the translation of building to drawing, then virtual visualization explodes the possibilities for how designers conceptualize and pragmatize the built environment – the methods of testing extend beyond the technical aspects of drafting lines on paper, or of allowing software programming to manufacture digital lines in a digital space of the computer screen, of ones and zeroes (Eastman, 2018).

Students in a program with a strong BIM foundation have an increasingly difficult time distinguishing the difference between representation and virtualization; this is especially true as BIM and other modeling techniques become more detailed and complex. In fact this blurring is an industry focus – the concept of digital twins ‘virtually’ evolving. (<https://www.ibm.com/topics/what-is-a-digital-twin>).

‘Virtual’ as we are proposing it, is the detailing of a set of building components for the purpose of creating a better understanding of a proposed configuration. This is critical for visualizing complex component arrangements that cannot be easily described in drawings and sketches. Essentially, we are taking a highly complex object and reducing it to virtual components – components that can be isolated and further detailed for situational development and correction.

‘Mockup’ is a method of framing the project exploration through the use of the analogy of construction site *mockups*. This allows us to focus on regions of exploration for specific sections of a facade. The intention is to not overwhelm the student with the other details and conditions of a full facade.

2. CLASSROOM PROJECTS

2.1 Our specific educational constraints

To set the context for the development of a Virtual Facade Mockup at our institution, SUNY Alfred State, it is important to understand the constraints. Our current modeling shop is located in a room on the fourth floor; artifacts transacted in and out of the space are limited to fitting through a 3’ wide door (standard threshold parameters). The school has provided some access to high-bay space, but this is limited in terms of functional access and performance. As well, such a space does not contain the necessary tools/machinery for effective modeling, experimentation, and research. Recently, we have initiated the construction of mini-mockups with our first-year students in our smaller lab with some success; even if the space has proven limiting in terms of faculty initiating projects at full- or near-scale construction. Moving to a virtualization of facade-models will allow us to explore at a scale and complexity not easily accomplished with current material and spatial resources.

2.2 Setup for the virtual project module

In the fall of 2022, we introduced the module of Virtual Facade Mockup as the culmination of our exploration of facades in the Design Studio 1 course. Modules are one week long explorations of a technical facet of architectural design. The first module explored detailing of a rainscreen wall construction using a pre-built BIM component containing all of the elements of a rainscreen design, including panels with capillary breaks, venting, pressure equalization space, exterior insulation, air and moisture barrier, etc. In the following week, modular curtain wall construction was explored and included extrusion design, attachment systems and calculating deflection from wind loading. Modules are composed of an introductory lecture on concepts and techniques, followed by an active learning experience using digital tools (Revit (BIM), Rhino, Dynamo, Testfit) as appropriate. Instruction for this component was pre-recorded allowing students an asynchronous learning experience, an accessible means to revisit, resaturate, and relearn instructional material.

The lecture component of the Virtual Facade Mockup includes an introduction to punched facades and building performance, overview of facade materials, visuals on facade fastening systems and thermal break techniques, finishing with real examples of punched facades. The lecture was given live and a pre-recorded version was made available for review.

The active learning introduction for this module varies from previous methods of step-by-step processing, to an overview of self-directed activity. In the video overview we describe the reasons for making mockups of facades for projects, show and describe visuals of attachment systems, and illustrate examples of virtual construction of facades. Then we give an example of the expected project deliverables, including model views, labels, sections, modularity, and renderings. Finally we describe and provide a 'start' model (Figure 3), containing components (brackets, extrusions, insulation etc.) that they might find useful (and necessary) in the construction of their project. This virtual kit of parts is not unlike a lab pack or the supplies in a real lab. Future development of the course might include other parts/components allowing students to make choices on the selection of construction elements, adding aesthetic performance and functional simplicity.

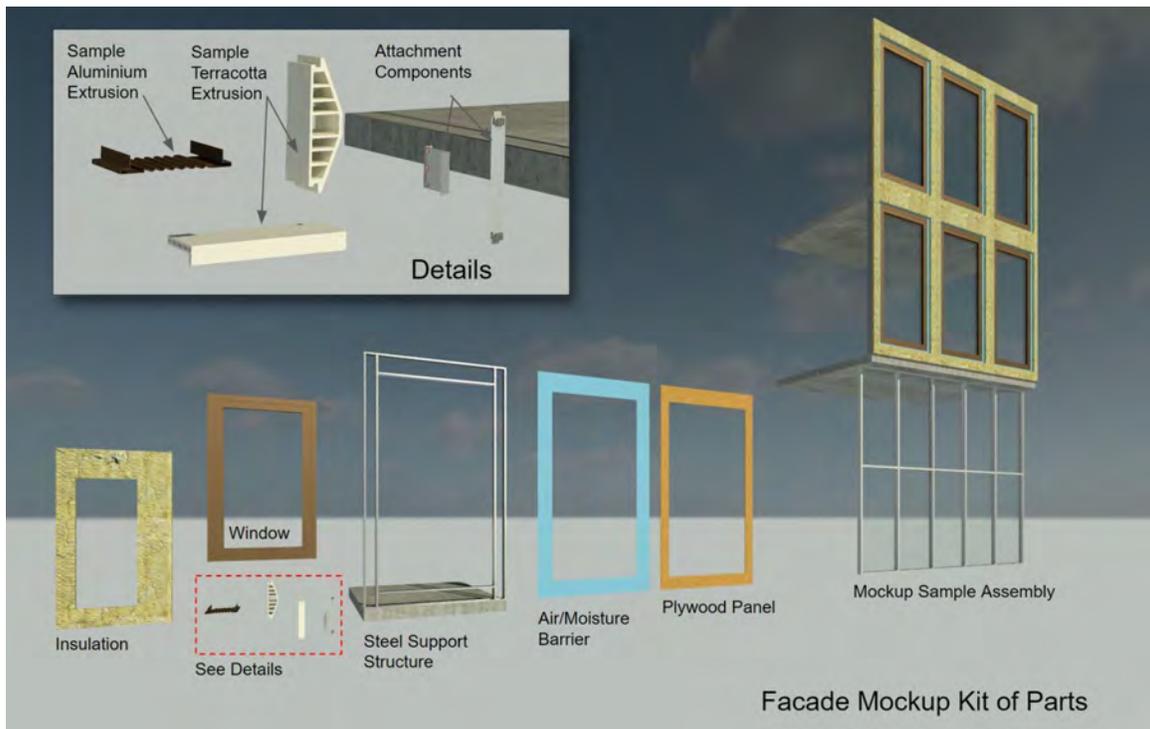


Figure 3: Start Module/Kit of Parts. Source: (Author 2023)

2.3 The first run of the module/class characteristics

The course for which we are testing this module is titled Advanced Structural Concepts. This is a technology course offered in the fifth year of our 5-year BArch program. In recent years students have requested access to this course earlier in their sequence, citing the content would be directly useful to studio and thesis work. Usually the class size is around 15 fifth-year students but this year has increased to 25, the additional students in their fourth year. These students, as a cohort, are highly motivated, noting a desire to take a required course earlier.

The course itself has evolved to keep pace with technical changes in the industry, including advancement in materials (e.g. Mass Timber ETFE), computation design tools, and generative design techniques. The focus on facades is a result of increasing awareness by the architectural community on building performance to help address environmental concerns.

At the completion of all project modules, students are asked to write a narrative describing their experience. Typical comments answer questions of how difficult they thought the project was, what they got out of it as a learning experience, and how it might be improved. The narrative for this project was captured along with the project screenshot on a spreadsheet so we could analyze the lesson in more detail. After reviewing the project in totality, a set of criteria was developed to judge alignment with perceived goals. By perceived goals we

mean those anticipated from the lecture content delivered and the project outline as presented. Next a rubric was created to map individual performance to selected criteria (Figure 4).

	A	B	C	D	E	G	H	I	J	K	L	M	N	O	P	
1	Last Name	First Name	project grade					Similar Facade Fatigue	Rainscreen Vent Gap	Details Structure	Thermal Break	Exterior Insulation	Instructional Support	Technical Comfort	Punched Opening	
16				This module was more fun than the rest. As much as I like having the videos I almost wish it was always a 20 minute video introduction and maybe another video or two explanation. From your master of the design. I like the work flow better because I usually spent the same amount of time I always do but, it was more organized. I would like more modules to have the style of learning in the future.												
17				In this module I explored the creation and development of modular wall mockup as well as the details and structural integrity of designing one. The panels are a terracotta veneer that is held in place by aluminum clips that are very similar to the ones that were used in the rainscreen system. They fit together to create a weaving pattern that will serve as an organic pattern that can be devised of two alternating panels that create a dynamic.												
18				This module explored the creation and development of modular wall mockup as well as the details and structural integrity of one. The panels I created are a blue-wood material accented by aluminum facades, with the vertical slats curved out for the window. The metal panels are supported by ground leveling with an air barrier in between, attached to metal framing. The metal framing attaches to the structural columns through simple brackets attached to both. To ensure the panels are connected accurately, each one has alignment pins on the top that connect to holes in the structural support, creating grooves for the center of a wood block, as well as ensuring the structural necessity of the panels to create the mockup.												
19				I didn't mind this module. It was a bit challenging to design my own system. I decided to combine the clips and rainscreen system, making my own simple rainscreen model. This helped me understand the systems a bit better but I already had a good understanding from the previous modules so I don't think this module was as educational as previous modules.												

Figure 4: Rubric Spreadsheet Excerpt. Source: (Author 2023)

2.4 Rubric criteria

2.4.1 Experience criteria

1. **Project Fatigue:** Too many similar experiences (Facade Fatigue). 3 affirmative out of 22 reported. Pedagogical response: Some early harsh criticism in the narratives made this appear to be a larger concern than it turned out with only 3 identifying it as an issue. Example comment “This module was very repetitive and, in my opinion, did not teach me anything new.” Still it is likely we will look to reduce by at least one the number of facade modules we present.
2. **Adequate Instructional Support:** 14 out of 22 reported. Pedagogical response: Here we were looking at comments to see if the instructional materials were adequate from the students narrative. Example comment indicating insufficient instruction: “I was very hesitant to start this project because I felt I did not know enough to complete it.” Likely introducing the project before the lecture will help students better connect lecture content to the exercise.
3. **Adequate Technical Understanding:** 14 out of 22 reported. Pedagogical response: Most students did not comment on needing more technical explanation even when their projects showed a lack of clear understanding. Example of an exceptional comment: “Maybe it would have been more helpful if we had more images of how that facade is created and how they are bolted on to the building.” More examples of attachment systems in simplified forms may help with this issue.

2.4.2 Understanding criteria as demonstrated in the project model:

1. **Understanding of Fundamental Rainscreen Concepts:** 9 out of 22 reported. Pedagogical response: Many students failed to identify or include a ventilation gap between the facade and the insulation. Possibly overwhelmed by other details, this fundamental omission is a cause for concern. The first way to address it is in making the labeling of this feature a project requirement, rather than relying on them to self identify.
2. **Credible Detailing of the Facade System:** 12 out of 22 reported. Pedagogical response: Technical bluffing in the details was apparent with students creating solid mass objects with no clear attachment methods or understanding of the hollow nature of the element to which they are attaching. Calling these issues out in examples during lecture might make students more accountable for what they model.
3. **Understanding the Location and Need for Thermal Breaks:** 4 out of 22 reported. Pedagogical response: This was an attempt to see how deep their understanding of building performance goes. While the information was presented and thermal break material was included in the start file, it was seldom used or labeled. Requiring the placement and labeling in a future project should help build more awareness.
4. **Proper Placement of Exterior Insulation:** 11 out of 22 reported. Pedagogical response: Many students underestimate the required thickness of insulation and many times place it in the incorrect location in the facade “sandwich.” Some additional review of thermal and moisture performance from earlier lectures and a refresher of coursework in Environmental Controls1 will help.
5. **Use of Punched Opening Concept:** 21 out of 22 reported. Pedagogical response: The idea of a punched opening concept was put forth to students as a way to increase facade thermal performance by reducing glazed area. While almost all students delivered facades with punched openings, almost none of them looked at minimizing glazing to save energy. The future project will require a specific ratio of glazed to opaque.

2.5 General outcome

More than half the students did exceptional work exploring facades at a deeper level than would have occurred in our program normally (see Figure 5).

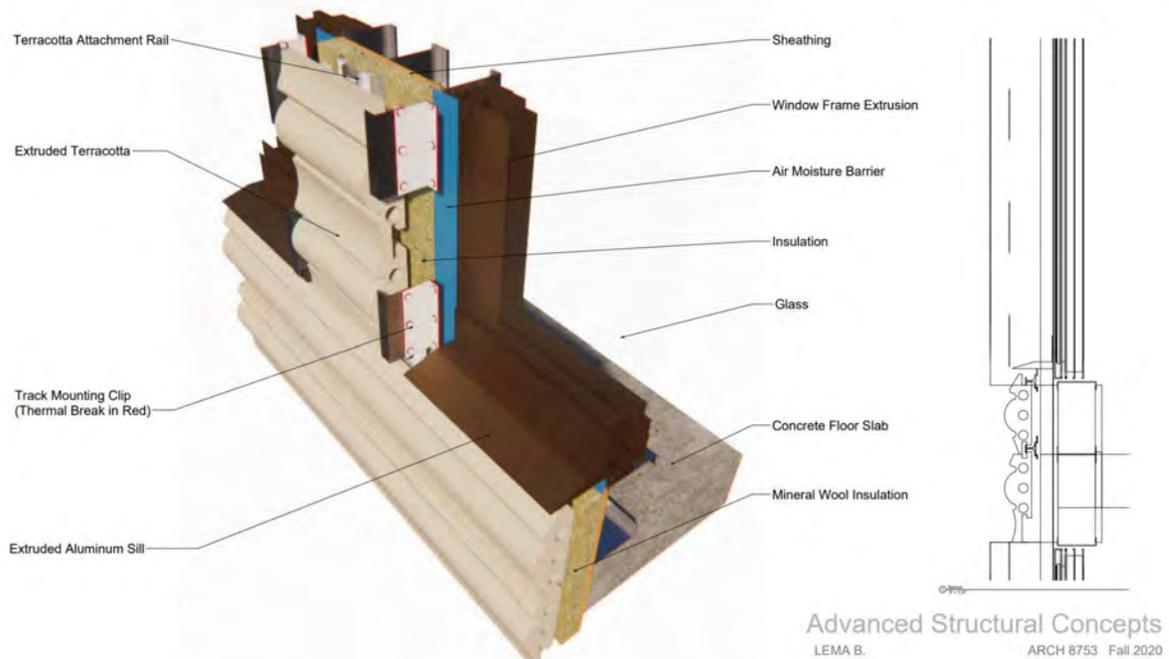


Figure 5: Sample of Student Work. Source: (Author 2023)

3.0 The need for balance with physical models and mockups.

Often, students in contemporary architectural education rely on virtual tools (drawings and physical models) as the beginning and end of a project's existence. Students rely on the tools at-hand in the virtual space; present is a temptation to understand a project as 'complete' without considering the implications of their work outside of a virtual workspace. An equally important extension of the virtual facade experiment is to create real-world applications of facades that are modeled. It is becoming apparent that as virtual tools have matriculated into the method most heavily relied on by students, it is important to reinforce to students and faculty alike that these modeled ideas have to translate into a physical form. These artifacts, whether in physical or digital form, articulate a space of representation, but as the virtual extends the sensory environment with greater specificity, the representation exists with greater concreteness or play; allowing the designer to modify and transmute in real time. Ultimately, the 'value' of what is real and what is representational becomes more robust, if not more universal. (Riegl, 1982) The difference between a classical approach to architectural representation (drawings and physical models) and a more contemporary, virtual approach (coding and a grammar of BIM), is the way in which the end product leaves its material trace. (Parikka, 2015) The artifact is stringent and reliant on its source manufacture, but its means and ends are garnered by the virtual work applied by the designer (and the student, in our case). Virtual means proctor a radical expansion of the design process, and leave a multitude (read: infinite) of archival nodes upon which designers can revert or develop.

3.1 The physical mockup

In our Design Studio 1 course we explore wood-frame construction in a modular residential design setting that provides a low cost and accessible opportunity to build a physical mockup (Figure 6). This simple physical experience allows students to cut, drill, and hammer real materials and understand them at a visceral level. Further, it helps students develop empathy for tradespeople facing the challenges of translating virtual to real artifacts.

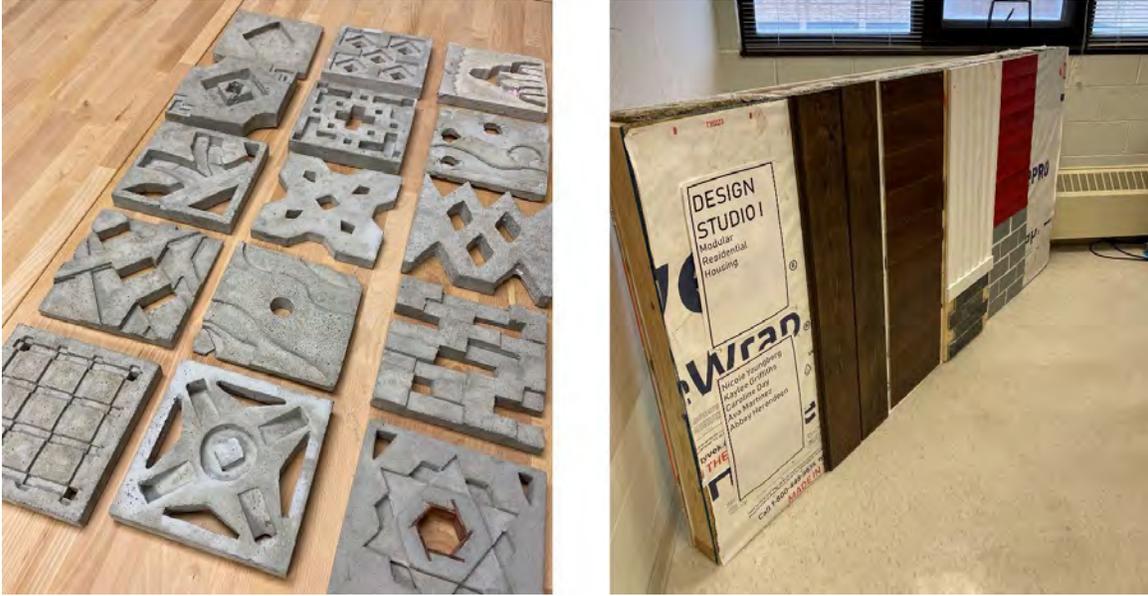


Figure 6: Student's work of tiles and facade mockup. Source: (Author 2023)

The mockup itself is a rudimentary understanding of the residential wall buildup. Although simple, the process establishes the relationship between the virtual iteration of the construction and the real. For the mockup, the students were allotted an amount of resources provided by the institution: OSB sheathing, Rockwool Insulation, $\frac{5}{8}$ " gypsum wall board, $\frac{1}{4}$ " furring strips, and Tyvek homewrap. Students worked in groups to assemble a traditional American wall buildup, with minimal instruction, allowing the students to determine what each element in their wall buildup was 'for'. For example, 16" O.C. studs can be represented both in plan and in a three-dimensional space, but how does that look in practice? What does 16" O.C. actually look like? What is $\frac{5}{8}$ " thickness on an exterior wall and how does it modify the interior partition?

On the exterior, students were given approximately 14- $\frac{1}{2}$ " between studs to apply their exterior facade material. Students were allowed to purchase the material directly or mock up difficult to find exterior finishes. In our region, aspects such as exterior concrete or GFRC siding are difficult to find, and the student population our institution serves have financial burdens that are not insignificant. The students were tasked with applying their facade as an accurate representation of how it would be done in the field. For example, students applied Z-Clips to the back of their wall panels and on the exterior OSB. Some students chose to use the furring strips to create an air gap. Others applied mesh backing and brick ties to mimic a traditional residential brick exterior.

The construction process provided students with the opportunity to understand the tactile nature of architecture, a process that is lost in the virtual realm. The students were also able to investigate the challenges with on-site construction. For much of the construction portion, there was considerable debate among students on how to assemble the stud framing. Many came to rest on the method that would be applied in the field: attaching the studs flat on ground and then "raising" the wall framing. Students also had the opportunity to understand the tools and methods of the trade: How does one cut evenly? What actually is a nominal dimension? How do we divide material of standard dimensions in a way that minimizes waste with limited materials? Perhaps the most difficult, "How do we add fractions?" One of the most influential of the real-world implications the students took away from the work was the weight and heft of construction and construction materials. The final mockups at 4'x8' with complete framing and exteriors were approximately 60lb.

To supplement the construction of the wall mockups, students were required to create a complete document set with wall and facade attachment details. The construction documents served much as they would in the field, as a bridge between the digital world and that of physical construction. Details of the attachments encouraged the students to investigate the methods in which we represent aspects using architectural graphic standards and how those standards reflect in the construction process. Within our curriculum, this course was taken in conjunction with Construction Technology I, where students begin their understanding of construction materials, standard representational techniques, and how they are applied.

With the position of the course in the first semester of the student's second year, the physical mock-up was intended as an introductory tool to both the students and the institution. For the students, it is likely their first

interaction with building materials, construction methods, and the tools of the trade. As an institution that has oriented its pedagogy toward applied learning and providing a real-world education, this project is a rudimentary introduction to the practicalities of using facade mockups in our architectural curriculum. With the relative success of a simple facade development project, there is a window for application in the future.

3.2 The balance between methods

Despite the distinct methods, the two methods of instructing facade design provide valuable comparative data. The virtual facades provide an accessible and cost-effective study of complex building systems. Students can investigate and consider a wide range of facade options and understand the interactive nature of building systems. The virtual space allows students to research, investigate and test with little consequence other than time. It further allows them to understand at a deeper level a facade system that may be infeasible to construct in physical form.

Although simplistic and regimented in nature, the physical model gives students the experience of working with building materials and understanding their interactions. It allows students to realize their ideas they have conceptualized in the virtual space and on their construction documents. The students connect the ideas that their decisions in a virtual space have consequences in built form, whether they be positive or negative.

The accessibility of these two methods is crucial in providing students with a comprehensive understanding of building systems. While the virtual methods allow for experimentation and a detailed understanding of contemporary building systems, the physical construction allows students to interact with the building components they have themselves designed, allowing them to see their work manifest in built form. Constructing the built form is a push and pull between the virtual and physical. The relationship is inextricably linked, and bridging the gap between the two is crucial for the comprehensive understanding of the student.

CONCLUSION

Introducing the methodology of virtual facade mockup construction into curricula has allowed us to develop manageable and meaningful hands-on construction experiences, while ensuring students get a deep technical understanding of high performance facades that would not be possible with current resources and course delivery methods. In a broader perspective regardless of resources adding virtual facade modeling adds a new means to understand and interrogate facade construction. Creating the aforementioned duality and its hybridization proctors a new method of epistemological formation for students, as well as faculty. Such a formation extends the pedagogic environment in ways that are adaptive and fluid, making the student as future-professional more conducive for revolutionary and re-evaluative change.

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XX-LAM: The Architecture of Curved Cross-Laminated Timber

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ABSTRACT: *Since its inception in the early 90s, cross-laminated timber has surged in popularity as a credible alternative to concrete and steel. Its myriad uses, based on advancing the materials science of timber composites have culminated in new methods of prefabrication, mass production and fast-track assembly. However, perhaps its most significant benefit is its proven capacity to sequester carbon. This paper suggests that to maintain the upward trajectory of mass timber, it should also subject itself to an ongoing process of formal and material experiments that are then evaluated as an architectural language. It presents a research project (XX-LAM) that explores these possibilities through an experimental approach to the act of making. In this case, the term “cross lamination” (or X-LAM) is adopted as a conceptual strategy wherein the material science of wood lamination is combined (or “crossed”) with the discipline of late modernist formal exercises like the New York Five’s “kit-of-parts problem” with particular reference to the work of John Hejduk. The research concludes by applying these forms to speculation on the architectural language of typical building typologies. It presents a series of iterations that combine vaulted ceilings, circular openings and curved vertical extrusions. These iterations produce new materiality, form and architectural language that are interpretations of “free plan”, “cycloid barrel vaults”, and groin vault architecture.*

KEYWORDS: cross-laminated timber, formalism, “kit-of-parts problem”

“If the 19th century was the century of steel and the 20th century the century of concrete, then the 21st century is about engineered timber.”

Prof. Alex de Rilke

1. FORMALISM & ENGINEERED LUMBER - TWO CONCEPTUAL POSITIONS

Since its inception in the early 90s, cross-laminated timber has surged in popularity as a credible alternative to concrete and steel. Its myriad uses, based on the advanced material science of timber composites, have culminated in new methods of prefabrication, mass production and fast-track assembly and, above all, its proven capacity to sequester carbon. However, in recognising the undeniable benefits of mass timber, the architectural profession, at times, appears to acquiesce to an architectural syntax defined purely by its means of production. This paper suggests that to maintain the upward trajectory of mass timber, it should also subject itself to an ongoing process of formal and material experimentation to be evaluated as an architectural language. It presents a research project, XX-LAM that combines fabrication studies of curved cross-laminated timber with a “formalist” approach to architectural synthesis. In this case, the term “cross lamination” (or X-LAM) is adopted as a conceptual strategy wherein the material science of wood lamination is combined (or “crossed”) with the discipline of late modernist formal exercises that include John Hejduk’s *Nine Square Grid / Kit-Of-Parts Problem*, New York Five and the influence of Historian Vincent Scully.

2. X-LAM – A “MASSIVE SYSTEM”¹

In many senses, CLT today can be seen as the next phase of the postwar expansion of forestry production. In the US, it is directly connected to the de-skilled construction industry and the postwar expansion of stud construction. Globally, this production scale has many big ag similarities, particularly adaptations of post-soviet military infrastructure to forestry in Eastern Europe. In the US, it is not surprising that certification construction grade CLT (ANSI APA PRG 320)² is based largely upon existing dimensional lumber strength grading or plywood certification. In this way, these emergent forms of timber lamination have segued neatly into large-scale forestry production where new facilities are, in many cases, extensions of existing mills, especially those with glulam capabilities. With few exceptions, these facilities deal exclusively with spruce, pine and fir (SPF) softwood lamstock and produce large billet (40’x10’) using planar hydraulic press beds. There is a similar homogeneity to the application of lamination adhesives. The majority of panels produced both in the US and Europe are bonded with polyurethane and melamine glue and are CNC cut to produce a prefabricated, dry assembly system that can outperform concrete (and often steel) for onsite construction. Under favorable circumstances, CLT can be exported for a global market, and both remain cost-effective while still achieving net carbon sequestration.³

The refinements of these bonding techniques go hand in hand with specific structural and formal constraints that vary according to program. These can roughly be categorized as cellular, planar tectonic systems for compartmentalized arrangements like housing on the one hand to a point-loaded trabeated language for open plan programs on the other. These systems then translate to CLT walls and slabs for the former and glulam

post and beam with mass timber slabs for the latter. These structural patterns, along with the increasing inclusion of CLT in the IBC have allowed many architects to use a basic construction technique to replace concrete and steel.

From this perspective, it is possible to imagine that architects will soon come to adopt CLT as “system” rather than a discipline or as building rather than architecture. We might argue that the expansion of engineered lumber is in danger of becoming industrialized to the point that we will miss the chance to establish its own architectural language. Furthermore, the “moral imperative”⁴ engineered lumber (sustainable, practical, affordable) may justify superseding the kind of disciplinary analysis that every emergent technology undergoes in complex architectural synthesis (space, proportion, promenade, and architectural composition). In recognizing the (undeniable) benefits of mass timber, the architectural profession, at times, appears to acquiesce to an architectural syntax defined purely by its means of production. At times its materiality adopts a similarly passive aesthetic stance, i.e. that the “natural” beauty of wood is enough in itself. The powerful eco-message of a new green architecture often seems to exempt it from disciplinary considerations like tectonic systems, formalism or notions of *Gesamtkunstwerk* – all considerations that might transform it into an architectural language of its own.

3. XX-LAM – “CROSSING” NINE-SQUARE-GRID COMBINED WITH CURVED CLT

With this in mind, in the fall of 2022 *PLAIN Design-Build* established the *XX-LAM Design Research Studio* to explore a series of new possibilities for mass timber architecture. The studio sought to challenge the current tectonic system of mass timber by combining ideas about architectural “formalism” with new techniques of bonding single curvature CLT. In this way, the studio was framed by a conceptual point of departure that adopted “cross lamination” as a theoretical strategy as well as a technical one. It proposed that the physical pattern of cross-lamination is also used as a metaphor for analytical, synthetic and creative activities with the aim of creating new hybrid conditions of architecture. From this strategy, we derived the name *XX-LAM* because cross-laminated timber is sometimes abbreviated to cross-lam or X-LAM, and the additional “X” refers to the conceptual strategy of “crossing”.

Having set up *XX-LAM* as a conceptual “lens” for exploring new forms of mass timber architecture, we then analyzed the theoretical precedents that might provide useful parallels to contemporary forms of engineered lumber. From a disciplinary perspective, these “formalist” exercises focused on the late modernist architectural theory of the New York Five as well as the work of historian Vincent Scully. Particular projects from these authors were, respectively *The Nine-Square Grid Kit-Of-Parts Problem* (Hejduk and the New York Five) and Scully’s 1974 publication, *The Shingle Style Today or The Historian’s Revenge*, both of which allowed us to draw parallels between the 60s / early 70s architectural theory and mass timber architecture at a number of levels.

These parallels offer a useful critique of overtly rational architecture. In speculating that mass timber is in danger of becoming overly logical in its repetition of structural formula, it is useful to remind ourselves that NY5 had come to a similar critique in the late 60s, i.e. that European and US modernism had reduced itself to dull, functional repetition⁵. If this is the case, then what might come out of a study of mass timber if we subject it to similar “principles of architecture as an autonomous discipline”? How might these exercises support a purely sculptural, spatial poetic of mass timber? Furthermore, can this supposition be further reinforced by the way the *kit-of-parts* idea appears to have an uncanny precursor in pre-cut flat-pack assembly systems of CLT construction (rough 80% of mass timber buildings are a prefabricated kit)? This parallel aided us in “functionless”, purely formal experiments of those “parts” by translating “point, line and plane” into glulam columns, beams and CLT panels. This offered us a way of seeing beyond the constraints of a purely functional grid i.e

“plan diagram itself could a subject of critical inquiry emerged from post-war architectural theory in Colin Rowe’s essay “Mathematics of the Ideal Villa” (1947). (Timothy Love)

It is difficult to avoid a renewed discussion about the language of wooden buildings in the US without considering the influence of Vincent Scully. While much of Scully’s argument (based on the idea that wood represents the historical narrative of American “identity”) may seem questionable today, his observations about the uniquely wholistic quality of timber seem much more prophetic. If we study parallels between the total wood *Gesamtkunstwerk* of many mass timber buildings and those chosen by Scully, similarities start to appear. In some cases, the buildings of Scully’s “second wave” seem to offer a kind of “proto CLT” language to them. These similarities are most notable in the work of Robert Gwathamy, Edward Barnes and Charles Moore⁶.



Figure 1: Charles Moore The Sea Ranch and Susan Jones' CLT House

By aligning contemporary mass timber buildings to those depicted in the *Shingle Style*, we can establish a path back to earlier theory and provide added influence to emerging forms of mass timber architecture. XX-LAM suggests that Scully provides a model to explore a possible third phase of his narrative, this time based on engineered lumber.

Finally, we felt that it was worth exploring another parallel in the aesthetic similarities of material homogeneity.

“While the kit-of-parts problem refocused design education on the definition and articulation of space, and on the enrichment of the “architectural promenade” (achieved with spatial elaboration), the exercises most decidedly de-emphasized the material aspects of architecture” (Timothy Love).

While it is true that the NY5 considered materiality a non-issue in the experimental phase of the nine-square grid, this sense of non-materiality went on to characterize many of the buildings that were eventually built. Many of these architects felt that by separating architecture from any distinct material associations, they would allow a rich variety of spatial relations to emerge more easily. Initially, this dematerialized architecture was seen as a way of stripping it from any cultural bias that comes with material choices⁷. Although this varied in the outcome, there was certainly an attempt to celebrate a kind of synthetic material indifference or anonymity. In the case of John Hejduk this led to an all-stucco rendered architecture, with Peter Eisenman, buildings appear to be made as if they are large architectural models, and with Richard Meier, the homogenizing, Purists associations of white modernism. These influences can also be applied to Brutalism and the celebration of the totalizing materiality of cast-in-place concrete. However, the parallel between these forms of architecture and new forms of mass timber architecture only lies in a shared sense of homogeneity. Frequently when you look at CLT buildings, particularly in the interior, they celebrate a total wood aesthetic and often use different types of engineered lumber to resolve all elements of that building (often to reduce the number of trades). While this produces the effect of giving them a similar homogeneity to New York Five architecture, this homogeneity has a radically different materiality. Mass timber buildings' advantages are that are homogenized through the natural texture of wood and are in stark contrast to the deliberately synthetic appeal of late modernist architecture in the USA.

4. DESIGN EXPLORATIONS- CURVED ENGINEERED LUMBER AND THE “KIT-OF-PARTS”

XX-LAM explores the potential of the homogeneous materiality of CLT to create beautiful, sculptural spatial conditions. Proposals adopt the plan as a spatial generator, with an emphasis on a free arrangement of basic elements of planar and cylindrical walls. All compositions modulated a sense of enclosure, and circulation within the nine-square structural frame. The iteration shown in Figure 2 was focused on movement through the space while arranging the elements along the grid in an absolute manner. The location of elements relates directly to either the intersections or midpoints of the grid.

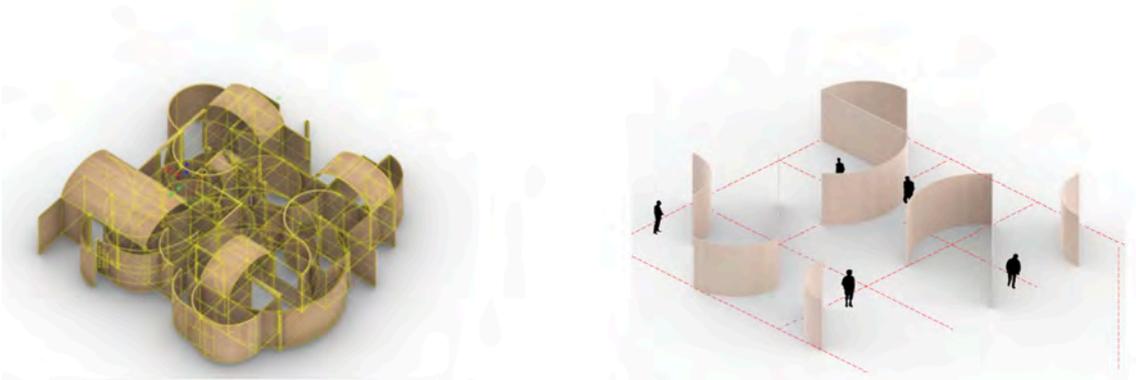


Figure 2: Jacob Urban - XX-LAM Studio Masters Student & Figure & Composite of all iterations - Jason Griffiths

"Use of planes and pure geometric volumes -- cubic and sometimes cylindrical; manipulation of two- and three-dimensional compositional systems -- such as grid patterns -- to modulate space, structure and surface.

The way to see plan as a spatial generator is by simplifying the plan as an arrangement of four basic architectural elements, columns, slanted walls, cross columns, and rooms, and each element forms a type of field that contains a gradient of enclosure, ways of circulation, and structural stability." (Roger K. Lewis)

XX - LAM then develops its conceptual position by simultaneously exploring abstract compositions while learning to fabricate construction-grade CLT in curvilinear forms. The initial explorations of Nine-Square-Grid arrangements were, at the same time, tested against our ability to resolve the technical challenges of full-scale fabrication.

After proposing initial grid layouts, the studio focused on vac-formed bending methods, lumber types, glue varieties, bending radii, connection conditions, and layer depths. This process allowed the studio to refine the parts for a full-scale installation.



Figure 3: Timber types and lay-up studies XX-LAM Studio

Testing a different number of layers included concentric arrangement in odd numbers (Figure 4 shows three, five, and seven) This uneven number of layers is used for strength to combat the internal compression and tension forces placed on the centre layer instead of allowing that force to act on the bonding surface if it were an even number of layers. Further consideration was given to the thickness of each layer until we settled on five layers of 3/8" that were efficient and thick enough to be considered for building. Testing thicker layers than 3/8" produced cracks along the length while thinner layers would begin to split across the width of the boards used in the longitudinal orientation.



Figure 4: Post vac-formed lay-ups - XX-LAM Studio

After exploring a range of possible different timber species, we settled on local pine and eastern redcedar. Both varieties of softwood were proved flexible and durable enough to withstand the forces of bending in a vacuum former and maintain shape when glue bonded with minimal spring back after drying. These varieties could be sourced with minimal moisture, which was important in allowing us to process the raw boards into the desired dimensions. Once bonded, this solid mass of wood and glue made these panels extremely flexible for structures and could accommodate perforations for mechanical fixing. This allowed us to connect panels with one-foot threaded rods that were fastened between hole perforations to complete multiple panel assemblies.

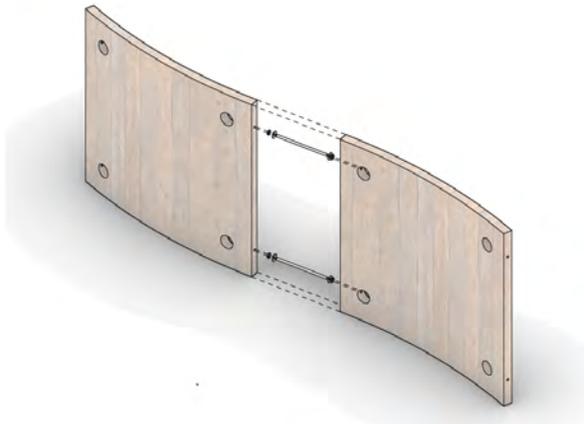


Figure 5: Jacob Urban - Panel-to-panel connection

The learning process directly shaped the final arrangements of *XX-LAM*. The homogeneity of the composition and its inherent strength as a construction material, proved incredibly durable when tested in full-scale arrangements. In the first assembly *XX-LAM Exhibition* at Omaha by Design in the fall of 2021, a combination of 5' and 10' radius panels were assembled in an interior configuration around an existing grid of wooded columns. These panel modules and mechanical fixing allowed us to quickly test different spatial arrangements at full scale. In the next iteration at Wesleyan's Elder Gallery⁸ we added more modules and reconfigured the arrangement as a vertical enclosure. This arrangement explored the implications of interior architectural moments within the field condition that refer to details of Hejduk's Project A - Diamond House configuration⁹. This arrangement was restricted to a concatenation of curved panels arranged with tangential continuity between panels to form a simple curved enclosure. While this arrangement suggested a complex curve, it could be simply formed by two radii and flat panels.

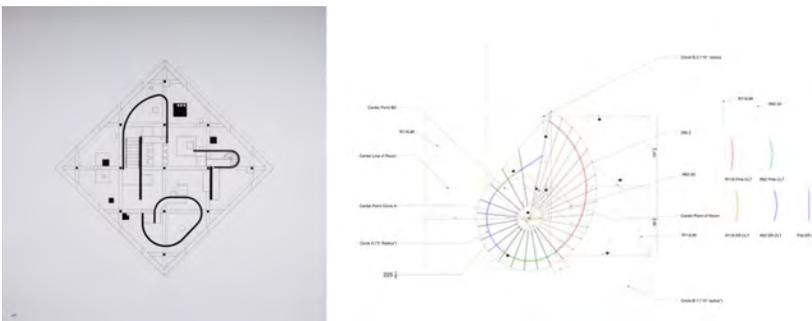


Figure 6: John Hejduk (1929–2000), Project A, Diamond House, 1969 and *XX-LAM* Installation at Wesleyan Elder Gallery



Figure 7: XX-LAM: OBD Exhibition fall 2021 and Wesleyan Elder Gallery summer 2022

These full-scale configurations led to a series of speculative multistorey typologies that propose three outcomes for an iterative syntax for mass timber buildings.

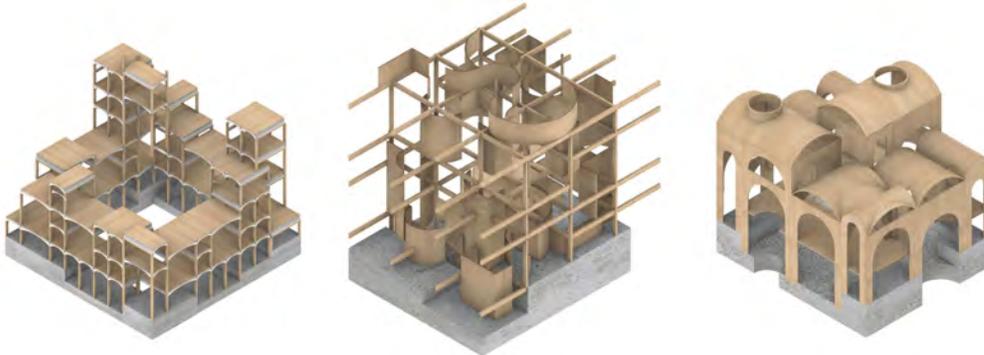


Figure 8: 3 Multistorey Speculative configurations - Jason Griffiths

Version I consists of point loaded glulam column structure with glulam beams and single-direction vaults of curved cross-laminated timber floors. This system is an extension of the Nine Square Grid in 1:2:1 proportional relationship. Grid spacing is on 10 and 20-foot centers and vault radii 10 or 20 feet. Vaulted slabs are composed of a permanent formwork comprised of a five-layer CLT vault, a layer of foam insulation, a poured concrete slab topped with a timber floor.

Version II consists of a point-loaded glulam column and beam structure with curved and planar CLT walls. This system is comprised of single curvature CLT walls that divide spaces between columns and are independent of structure. Formal studies demonstrate free-floating or intersecting column and wall proportional relationships. Grid spacing is on 20-foot centers with curved walls in 10 and 20-foot radii. Curved wall spaces are created through concatenation of curved wall radii joining with tangential continuity or at 90 degrees with planar CLT walls. The floor system (not shown) consists of CLT slabs in composite concrete and foam insulation or suspended floor arrangements.

Version III consists of planar CLT wall and floor structure with single curved vaulted elements. This system is arranged on a 1:2:1 proportion with single, double and triple height volumes. Curved CLT elements comprise mostly of vaulted roof structures in 10 and 20-foot radii with one-directional spans of 10 and 20 feet. These vaulted structures are arranged as barrel vaults and groin vaults with spans intersecting at 90 degrees. Planar, curved CLT elements also include cylindrical light wells. Planar CLT elements include semicircular arches and circular/ semicircular CLT floor penetrations.

CONCLUSION

In the last 20 years, we have seen a remarkable proliferation of mass timber buildings, beginning first in Central Europe and then subsequently in numerous locations around the globe. In North America, this began first in Canada and the Pacific Northwest and then subsequently within the southeastern states, along with a considerable scattering within most US cities. The bulk of these buildings refines a five to six-story mid-rise typology that results in a simple trabeated architectural syntax of a point-loaded column and beam structure with planar floor slabs. While this arrangement offers clear benefits over concrete and steel from both fabrication and sustainability perspectives, these attributes alone may mean that mass timber may circumvent a conscious discourse on their architectural syntax. Without this input, the future of mass timber buildings as an architectural language may stall as they are fast-tracked into a standardized system of construction.

Project XX-LAM is a research project that speculates on potentially diverse forms of timber architecture by adding single-curvature planes to the current palette of available mass timber elements. This research combines the technical challenges of fabrication with experiments into autonomous, spatial and compositional possibilities. Adding this element of curvature allowed us to reconsider the current point-loaded grid arrangement as the “frame” element within the “kit-of-part nine-square grid” exercise. This parallel, along with a homogeneous timber, materially draws many parallels with the disciplinary discourse of late 60’s architectural theory in the US. By combining these technical and cultural factors, XX-LAM speculates on a potential syntactical procedure to define a new architectural language for mass timber buildings.

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John Hejduk, *Plan for Texas House (1953-1963)*. John Hejduk, *Collection Centre Canadien d’Architecture/Canadian Centre for Architecture, Montréal © CCA*

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- ¹Ted Cavanagh refers to Thomas Hughes’s use of the term " Massive System" to describe the scale of stud production and industrialization of forestry in the US.
- ²ANSI/APA PRG 320: Standard for Performance-Rated Cross-Laminated Timber covers the manufacturing, qualification, and quality assurance requirements for cross-laminated timber (CLT). This certification has been adopted for most CLT buildings in the US and is included in the International Building Code IBC
- ³The most recent example of this is White Architecture’s Sara Kulturhus in Skellefteå - one of the world’s tallest wooden buildings. Therese Kreisel, Skellefteå’s head of urban planning, says that Sara kulturhus has been constructed from 12,200 cubic meters of wood from trees harvested from within a 60km radius of Skellefteå. The amount of carbon dioxide stored is equal to approximately 13,500 flights from Stockholm to New York
- ⁴The 1982 debate between Christopher Alexander and Peter Eisenman. Eisenman argues against a “moral imperative” within architecture that ignores the significance of disorder and disharmony. This term might be applied to mass timber architecture if it is solely predicated on sustainable principles. http://www.kataraxis3.com/Alexander_Eisenman_Debate.htm contrasting Concepts of Harmony in Architecture
- ⁵Timothy Love’s *Kit-of-Parts Conceptualism* describes the deliberate manner in which formalism of the nine-square grid problem deliberately deflected from functional considerations and focus upon architectural form as an autonomous exercise.
- ⁶Each of these examples are drawn from Scully to illustrate the similarities between contemporary CLT buildings and what Scully advocates for in *The Shingle Style Today*. These similarities are most apparent in the interiors with boarded walls and solid timber for load bearing structure especially at Sea Ranch.
- ⁷In many ways, this process of stripping back architecture to fundamental principles can be traced back to similar exercises like the early Bauhaus Vorkurs program. Johannes Itten’s preliminary courses for students entering the program brought all students to a similar starting point to disinvest them of any precognition of architecture in much the same way as *The Nine-Square Grid*
- ⁸The aim of each exhibition was to keep adding to the installation until it could become a complete building. The first two installations have led to a third phase currently under construction as a “blind” for viewing prairie Dogs at UNL’s Cedar Point Bio Station
- ⁹This arrangement was also informed by enclosures within Corbusier’s *Mill Owners’ Association Building*, in Ahmedabad especially the curved panelized auditorium on the third floor.

Precision and Constructability: Formwork Design for the Pulitzer Arts Foundation in St. Louis

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ABSTRACT: Construction means and methods and the ingenuity of tradespeople are often de-emphasized when discussing award-winning architecture. Means and methods are contractually isolated from the architect's design and regularly the specifics are not documented as tradespeople seek to protect their own knowledge. Through the example of the Pulitzer Arts Foundation, this paper provides a narrative on how excellence can be achieved, not just through design, but also through construction means and methods. As a case study, this paper considers the specifics of the design and installation of the formwork for the Pulitzer Arts Foundation in St. Louis which was completed in 2001. It frames construction decisions within a broader discussion of the difference between precision and accuracy. It examines measure in relation to constructability, and how error was handled not on a case-by-case basis but through an ever-evolving process of refined decision making. Discussion includes the selection of the formwork material, processes for maintaining consistency in attaching the formwork to the structure, adapting the Peri Formwork system to meet the specifics of the project, and how the team invented individual solutions to fit the particularity of the pours. It examines how the legacy of the precision of Japanese construction was scaled and translated to the United States, allowing this project to meet the standards of quality that Tadao Ando established in projects in his home country.

KEYWORDS: Means, Methods, Constructability, Concrete

INTRODUCTION

When Pritzker Prize winner Tadao Ando presented Emily Pulitzer with his design for the Pulitzer Arts Foundation in 1993, the drawings expressed his ideas through a few juxtaposed rectangles. While extremely understated, these initial drawings served to define the geometry of the building and the rules for its construction. This form created photographic-like surface planes across Tadao Ando's architecture that captured the concrete's variation in color and pattern. Precision of construction allowed this variation to be ascribed to the nature of the material rather than to deficits in craftsmanship. Total alignment required total exactness, and the tradespeople on the project were tasked with developing means and methods to achieve scrupulous precision in each concrete wall. Fundamental to this was the design and erection of the formwork.

1. CRAFT, ENGINEERING, AND AESTHETICS

Tadao Ando's work seeks a Platonic purity of form. However, as one approaches the building closer and yet closer, new ranges of resolution show "new complexities of newly perceived formal elements."¹ For example, the aligned circles of the form tie holes are easily perceived many feet away. But as one moves closer, one notices the nearly imperceptible imprinted pattern left by the screw heads that attached the form liners to the formwork. Only 1/8th of an inch in diameter, those screw heads are perfectly aligned across the panel. As one moves closer to within inches of the surface, one loses focus on the screws, and now notices the crispness of the geometry of the holes left by the form ties. Each step forward reveals new layers of detail.

In handmade carpentry, craft can be evaluated by the skill of the hand using the tools of the trade. The carpenter's body is part of the making – the slight turn of the finger or imperceptible push of the hand is controlled by the well-trained eye. David Pye, in his book "The Nature and Art of Workmanship," coined the term the "craft of risk" as exhibiting work that is most attuned. Pye defines this type of workmanship as "the quality of the work is not predetermined, but depends on the judgment, dexterity, and care which the maker exercises."² He asserts that working in a manner that is predetermined, certain, or unchallenging fails to attain the craft of risk. The mind in concert with the eye and hand controls and advances the work. By contrast, in engineered production, calculated precision is accomplished through machining – or the design of tools and machines to produce goods. The engineer solves the problem, and the machines deliver the answer. The result is a consistent and interchangeable solution. It is calculated, and success is measured by how closely the product meets the tolerances as specified.³ Both the concrete and the formwork system at Pulitzer are fundamentally engineered products. However, instead of designing machines and predetermined processes to deliver the goal of perfection, success relied on the individual skill and craft of the tradespeople as they tailored the use of these engineered materials to the specifics of the design.

The aesthetics of Tadao Ando's work emphasize alignment and smoothness. The perfection of the formwork is important to producing the beauty of this outcome, but the specific craft of making the formwork itself is not

part of the overall aesthetics. The formwork is eventually cast away. Aside from the signature pattern of circular indentations that indicate the location of the form tie holes, no mark of the formwork construction methods shows in the final surfaces.

Additionally, Tadao Ando did not wish for the construction team to adopt Japanese joinery methods. Instead, he preferred that the team use the methods with which they were familiar, but at the highest level of craft. The construction team used traditional American cabinet joinery methods to maintain alignment, and to keep joinery tight. Biscuit joints provided alignment between adjacent form liners, while details such as light fixture inserts mounted to the formwork were connected with dadoes using routers, and then gasketed to prevent leakage. The differentiation of creativity and beauty as separate from exhibiting the mark making of craft (or *techné*) is recent in Japanese culture. The study of Aesthetics is an entirely Western construct, and it was only with the opening of Japanese culture to the West in the 1870's that this dichotomy was introduced. Previously, the making of the object and the object itself were considered inseparable.⁴

2. PRECISION, ACCURACY, AND MEASURE

Tadao Ando required no deviation and no variation. The pours had to be both precise and accurate. *Precision* gages how close measurements are to each other, while *accuracy* focuses upon how close a measurement is to a predetermined dimension or number. Physically, the eye can easily see roughly the width of a fine human hair. Objects smaller in width tend to visually converge when placed adjacent to each other. Touch is noticeably more sensitive with surface patterns at the size of a micron (1/25,400 of an inch) distinguishable as a fingertip moves across a surface.⁵ Beyond sight and touch, measure is often in reference to an external device. As measurement is rounded up or down to a nearest mark, closer and finer fittings or increments allow for less error. At the Pulitzer, benchmarks for accuracy across the exterior of the building were equivalent to those established for millwork on the interior of the building.

At Pulitzer, from pour line to pour line the dimension is exactly twelve feet. It is not 12 feet and a 1/16th. It's not 11 foot and 11 7/8". I can go any place in that building right now, and I can take anybody's measuring tape out there and I'll bet my life on the fact that it'll measure 12 feet exactly. The tolerances are that close, and the fact that the team was able to hit those tolerances, that's the amazing part.

Steve Morby, Project Superintendent

The formwork needed to be straight and plumb. Initially the surveyor could stand on the ground and use a transit to establish elevation heights into the lower level on pier caps and the lower walls. These elevations set the initial horizontal lines that were used to establish the expansion and control joints, and the pattern of the formwork. However, once the lower-level walls were done, the team recognized that alignment had to occur within the building. The team poured construction decks which were later covered with a poured concrete walk surface. The concrete construction deck became the place from which measurements were taken. To establish a reference line a straight line the length of building was scribed by saw into the deck surface five feet off the center line of where the walls would be poured. By establishing this datum line any variation in the edge of the concrete deck became unimportant. For an eighteen-inch wall the center line had a nine-inch offset. Thus, the exterior walls were set 5'-9" off from the inscribed datum line. All measurements were made off of the datum to preserve accuracy.

Assembling the formwork, we had to ensure it was straight... The deck of a building is a perfect place to establish that straight line. You have already shot it in and it is level with the joists and it has a solid deck running back to where the top plate is in. Now you know that when you stand that wall, and you check the plumb corners that they are going to be plumb because you just measured it out on the deck. If you do that same wall on gravel, there is no guarantee that the wall is going to be straight.

Steve Morby, Project Superintendent

The structural grid of the building established the center lines for the walls. To create a reference vertically within the building, the team used the same datum line methodology to set a perfectly horizontal line along the entire building, set five feet up from the deck. All locations of elements in the walls, from openings to recessed lights, to cabinetry and interior details were measured up or down from the horizontal line. The construction team learned this method from a millwork company in Chicago. This horizontal datum provided quality control. An installed finish floor might not be completely flat, with varying elevation tolerances. To measure up from a finish floor to set millwork or openings could introduce error. Instead by measuring down from the datum accuracy could be controlled.

2.1 Units of measure

The Pulitzer was built using the Imperial system, while many of Tadao Ando's buildings are constructed using the Metric system. In Japan, the Metric system is considered in parallel with traditional dimensions of the Ken. The design of Japanese architecture is based upon a system of proportions between components (*kiwari-jutsu*) with Japanese aesthetics often defined by simplicity of these proportional relations. The Ken originates in the measure of the width of a post and lintel structural bay in traditional Japanese architecture, with that length depending upon the innate strength of wood.⁶ The resulting proportional or fractional system is defined

as follows: the Ken is divided into 6 Shaku, which is divided into 10 Sun, which is then divided into 10 Bu, and subdivided then into 10 Rin.⁷ The Rin sets the tolerance of traditional carpentry. By contrast carpentry in the United States typically uses tolerances of 1/8th to 1/16th inches at the scale of architecture and cabinetry. Smaller tolerances, +/- .1 mm, can be reached for engineered and machined objects.

Japanese Fractional System and Tolerances

1 Ken = 6 Shaku = 60 Sun = 600 Bu = 6000 Rin

1 Ken = 180 cm = 70 in

1 Rin = .3 mm = 1/96"

Imperial Fractional System and Tolerances

1/8" = 3 mm

1/16" = 1.58 mm

1/32" = .79 mm

Just as Tadao Ando's work adapts to tolerances specific to the measuring system of a culture, the overall proportional system of the design relates to the measurement of standard dimensional sheathing in the region. The Pulitzer Arts Foundation proportional module is based upon a standard 4x8 sheet of plywood. In Japan and in Europe, Ando's module is based on standard metric sheet goods. This smaller size changes the proportions of the standard formwork panel, resulting in one less horizontal row of form ties.

Despite the fact that Tadao Ando elected to adopt Imperial measurements, the construction team still had to contend with coordinating with metric. The team selected the Peri Formwork system to support the form liners. The form liners were 4x8 sheathing, but the shoring, walers, and other support structures followed spacing based on metric dimension. The construction team developed processes for assembling the Peri Formwork system so that the 2'-0" form time spacing remained uncompromised.

2.2 Precision in installation

If accuracy was achieved through cutting a datum line in the building, precision occurred through the development of installation processes. For three years, it was one carpenter's job to prepare the 4x8 form liners for assembly, maintaining quality control across the building. Tadao Ando required alignment of the screws that connected the form liner to the support system. The screws had to align across a twelve-foot straight edge. Quality control was achieved by designating a single person to layout the formwork design and to screw the forms to the gang system for the entire project.

Additionally, tightening the wing nuts on the clamps needed to be consistent to maintain quality control. The clamps on the cone ties needed to be tightened enough that they did not leak, but not so tight that the form liner was imprinted. After eight months of developing a tightening procedure in the lower level of the building, two carpenters with three-pound sledgehammers precisely tightened the wing nuts across the remainder of the building.

3. CONTROLLING ERROR

To construct perfect formwork the construction team developed processes to anticipate and control error. The science of error analysis studies uncertainties, estimating and reducing errors in three areas:

1. Looking at the likelihood of an error to occur based on probability.
2. Recognizing how often an error happens, by focusing upon its pattern of distribution.
3. Understanding where an error may propagate or become larger or multiplied due to the way something is measured or made.⁸

The construction team addressed each of these areas with processes that emphasized reliability, traceability, and quality control. As a result, the team could identify errors quickly, isolate them, and then develop processes to reduce their impact.

The process of selecting and preparing the form liner exemplifies these error handling processes. At the Pulitzer Arts Foundation, the construction team tested four sheathing products: Enviroform, polyethylene coated plywood, plastic laminate, and Fin Form.

3.1 Enviroform and the likelihood of error

Tadao Ando's first project in the United States was Eychaner House. The team selected Enviroform as the liner system for the formwork. The construction team identified black stains on the surface of the concrete after pours. Consulting with the manufacturers, the team analyzed the error. Enviroform was made of rapidly renewable softwood, and the softwood contained significant sugar resin. During the curing process, the concrete reached high temperature. If there was a scratch on the surface of the formwork, sugar resin would

move to the surface of the concrete, transported by liquid in the concrete. As it came to rest along the surface, and the temperature increased, the sugars would burn and turn black. After using Enviroform for Eychaner House, the team was hesitant to employ it at Pulitzer, as scratching in conjunction with the heat of curing increased the likelihood of quality control issues.

3.2 Plastic laminate liner and the distribution of error

As the team began pouring the lower-level walls at the Pulitzer Arts Foundation, they tested additional sheathing. Polyethylene coated plywood acted like a Visqueen coated plywood. The team also tested plastic laminated onto plywood. The plastic laminate was so smooth that it created a mirror like surface on the concrete. Tadao Ando was interested in this form liner, but the team could not guarantee that they could reliably achieve the mirror like surface across every pour as weather and temperature changed. In the end, Tadao Ando and the team selected Fin Form liner. This ½" thick panel could withstand up to five pours without degrading, and the resulting poured surface was reliably similar in terms of quality.

3.2. Variation in sheathing and the propagation of error

Error propagation can occur when variations in tolerance are not controlled. A thirty-second of an inch seems a small increment, but across the length of a building a recurring error can result in inches of difference. The Pulitzer Arts Foundation required alignment both vertically and horizontally, relying upon the expectation that all modules were the same. Tolerances of 1/16" across the 4x8 module, which might be allowable in a plywood mill, had to be accounted for so that variation would not be visually perceptible on the wall. Across the three-year construction span, the team labeled and marked different mill runs, and their associated variations in dimensions to ensure that the form liners would fit together like puzzle pieces, and appear perfectly aligned. This traceability enhanced quality control and decreased the propagation of error.

4. CONTINUOUS IMPROVEMENT

One of the hallmarks of Tadao Ando's work is an emphasis on continuous improvement to the means and methods by which a project is constructed. This process is a feedback loop. As new construction processes develop ever smaller tolerances can be achieved in the design. Tradespeople are encouraged to rethink the ways they accomplish work to constantly improve their craft. These methods are not without risk - as one gets ever closer to perfection new hurdles appear.

Tadao Ando's emphasis on continuous improvement echoes processes that were developed in Japan by Dr. W Edwards Deming, Masaaki Imai, and Shingeo Shingo. These processes were initially introduced as management principles during the Marshall plan to aid in rebuilding Japan's manufacturing capability. Japanese culture embraced these principles and companies such as Toyota became known for continuous improvement processes that sought reduce inefficiency, decrease waste, and increase precision, and quality. Continuous improvement processes implement incremental changes, relying upon workers and tradesmen to suggest improvements. This encourages all workers to be active participants in design and production.

These methods are traditionally applied to replicable processes found in engineering and manufacturing. Codified in the ISO 9000 standard as Continual improvement Processes, these methods are embraced by sectors such as the automotive and aeronautical industry. By contrast, Tadao Ando introduced this kind of thinking to the craft-based work of design and construction. Through emphasizing improvement, Tadao Ando is able to motivate tradesmen to continuously engage in the 'craft of risk' as described by David Pye.

For example, at the Pulitzer Arts Foundation, the construction team selected the engineered Peri Formwork System to support the forms. The system is composed of a bulkhead at the bottom of the form connected to channel iron walers supported by poplar trusses. The trusses are screwed to ¾" plywood sheathing, and then skinned with the Fin Form liner. The entire assembly, in addition to clamping assemblies, provided nearly three feet of thickness. The combination of elements made the system extremely strong and straight along its length.

However, when the building required a corner, the thickness became an obstacle. This thickness prevented locating form ties on the edge of the corner. The corner could not be fastened properly, and this became an opportunity for leakage. In most applications, a material would be used to clad the pour along the facade, so the corner would be hidden. But at the Pulitzer Arts Foundation, if water leaked from the corner, then discoloration, sand streaking, and the loss of cement around aggregate could occur. To resolve this, the construction team designed an outside corner detail, converting the last eight feet of formwork to stick built prefabricated corner panels. These panels were milled so that they tied into the Peri Formwork System, providing a hybrid solution that appeared seamless. The team were able to decrease the depth of the prefabricated assembly placing cone ties near the edge of the corner to achieve full seal of the corner. While

the solution brought together two dissimilar assemblies, the final form of the concrete wall appeared pure and continuous.

Initially the Peri construction company sent their forms fully assembled. However, the team found it was difficult to align them along the vertical direction across the 24-foot-long panel sections. The construction team realized that in order to improve alignment, the Pulitzer Arts Foundation jobsite had to request becoming a factory in the field for Peri. Assembly needed to occur onsite by the construction team, instead of being prefabricated at the factory and delivered. This was highly unusual, but it was necessary to ensure that all the systems could coordinate across the layers of structure.

To assemble the form, the inside and outside panel were laid across from each other...This allowed the through bolts to be centered in the panel from side to side locating the signature pattern of round indentions, or holes, across the face of the concrete walls in Ando's buildings.

Steve Morby, Project Superintendent

Because of the strength of the Peri formwork, the engineers calculated that it was not necessary to provide form ties across the face of the formwork at all locations. However, Tadao Ando still required the signature pattern of circular indentions indicating the location of the form tie holes spaced two feet apart. The construction team found this to be an opportunity for improvement and advancing quality control. The team developed drawings to document the design of each panel, similar to shop drawings but at the scale of the entire building. These drawings allowed the construction team to visually match both sides of each form to make sure that all dummy holes aligned. If a dummy hole was mismatched with a true hole, it could introduce a hole in the form, and a corresponding opportunity for leakage. The shop drawings also allowed for coordination and change to the form liners to accommodate placement of light fixtures, hose bibs, and outlet face plates. The drawings were produced in Autocad by the construction team, with the development of symbols and color coding to designate different form tie details and conditions. These drawings promoted the ability to reuse of form liners multiple times – allowing coordination between similar layouts, until enough inserts for electrical and plumbing infrastructure interrupted the form liner's surface, or repetition of pouring led to degradation of surface.

In addition to rethinking the assembly of the support for the formwork, and developing whole building shop drawings, the team also interrogated the form tie that Peri construction company used with the system. The "B-30 Dayton Superior Coil Tie" is a spreader that defines the width of the wall. The tie fits into a ¾" PVC pipe. A cone interlocks with the spreader to close the assembly and seal it to create the crisp edge along the round indentions that make up a grid on the surface of the concrete wall. During pouring, the construction team discovered that there was a manufacturing defect in the cones. A small chip missing in the sleeve resulted in the cone not fitting seamlessly against the PVC pipe. Water could leak through the chip, changing the cement water ratio to cause black rings around the holes, or in worse cases sand streaking.

In a normal application, leakage was not critical; by contrast, in our situation leakage was really everything.

Steve Morby, Project Superintendent

The team developed a solution: a single layer of electrical tape wrapped once around the cone and PVC pipe provided the correct amount of seal, without spoiling the surface of the pour. It was this kind of thinking and attention to detail that exemplified the continuous improvement that Tadao Ando desired.

CONCLUSION

The selection of the formwork material, the adaption of the Peri Formwork System to meet the specifics of the project, and the invention of individual solutions to fit the particularity of the pours all serve as ways in which the construction team provided quality control, reliability, and traceability at the Pulitzer Arts Foundation. The tradesmen not only drew upon their existing construction knowledge but also developed new methods for assembly and installation. In so doing, they developed ways to best use resources and created flexibility when needed. The design, production, and installation of the formwork serves as a case study for establishing standards of precision, accuracy, and error control during construction, while maintaining hand crafted detail.

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The Mizer's Ruin – Circular Economies and Atypical Forestry in the Great Plains

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ABSTRACT: *In Midwestern agricultural regions, there is a certain amount of confusion over the classification of native tree species. This is especially true of the eastern redcedar tree, which is often described as “invasive” despite being one of the most established native trees in the US. This paper titled The Mizer’s Ruin–Circular Economies and Atypical Forestry in the Great Plains describes the impact of this phenomenon and how it determines certain forms of architecture based on mass timber assembly systems. The paper explores the impact of classification in terms of trees considered “desirable” for lumber production and those that are excluded. It highlights the potential effect of the diversification of plant species within industrial farmland and tree species within lumber-growing regions. The paper suggests that the persistent treatment of native trees in the Midwest as “invasive” creates a de facto reclassification allowing for systematic destruction and removal. It explores how the terminology of “certified” forms of production creates an implicit bias that ultimately affects the production of sustainable materials and timber-based architecture. The dichotomy between the classification of “native” and “invasive” applies particularly to the eastern redcedar tree because it tends to disrupt industrial farming (harvesting machinery, pivot wells and so on). Here the comparative terms “native” and “invasive” are important because reclassification sanctions removal and destruction to increase crop production without considering the tree’s value. The session will then describe a case study project (The Mizers’s Ruin) that provides an alternative solution through small-scale, strategic extraction of “invasive” trees that supports a local, circular economy. It will explain the concept for this project with reference to vernacular building methodologies and in terms of sustainable harvesting and construction. This concept will focus upon two unique aspects of the project: as part of local forestry production and the adaptation of prescribed burning techniques in the latter stages of construction (it’s burnt after it’s built to provide a protective fire-resistant surface). The paper will then contextualise the project via Stephanie Wakefield’s studies of resilient “Back Loop” systems (explicitly wildfires) as a way to consider alternative approaches to Midwestern farmland. These ideas are explicitly developed in Mizer’s Ruin with reference to Wakefield’s studies of entropic systems like wildfires and the emergent ecologies of “invasive” tree species. The paper concludes with a description of the final project and key aspects of its design as a micro dwelling. It describes its objectives in engaging local forestry, alternative construction and measurable benefits of carbon sequestration. It provides a broader evaluation of potential new sources of sustainable materials that overcome the obstacles of biased classification and of selective preference for large-scale industrial production.*

KEYWORDS: Resilient, Invasive, eastern redcedar, mass timber

1. NATIVE AND INVASIVE TREES

The classification of eastern redcedar (*Juniperus Virginiana*) often blurs the boundaries between official and quasi-official terminology. The Nebraska Conservation Roundtable state that it is a “native” tree that has always been a fixture on the Nebraskan landscape” while the USDA classifies it as native in most eastern states as well as midwestern states that include Nebraska.¹ However, this distinction is often overlooked when it comes to a prevailing narrative within the farming community that blurs the distinction and often underplays the USDA guidelines. In part, this is due to caveats that exist within these guidelines that suggest an invasive plant species is one “Whose introduction causes or is likely to cause economic or environmental harm or harm to human health”.² Although this doesn’t sanction reclassification, “economic or environmental harm” has been widely adopted as the pretext for assuming it is invasive. Often the observation that it behaves like an invasive plant appears to provide enough justification for intervention and removal.

Much of the impetus behind this is generated by growing concern and increased visibility of eastern redcedar in the landscape. Within the central US, eastern redcedar is the most successful tree and has expanded more than any other within the Midwest and Great Plains. In Nebraska, it achieves the greatest forest density in any Midwestern state. This expansion has been matched by an increasing list of negative impacts that include loss of native grasslands, reduced grazing, altered forest structure, degradation of riparian communities, and an increase in wildfires.³ This expansion also negatively impacts the state economy, especially within farming communities facing the cost of removing trees from pastures and crops and disentangling them from infrastructure and irrigation systems. While economic disadvantages are not constrained to agriculture, there is widespread agreement that the cost of removal (Av 600/acre) is overburdening the systems in all sectors. While state and federal intervention exists, the practice of slash-and-burn on private land is seen as a more immediate solution. Guidelines that attempt to introduce more productive uses through forest management

procedures like product and market development and business opportunity through biofuels are met with limited success.

However, the immediacy of these issues often overlooks the wider historical context that might be seen to have contributed to the current problem. It might be argued that the current success of the eastern redcedar tree is due, in part to its adoption and adaptation into shelterbelts as part of federal intervention to prevent soil erosion during the Dust Bowl era. Ironically, eastern redcedar at that time was seen as part of the solution for an environmental problem in a way that inverts the current narrative of its negative environmental impact.

The ambiguity of eastern redcedar is further compounded by the history of its relationships to wildfires in the Midwest. Most contemporary sources cite overwhelming evidence that its exponential expansion has made a considerable contribution to the increasing threat of wildfire in grasslands and forests. In 2002 Nebraska experienced the second worst year for wildfires on record despite the Nebraska Forest Service's increased planning and fire mitigation resources. Among these activities, forest management plans focus heavily upon removal, which mostly adds to the generally negative, quasi-invasive perception of er.

However, the deeper history of forest fires provides a different perspective on the issues (and potentially different responses). It can be argued that the current problem is only a recent phenomenon and can be directly attributed to settlement farming and the rapid advance of industrialized agricultural practices. The increase in areas of cultivated crops and cattle almost completely eradicated the wildfires that historically restricted the growth of eastern redcedar. While the sources of these fires are debated, there is widespread recognition that grassland fires once kept eastern redcedar in check (pre-settlement burning occurred on Native American territories to promote buffalo grazing pastures). Once these fires were abated, the change to the ecosystem provided favorable conditions for the long-term build-up of forest fire fuels and the unprecedented scale and intensity of the fires we see today. While prescribed burns are a common land management practice today, there has been a steady re-emergence of new prescribed burning techniques in an attempt to reestablish the prehistorical and pre-settlement practices and control the expansion of eastern redcedar.

All of this suggests a much more complex picture than initially meets the eye. It also suggests that there is a necessity to look beyond the current narrative and establish a broader conceptual base for strategic intervention.

2. WILDFIRES AND THE BACK LOOP

Since 2017 the *PLAIN Design Build* collective has focused on projects that explore midwestern forestry. *PLAIN* works at the intersection between architecture and forestry and invests in a broad spectrum of projects driven by applied research for timber architecture. While this includes the emerging technology of mass timber, it also explores atypical forestry production and alternatives to mainstream timber construction. *PLAIN* projects adopt an adaptive response that seeks resilient models within the built environment. Much of our work explores alternatives to linear models of production and promotes non-extractive models of the circular economy.

Part of our approach is informed by historical reminders that all systems of expansion are continually susceptible to entropic collapse. This critical standpoint is based on the assumption that the more successful a system becomes, the more vulnerable it may be to collapse. In this respect, many *PLAIN* projects are informed by ideas based on the concept of the "Back Loop"⁴ and argue for the importance of understanding unplanned events in relation to planned events. It juxtaposes accelerationist periods of the Anthropocene with models of resiliency found in deeper periods and successive "epochs".

The Back Loop is described by the figure-of-eight diagram that contains a front loop (planned events that follow a predictive model of industrial expansion, greater access to travel, global trade and so on), followed by an unexpected event (a natural disaster, conflict, global pandemic) that then, in turn, leads to a "back loop" (a series adaptive and resilient responses to the unexpected event) that eventually leads to reorganization. "For ecologists, every system (a forest, a body, a city, etc.) goes through a cycle with two phases, what they call a "front loop" and a "back loop" (together making up the "adaptive cycle"). The front loop is seen as progressing from an initial growth or exploitation phase to conservation and seeming stability, while in a back loop, those structures come apart, leading to a period of destabilization, fragmentation, confusion, and release but also great potential for experimentation, reorganization, and transformation." (Wakefield 2021)

3. THE MIZER'S RUIN

This strategic approach and past projects (especially the ASHED project that adapts as borer beetle-kill wood) has provided a model for our latest project the Mizer's Ruin. This is a 200 sq. ft. micro dwelling built from eastern redcedar at the University of Nebraska's Cedar Point Biological Station near Ogallala, Nebraska.

Funded by the Nebraska Environmental Trust (NET), this project has been established to explore a low-carbon fabrication system that engages directly with local forestry production. It seeks to reimagine the current slash-and-burn policy for the “invasive” eastern redcedar and develop an alternative scenario to the current practice of systematic removal and destruction.

The Mizer’s Ruin adopts two interpretations of the “Back Loop” that inform our approach to using local forestry production in architecture. In the first case, it is considered the beneficiary of the entropic agent within a whole front-loop system, i.e. it looks to explore the by-products of the rapid expansion of eastern redcedar (an “unplanned event”), within industrial agriculture. In the second it proposes a circular economy that proposes a front loop process of expansion (timber, milling, construction) that is followed by a planned disassembly and reuse for alternative purposes beyond the useful life of the building.

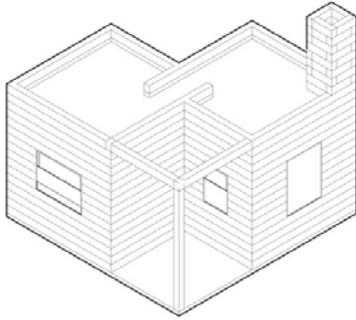


Figure 1: Mizer’s Ruin – Microdwelling fabricated from locally harvested eastern redcedar.

4. LOCAL FORESTRY

The issue of forestry management is central to the project, although PLAIN Design Build⁵ had begun exploring possible uses for ER the Baxa cabin in 2016. This led to an analysis of the widely practised slash-and-burn forest fire mitigation policy that has, up until recently, been the customary practice on our site at CPBS. Our intervention within the process was established by adding new terms to the Forest Stewardship Plan around the site of our project.

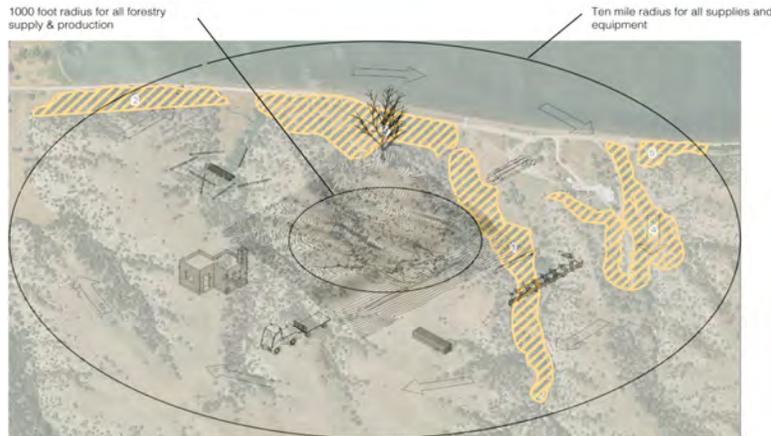


Figure 2: Eastern redcedar stands to be harvested for the site (hatched) and supply radius (nts) at Cedar Point Bio Station-Ogallala NE

“The goal of this management is to provide sawlogs for milling and construction while leaving the land with the capacity to produce future crops of desirable cedar. In all stands, hardwoods will be preserved. Stand 4 also contains saw logs, but management prescriptions will be aimed at creating safe, defensible space in case of wildfire.

For all stands: Harvest all large cedar (trees will be marked), limb, and pile with butt-ends towards easiest egress. Trees may be left whole after limbing, no further processing (i.e., cut-to-length) is required. Coordinate with Cedar Point land manager if the contractor has the ability to skid logs to processing site.”
 (Nebraska Forest Service Forest Stewardship Plan for the site)

This plan is unique to er forestry practice in the way it provides for the selective extraction of saw logs that we determined to be useful for the primary structure and components of the interiors. The extent of the plan is determined by the areas of the site most vulnerable to forest fire also determined the outer radius of all our timber supplies. It allowed us to explore a mass timber construction system constrained by a one-thousand-

foot radius from the cradle to the site. This effectively meant that most of the stages 1-5 of the *Whole Life Carbon Assessment* ⁶ were easily within walking distance of our building.

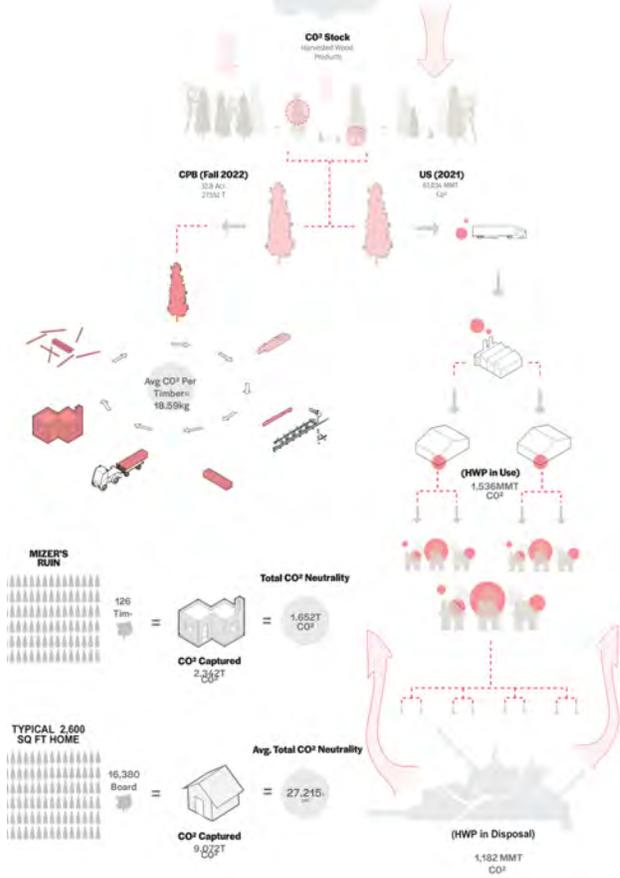


Figure 3: Carbon Sink and Neutrality Comparison - Grant Wolfe

This constraint had to be matched with in-the-field harvesting, milling and fabrication systems that could radically reduce embodied energy created by transportation from factory to gate. Each phase of the construction was scrutinized for its transportation implications and was eradicated if we felt it was extended beyond a local radius of 10 miles.⁷ However, the majority of the material for the primary structure remained less than 300 feet from the site, mostly due to the extensive use of mobile forestry and milling techniques with the wood mizer.

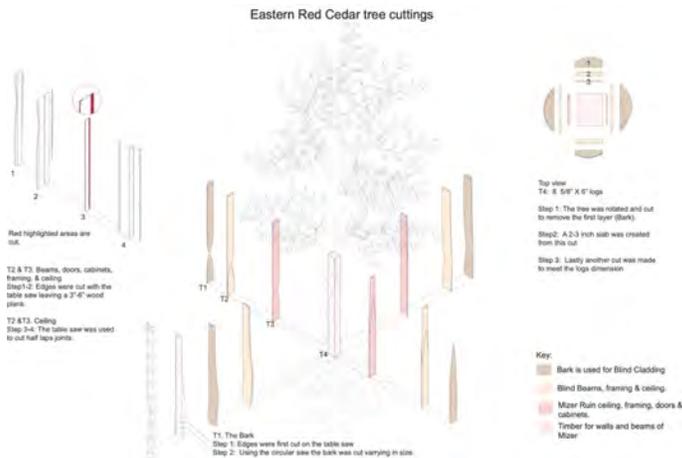


Figure 4: Whole tree analysis

These constraints also allowed us to develop a “whole tree” awareness for diverse uses of eastern redcedar beyond our project. Furthermore, it also challenged us to include other local trees, particularly green ash, hackberry, and cottonwood, all of which have limited appeal to mainstream lumber production. In many cases, we were able to offset employment expenses by donating milled lumber in what can be considered part of a “gift” or “sharing” economy.⁸

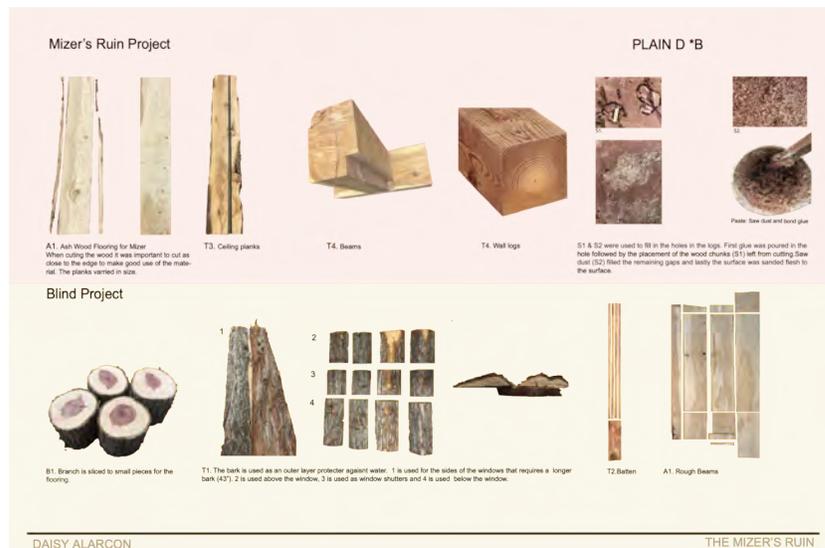


Figure 5: Ongoing reflection of diverse timber uses from eastern redcedar and ash

5. MASS TIMBER

From these constraints emerged a unique form of assembly that provided a way of thinking about mass timber based on a localized system of production. It provide solutions to the majority of the primary structure as well as much of the secondary and tertiary elements. While this project did not involves techniques of adhesive bonded timber composites commonly considered engineered lumber (like CLT) it remains within the broader category of mass timber as a solid, monolithic slab of stacked wood. The additional steps of planing and pressure bonding would have required factory-based facilities that would undermine our constraint of a 10-mile radius. Instead, it promotes the inclusion of diverse types of mass timber that are closer to dry jointed versions like Interlocking Cross Laminated Timber (ICLT)⁹ or the mechanically fixed nail-laminated or dowel-laminated versions of factory-supplied products from StructureCraft.¹⁰ These influences allowed us to work with rough-cut lumber that could be spline jointed with enough mechanical connection pressure generated from 10”-12” engineering screws.

While this entire system is already in line with net-zero (or net positive) embodied energy analysis for LCA phases A1-A5¹¹, the most significant aspects of the project lie in later phases of disassembly that cannot be met by other forms of engineered lumber (especially adhesive bonded CLT). In most cases, the end-of-life scenarios (Phase D)¹² for mass timber building are understandably speculative. However, for Mizer’s Ruin, simply reversing the mechanical fixings procedure and disassembling the logs provides a viable reuse scenario. After it is disassembled, most of the primary structure would require minimal milling to establish a realistic re-use to complete the final link in a circular material flow diagram.

This process is currently evaluated by a system of regular documentation and on-the-fly auditing (carbon, student effort, collaboration) that help shape our awareness of the impact of design decisions and alterations as the project reaches completion. This ongoing process of phased, summative analysis allows us to present an argument for a circular economy that promotes mass timber construction in rural western Nebraska. While the project is scheduled for completion in the summer of 2023, our ongoing evaluation has been essential in shaping the final stages of construction.

CONCLUSION

The Mizer’s Ruin is an experimental project for a micro dwelling that speculates on the potential of an “invasive” tree as the basis of a circular economy in the Great Plains of the USA. It seeks to negotiate the misassumption of its (miss) classification by intervening in the current practice of removal and destruction within the agricultural regions of Nebraska. By applying the constraint of a circular economy, it re-images each facet of

mass timber production, from forestry and milling to assembly. It establishes an alternative material flow that helps diversify forestry while contributing to the wider discourse of mass timber construction technology.

This approach attempts to place the project within the deeper history of the entropic cycle of growth and destruction within the Midwest ecosystem, especially those affected by wildfires. It establishes an architectural response to Stephanie Wakefield's studies of resiliency by adapting a "bi-product" of an unplanned event within the "Back Loop" diagram. It suggests a prototype project that can be adapted to other regions with similarly "unplanned" forests and to the increasing occurrence of wildfires within the Midwest.

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ENDNOTES

1. The most common source of plant classification <https://plants.usda.gov/home/plantProfile?symbol=JUWI>
2. <https://www.fs.usda.gov/wildflowers/invasives/index.shtml>
3. Ibid.
4. The term the Black Loop is extensively developed through Stephanie Wakefield's publication Anthropocene Back Loop.
5. Most of our design build projects are carried out through PLAIN Design Build <http://plainsdesignbuild.com/>
6. Whole Life Carbon Assessment RICS Professional Statement referenced above and structured around the EN 15978 modular system for whole life carbon assessment.
7. This was limited to local supplies and rentals but does not include student transportation.
8. This happened mainly with former students wanting to be involved in the project and providing help.
9. Interlocking Cross Laminated Timber (ICLT) is a prefabricated cross-laminated solid wood wall and roof panel developed by Euclid Timber, LLC. Similar to Cross-Laminated Timber (CLT) developed in Europe, ICLT is fabricated from 2-7 layers of alternating direction 3" x 6" to 3" x 8" pine stock milled from waste wood. Unlike other solid wood panel systems, however, ICLT utilizes no fasteners and no adhesives reduces overall capital cost for either stainless fastener purchase and install or press purchase and set up associated with glue lamination. Conversely, standard mills and timber fabricators looking to diversify their product offering may produce ICLT with existing infrastructure and equipment.
10. Structure Craft are instrumental in advancing dry jointed mass timber especially dowel laminated timber and provides credible end of life scenarios for non-adhesive based timber lamstock.
11. Life Cycle Assessment for construction- ISO. 2017. Sustainability in buildings and civil engineering works- Core rules for environmental product declarations of construction products and services. International Organization for Standardization. Second edition (ISO 21930:2017-07) 80pp.
12. Ibid.

Earth Made Urban Living: Earthen Construction Materials and Techniques for Contemporary Housing

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ABSTRACT: A recent press release by Freddie Mac states three major challenges the US currently faces: a sparsity of affordable housing, skilled laborers, and sustainable materials. A significant portion of the population across the US Gulf South region lacks access to affordable housing, a fundamental element to bringing down homelessness, developing employment opportunities, and encouraging economic prosperity. This 4th & 5th year studio concentrated on the potential of earthen construction materials and techniques, specifically compressed stabilized earth blocks (CSEBs) which are reasonably priced, widely available, and sustainable, as a potential resource to address present-day housing challenges. The aim was to develop design proposals focused on contemporary, cost efficient, urban housing for up to 40 families using earthen building technologies suitable for use in environments with a hot wet climate. Over the course of the semester, students engaged this challenge using virtual and hands-on techniques to develop design proposals constructed of earth block building assemblies. In congruence with explorations into site, program, organization, structure, enclosure, and systems, investigations into earthen property attributes, block design and fabrication methods, and wall erection strategies were happening at the same time. Working concurrently, students utilized both architectural representations (scaled drawings) and actual material mock-ups (full size building components and assemblies) to guide the design process. Prototype interlocking compressed earth blocks were designed and then fabricated using a CINVA-Ram manual press with inserts shaped to specific block forms. Earthen mixtures composed of varying percentages of silt, sand, clay, additives, and water were developed relative to the specific block geometries to minimize cracking and enhance structural performance. Following fabrication, the blocks were stacked, at varying orientations, into wall assemblies allowing students to test drawn design decisions and inform potential revisions to the proposed building enclosures.

Critical questions explored included: Are there by-products of regional industrial processes that are readily available, cost effective, and sustainable that could be used as an additive in the earthen mixture to strengthen CSEBs? How can CSEB walls be assembled to a consistent set of standards in communities that only have access to minimally trained constructors? How can CSEB walls, customary to hot dry central US regions, be modified to perform in hot wet coastal US regions dependent on air conditioning to reduce humidity and climatize interior spaces?

Students engaged questions critical to earthen construction materials and techniques for contemporary housing at multiple scales, simultaneously addressing inquiries into context/site/building and materials/components/assemblies. This diverse approach presented students an opportunity to explore in a boundless undefined manner, continually open to the influence of new discoveries through the iterative processes of drawing, fabricating, and assembling. Students worked in teams (2, 3, or 4 persons), engaged this challenge, using virtual and tactile techniques, and developed contemporary housing design proposals constructed of earth block assemblies. This was a very hands-on studio with approximately 50% of the time devoted to fabricating earth blocks, constructing block wall assemblies, and details.

KEYWORDS: Earth, Construction, Fabrication, Assembly, Housing

1. MOTIVATION

A recent press release by Freddie Mac states three major challenges the US currently faces: a sparsity of affordable housing, skilled laborers, and sustainable materials. (http://www.freddiemac.com/fmac-resources/research/pdf/Dec_Insight_Press_Release.pdf)

2. PROBLEM

A significant portion of the population across the US Gulf South region lacks access to affordable housing, a fundamental element to bringing down homelessness, developing employment opportunities, and encouraging economic prosperity.

3. APPROACH

This 4th and 5th year option studio concentrated on the potential of earthen construction materials and techniques, specifically compressed stabilized earth blocks (CSEBs) which are reasonably priced, widely available, and sustainable, as a potential resource to address present-day housing challenges. The aim was to develop design proposals focused on contemporary, cost efficient, urban housing for 30 to 40 families using earthen building technologies suitable for use in environments with a hot/wet climate.

Are earth construction materials and techniques a contextually viable building alternative capable of addressing the numerous ecological issues of pressing concern in our contemporary society?

Over the course of the semester, students engaged this challenge using virtual and hands-on techniques to develop design proposals constructed of CSEB building assemblies. In congruence with explorations into site, program, organization, structure, enclosure, and systems, investigations into earthen property attributes, block design and fabrication methods, and wall erection strategies were happening at the same time.

3.1 Earthen property attributes and compositions

Commonly used around the world as an abundantly available building material for housing, earth is rarely considered as a viable contemporary option for construction in the US Gulf South. Developing an understanding of earthen property attributes and compositions was a critical first step to realizing the potential of earth as a modern construction material.

Sourced from Southern Louisiana, the earthen material was extracted from a depth of greater than 3 feet to establish a base mixture made up of non-organic particles. This was necessary to start with a consistent composition comprised of identifiable components which could be analyzed to ensure the structural stability of the earth blocks. The extracted soil was tested and plotted on a US Department of Agriculture soil classification map to establish if the mix percentages were within the guidelines suitable for construction (USDA 1999). Earthen mixtures, composed of varying percentages of silt, sand, and clay, vary widely from one location to another. Knowing the ratio of components is key to understanding how the material will perform in a particular context (Kumar et al. 2018). Composed of high percentages of sand and silt and a low percentage of clay the earth mixture was classified as a sandy loam. This classification was within the guidelines, but at the outer limits of acceptable compositions. The high sand percentage provided sufficient strength; however, the low percentage of clay reduced the ductility of the material.

To address the near sub-optimal composition of the earthen mixture varying percentages of stabilizer were tested to address potential structural and durability concerns. Both cement and lime were considered as possible stabilizers. Although the less sustainable alternative of the two options, cement was used to stabilize the earthen mixture due to availability and cost effectiveness. Lime would have been the superior sustainable choice and interestingly could have been produced from an abundance of locally available oyster shells. However, this time-consuming process was unfeasible given the constraints of the semester schedule. A range of compositions that included 5 to 15 percent cement in the earthen mixture were tested and formed into blocks. Ultimately most blocks included around 10 percent cement, a convenient balance especially when taking into consideration the straightforward mix ratios. Based on previous research, this amount of stabilizer was more than sufficient given the earthen material composition. However, due to the hot/wet Southern Louisiana environment, which receives over 60 inches of rainfall annually, the inclusion of a stabilizer would help ensure the durability of the blocks when exposed to these natural conditions. Intriguingly, the naturally high-water content in the atmosphere may be beneficial to the curing process and allow the strength of the blocks to continue to increase over a prolonged time, a phenomenon observed in previous research (Holton et al. 2018).

Preparing the earth to fabricate blocks required reducing the particle sizes to less than ¼ inch. This was achieved through a process of hand pounding the material in a mixing tub with rubber mallets and then passing it through a metal screen. The reduced particle size allows for the earth to be more evenly mixed with the stabilizer while also increasing the surface area and yielding greater cohesion when compressed in a mold. In addition, smaller particles produce more consistently dense blocks which perform better structurally and are less susceptible to weathering. Due to the low percentage of clay, which can be quite hard, this step was relatively efficient. Following crushing and sifting, the stabilizer was incorporated with the earth and these dry components were then combined with a ratio of 8 to 12 percent water (Fig. 1). This percentage fluctuated depending on how dry the earth was, amount of stabilizer used, and the level of humidity.



Figure 1: Multi step process to prepare the earth mixture for block fabrication. Source: (Author 2020)

In some cases, it was necessary to structurally compensate for specific block geometries through the inclusion of additives in the earth mixtures to minimize cracking and enhance structural performance. Block shapes with angles ranging from 45 to 90 degrees were especially susceptible to cracking during the drying process. The corners were also potential points of failure depending on their orientation when stacked in wall assemblies. To improve the performance of blocks with these geometric characteristics, especially L, T, and U shapes, a range of organic and non-organic fibers were tested. Depending on the overall size of the block, the most successful additives were hay, bagasse, and coconut. The fine bagasse and coconut fibers were easy to mix and functioned well in lighter weight small to medium size blocks under 12 inches, while the courser hay fibers responded suitably to the increased weight of larger blocks. In our location and for most block types, bagasse is the more sustainable alternative. It is a locally available by-product of the regional sugarcane crushing industrial process. The inclusion of the material as an additive helps to address the control of waste that would otherwise be burned.

3.2 Block design and fabrication methods

Prototype interlocking CSEBs were designed and then fabricated using a CINVA-Ram manual press with inserts shaped to achieve specific block geometries. Constructed out of $\frac{1}{4}$ " thick plate steel, the manual press is primarily comprised of a compression chamber, cam action lever, and stabilizing legs. To fabricate a block; the earth mixture is placed in the chamber, the chamber pivot lid is closed, the lever is lifted from a horizontal position to a vertical position and engaged with the top of the lid. The lever is then returned to the same horizontal position to compress the block. After compression, the lever is lifted back up past the vertical position, the lid is opened, and the lever is placed in the opposite horizontal position to lift the block out of the press. This process produces a maximum 10"x6"x3" generic module size, a parameter of the press that presented a clear framework for the students to work within (Holton et al. 2018). Inserts of varying shapes were developed to place within the manual press compression chamber along with the earth mixture to modify the geometry of the generic module size (Fig. 2). A primary goal was to develop interlocking block forms that would allow the CSEB walls to be more easily assembled to a consistent set of standards. This objective is especially important for building in communities that only have access to minimally trained constructors.



Figure 2: Compression chamber with insert, adding the earth mixture, and compressing the block. Source: (Author 2020)

Initial insert design strategies focused on primarily modifying the top and bottom 10"x6" block surfaces with a centrally located projection on one side and recess on the other. These modifications, typically in the shape of a circle, square, or cross allowed the blocks to interlock in a stacked pattern (Fig. 3). To achieve a greater variety of possible bond patterns double projections and recessions, one on each half of the 10"x6" surfaces, were developed (Fig. 3). The increased number of projections allowed the blocks to interlock when overlapped in a running pattern. This strategy also allowed the blocks to interlock when placed perpendicular to one another, an effective technique to secure wall assemblies with corners and/or multiple wythes.

Continuing to expand on the potential relations between juxtaposed blocks, the use of interlocking projections and recessions with unequal dimensions were investigated. The iterations tested included a design with double circle projections on one block face and a continual lozenge cross recession on the opposing face. This provided a loose fit between blocks while still allowing them to interlock, further expanding the potential relationship between blocks from solely orthogonal to an almost infinite array of non-orthogonal patterns.



Figure 3: Geometric refinements: single cross, double cross, double cross & edge. Source: (Author 2020)

Elaborating on these interlocking stretcher and header block orientations, additional inserts were developed for the 10"x3" and 6"x3" surfaces. This further geometric refinement of the double cross on the 10"x6" block surface along the 3" faces made it possible to also interlock the blocks when placed in a rowlock or rowlock stretcher orientation (Fig. 3). In another iteration, additionally focused on the smaller block faces, a continuous 90-degree tongue and groove interlocking ridge and channel were investigated. The uninterrupted nature of this system allowed for shifting and/or sliding configurations that had the potential to incorporate voids of varying sizes between adjacent blocks. With this interlocking strategy the blocks could be potentially placed in a soldier or sailor orientation, adding to the range of possible adjacencies explored in the student's investigations.

In concurrence with these explorations into geometry, working hands-on, fabricating the blocks, was equally challenging. Making and using the inserts was very much a trial-and-error process. Taking into consideration available equipment and resources, cost effectiveness, and time constraints the inserts were fabricated out of wood. Depending on the intricacies of the geometry the type of wood used played a crucial role in the durability of the insert. Simple forms could be constructed out of a medium to heavy grained hard or soft wood while complex forms were more successfully constructed from medium-density fiberboard to prevent cracking. Of course, craft, precision, and overall quality of the constructed insert were essential to fabricate blocks with accurate dimensions, a necessary attribute to properly interlock (Fig. 4). This proved especially difficult when attempting to construct circular and angular forms, or rounded edges.



Figure 4: Removing the insert from the press and unmolding the block. Source: (Author 2020)

The use of inserts to shape the block modules also added unforeseen complications to the fabrication process. Due to the increased surface area of the forms, the unmolding and insert removal process became more complicated, initially producing torn, cracked, warped, and damaged results. To reduce adhesion between form and block an assortment of surface finishes ranging from several layers of high gloss paint to plastic coated films and tapes were tested. Along with the use of a release agent, such as oil or silicon spray, the unmolding process was fine-tuned and became consistently successful (Fig. 4). Of note, in some cases, the relative humidity from one day to the next could be an additional factor and influence the unmolding process. Ultimately, working through multiple iterations, students gradually refined the inserts and expanded the ways in which the resulting CSEBs could be interlocked and oriented.

3.3 Wall erection strategies

Following fabrication, the blocks were stacked, at varying orientations, into wall assemblies allowing students to test design decisions and inform potential revisions to proposed building enclosures. Like the fabrication phase, bringing the blocks together in a unified construction was very much a trial-and-error process. Erecting walls that were straight in plan and section with level courses was a primary concern to achieve structurally stable assemblies. The block building sequence of dry stacking, unstacking, reorienting, and restacking was repeated multiple times to find the most secure placement for each module. This methodical succession of steps, primarily due to the imperfections of the handmade blocks, was necessary to achieve assemblies as safe and secure as possible. Numerous plan configurations, linear, two linear segments connected by a 90-degree corner, and curved, were tried to find the soundest arrangement for each unique block type. Typically, a corner or curved plan resulted in the most well-built assemblies, however, these organizations were only possible with some of the interlocking block CSEB geometries (Fig. 5).

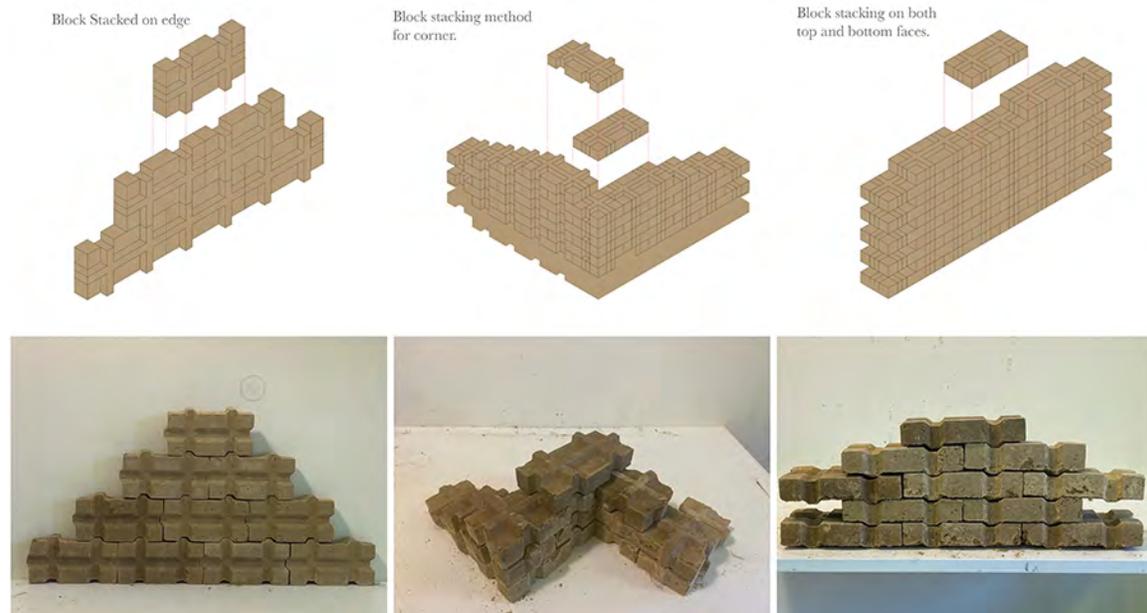


Figure 5: CSEB wall configurations. Source: (Author 2020)

Although most test builds remained as dry stacked assemblies, varying block adhesion strategies were explored. Mortar, masonry adhesive, and concrete with steel reinforcing were all viable options. In response to the material composition of the blocks, a mortar mixture of earth, sand, and cement was used for the assembly mock-ups. Much the same as the CSEBs, the inclusion of cement had the benefit of increasing the strength and durability of the mortar even though a greater percentage was necessary to achieve an appropriate level of solidity. The incorporation of sand also added to the overall strength of the blend. Working with the mortar presented many challenges for first time or minimally trained constructors. Even though the material ratios were carefully measured it proved difficult to bring the combination of constituents to an even and consistently dense mixture. These complexities resulted in mortar that would often have minimal adhesion to the block face and inconsistent thickness between block surfaces. Despite the fact it was the messiest and least predictable operation in the whole fabrication and assembly process, using the earth sand cement mortar to adhere the CSEBs was a critical step to understanding the potential capacities of this building technique.

Working concurrently, students utilized both the material mock-ups (full size CSEB building components and assemblies) and architectural representations (scaled drawings) to guide the design of assemblies for multi-

story contemporary urban housing proposals. As is often the case in urban sites, the size of the lot required a multi-level vertical structure to accommodate the 30 to 40 family living units outlined in the program. Taking into consideration the site constraints and depending on the organization of each proposal, the building designs would need to rise 70 to 100 feet in height. To accommodate the structural loads and forces commonly affiliated with mid-rise typologies it was necessary to explore novel hybrid approaches to reinforce the primary building material, the CSEBs.

Three main approaches to the structural system were examined: a concrete frame, a steel frame with cantilevered trusses, and concrete load bearing walls. In the concrete frame system, the one most typically associated with multi-story housing projects, the CSEBs were used as formwork for the columns. Inspired by the Roman constructions at Ostia Antica, where masonry was used as permanent formwork for concrete walls, this strategy proposed CSEBs stacked into hollow columns for concrete to be poured into. The blocks would bind to the concrete, remain in place, and reduce overall amount of concrete normally used for this type of construction (Fig. 6). The steel frame system, influenced by large scale bridge structures, proposed a central super structure around the building core with cantilevered trusses supporting CSEB clad living units. In this scheme the perimeter of each block wall would be supported by steel plates on four sides to form a solid wall element that could be hung from and anchored to the cantilevered steel trusses. Comparable to the concrete frame system, the concrete load bearing wall design also proposed to use the CSEBs as formwork that would remain permanently in place. In this scenario the compressive strength of the blocks would work in tandem with the concrete to help support and distribute the building forces (Fig. 6).

In addition to the structural systems each of the design proposals used CSEB partition walls, spanning up to 10 feet in height, to enclose individual programmatic spaces. Unencumbered by the need to transfer building loads these lighter and thinner block wall assemblies engaged several environmental and social topics. Depending on the program of a particular area, walls of varying porosities were developed that allowed for natural ventilation and light. Similarly, contingent on the public/private character of the program, these openings also provided for visual and audible connectivity between spaces. This potentially endless variation in pattern and texture, made possible by modifying the module spacing and orientation, articulated the scale and expressed the unique capabilities of the CSEBs as a building material and the wall surfaces, they composed.

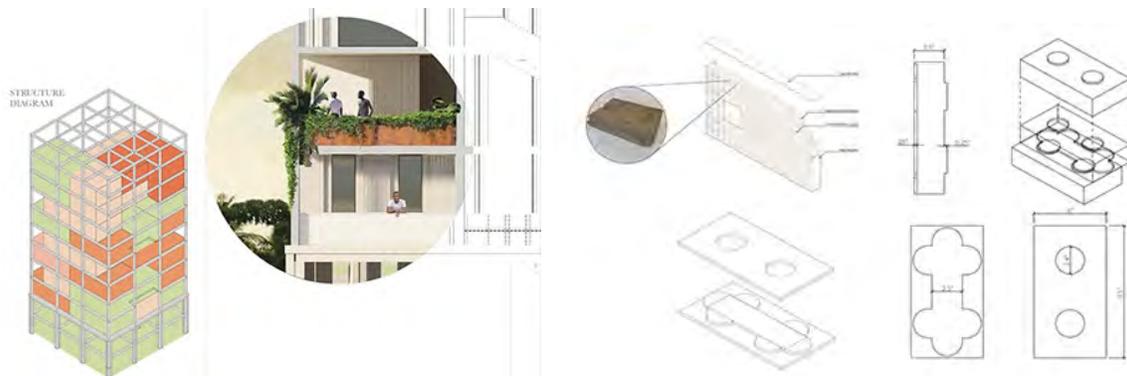


Figure 6: Frame and load bearing wall structural systems. Source: (Author 2020)

4. RESULTS

Students engaged questions critical to earthen construction materials and techniques for contemporary housing at multiple scales, simultaneously addressing inquiries into context/site/building and materials/components/assemblies (Fig. 7).

Questions explored included:

Is it feasible to use locally available earthen materials, composed of varying ratios of silt, sand, and clay, to build enduring structures in a hot/wet environment?

Are there by-products of regional industrial processes that are readily available, cost effective, and sustainable that could be used as an additive in the earthen mixture to strengthen CSEBs?

How can CSEB walls be assembled to a consistent set of standards in communities that only have access to minimally trained constructors?

How can CSEB walls, customary to hot/dry central US regions, be modified to perform in hot/wet coastal US regions dependent on air conditioning to reduce humidity and climatize interior spaces?

This was a very hands-on studio with approximately 50% of the time devoted to fabricating earth blocks, constructing block wall assemblies, and details. This diverse approach presented students an opportunity to explore in a boundless undefined manner, continually open to the influence of new discoveries through the iterative processes of drawing, fabricating, and assembling. Students worked in teams of 2 or 3 members, engaged this challenge, using virtual and tactile techniques, and developed contemporary housing design proposals constructed of earth block assemblies. The resulting fabricated blocks, constructed wall assemblies, and mid-rise housing designs attest that earth is a viable building material for use in an array of building types that span various scales and meet the expectations of a contemporary way of living. The project proposals verified that earth construction materials and techniques have the capacity to effectively engage and positively respond to the very important present-day questions of contextually viable and sustainable resources and how these commodities are utilized in a socially beneficial and ecological way (Fig. 7).



Figure 7: Earthen construction for contemporary housing. Source: (Author 2020)

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Carbon Sequestering and Structural Abilities of Eucalyptus Cloeziana

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ABSTRACT: *In our time of urgency of climate action in the architecture/engineering/construction industry, new low-carbon building materials can very well be part of the solution, especially when these materials exhibit superior performance compared to existing materials. Low-carbon Eucalyptus Cloeziana (kloh-zee-ah-nuh), commonly known as Gympie Messmate, is a fast-growing hardwood native to Australia. Its quick growth makes it advantageous for carbon sequestering while its strength class lends itself to structural applications. Market research in the US shows a trend of growing demand for timber, especially mass timber. This is in line with SE 2050 Challenge which states that “All structural engineers shall understand, reduce, and ultimately eliminate embodied carbon in their projects by 2050”. This research paper reports on applied research in which the first author, with the help of two faculty, experimented with the use of Eucalyptus to replace Douglas Fir in roof structures. A life cycle carbon analysis was conducted and resulted in defining the measurable performance of Eucalyptus Cloeziana.*

This paper investigates market potential as well as the environmental benefits and challenges to using Eucalyptus Cloeziana as a structural material for buildings. Although it may grow in the North American climate, Eucalyptus is currently not commonly found in the US. It grows and is commonly used in Australia, where its manufacturers provide the necessary environmental impact information in the standard format of an Environmental Product Declaration (EPD). An EPD follows a product throughout its life cycle, including values for global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, and abiotic depletion potential. The author used the material’s EPD to conduct a comparative study, in which the performance of Eucalyptus was compared to the structural use of steel and Douglas Fir, using data of the same geographical region. The case study demonstrates the comparative properties and performance of Steel, Douglas Fir, and Eucalyptus in terms of embodied carbon and structural weight within a single structural bay. Although Eucalyptus has higher carbon content (negative carbon) than Douglas Fir per weight, the study showed that because the softwood system requires larger volume of wood than the hardwood system, the Eucalyptus structure weighs less than Douglas Fir. Because softwood sequesters more carbon due to its slow growth, Douglas Fir sequesters more carbon per structural bay. Eucalyptus sequesters less carbon (per structural bay) but since it grows twice as fast compared to Douglas Fir, it has market advantages that are not measured by the simple metric of embodied carbon.

KEYWORDS: decarbonization, sustainability, structural systems, eucalyptus cloeziana, life cycle analysis.

INTRODUCTION

Carbon dioxide is one of the major emissions causing global warming, and it is estimated that the built environment accounts for approximately 39% of global carbon emissions, with approximately 28% coming from building operations and 11% from the building materials and construction (Architecture 2030 2021). Lowering the embodied carbon in building materials is essential to reaching zero-carbon by 2050. This paper addresses embodied carbon in the structural system and tests the hypothesis that the use of E. Cloeziana in timber construction will reduce the total embodied carbon of the structural system. According to market survey conducted by the American Institute of Steel Construction (AISC), the use of timber is on the rise, which is now approximately at 10% of market share, up from around 7% in 2009. The use of concrete is also on the rise, while structural steel and masonry are on the decline (AISC 2020). This transformation in the market is partially due to the 2021 International Building Code (IBC) update, the rise of biophilic design, and the climate crisis as a threat to future generations. In the latest update of the IBC (2021 Edition), mass timber buildings are now allowed to reach up to 18 stories (ICC 2021). Wood is also a commonly utilized strategy of biophilic design which improves the quality of a space. Incentive programs such as WELL and LEED rating systems reward healthier and more sustainable projects, providing a metric for designers to aim for. It is worth noting that architects are not the only professional group promoting zero carbon. Structural engineers set up their own initiative, the SE2050 Challenge, which states “All structural engineers shall understand, reduce, and ultimately eliminate embodied carbon in their projects by 2050” (Simonon, 2021). Structure accounts for up to 80% of the embodied carbon in the building envelope (ULI 2020) and if it is built using low embodied carbon materials, the result will be a significant reduction in the building’s overall embodied carbon. While foundation systems are primarily concrete, a material with a large amount of embodied carbon, the rest of the systems can be offset with low-carbon materials.

1. TIMBER CONSTRUCTION

The construction industry is always evolving and accepting new materials. Now, we have engineered wood products (EWPs) that can rival the strength of steel. Cross-laminated timber (CLT) offers increased strength, longer spans, and shallow depths, benefits which were previously only attributed to steel. CLT can even be more sustainable when made of lower grade wood that is not normally used in construction, as CLT assemblies can be made of any of the softwood species recognized by the American Lumber Standards Committee where it conforms to ANSI/APA PRG 320 (APA 2019). Other EWP products are available, such as, but not limited to, nail-laminated timber, dowel-laminated timber, glulam, and parallel strand lumber. However, a barrier to increasing timber market share is the concern over life safety and fire protection. Heavy and mass timber construction both have a natural defense against fire due to the volume of the wood itself, forming a protective char barrier on the outside while the interior is preserved, maintaining some structural capacity. For example, some CLT wall assemblies can achieve a fire rating of three hours (McLain 2021). Another concern over the use of wood is the cost, when compared to low budget construction types such as masonry, prefabricated metal buildings, and concrete. On the other hand, wood is still an attractive material for construction because it is lightweight, adjustable, and available almost anywhere in North America.

2. EUCALYPTUS CLOEZIANA

2.1 History of use

Eucalyptus Cloeziana, commonly called Gympie Messmate, has been grown in Australia for construction purposes for many years. It is currently used in home framing, flooring, exterior cladding, and furniture. As the timber is naturally resistant to decay, it lends itself to exterior construction such as wharf and bridge construction, railway sleepers, mining timbers, transmission poles, landscaping, and retaining walls (DOA 2013).

2.2 Present day use

Eucalyptus Cloeziana is suitable for many product types, as sawn lumber, veneer-based panels, and round poles (DOA 2013). Today, it is grown around the world and has plantations in China, Sri Lanka, Brazil, and several African countries such as Congo, Kenya, Malawi, Nigeria, Zimbabwe, Uganda, and Zambia (Harding et al 2012) and (Atyeo et al 2008). A Netherland-based company, Gessel Senel Timbers (GS Timbers) has been providing E. Cloeziana across Europe, claiming to have discovered a method of sawing the material into dimension lumber. Their catalogue explains the forestry operations of harvesting, sawmilling, and processing, and their plantations are certified by the Forest Stewardship Council (FSC) under a larger group of companies, Phylum B. V. The company discovered that E. Cloeziana is a fast-growing timber, providing an alternative to endangered hardwood species. Where it is one of the heavier and stronger species of Eucalyptus, it performs well in heavy construction. They offer it in both poles and sawn lumber dimensions (GS Timbers 2019), with poles being most efficient use of the lumber, where the only machining applied is debarking (TU Delft 2009). E. Cloeziana is also readily adjustable in the field, it saws, machines, dresses, and dries easily (DOA 2013) and (Atyeo et al 2008). This, along with its potential in engineered wood products, shows potential for construction.

3. ENVIRONMENTAL PERFORMANCE

3.1 Environmental product declaration comparison

An Environmental Product Declaration (EPD) is a tool to compare the environmental impact of a product throughout its entire life. The main categories for comparison are global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, and abiotic depletion potential. Global warming potential refers to the total carbon and greenhouse gas emitted from the creation and use of the product. Ozone depletion measures the ozone layer damaging gases while acidification measures acidic gases. Eutrophication measures the nitrates and phosphates that would be released into the water in a system. Photochemical ozone creation refers to nitrogen oxides and VOCs that cause smog, and abiotic depletion refers to the use of non-renewable resources (Rockpanel 2021). For the case study that follows, Eucalyptus, an Australian hardwood, is compared with softwood and steel declarations in the same region. Both wood EPD's are based on an industry standard across multiple companies instead of a specific product while the steel EPD is based on all hot-rolled products within a single company. Of the nine hardwood companies that provided measured data for the EPD, all of them produced Gympie Messmate (Wood-Solutions 2017). All three of the declarations focused only on the production and end of life stages of the material, as use of the product wouldn't affect any of the above categories, and the impact of transporting material depends on the location of the project.

The global warming potential for producing one kilogram of sawn hardwood and softwood is negative because the trees absorb carbon over their lifetime, offsetting the carbon created during production. Thereby creating a total of -1.1 kg of carbon dioxide for the hardwood and -1.4 kg for the softwood (Wood-Solutions 2017). Conversely, steel has a much higher value because producing an equivalent amount of steel produces 3.3 kg of carbon with no offsetting (Fig. 1) (Liberty GFG 2016). The energy required to produce the kilogram is lowest in hardwood at 20 MJ, surpassed by softwood with 25.3 MJ, and topped by steel at 37.5 MJ (Fig. 1). The water used in production follows the same pattern as the energy required, hardwood needing 1.5 kg of water, softwood needing 1.8 kg, and steel requiring 9.4 kg (Fig. 2). The water for producing the wood does not account for the water used in growing the timber, which is known as green water consumption, in the forest/plantation hardwood requires much more than the softwood, 1155.3 kg compared to 547.4 kg (Fig. 2).

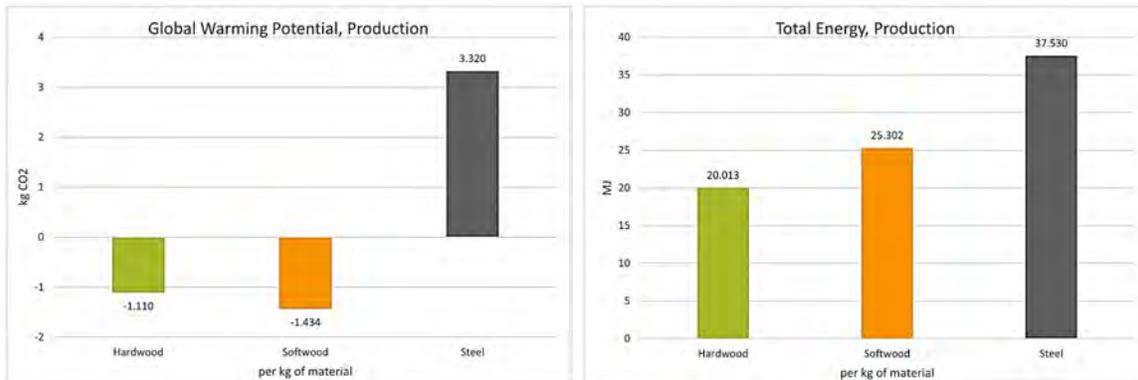


Figure 1: Global warming potential (left) and total energy in production (right) per kg of the material.

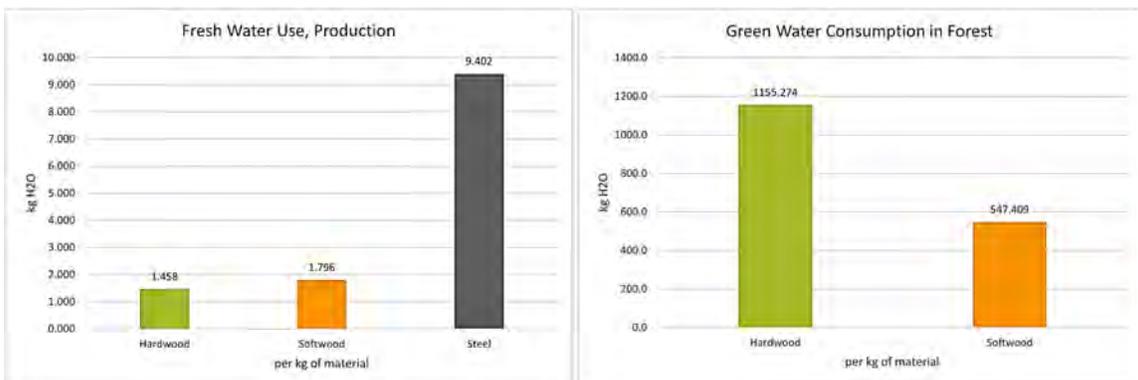


Figure 2: Fresh water use in production (left) and green water consumption in forest before production (right) per kg of the material.

At the other end of the life cycle analysis, the products are given an assortment of options as to their end-of-life stage. In Australia, hardwood has five options: energy recovery, recycling, reuse, landfill (typical), and landfill (NGA). Energy recovery is described as shredding and combusting the wood, replacing coal in the power grid. Recycling is the process of turning old wood into woodchips. Reuse is taking the material and directly reusing it without further processing. The two landfill options are based on bioreactor lab research, accounting for a certain amount of the carbon being degradable. The NGA value comes from Australia's National Greenhouse Accounts and is associated with the degradation of lumber in anaerobic conditions (Wood Solutions 2017). The softwood shared the same end-of-life options as the hardwood, excluding reuse. Steel had two options: disposal and recycling; recycling accounts for the scrapping and repurposing of steel while disposal refers to steel that ends up in the landfill (Liberty GFG 2016) Only the recycling and reuse modules have been compared in the end-of-life scenarios, as they were the common options. The global warming potential is least in recycled softwood and highest in recycled steel. The recycled softwood produced .1 kg of CO2, reused hardwood produces 0.2 kg, recycled hardwood 0.4 kg, and 1.2 kg were produced with recycled steel (Fig. 3). As for energy used in the end of life, reused hardwood is the least with -1.2 MJ, recycled softwood is next at -0.1, then recycled hardwood with 0.5 MJ, and steel uses the most with 15.3 MJ (Fig. 3). Freshwater use is the least in reused hardwood and the most in recycled steel. The reused hardwood uses -0.9 kg of water, recycled hardwood uses 0.7 kg, recycled softwood uses 0.8 kg, and steel uses 7 kg (Fig. 4).

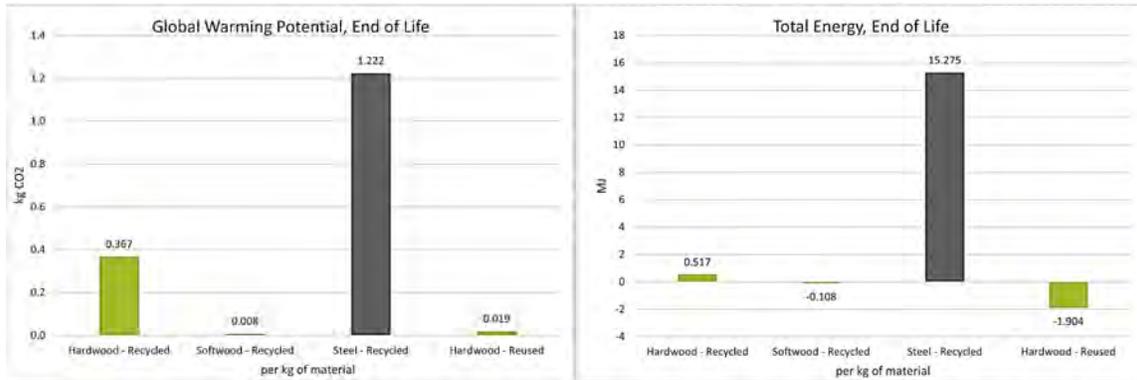


Figure 3: Global warming potential (left) and total energy (right) at end of life per kg of the material.

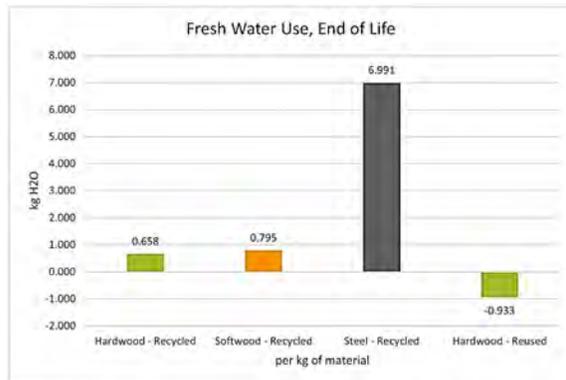


Figure 4: Fresh water use at end of life.

3.2 Carbon sequestering potential

Carbon sequestration is the process by which plants take CO₂ out of the air and create useful biomass. At harvest, the lumber of American softwood species contains 52.1% carbon (Birdsey 1992), and *E. Cloeziana*'s contains 55% carbon (DOA 2013). With an average carbon percentage, the densities of two species can be used to compare the amount of carbon in each (Fig. 5). The average air-dry density for Douglas fir, a typical structural timber, clocks in at 530 kg/m³ (33 lb/ft³) (The Engineering toolbox 2021). At 52.1%, 265 kg/m³ (16.5 lb/ft³) of the fir tree is carbon. Plantation-grown *E. Cloeziana* has an average density of 800 kg/m³ (46.8 lb/ft³) (Business Queensland) with 440 kg/m³ (27.5 lb/ft³) being carbon. Comparing the two numbers, the Eucalyptus contains 110 kg/m³ (6.9 lb/ft³) more carbon than the Douglas fir. The speed at which each species matures is another important factor when comparing the carbon sequestering potential.

3.3 Growth speed

Douglas Fir takes 40-60 years before it can be harvested for lumber (Loucks 2021) whereas *E. Cloeziana* can be harvested starting at 20 years (DOA 2013). If both trees are planted at the same time, the *Cloeziana* sequesters more carbon in 20 years than the Douglas fir does in 40, as shown in Figure 5. If continuously planted and harvested in a plantation, the accumulated carbon in the Eucalyptus plantation is exponentially higher than the fir plantation. To find the carbon sequestering rate, the total carbon at the end of the tree's life is divided by the years it takes to grow it, e.g., fir takes forty years to be harvested, and will contain 276.1 kg/m³ of carbon at that time. 276.1/40 gives it a rate of 6.9 kg/m³ of carbon absorbed per year. This does not accurately represent the actual rate of carbon sequestration throughout a tree's life, it simply provides a means of comparing the carbon in each species over time. The quick growth of the *Cloeziana* also bolsters the timber, for its shorter juvenile phase means it reaches its mature mechanical properties quicker than other eucalyptus species (Bailleres et al 2008). *E. Cloeziana* has clear advantages due to quick growth, especially when evaluating from a quicker replenishment potential.

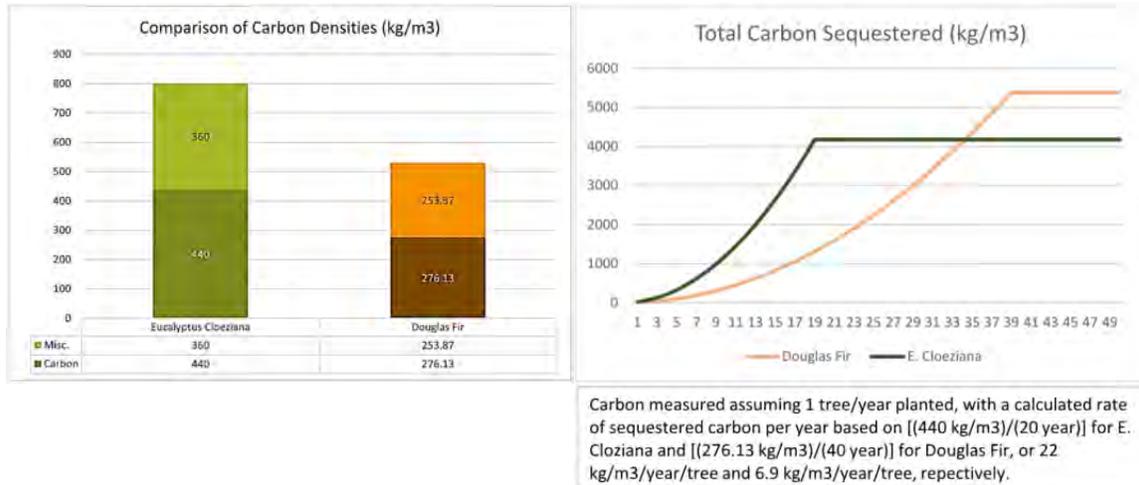


Figure 5: Carbon densities (left) and carbon sequestered per year (right) in kg/m3 of Eucalyptus Cloeziana & Douglas Fir

3.4 Durability class

Gympie messmate produces wood rated durability class 1, lasting more than 25 years below ground and over 40 years above ground. The five classes are defined according to the EN 350-2 standard, with 1 being the most durable and 5 being the least (BSI 1994) (Wild Deck Company 2021). Along with resisting natural decay, E. cloeziana is resistant to Lyctine borer and termite attacks (DOA 2013). Native grown timber typically has better structural properties than the plantation grown timber of the same species, however the plantation grown trees show equivalent performance (Bailleres 2008) and the only major difference is the plantation trees typically have a smaller log size on average (Harding et al 2012).

3.5 Strength class testing and results

After cyclone Larry, felled trees of multiple species were gathered for strength testing, noting that while the wind had snapped most trees along their trunk, the Cloeziana trees were intact, having been pulled up with their root ball still whole (Francis et al 2008). In testing the strength of hardwoods, EN 338 has a range of standards for timber strength. These classes range from C14-C50 for softwood species, and D30-D70 for hardwood species. To qualify for a strength class, the species must meet the minimum values for strength, stiffness, and density (Lawrence 2005). One issue with the strength class system is that while it works well for softwoods, hardwood species may fit into one class for bending, but its lower stiffness and density means it must be placed in the class below it (Lawrence 2005).

After thorough testing by the FWPA (Forest & Wood Products Australia) and Delft University of technology, courtesy of GS Timbers, E. cloeziana was given a strength class of D50. The D50 strength class boasts a modulus of elasticity of 19,800 N/mm² (2,871,747 psi), a modulus of rupture of 89 N/mm² (12,908 psi), and a density of 656 kg/m³ (40.95 lb/ft³). The paper goes on to say that for design that only depends upon bending strength, the f_m , k and E values for strength class D70 can be used (TU Delft 2009).

4. POTENTIAL FUTURE USE

4.1 Veneer-based composites

Looking into the future of construction, E. cloeziana shows potential for use in engineered wood products. For veneer-based engineered wood products, it was shown that E. cloeziana could produce twice as many usable veneers than another Eucalyptus species (Atyeo et al 2008). Veneers from Gympie messmate had previously been graded and used in plywood panels, and testing these panels resulted in them being placed between the F22 and F27 stress grades (Harding et al 2012). For comparison, pine plywood lands itself in the F14 grade (Atyeo et al 2008). Table 5-1 from the SAA Timbers gives measured values for these grades, with F27 having almost twice the bending capacity that F14 does (Table 4 (SAA 1988), showing that cloeziana plywood has potential for heavier construction applications.

4.2 Engineered beam

While the veneer-based wood products in Harding's report were being tested for E. Cloeziana, the wood was also being tested for its potential in glue laminated beams. Four beams were created and tested for strength, stiffness, and bending. The beams ended up fitting into the GL10 glulam rating. All beam samples also passed the requirements for bonding (Harding et al 2012), proving E. cloeziana has potential for engineered beam products.

5. CASE STUDY

5.1 Introduction

The case study is a fire station, focused on a singular structural bay. The dimensions for the bay are 24'-0" by 48'-0", spanned by semi-bowstring trusses in the 48-foot direction and purlins in the 24-foot direction, as shown in Figure 6. The lateral force resisting systems are specially reinforced masonry walls, leaving gravity loads to the roof framing. To compare the 3 different materials, 3 corresponding models were created in RISA 3D structural analytical design software, in which only the trusses and purlins will be compared (Fig. 6). To account for the curved roof diaphragm, dummy members had to be placed in the model and given the designation of RIGID so RISA would not design them. In the steel model the beams were placed at 6'-0" on center while both wood models had the beams set at 4'-0" on center. The dead load is comprised of the roof sandwich and the building systems while the live load is a standard 20 psf for roof loading from ASCE 7-10. The roof is comprised of metal roof panel, vapor barrier, rigid insulation, and structural oriented strand board (OSB) for the two wood models, and metal roof decking in place of the OSB for the steel model. The building systems include ductwork, sprinklers, lights, lath ceiling, and collateral loading; in total the wood models had a dead load of 1220.9 Pa (25.5 psf) and the steel model had 1175.5 Pa (24.55 psf).

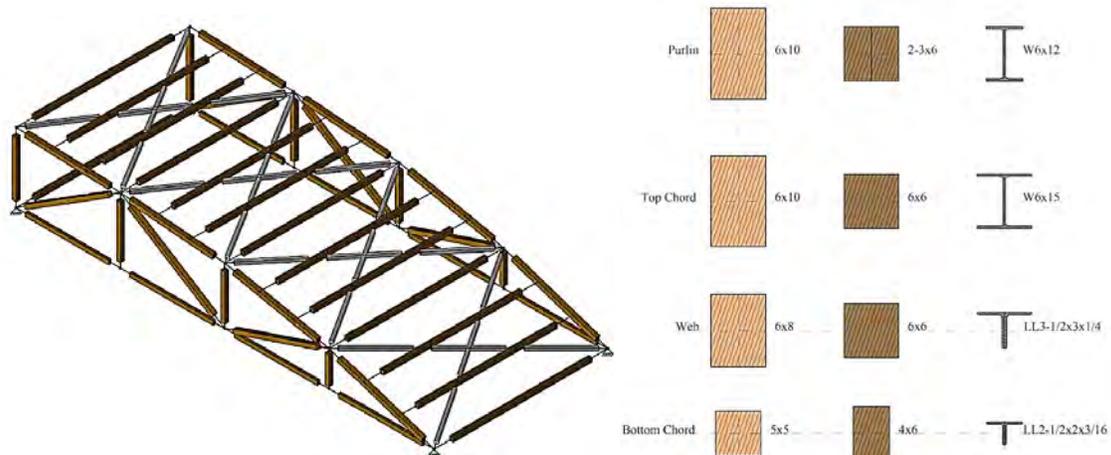


Figure 6: Bay model (left) and member sizes (right) showing the same truss design for the three materials.

5.2 RISA output

The bay models were put into the structural analysis program RISA and had parameters set to find the most economical size by beam, top chord, web, and bottom chord. As a result, the Douglas fir model returns a purlin and top chord size of 6x10, web size of 6x8, and a bottom chord size of 5x5. The E. cloeziana has a purlin size of 2-3x6, top chord and web size of 6x6, and a bottom chord size of 4x6. The steel has a purlin size of W6x12, the top chord is a W6x15, the web is a LL 3 1/2 x 3 x 1/4 and the bottom cord is a LL 2 1/2 x 2 x 3/16. The steel model required the web and bottom chord members be changed to double angles as they were bottoming out at the smallest wide flange shape. The member shapes are visually compared in Figure 6.

5.3 Embodied carbon and structure weight

To meet the required stiffness, the Douglas fir required much thicker members, where the Eucalyptus and steel did not. In comparing the total weight of the structure for the bay, the Eucalyptus ended up at the lightest with only 2138 kg (4715 lbs.) of wood, with steel following closely at 2661 kg (5868 lbs.) and tailed by the Douglas fir with a total weight of 2999 kg (6614 lbs.) (Fig. 7). Despite the steel having a lighter dead load with the decking, it was not the lightest structural system. The weight of the eucalyptus required for the structure is only 70% of the required weight in fir. When comparing the carbon that's been created in the production of the structure, steel leads the way at 8835 kg (19481.76 lbs.) of CO₂, cloeziana is second with -2373 kg (-5233.65 lbs.), and Douglas fir has the most offset with -4301 kg (-9484.23 lbs.) (Figure 8). The embodied carbon of each system is calculated by multiplying the factors found in the production module of each EPD by the total weight of the structure. The global warming potential for each material was converted to kg of carbon dioxide per kg of material. Therefore, multiplying the total weight of each structural system by their corresponding embodied carbon factor, the total carbon of each system could be quantified. Only the value for production was used since no demolition plans would be specified. When comparing the two wood species, the Douglas fir structural system offsets more carbon than the eucalyptus system, explained by the difference in required weight between the two structures. The softwood system requires more wood than the hardwood system does, therefore sequestering more carbon (Fig. 8). When faced with these numbers it is important to remember the efficiency of a structural system, the quick growth speed of the eucalyptus, and the cost of

material. The growth rate compared to traditional wood species used for construction would increase the supply to meet the increased demand, therefore bringing prices down.

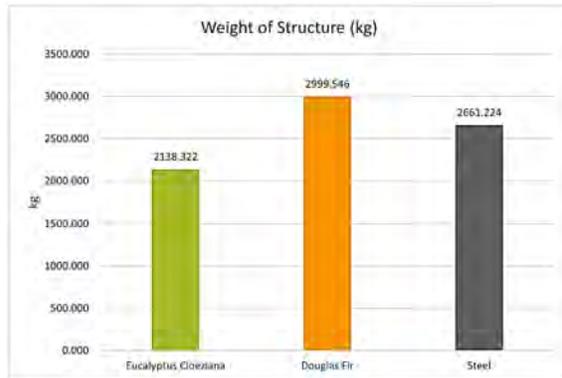


Figure 7: Weight of structure

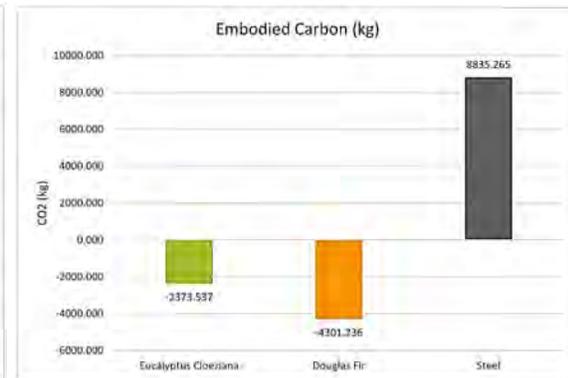


Figure 8: Embodied Carbon

CONCLUSION

Although the Douglas Fir option in the presented case study is shown to have the least amount of embodied carbon based on production, the use of Eucalyptus cloeziana should not be discounted. When considering the comparable amount of sequestered carbon and the shorter growth and harvest cycle of E. cloeziana, it can be seen that there are merits to this material that are not reflected in simply looking at the embodied carbon value. One issue is that this study highlights is the inadequacy of embodied carbon values, which focus on production alone, to reflect the environmental impacts of land use, water use, amount of material used, sequestered carbon, and growth/harvest cycles in the consideration of structural materials and their environmental impacts. To address this, further study would be required, with the possibility of devising additional metrics for these factors. It should be mentioned that some of these factors may shift some of the balance to the benefits of steel as well as E. cloeziana. However, as can be seen from the study, E. cloeziana has the potential to be a viable and sustainable option for building structure.

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Future of Thermal Insulation, Zero Carbon Options

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ABSTRACT: *The paper is looking into the future of thermal insulation to come up with a fair assessment of traditional and innovative alternatives. The building industry is now looking into not only reducing operational energy, but also embodied energy. A general look at thermal insulation materials currently used in buildings shows an urgent need to transformative change in the market towards low-carbon materials. Since market changes typically take time and face resistance, it is time to find out which future materials are ready to replace the traditional ones. Considering thermal performance of the building envelope, thermal insulation is the layer that contributes the most to overall thermal resistance. High performance buildings call for higher levels of thermal resistance. This research project acknowledges the need to assess embodied carbon of thermal insulation. First, a review was conducted of insulation types available in the American market. A sample of materials was selected based on availability and market share. The sample includes fiberglass bass insulation, cellulose, extruded Polystyrene, and spray foam. Second, a typical wall assembly for a house in the U.S. was defined and modeled using the selected types of insulation materials. Location of the study set to Oklahoma and the baseline wall assembly was in compliance with IECC 2018. Total R-value of all tested wall assemblies were kept the same in order to limit the analysis to embodied energy, since operational energy would be equal in all cases. Then, life cycle carbon analysis was performed in Tally to assess the insulation types. Research results showed that Insulative Cork Board had the best performance (lowest carbon footprint) among the types of materials selected. Cork Board undergoes extensive testing of the final product with third-party certification and verified EPD (Environmental Product Declaration), resulting in high-quality input data for carbon analysis. The next contender among the innovative insulation materials is Mycelium. Mycelium is still a new product to the market and there has not been any certification performed to ASTM standards.*

KEYWORDS: Decarbonization, Insulation Materials, Building Envelope, Life Cycle Analysis, Building Innovations

INTRODUCTION

Building insulation plays an important role in the lifespan of a building. It improves the thermal comfort and well-being of the occupants while reducing energy consumption. However, most materials used are manufactured using mined and/or fossil fuel-based materials. These materials are by-products of oil and are being used in increasing quantities, which will eventually lead to problems associated with material depletion and its disposal during its end-of-life stages. One sustainable solution suggests the use of biodegradable materials. There have been several attempts to develop biomaterials. The comprehensive study entails the comparative documentation of these following attributes: carbon emissions, cost, protective features, production and manufacturing, market shares, durability, acoustics and energy analysis. In order to produce a well-rounded report, a handful of materials were selected to analyze against the project objective. The non-renewable products are materials that have the highest market shares for oil-based insulation and will serve as a basis of expectation for the insulative properties in the renewable materials. Along with mycelium, the highest market shared materials that will be analyzed are soy-based insulation, hempcrete, rigid cork, and cementitious foam; all of which are utilized as lateral comparison. Software was utilized for comparative analysis. Tally analyzed the life-cycle analysis performance while EC3 organized the visual of carbon flows.

1. METHOD -- MATERIAL OVERVIEW

1.1. Conventional insulation materials

- *Fiberglass Batt:* It is made primarily from silica spun into glass fibers with a binder. Most fiberglass insulation has at least 30% recycled-glass content. Low-density fiberglass may be less effective under very cold conditions due to its tendency to allow for air movement, but high-density products are available.

- *Extruded Polystyrene XPS:* XPS is thermoplastic, closed-cell foam insulation derived from petrochemicals. But XPS's excellent moisture resistance, high compressive strength, and low cost make it a popular insulation material particularly for below-grade applications.

- *Spray Foam Closed Cell:* It can be used for an exterior foundation, with proper drainage. While the blowing agent is non-ozone depleting, it is potent for greenhouse gas, with a high global warming potential (GWP).

- *Spray Foam Open Cell:* Compared to closed-cell SPF, open cell products use significantly less material, making it less expensive. However, open cell insulation achieves a much lower R-value and is not as effective at stopping moisture flow. It cannot be used below grade or in high-moisture applications.

- *Cellulose*: Cellulose Batt is made from recycled newspaper by hammer milling but also requires other fibers, binders, and borate-based and/or ammonium sulfate flame retardants. Of the five analyzed components, closed-cell extruded polystyrene has the best R-value per inch at 7.1 per inch, however it has a high carbon footprint per square foot in comparison to the other conventional materials.

1.2 Innovative insulation materials

- *Soy-Base Spray Foam*: A high-performance, versatile spray foam insulation designed for residential construction. Its unique formula incorporates recycled plastic bottles and renewable oils to create high-performance, closed-cell spray foam insulation. It combines multiple control layers into a single application.

- *Cementitious Foam (Airkrete)*: An inorganic, foamed magnesium-oxide cement insulation, and is good for people with chemical sensitivities. There is no off gassing, and it requires no flame retardants to remain noncombustible. The cured foam does not function as an air barrier.

- *Insulative Cork Board*: This versatile material is formed into a semi-rigid board as an insulative panel. It will not lose R-value over its lifetime unlike XPS. Since cork has a high vapor permeability than foam, there is a reduced risk of moisture issues in the wall assembly that can potentially extended the structure's lifespan.

- *Hempcrete*: A biocomposite material that is a mixture of hemp hurds, lime, sand, and pozzolans. It is easier to work with than traditional lime mixes and acts as an insulator and moisture regulator. It is a lightweight material that is ideal for most climates, and it combines the insulation and thermal mass into one.

- *Mycelium*: This insulation board is an R-4-per-inch rigid material made from mycelium that are grown in agricultural waste materials.

Insulative cork board is the best in terms of renewability, carbon absorption and certifications. However, the next contender for an innovative insulation is going to be the mycelium insulation. Mycelium is still a new product to the market and there has not been any certification performed to the ASTM standard making it difficult to produce a solid conclusion based on qualitative information alone.

1.3 Software utilized

- *Tally* utilizes BIM data to perform a life cycle assessment based on the quantities of materials used. For simplicity, ceilings and floors were omitted and the interior was assumed to be finished with a gypsum wall board. The emphasis was on the envelope itself so specific data points could be excluded from the analysis.

- *EC3* used the tedious data inputs from Tally and processes it into an organized visual of carbon flows based on the materials present in the assembly.

2. METHOD -- ENERGY SIMULATION

2.1 General information

This section compares different insulation technologies discussed in the previous section. For this purpose, a basic wall assembly was created to produce LCA data for the conventional insulation. By utilizing the IECC 2018, the comparison baseline is created for needed to explore and compare (Table 1).

Table 1: Wall Assembly. (Author 2021).

Location	Oklahoma
Climate zone	3A
Wall dimension	4'-0" wide x 9'-0" tall
Wall thickness	3 ½" to 7 ¼"
Stud spacing	24" O.C

2.2 Material properties

Attributes Table to Compare Insulations: This study was initially approached with an excel sheet that was utilized to compare the characteristics and attributes of the insulations in one place. This table (Table 2) also displays two materials that were later removed due to a lack in information.

Cost For Insulation: This excel sheet was used to compare the cost per square foot and the cost for the R-Value per square foot. It takes the given price from a construction material supplier whether it was for one board or measured coverage. If it was a measured coverage the total price was divided by the area that was given by the company. This gave the price per square foot at 1" thick. This price was then multiplied by required thickness (Table 3) of insulation to meet the R-Value from the IECC 2018 code.

Table 2: Insulation comparison

	Brand	R-value per inch	Carbon emissions	Water resistant	Pest resistant	Fire resistant	Density lb/cft
Fiberglass batt	Owens	4.06	2.18124 kgCO ₂ /M ²	< 5% ASTM E96	ASTM C1338	ASTM E84 UL723	0.116
XPS – Extruded	Dupont	5	9.03 E1 kgCO ₂	1.5 ASTM E96	ASTM C1338	ASTM E84 UL723	0.15
XPS - Extruded	Owens -Foamular	5	2.19 kgCO ₂ /M ²	ASTM C578 Type IV	ASTM C1338	ASTM E84 UL723	0.15
Spray foam (Closed cell)	Demilec Huntsman	7.1	N/A	ASTM E96	ASTM C1338	NFPA 285	2
Spray foam (Open cell)	Demilec Huntsman	3.8	N/A	ASTM E96	ASTM C1338	NFPA 285	0.45
Cellulose	Greenfiber	3.7	N/A	ASTM C1338	ASTM C1338	Extremely Flammable	0.519
Soy-based insulation	Demilec	7.4	> 0.5–4.9 kgCO ₂ /M ²	ASTM E96	ASTM C1338	ASTM E84 NFPA 286	2.1
Hempcrete	Hempitecture	3	–2454.21 kgCO ₂ E/M ²	< 5% ASTM C1104	Yes	Class b s1d0 EN Standard	7
Hempcrete	Hempecosystems	3.1	–2454.21 kgCO ₂ E/M ²	< 5% ASTM C1104	Yes	Class b s1d0 EN Standard	7
Rigid cork insulation cork board (IBC)	Corktherm	3.61	–1.91 kgCO ₂ /M ²	0.5 kg/m ² EN1609	Yes w/Treatment	Euro Class E EN 13501–1	7
Cementitious foam	Airkrete	3.9ASTM C518, 6 per DLS report	D5116 carbon negative	ASTM E96	ASTM C1338	ASTM E84-81A	5
Mycelium	Ecovative designs	4	Carbon negative	Yes	Yes w/Treatment	Low with no Silica added	59–552 (kg/m ³)

Table 3: Insulation Costs

-	Brand	Cost Given	/	Coverage sqft	=	Cost per SQFT	*	Thickness of Insulation	=	Cost for R-Value / sq ft
Fiberglass Batt	Owens	38.32	/	48.96	=	0.783	*	-	=	\$0.783
XPS - Polystyrene Extruded	Dupont	32.98	/	32	=	1.030625	*	4	=	\$4.12
XPS - Polystyrene Extruded	Owens - Foamular	23.25	/	32	=	0.727	*	4	=	\$2.91
Spray Foam (Closed Cell)	Demilec Huntsman	1.50 @ 1in thick	-	-	=	1.0 / 1 in	*	2.82	=	\$2.82
Spray Foam (Open Cell)	Demilec Huntsman	\$0.54 per sqft @ 1"	-	-	=	0.54	*	3.421	=	\$1.85
Cellulose	Greenfiber	\$3.43 for 19 lb	/	22.7	=	0.151	*	-	=	\$0.15
Soy Based Insulation (Closed Cell)	Demilec	3.00/ 1in	-	-	=	3.00 sqft	*	2.703	=	\$8.11
Hempcrete	Hempitecture	54.99	/	19.98	=	1.25	*	6.45	=	\$8.06
Hempcrete	Hempecosystems	54.99	/	19.98	=	1.25	*	6.45	=	\$8.06
Rigid Cork	Corktherm	1.79	-	1	=	-	*	5.54	=	\$9.92
Cementitious Foam	Airkrete	1	-	1	=	1.00	*	5.13	=	\$5.13
Mycelium	Ecovative	1.71	/	1	=	1.71	*	5	=	\$8.55

2.3 Wall structuring

Wall Assemblies: To represent the most typical case of residential construction, 2x6 wood stud wall is selected for simulations. The sheathing and interior layers are kept the same for each case. The exterior finish layer that is applied is a wood siding layer and a brick veneer layer. Different types of insulation materials are selected. The simulated cases are named in correspondences to the different insulation materials used in the wall models (Table 4).

Table 4: IECC 2018 Wall Thickness (IECC 2018).

-	Brand	Total R-Value	/	R-Value per Inch	=	Thickness for R-Value'	Wall Stud Frame
Fiberglass Batt	Owens	20	/	4.06	=	4.926108374	2 × 6
XPS - Polystyrene Extruded	Dupont	20	/	5	=	4	2 × 6
XPS - Polystyrene Extruded	Owens - Foamular	20	/	5	=	4	2 × 6
Spray Foam (Closed Cell)	Demilec Huntsman	20	/	7.1	=	2.816901408	2 × 4
Spray Foam (Open Cell)	Demilec Huntsman	20	/	3.8	=	5.263157895	2 × 6
Cellulose	Greenfiber	20	/	3.7	=	5.405405405	2 × 6
Soy Based Insulation (Closed Cell)	Demilec	20	/	7.4	=	2.702702703	2 × 4
Hempcrete	Hempitecture	20	/	3	=	6.666666667	2 × 8?
Hempcrete	Hempecosystems	20	/	3.1	=	6.451612903	2 × 8?
Rigid Cork	Corktherm	20	/	3.61	=	5.540166205	2 × 6
Cementitious Foam	Aircrete	20	/	\$3.90	=	\$5.13	2 × 6
Mycelium	Ecovative	20	/	4	=	5	2 × 6

3. TESTING AND RESULTS

3.1 Conventional data

To analyze the conventional materials, Tally was used to create diagrams representing each type of insulation under this category. Tally's database had the selected brands information available to study the lifecycle analysis of each material within a wood stud wall with typical wood siding or brick siding. (Fig. 1).

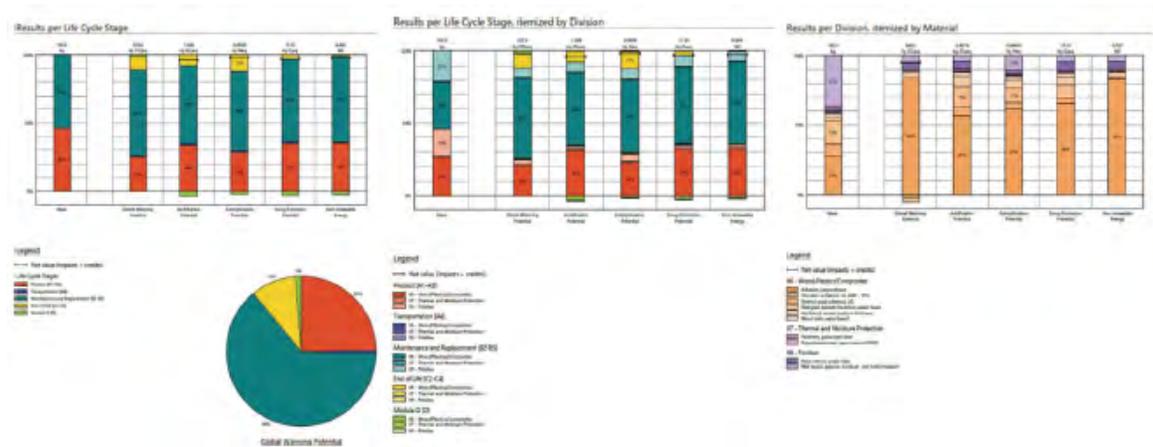


Figure 1: Tally results. (Author 2021).

Each set of data given determined what portion of the product had the greatest impact in terms of carbon emissions by lifecycle stage (left), division (center), and material (right). The lifecycle stage diagram breaks down which portion of the material's life has the most global warming potential within a vertical bar chart and pie chart. By division takes the lifecycle stage further and breaks it down into components based on finishes, thermal and moisture protection, and wood/plastics/composites. Lastly, the final diagram displays what material within the insulation is causing the most output. The data obtained for wall assemblies was similar because the masonry brick and standard lime mortar produced the most carbon. This unfortunately overrode the data about the insulation due to the large amounts of carbon released during the production of masonry. - *Fiberglass Batt / Wood Wall*: Lifecycle Stage: Most impactful stage: Maintenance and Replacement.

Conclusion: Common insulation, however it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement. Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane. Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case.

- *Fiberglass Batt / Brick Wall*: Lifecycle Stage: Most impactful stage: Product. Conclusion: Fiberglass batt is one of the most common insulations used today in residential buildings, the increase in global warming potential it likely because of the brick veneer. By Division: Most impactful stage: Maintenance and Replacement – Masonry. Conclusion: The masonry that added to the amount of embodied carbon in this wall assembly. By Material: Most impactful Material: Generic Brick and Lime Mortar. Conclusion: Itemizing the wall assembly by the material, Tally gave the results that 73% of the resulting global warming potential is marked up to the masonry in the envelope.

- *Extruded Polystyrene XPS*: Wood Wall Lifecycle Stage: Most impactful stage: Maintenance and Replacement. Conclusion: Common insulation, however once it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement. Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane. Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case.

- *Spray Foam Closed Cell / Wood Wall*: Lifecycle Stage: Most impactful stage: Maintenance and Replacement. Conclusion: Common insulation, however it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement- Wood/Plastics/Composites Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane. Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case.

- *Spray Foam Open Cell / Wood Wall*: Lifecycle Stage: Most impactful stage: Maintenance and Replacement Conclusion: Common insulation, however it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement - Wood/Plastics/Composites. Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case. Sustainable design, as shown by this data should begin at the design of the envelope.

- *Cellulose / Wood Wall*: Lifecycle Stage: Most impactful stage: Maintenance and Replacement. Conclusion: Cellulose is another common insulation type that is somewhat being phased out due to its health risk, and amount of maintenance of the product. Due to the cellulose fibers settling, it needs to be replaced so that the R-value may be maintained. Its embodied carbon is likely released as it ages and it will eventually cost more due to the consistent replacement. By Division: Most impactful stage: Maintenance and Replacement - Wood/Plastics/Composites Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Cellulose. Conclusion: The breakdown of the wall assembly shows that the polyurethane adhesive and the blown-in cellulose insulation is what contributes the most to the overall global warming potential of this specific wall assembly.

3.2 Innovative data

Unfortunately, due to the limitations of the LCA programs, there was not a similar way to organize the data for the Innovative insulations that were reviewed for this study. Instead, a qualitative analysis was performed using a point system that was inspired by the LEED points and accreditation system. To the Left (Top) the table shows the selected attributes of the insulations in the first column. This covers the basics for renewability, carbon emissions, safety features, market presence, and many more. The table then compares the attributes of the selected insulations from a scale of -2 to 2 and these are labelled as such (Tables 5 and 6):

Table 5: Qualitative data for innovative insulations. (Author 2021).

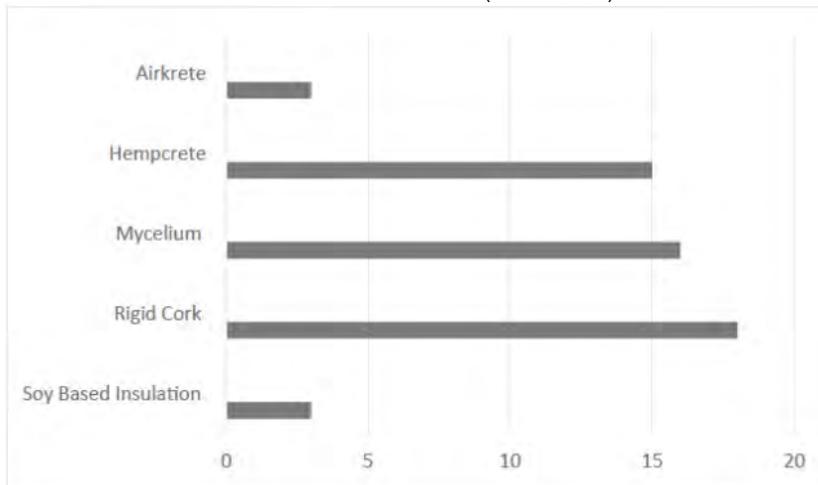
-	Soy Based (Closed Cell)	Hempercrete	Rigid Cork	Cementitious Foam	Mycelium
Carbon Absorption	0	2	2	2	2
Carbon Emissions	-2	0	-1	0	0
Fire Resistant	2	2	1	2	1
Water / Mold Resistant	2	2	1	1	-1
Pest Resistant	2	2	1	2	-1
Renewable	-2	2	2	-2	2
Recyclable	-2	-1	2	-1	2
Biodegradable	-2	1	2	-2	2
Availability	2	2	-1	1	2
Market Presence	2	1	2	-1	1
Skilled Labor Required	-2	-1	2	-1	1
Waste Production	-2	1	2	-2	2
Certifications	1	-1	-1	1	-1
Sound Absorption	2	2	2	1	2
Added Air Barrier	2	1	2	2	2
Total Points	3	15	18	3	16

Table 6: Point system for innovative insulations. (Author 2021).

-2	Negative environmental impact and/or no
-1	Possibly but not proven
0	Not applicable/Not available
1	Yes, but does not have certifications
1	Yes, and has been certified by company

The insulations were then measured according to whether the information was available, had a positive impact on the environment, had no information available, and had a negative environmental impact. The chart to the Left (bottom) then measures the insulations in comparison to each other based on the score that they received from the qualitative insulations (Table 7).

Table 7: Qualitative data for innovative insulations. (Author 2021).



3.3 EC3 Sankey Diagram

EC3 used the tedious data inputs from Tally and processes it into an organized visual of carbon flows based on the materials present in the assembly. The resulting chart shows what materials are demanding the most carbon. These Sankey diagrams summarize all the energy transfers taking place in the lifecycle process of the wall assembly. The thicker the line or arrow, the greater the amount of energy involved (Fig. 2).



Figure 48 - Sankey Diagram from EC3 for Cellulose Insulation

Cellulose

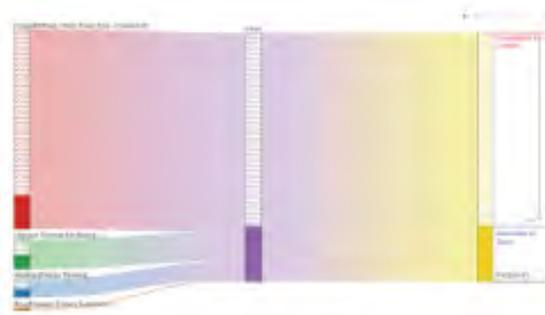
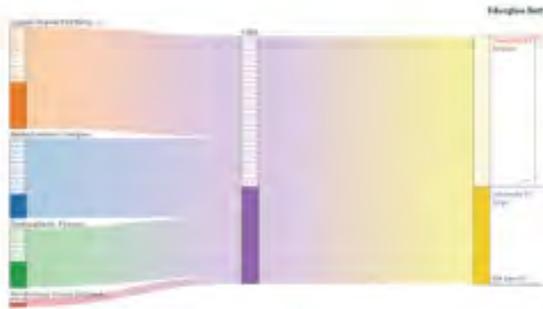
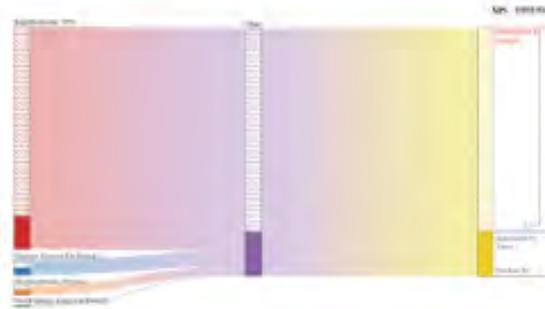


Figure 49 - Sankey Diagram from EC3

Closed Cell Spray Foam



Fiberglass Batt



Extruded Polystyrene XPS

Figure 2. Sankey diagram from Ec3. (Author 2021).

CONCLUSION

In this study, the carbon emissions and characteristics of a residential wall assembly are studied by modeling two different wall assemblies in Oklahoma's climate zone 3A. A side-by-side comparative study was performed for different types of building insulation materials, which provide a better understanding and design alternatives for this field of study. The results show that insulation materials have a significant influence on the carbon footprint and overall performance of the building. Among all the types of insulation materials discussed in this research, ICB (Insulative Cork Board) is the best performing one regarding both carbon absorption, lightweight density, and thermal capabilities. Using ICB will allow for carbon to be absorbed from the built environment and still perform thermally while being the most sustainable material. The only negative is that the market is available more in the European area, however the United States would be capable of growing the Cork Oak in a simulated climate! The one issue with the study that occurred during the duration of the research was the limitations of the LCA data programs. A lot of the innovative insulations have not sought-after certifications and therefore are not in any of the cradle-to-cradle databases. This was a limitation that I specifically found with Tally. Tally's database does not contain the capability to access new forms of data outside of the initial library, nor does it allow for any customization of the materials in the program in order to manipulate the library for the specific needs of innovative insulations. This does prove that our studies in a more sustainable insulation have a lot more work to do but there are large steps that have already been taken towards the future of our built environment.

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Learning Through Lightness

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ABSTRACT: This paper documents the methods and results of a one-semester design-build seminar that synthesized sensor technology, computational design, digital fabrication methods, and construction practices in the design and construction of a light-weight interactive installation. Asking the question “how can the concept of lightness serve as a pedagogical tool for framing small-scale design-build projects?” students in this course wrote custom software for evaluating the thermal performance of lightweight material choices. The result is a novel and disassemblable accessory dwelling unit (ADU) prototype that eliminates active systems and reduces material excess through digital intelligence. An overview of Buckminster Fuller’s early work on geodesic structures with students at Black Mountain College in the summers of 1948 and 1949 serve to ground the research and frame lightness as a framework for teaching students the complexities of construction through experiential learning within an academic context.

KEYWORDS: Design Pedagogy, Design-Build, Digital Fabrication, Computational Design, Interactive Architecture

INTRODUCTION

This paper explores the concept of lightness as a pedagogical framework for realizing short-term design-build projects with students of architecture. At its core, the investigation advocates for the design-build model as an impactful method for distilling the complexities of building through a curriculum that draws upon John Dewey’s experiential approach to education.¹ Two factors, however, make teaching design-build studios a challenge: 1) the lengthy process of building due to the time intensive process of construction itself, and 2) the growing complexity of construction today due to the involvement of multiple trades and the need to integrate an increasing number of building technologies. These conditions make it difficult for architecture students to holistically experience and understand the act of building within the contexts and constraints of architecture education.

As a solution to this situation, this paper proposes using the concept of lightness as a framework for adapting the complexities of building to the contexts of architecture schools and, in turn, leverage the design-build model as an opportunity for experimentation and innovation. As a point of reference, this investigation looks to Buckminster Fuller’s early work on geodesic domes and his first teaching assignment at Black Mountain College from 1948-1949 to learn how small-scale design-build projects premised on lightweight construction can provide a meaningful and heuristic educational experience in building design.

1. CONTEXT

This paper asks the question: “how can the concept of lightness serve as a pedagogical tool for framing small-scale design-build projects?” As a grounding reference for the research, this investigation looks to Buckminster Fuller’s work on geodesics and the method in which he translated his early conceptual models into inhabitable forms alongside students at Black Mountain College. Founded in 1933 in western North Carolina, the institution became a testing ground for pedagogical innovation in the arts under the leadership of Josef and Anni Albers and others until its closing in 1955. As the inaugural visual arts program leader, Josef Albers brought an emphasis on experimentation and an experiential approach to arts education that were derived from his own familiarity with John Dewey’s philosophy of “learning by doing” and his experience as the instructor of the Preliminary Course (Vorkurs) at the Bauhaus prior to his arrival at Black Mountain.²

It was within this culture of testing and creative innovation that Buckminster Fuller arrived for his first teaching assignment in 1948. Josef and Anni Albers, John Cage, Merce Cunningham, Willem de Kooning and Fuller formed a core faculty that were joined by approximately seventy-five students at the College’s 1948 summer session. Fuller at the time was developing his own research on lightweight forms of construction, an idea that was represented by his aluminum and steel Great Circle Sphere Model—a network of overlapping flat circular members that distributed forces along the exterior without need for interior bracing.³ It was at Black Mountain where Fuller’s nascent geodesic design principles intersected with the College’s exploratory culture to convert his conceptual models into occupiable forms. This translation was made possible through a novel pedagogical vision developed in collaboration with John Cage and Merce Cunningham. In an interview with Mary Emma Harris, Fuller recalled how, “John Cage and Merce and I had breakfasts every morning out under the trees”

during which time they developed the concept of their “finishing school,” where they would “finish anything” and “really break down all of the conventional ways of approaching school.”⁴

It was with this attitude towards execution in which Fuller worked with students to erect the first attempt at a geodesic dome. While the subsequently named “Supine Dome” failed to rise due to the damp morning conditions and the insufficient strength of the commercial venetian-blind slats used for its construction, the process proved to be a valuable learning experience.⁵ Despite Fuller being aware that the slats lacked the strength to support the structure, he pushed on in an effort to see the project through with the students and advance his philosophy of lightness by demonstrating buildings could be constructed incrementally with lightweight materials.⁶ While the efforts of that summer proved to be unsuccessful, Fuller’s ability to simplify the act of building into a tangible and experiential process framed the exercise not as failure, but as a first step in a larger design project. The lessons learned from the Supine Dome were on full display the following summer when Fuller returned—this time as the summer session organizer with the resignation of Theodore Dreier and Josef Albers—and realized a free-standing version of the dome, this time using linear elements and connecting nodes.

Fuller’s teaching at Black Mountain holds resonance today in an era where the process of building is an ever increasingly complex process. By taking cue from Fuller’s focus on small-scale lightweight structures, we can learn to frame the design-build model not as a one-off exercise, but rather as a collective series of experiments towards a long-term strategy for design.

2. METHODOLOGY

The Color of Air is an installation that explores the pedagogical potential of small-scale lightweight design-build projects to holistically understand and analyze the process of building. The project was designed, fabricated, and constructed with undergraduate and graduate students through a one-semester seminar course at the University of Tennessee College of Architecture + Design. The installation synthesized sensor technology, computational design, digital fabrication methods, and construction practices in the design and construction of an accessory dwelling unit (ADU) prototype that offset material excess with digital intelligence. As a pedagogical exercise, the design-build project introduced students to the process of building through an experiential approach to construction.

The installation is an 84 square-foot tea house designed to eliminate the need for active systems through lightweight materials and the integration of sensor technology. (4) air inlets at the corners of the floor and door and (2) along the roof ridge induce natural ventilation flows within the space through a stack-effect. Movable furniture and the doorway located at the corners create a system for modulating airflow through the interior. The project incorporates temperature, humidity, and airflow data collected from sensors to design a dynamic facade system that allows visitors to understand both interior and exterior thermal conditions through their physical interactions with the structure (Figure 1). Through its small scale, legible constructability, and interactive interface, the installation proposes a lightweight dwelling prototype that can communicate and respond to local contexts and conditions.



Figure 1: The project supplants active systems and material excess with digital intelligence—red and blue hues convey warmer and cooler interior temperatures respectively. Source: Authors

2.1 Lightness as a model for integration

At a pedagogical level, lightness served as a framework for distilling the complexity of building down to core concepts that could be explored in a single project. Drawing upon Fuller’s concept of a “finishing school,” the installation was envisioned as a one-semester exercise in which students could experience the design, development, construction, and evaluation of a building from beginning to end. Conceptually, this approach

impacted the installation's design in two ways: 1) the project's physical size, and 2) the elimination of active building systems and the excessive use of materials.

The solution was to frame the installation as a heuristic device and feedback loop for understanding the thermodynamic principle hot air rises. By communicating the structure's thermal conditions through an interactive facade system, the need for active systems or excessive materials could be supplanted by users' own experiential understanding of the project and the way it performs.

As a result, The Color of Air necessitated integrating sensor technology, computational design, digital fabrication, and construction practices to collect data, operate its interactive facade system, create lightweight and customizable members, and provide structural stability where necessary. Perhaps the most compelling representation of this integrative approach was the project's construction documentation that expanded upon the conventional drawing set to include CNC cut files, Arduino C++ scripts for reading sensor data and controlling the addressable LED lights, and JavaScript code for parsing local weather data to be used in comparison with internal temperature and humidity data readings (Figure 2).

By committing to a concept of lightness, the project was able to remain at a small scale and free from active systems and the use of excessive materials, which in turn allowed for a level of experimentation evocative of Black Mountain College's culture and attitude towards arts education.

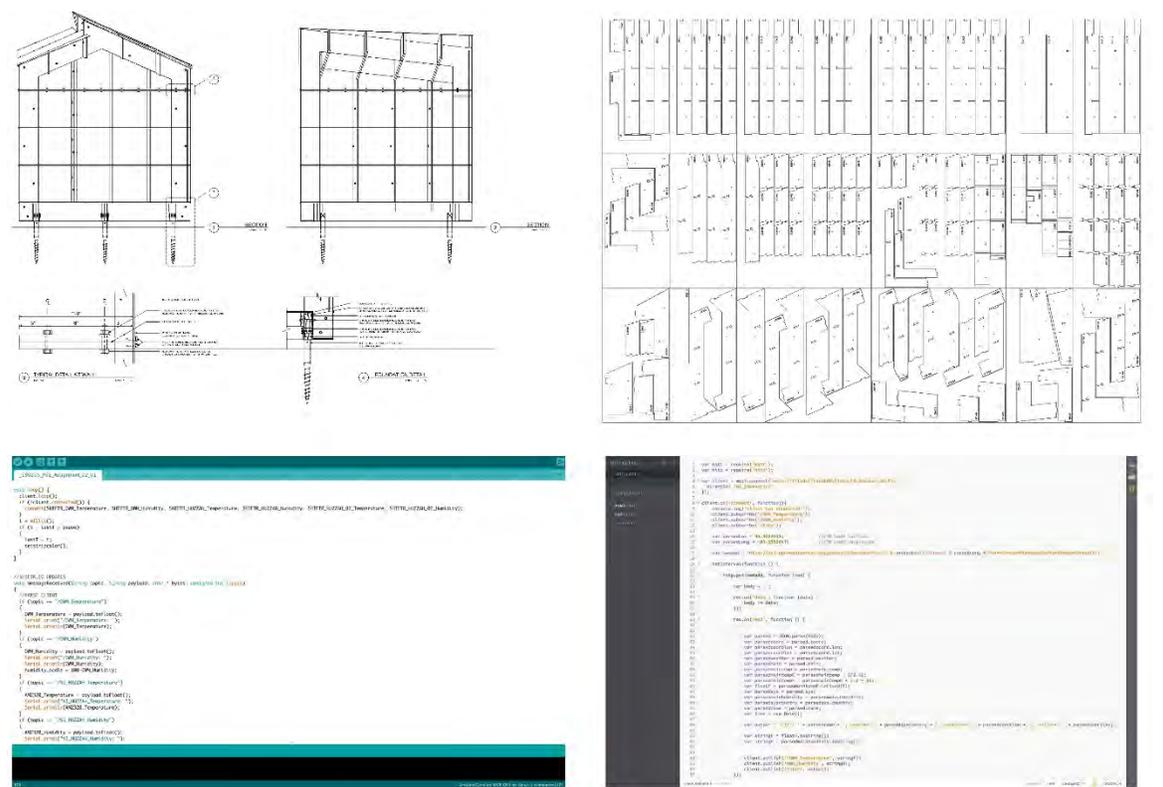


Figure 2: Clockwise from top left: sheets from the drawing set, CNC mill files for fabrication, JavaScript code for parsing local weather data, and an Arduino C++ script used for reading the sensors and controlling the addressable LED lights. Source: Authors

2.2 Designing for disassembly

Lightness as a concept for construction served the project in two ways: 1) the process of building and re-building the installation operated pedagogically to reinforce the students' understanding of how the project was designed and constructed, and 2) the project's ability to be disassembled allowed students to test the installation's performance in two different site contexts.

Three significant choices were made regarding the project's materiality. The first was the use of 3/4" radiata plywood for the walls' and roofs' primary structure. The customized design of these elements necessitated the use of the CNC mill and in turn a plywood material that could both be cut and provide structural rigidity. 3/4"

was determined to be an appropriate thickness and radiata was selected for its clean appearance and relatively inexpensive cost. The second choice was the use of clear corrugated polypropylene for the exterior cladding. This material was selected for its translucent appearance that would permit the interior to be naturally lit during the day and allow for the LED lights to illuminate the exterior at night. The third choice was the use of American Ground Screw U-Model ground screws as a foundation for the structure. This foundational system was selected to provide a temporary foundation as the project was designed to be transported and eliminate the need for the energy intensive use of concrete. Originally designed for mailboxes and exterior decks, the installation's size provided an opportunity to test this foundation system for small-scale dwelling structures.

The installation was designed with the two constraints in mind: 1) the project must be buildable by the author and students without the use of a crane, and 2) the installation must be disassemblable and fit within a U-Haul truck for transportation. To be both lightweight and structurally sound, a hybrid construction method was employed for the installation (Figure 3). CNC milled plywood was used for the wall and roof structure and a conventional wood framed floor was used to support the building. For the installation to be disassemblable, the walls and roof were designed as modular bays approximately two feet wide and connected with thru bolts. The overall structure was designed to be transported in a single 26-foot-long U-Haul truck (Figures 4). As a prototype for ADU construction, the project is designed to be transported through a side yard and erected by a team of two or three individuals without the use of a crane.

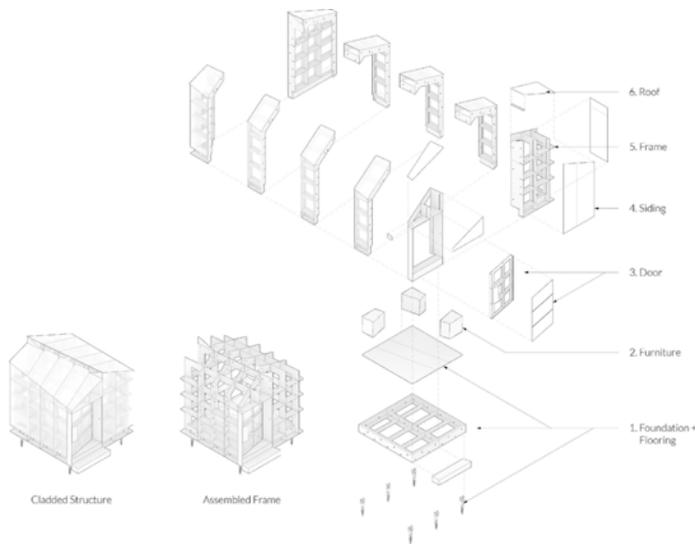


Figure 3: A hybrid construction system that combined traditional wood framing with digital fabrication methods was used for the project. Source: Authors



Figure 4: The installation was designed to fit within a single 26-foot-long U-Haul truck. Source: Authors; and photograph of the installation loaded for transportation. Source: Authors



Figure 5: The first phase of construction is the marking and installation of the temporary ground screw system. Source: Authors; and The ground screws provide a lightweight and ecological alternative to conventional concrete footings. Source: Authors

The phasing of the installation's construction is a three-part process. The first is the marking and installation of the ground screw foundation system (Figures 5). Next is the setting of the wood framed floor. Lastly is the erection and bolting of the plywood walls and roof. The structure's modular design allows for it to be constructed in a single day (Figure 6). Through its operable ventilation system and translucent skin, occupants can modulate the building's thermal performance and engage with the environmental conditions of the local area (Figures 7).



Figure 6: The integration of digital fabrication methods and construction practices enable the structure to be built in a single day. Source: Authors



Figure 7: Occupants can modulate the structure's thermal performance through operable doors and openings. Source: Authors; and the installation's translucent and lightweight skin allows occupants to engage with the environmental conditions of the site context. Source: Authors

3. RESULTS

From a pedagogical standpoint, the project had two significant outcomes. The first was the installation's small size, elimination of active systems, and restrained use of materials enabled students to execute the installation in a single semester. Furthermore, the limited scope of the project allowed them to take an active role in the design, development, construction, and evaluation of the building from beginning to end. As a result, students were actively engaged throughout the project, and they had a thorough understanding of the installation's design and how it performed.

A second outcome was the installation's ability to be disassembled enabled students to rebuild it on two different sites. The process of constructing the structure multiple times reinforced their understanding of the structure and framed the act of building not as a one-off exercise, but instead a series of experiences that could be applied in different situations and conditions. Being able to study the structure in two different locations additionally demonstrated the impact varying site conditions can have on a building's performance.

From a construction standpoint, the project demonstrated how temporary foundation systems can provide novel solutions for small-scale dwellings. The ground screws' capacity to support structures of this size show they can serve as an effective alternative to the energy intensive use of concrete. Furthermore, their ease of installation and relatively small size make them a viable solution for temporary structures that must minimize their impact on the site and soil.

CONCLUSION

By leveraging lightness as a framework for design-build studios, we can distill the complexity of building down to foundational concepts for students of architecture. Drawing upon the lessons of Buckminster Fuller and his interactions with students at Black Mountain College, a lightweight approach to building positions the act of construction not as isolated incidents, but rather steps within a larger design process. By keeping the scope small, educators can frame the design-build format and the process of design, development, construction, and evaluation as an iterative and recursive model for disciplinary experimentation and innovation moving forward.

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Building Ecosystems: Hybrid Materialities for Collective Urban Infrastructures

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ABSTRACT: The ultimate purpose of this research is to propose new models of urban infrastructures and collective spaces for social interaction based on the integration of material, structural, and environmental systems. Accordingly, the prototypical installation presented in this paper works as a preliminary concept developed as result of a collaborative and interdisciplinary research approach conducted at Rice University and involving expertise in the fields of structural, civil and environmental engineering, materials science, music, and architecture. The project lends itself to operate as a prototypical flexible module with the potential to be deployed onto any pre-existing urban rooftop or public area. The modular system is comprised of hollow ceramic pieces acting as structural columns and water collectors, a modular ceramic floor elevated on pedestals, a lightweight space truss structure, and a waterproof membrane that captures and cleans rainwater through its expansive surface. Subsequently, the rainwater would be channeled through the hollow ceramic columns, from which it would be diverted to pipes below the elevated floor and collected into modular water tanks uniformly distributed within the elevated floor. The water management system as proposed would work to alleviate the effects of flooding and drought through storage as well as release and reduce runoff by capturing water and redirecting it into the tanks (Castellón, D'Acunto, Bertagna, López Cardozo 2021). Besides, the materiality of the modular ceramic columns, with their low thermal conductivity, could potentially provide energy-saving cooling benefits. The resulting prototype integrates structural and material strategies to optimize construction aspects related to transportation, assembly and disassembly of building components, as well as thermodynamic questions related to heat transfer and water cycles while helping to foster a sense of community and social interaction. This paper focuses on the description of the material processes implemented in the design and construction of the installation. The resulting prototype acts as a proof of concept for future developments of the project.

KEYWORDS: Architecture, Material processes, Building ecologies, Structural design, Modular construction

INTRODUCTION

An ecosystem can be simply defined as “the community of living organisms (microbes, plants, and animals) and the physical environment (the habitat) they occupy.” (Sala 2020, 29). Etymologically, it comes from the ancient Greek word *oikos*, that means “family” and “house”. Accordingly, living organisms and their physical environment are consubstantial and interrelated parts of an ecosystem. From an architectural perspective, this intrinsic relation has a fundamental impact in the quality of our living space (our habitat) but also in the way we build and sustain it. Consequently, a healthy and qualitatively rich urban ecosystem can only be the result of a balanced relation between our diverse social, political, and economic structures and our technical, material, and natural resources. In this regard, architecture acts as a reflection of our society, including our arts, techniques, sciences, culture, and politics (De la Sota 2020, 46). Our cities are material ecosystems and the way we conceive and build them have a massive impact in our local and global communities. In fact, this inherent connection between our material ecosystems and our building culture is in the origin of our built environments across the globe. It was Vitruvius, in his treatise “*De architectura*” (written in the late 1st century BCE), who explicitly identified how some primitive communities built their living spaces with branches and leaves, while others excavated caves into the mountains and some others, mimicking the way birds made their nests, built their living spaces with small branches and clay (Vitruvius 1995, 95). Thus, each building process was based on the transformation of the specific natural context as well as on the availability of local materials and resources. Consequently, different communities around the globe developed their own material cultures, techniques, and crafts in consonance with their distinct surroundings and natural ecosystems. Accordingly, the German architect Gottfried Semper in his book “The four elements of architecture” (written in 1851), would differentiate four distinct building elements: hearth, roof, enclosure, and mound, as well as their corresponding traditional crafts: metallurgy/ceramics, carpentry, textile/weaving, and earthwork (Semper 2011). Based on this building taxonomy, he would classify building crafts under two main categories: the *tectonics* of the lightweight frames, and the *stereotomics* of heavyweight components (Frampton 1995, 5). This building dichotomy can be simply distinguished by, on the one hand, a material ecosystem resulting of earth-based, mineral, and heavyweight construction materials such as stone, glass, or clay, and, on the other hand, a material ecosystem rooted in fibrous or lightweight construction materials such as wood, steel, or textiles. These two extremely differentiated material ecosystems have evolved throughout generations producing composite materials such as for example reinforced concrete, reinforced ceramics (Castellón 2012),

or composite materials based on glass fibers or carbon fibers. In most of the cases, these hybrid systems improve greatly the properties and technical performance of the separate materials that conform them. In parallel to these innovations, emerges the concept of “hybrid materialities” at the architectural scale in which the hybrid outcome (produced by a combination of tectonic and stereotomic materials) becomes the result of an unconventional, unexplored, or creative combination of innovative and traditional techniques and processes. The proposed installation “Building Ecologies” is the result of hybrid materialities that combine architectural, structural, and environmental strategies informed by social, cultural, and ecological awareness.



Figure 1: “Building Ecologies”, Installation at POST Houston. Source: (Dyvia Pande 2023)

This installation (Figure 1), exhibited at POST Houston from November 2022 to April 2023, stands as a preliminary attempt to materialize this conceptual approach as result of an interdisciplinary research model involving the departments of architecture, music, material sciences, and civil & environmental engineering at Rice University, as well as manufacturing experts in the fields of ceramics, textiles, and steel fabrication.

Among the different potential implementations of this project in a specific urban context, the proposal is focused on urban rooftops. Specifically, the objective of this research is to unfold hybrid structural and material strategies to retrofit existing rooftops in urban areas by embracing contemporary and traditional techniques and generating active spaces for community use and social interaction. Besides, the main functional aspect of this modular structure is the collection, treatment, and storage of stormwater and rainwater. Therefore, in addition to creating new spaces for communal use, it would offer the opportunity to reuse collected water for agricultural irrigation systems (Castellón, D’Acunto, Bertagna, López Cardozo 2021) as well as hydronic systems for heating and cooling. Accordingly, the project lends itself to operate as a prototypical flexible module with the potential to be deployed onto any pre-existing urban rooftop or public area.

Following the stereotomic and tectonic material categorization introduced above, the resulting modular prototype responds to a combination of diverse material systems and manufacturing strategies.

On the one hand, it is a combination of stereotomic material systems (including hollow ceramic pieces acting as structural columns and water collectors, and a modular ceramic floor elevated on pedestals), and tectonic material systems (including a lightweight space truss/tubular steel structure and a polyester membrane that captures and cleans rainwater through its expansive surface). On the other hand, this combination of material and structural systems relates to hybrid (digital and analog) manufacturing techniques and processes such as extrusion and robotic cutting for ceramics, steel welding, waterjet cutting, or digital cutting for textile materials. The following chapter 1 (stereotomic) and chapter 2 (tectonic) describe in detail the different parts of the prototype and in particular the structural, and manufacturing processes and strategies developed for this project. Finally, chapter 3 (building ecosystems) sets forth the description of the final installation as well as the conclusions of this research and future developments.

1. STEREOTOMIC: THE ELEVATED FLOOR AND THE HOLLOW CERAMIC COLUMNS.

1.1 The elevated floor

Considering that the proposed building infrastructure would be potentially implemented on top of irregular surfaces, the floor is conceived as an elevated platform. Hence, this platform responds to a design strategy that on the one hand, raises the view towards the surrounding area and, on the other, negotiates with the pre-existing ground condition by placing carefully punctual supports on top of it. This architectural concept was masterfully expressed in the essay "Platforms and plateaus" by the Danish architect Jørn Utzon: "a completely independent thing floating in the air, separated from the earth, and from there you see actually nothing but the sky and the passing clouds - a new planet." (Utzon 1962, 146). Besides, the flatness of the platform emphasizes the formally expressive canopy and so "the contrast of forms and the constantly changing heights between these two elements result in spaces of great architectural force." (Utzon 1962, 147).

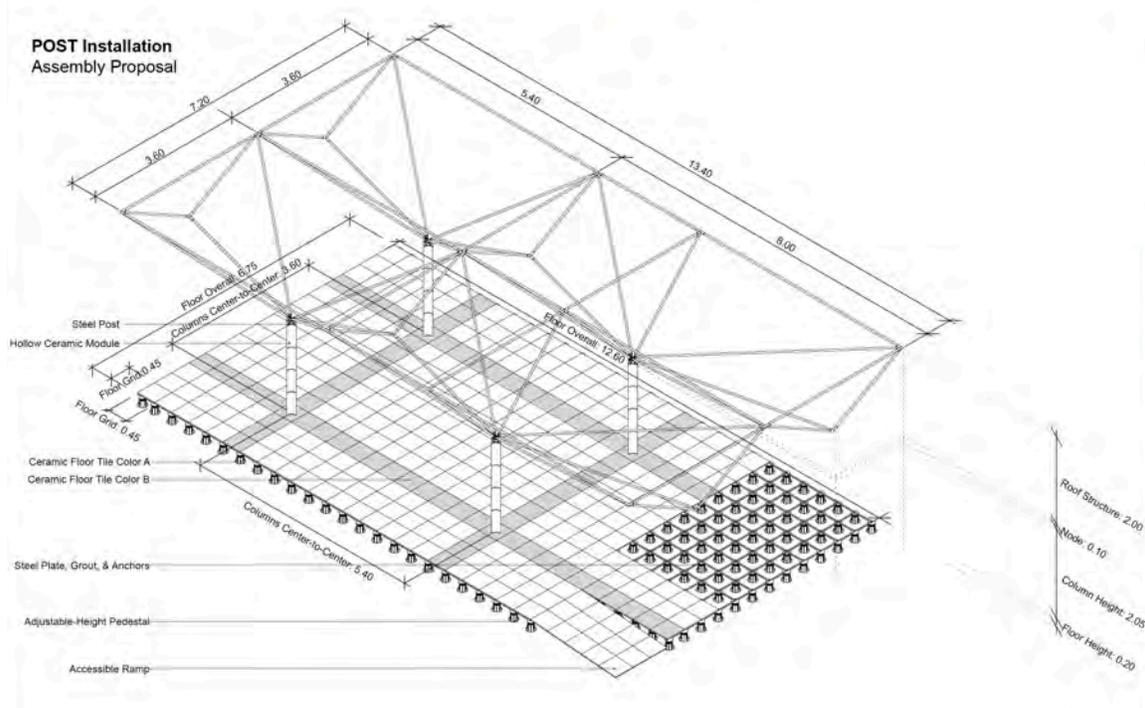


Figure 2: "Building Ecologies" Installation. Axonometric view. Source: (Juan José Castellón, 2022)

In addition to that, and speaking from a thermodynamic perspective, the elevated floor could be potentially activated as a thermally active surface (Moe 2010) taking advantage of the anticipated hydronic system (i.e. water tanks and pipes running below it) in combination with the appropriate material choice (in this case ceramic tiles). Hence, the floor's temperature could be controlled and regulated to achieve the optimum temperature uniformly distributed through its surface and an adequate thermal comfort for the inhabited area. For this purpose, the elevated floor is composed by adjustable pedestals and ceramic floor tiles (Figure 2). The floor surface was developed in collaboration with the ceramic company Cosentino, which provided 16 slabs *Dekton Umber* of 321cm (L) x 144 cm (W) x 2cm (H) each. *Dekton* is Cosentino's innovative ultracompact surface, a technological material composed of a blend of raw materials, porcelain, and glass. After receiving all the slabs, they were cut into tiles of 45x45 cm. using waterjet technologies. The tiles dimensions respond to an adequate scale for handling and placing them by one person with little effort, as well as to the intention of producing a minimum waste of material while cutting the slabs. Finally, the flooring was installed to guarantee the precise alignment of the entire surface using self-leveling adjustable pedestals made from 100% recycled material. The modularity and flexibility of the floor system also guarantees the potential integration of additional elements such as water tanks and soil boxes as well as facilitates an easy assembly and disassembly process.

1.2 The hollow columns

As previously mentioned, ceramics is an appropriate material to integrate structural and thermodynamic aspects in relation to water use, water storage, and water channeling. In fact, it was one of the main materials used by ancient Greek, Roman, and Islamic cultures for the design and construction of water infrastructures.

For example, the Romans used terracotta pipes to supply water to their villages and cities. Such pipes were built in tapered sections to guarantee a fast and effective connection between the different pieces conforming the pipes for the water infrastructural network¹. Therefore, terracotta pipes were used for a variety of purposes such as storm water collection from roofs, as well as channeling wastewater, or fresh water from springs and aqueducts. Subsequently, this water was directed to cistern systems, sewage and drainage systems, palaces, or to public water supply networks such as public fountains or irrigation systems for courtyards and gardens². In addition to this architectural tradition and in relation to its thermal properties, ceramic materials have low thermal conductivity which makes it an ideal material for storing and keeping water temperature constant for specific uses (e.g. used in pots for food or for storing and drinking fresh water in farming areas). Finally, from a structural perspective, ceramic materials have excellent behavior under compression loads but a poor structural performance resisting tensile strengths. Therefore, harnessing the structural potential of ceramics and brick construction, and rooted in the tradition of the *Catalan vault*, master builders and architects such as Rafael Guastavino, Antoni Bonet i Castellana, or Josep Lluís Sert, designed and built magnificent projects based on this traditional technique. However, it was the addition of metal reinforcement by conceived by engineers such as Eduardo Torroja or Eladio Dieste which expanded the architectural potential of ceramics as building materials. Specifically, Dieste invented his so-called “reinforced ceramics”, a structural system based on the hybrid integration of ceramic bricks and steel bars reinforcements (Castellon 2012).



Figure 3: Hollow ceramic piece “Star” by Juan José Castellón, manufactured by Ceràmica Cumella. Left: robotic arm producing the interlocking connections / right: final pieces. Source: (Frau Recerques Audiovisuals 2021).

Following this tradition in the use of reinforced ceramics and recovering its application for the design and construction of water infrastructures in different urban and cultural contexts, the columns of the installation were conceived as discreet hollow ceramic pieces acting both as structural elements to support the canopy structure and as water pipes and collectors with the potential to channel rainwater from the membrane to the anticipated system of pipes and water tanks distributed below the elevated floor (Figure 2).

The “Star” piece, developed in collaboration with the manufacturing company *Ceràmica Cumella* in Granollers (Spain), was produced by implementing two main manufacturing processes: extrusion, and robotic cutting.

Firstly, the final form of the hollow piece is the result of an extrusion process of the ceramic mixture through a custom-made metal template under a constant applied pressure producing a homogeneous and constant extruded piece. This is followed by the precise cut to the final length of the piece using a cutting wire system mechanically controlled as part of the extrusion process. Consequently, the final hollow pieces (Figure 3, right) are 50cm. long and 18cm. wide. Again, these dimensions were decided in relation to the human scale and to be easily handled, shipped, assembled, and disassembled by one or two people.

Secondly, a robotic arm was used to produce the interlocking mechanical connection using a subtractive fabrication method to generate the male and female connections in both ends of the piece (Figure 3, left). Taking advantage of the soft condition of the ceramic mixture before firing it into the kiln, the robotic arm is supplemented with a metal wire extension whose movement can be precisely controlled through a computer-aided software to remove the parts of the piece that make possible the interlocking connection. The resulting piece produces a modular interconnected system that is flexible and able to be adapted to different heights and spaces. In the case of the installation, the columns were built using 4 pieces per column resulting in a total height of approximately 2.05 m. The connections include a 1cm. EPDM rubber joint to guarantee a flexible

assembly and avoid friction between pieces. These joints were precisely fabricated following the exact section of the hollow piece using waterjet cutting technologies.

Considering the limited behavior of ceramic structures under tensile stresses, a posttensioning system is currently under development inspired by the series of sectional concrete beams, or “concrete bones”, invented by the Spanish architect Miguel Fisac in the 60’s (González Blanco, 2007). However, only for the purpose of this installation, a steel tube was placed within the hollow section of the column and anchored to the ground to guarantee the safety and stability of the structure against horizontal loads.

2. TECTONIC: THE SPACE TRUSS AND THE MEMBRANE.

2.1 The space truss

The structure for the membrane was designed following two main premises: first, using the minimum possible amount of material and second, achieving a highly efficient and lightweight structure which would be at the same time easy to be assembled, transported, and disassembled. Consequently, a space truss structure emerged as the ideal solution to achieve these fundamental goals. A space truss is a highly efficient structure due to its triangulated geometry which is based on a tetrahedral grid. Accordingly, the triangular arrangement of the structural bars makes it statically stable and extremely resistant against deformation. In fact, the first structure of this type was conceived by the inventor and scientist Alexander Graham Bell who patented “a system of prefabricated steel tetrahedrons that could be assembled to construct space trusses of different forms” (Muttoni 2006, 158). This structural typology was also masterly applied by architects and engineers such as Buckminster Fuller, Robert Le Ricolais, or Konrad Wachsmann in the design and construction of highly innovative and environmentally aware lightweight structures.



Figure 4: left: space frame mock-up, right: manual welding of steel knots. Source: (Frau Recerques Audiovisuals 2022)

In this context and with these references in mind, the proposed canopy structure for the installation is a space truss composed of four triangulated modules (Figure 2) consisting of steels tubes and steel knots.

The structure was developed in collaboration with the manufacturing company *Industrias BEC* in Arenys de Mar (Spain) which provided and cut 70 galvanized steel tubes of 40mm diameter ranging in length from 1800 to 3600 mm, and 13 galvanized steel tubes of 34 mm diameter and 470 mm length. In addition, 22 custom-made stainless-steel knots-joints were digitally cut with waterjet technologies from standard steel tubes and manually welded by a sculptor to connect precisely all the tubes composing the knots and meeting in different angles (Figure 4, right). A mock-up of the system was assembled in Arenys de Mar (Figure 4, left) as a proof of concept of the final structure that was finally manufactured and shipped from Barcelona to Houston.

2.2 The membrane

The membrane was designed and developed in collaboration with *Industrias BEC* as an integral part of the space truss. Accordingly, it has two main functions: to provide shade and shelter, and to collect rain and stormwater through its expansive surface and direct it to the interior of the hollow ceramic columns. In terms of materials, it is a polyester membrane that protects against UV and bad weather, while preserving the level of natural light transmitted. This translucent, waterproof fabric produced by the manufacturing company Serge Ferrari (product Soltis 96) is ideal for pergolas and shade canopies. Besides, the faceted membranes following the triangular geometry of the space truss, were tailored using a large format Zünd digital cutter (Figure 5, left) to achieve the required geometrical precision and design quality, and it was attached to the space truss using standard plastic flanges for a uniform distribution of the tensile forces in the membrane and to avoid wrinkles on its surface (Figure 5, right). Finally, the steel tubes at the perimeter were wrapped by additional textile covers that were attached to the structure using Velcro for an easy assembly and adjustment on site. The resulting membrane structure expresses its integral, functional, and aesthetic character through

the faceted geometry and its translucent materiality which confers interesting lighting conditions to the space throughout the changing days and seasons (Figure 7).



Figure 5: left: digital cutting process, right: attaching the membrane to the frame. Source: (Author, Frau Recerques 2022)

In parallel to the architectural, material, and structural aspects of the prototype, the question of rainwater collection, water treatment, and water reuse is introduced through the potential application of a coating solution developed by the team of Dr. Qilin Li at the department of Civil and Environmental Engineering at Rice University. In this regard, an important challenge in the implementation of water harvesting, storage and treatment system in a building structure is the need to achieve these functions without using chemicals. Traditional water systems use large quantities of chemicals for disinfection and control of biological fouling. In the design considered in this project, rainwater harvesting is achieved through solarthermal disinfection coatings in the membrane canopy using low cost, photothermal nanomaterials that convert sunlight highly efficiently to heat, which inactivates bacterial and viral pathogens without releasing any chemicals or inducing antimicrobial resistance (Loeb, Kim, Jiang, Early, Wei, Li, Kim, 2019). This not only disinfects the rainwater collected, but also prevents biological fouling of the textile canopy, all without using any electrical energy or chemicals.

3. BUILDING ECOSYSTEMS: THE INSTALLATION

The final installation was built in one of the exhibition rooms at POST Houston (Downtown Houston's hub for culture, food, and recreation) and it is composed by 4 structural modules (umbrella-like structures) including space frame, membrane, ceramic column, and elevated ceramic floor on pedestals.

The total dimension of the installation is 13.40 m (L) x 7,20 m (W) x 4,35 m (H). These dimensions respond to the intended architectural qualities as well as to the free space available due to the existing columns and installations in the building (Figures 1 and 7). Thanks to the high flexibility of the prefabricated modular system developed for this project, the position and dimensions of the structure was adjusted according to the spatial constraints and the design intentions (Figure 2). In this regard, two of the umbrella-like modules are smaller and symmetric and have a length of 5.40 m, while the other two are larger (also symmetric) and have a length of 8 m cantilevering towards the main entrance of the installation. This design gesture is conceived to welcome and receive the visitors. Besides, the geometrical axis of the installation is aligned with the axis of the entrance to ensure the full perception of the space and its symmetrical condition. Furthermore, the modulation of the floor tiles defines the exact position and span between the ceramic columns, 5.60m (L) x 3.60m (W).

Regarding the construction sequence, the complete installation was easily and quickly assembled by two to four people using a simple equipment thanks to the lightness and easy to handle dimensions of all the building components. Accordingly, after unpacking and organizing all the pieces, the space frame was assembled, and the membrane was attached to the frame in approx. 4 hours (Figure 6, steps 1 to 3). Then the structure was gradually lifted and leveled using 12 adjustable steel cables uniformly distributed and attached to the upper tubular frame and to the existing concrete ceiling (Figure 6, step 4). Once the space frame was adjusted and leveled to the required height, the ceramic columns were placed and anchored to the existing ground through four steel tubes placed inside the four hollow ceramic pieces forming each column (Figure 6, step 5). Finally, the floor pedestals were adjusted and distributed to receive the ceramic tiles (Figure 6, steps 5 to 8).

In addition to the physical installation, a lighting system, a video installation, and a soundscape evoking the sound of raindrops hitting the membrane and streaming inside the columns and below elevated floor was composed in close collaboration with the composer Kurt Stallmann (Prof. of Music Composition and Theory at the Shepherd School of Music at Rice University).

The installation was disassembled on the 30th of April 2023 after the 5 months of public exhibition. This process was conducted in reversible order to its construction producing minimum waste and keeping and packing all the components with the possibility to be fully reused and reassembled in an alternative site.



Figure 6: "Building Ecologies", Assembly Sequence. Source: (Author, Juan José Castellón, 2022)

4. CONCLUSIONS

In conclusion, the resulting prototype and installation is conceived to integrate holistically structural, material, and environmental questions through architectural design. Furthermore, it is inspired by the way that our natural ecosystem is shaped as "a true circular economy where there is no waste, but everything is reused and transformed to produce something else" (Sala 2020, 57). Besides, this project is presented as a model of interdisciplinary research at Rice University involving expertise in the fields of structural & environmental engineering, music, material sciences, and architecture. The installation demonstrates the potential of hybrid design strategies to materialize contemporary buildings and water infrastructures in which questions of modularity, prefabrication, transportation, thermodynamics, and structural assemblies play a fundamental role in the design of integrated building systems. Consequently, the project lends itself to operate as a prototypical flexible module with the potential to be deployed onto any pre-existing urban rooftop or public area.

However, questions related to its potential implementation in an outdoor space remains untested as well as questions related to the proposed water cycles, water treatment, and use for irrigation purposes or as part of heating and cooling hydronic systems. Besides, further developments of the project should incorporate structural questions including dimensioning the structure responding to wind loads, and the development of a posttensioned solution for the sectional ceramic columns. Regarding the water systems, the integration of water pipes and tanks for water storage and reuse and the study of filtration materials that could serve architectural and/or structural functions, e.g., ceramic membranes or fabric filters driven by gravity, as well as a biomimetic approach to design the self-cleaning surface morphology of the canopy fabric to minimize bacterial attachment are still research questions under development.

Finally, the research will explore potential programmatic strategies such as the integration of cultural, and agricultural activities that could help to promote and foster a sense of community and social interaction.



Figure 7: "Building Ecologies", Installation at POST Houston. Source: (Dyvia Pande 2023)

ACKNOWLEDGEMENTS

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Ecological Tectonics: Rethinking Construction through Material Reuse, Recycle, and Reclaim

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ABSTRACT: Over the past two decades, the global demand for mineral-based building materials has experienced a threefold increase, with three materials – concrete, steel, and aluminum – alone contributing a significant portion of global carbon dioxide emissions at 23% (IEA 2018). The pressing environmental predicament has instigated architects and builders to reevaluate the relationship between material, the environment, construction processes, and labor. Though there has been a growing professional responsibility to prioritize ecologically conscious architectural practices, often conveyed through prescribed formulas such as building energy simulations and the LEED rating system, comprehending the environmental impact and assuming a responsible approach is becoming increasingly challenging.

The paper presents a pedagogical experiment, developed in the form of an architecture seminar, that seeks to redefine and examine the concept of sustainability through the lens of material circularity. The seminar explores three distinctive approaches to building materials and construction, each aimed at rethinking conventional methodologies. The first approach, assembly for reuse, challenges the conventional idea of permanence by considering construction and deconstruction as equal partners. The second approach, upcycle material construction, repurposes discarded and obsolete products as building components. The third approach, reclaimed material construction, focuses on salvaging building materials through the careful process of dismantling and demolition, transforming them into new building elements.

The seminar employs a bottom-up learning and construction strategy, incorporating "found materials" such as waste (fabric, paper, plastic, and construction debris) and standardized building products (lumber and concrete cinder block) to construct full-scale wall mock-ups. Through these operations and building techniques, the seminar seeks to challenge the traditional use of fossil-based and petroleum-based materials and discover new material possibilities and tectonics. While creating a truly circular value system in construction is a complex and challenging task, the pedagogical objective is to engage students in raising awareness about material ecology and the construction process, thereby laying the foundation for future practices and contributing to finding solutions to environmental problems.

KEYWORDS: Sustainability, Circular Construction, Material Reuse, Material Ethics, Pedagogy

1. PEDAGOGICAL SHIFT

1.1 Towards material circularity

Through the progress of technology and streamlining production, fabrication, and assembly, the extraction and manufacturing process of building materials is often overlooked in our material choices. Hence, the conventional materials adopted in architectural education are frequently viewed as omnipresent and limitless. This narrow perspective deters the architecture discipline from recognizing the environmental impact of their actions and perpetuates the contemporary building practice with a receptive attitude and indifference toward material sourcing.

In light of the pressing need for accountability in the use of carbon-intensive materials, revamping the current pedagogical approach towards the teaching of materials in the way how and why has become increasingly crucial. The curricula for design and building technology must evolve to provide a comprehensive understanding of material ecology, fostering a newfound connection between architects and materials. To mitigate waste and extend the lifespan of materials, it is necessary to embrace recovery-oriented design and construction by exploring biogenic materials and reusing components in the built environment. Pedagogy must focus on establishing a framework that prioritizes physical and technical constraints, allowing students to consider a wide range of factors with a focus on the impact of their choices. By addressing questions of material adaptability and constructability early in the design process, students are propelled out of the conceptual and representational phase and into the search for sustainable solutions that align with the environmental and stewardship values of society.

1.2 Course structure

The pedagogical setting and explorations featured in this paper were part of a seminar entitled "Wall Craft," offered to students in the Department of Architecture at Kansas State University. The seminar was held once a week for three hours and was open to fourth and fifth-year architecture students. The course delved into the design and creation of various interior and exterior wall systems, focusing on material obsolescence and circularity and the potential to create alternative ways to construct walls. The wall has long served as a site of

experimentation and innovation in architecture, and this seminar aimed to deepen students' understanding and engagement with building materials that minimize their environmental impact and promote sustainable design practices.

The course commenced with a series of discussions focusing on topics such as circularity, labor, constraints, and constructability. This was achieved through a combination of readings, an environmental impact assessment, and an examination of built precedents. Following a comprehensive introduction to the concept of material circularity, the course shifted its focus to the principle of 'craft as research.' This research was broken down into two components: prototyping and wall fabrication. The first study engaged in hands-on experimentation and testing of locally accessible materials, using prototypes to explore the materials' properties and potential. The students worked in pairs to construct the multiple prototypes, which were at a scale of 2-4 ft (0.61-1.22m) tall. The prototypes tested various concepts of assembly for reuse, upcycling, and construction with reclaimed materials. This included innovative designs such as a screen system made from sliced fence posts, cladding made from papercrete through recycling paper, and a wall cast with construction debris (e.g., Fig 1). The multiple rounds of testing sharpened the students' problem-solving and critical-thinking skills, encouraging them to challenge conventional material culture and usage.

The second part of the course was devoted to the creation of a 6ft (1.82m) tall mock-up that exemplified the principles of material reuse, recycling, or reclaiming. While participants were given the freedom to choose their materials, they were also encouraged to utilize readily available resources within their local or regional area to challenge conventional notions of material obsolescence. This provided an opportunity to cultivate a more positive impact on the life cycle assessment through the creation of a Material Passport, which would enable tracking and management of material flows and reduce transportation mileage. In the pursuit of practical knowledge and technical limitations, building mock-ups were envisioned to unveil and demonstrate various aspects of the application, disconnecting from the actual building (Geiser 2021).



Figure 1: First prototypes through precedent studies and material experimentations. (Author 2022)

1.3 Assessment of environmental impact

A succinct analytical examination was conducted to evaluate the environmental impact of conventional material utilization. The study critically analyzed existing and pre-existing material types in relation to wall assembly methods, exploring various platforms and graphs for evaluating material lifespan and carbon footprint. The course introduced the students to the Construction Material Pyramid¹, an interactive online tool developed by the Centre for Industrialised Architecture (CINARK) at the Royal Danish Academy (e.g., Fig 2). This interface enables visualizing and calculating the various environmental impacts of different materials using Environmental Product Declarations (EPD) and calculates the materials' initial phase of construction (i.e., until the material is on site). The students studied different wall structures and applied their knowledge of material type, dimension, and volume to the Construction Material Pyramid. The calculation focused on the used material amount in the wall of 3 feet wide per single floor to compare different buildings. In a brief period, students were able to compute several environmental impacts measurements such as Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potentials (POCP), Acidification Potential (AP), and Eutrophication Potential (EP) (e.g., Fig 2). A class discussion was dedicated to comparing the calculations and comprehending the disparities between collective assumptions and actual environmental impact.



Figure 2: The Construction Material Pyramid. (CINARK 2023); and environmental impact calculation of Norvento Headquarters's wall using the Construction Material Pyramid. (Student: Libby Couture 2022)

2. CRAFT AS RESEARCH

Architecture students often perceive materials as codified products, relegating the creativity of material application to material specialists. In "Valuing Material Comprehension," James Carpenter challenges this notion by questioning the separation of materials knowledge from the design process. Carpenter notes that the term "craft" has acquired a negative connotation with architects since the Industrial Revolution (Carpenter 2010).

However, to break away from the confines of conventional practices, an understanding of craft and making is essential in fostering a learning culture that inspires students to challenge existing design tools and techniques, which may become irrelevant in the near future. This chapter introduces student research projects from each principle, highlighting the process of discovering constructability and navigating material constraints.

2.1 Assembly for Reuse

The demolition of buildings often results in the waste of materials that still have a lifespan longer than the building itself. The use of adhesives and fasteners, such as glue and screws, hinders the reuse of building components by permanently connecting them. The solution to this problem is to employ fastening methods that do not restrict future disassembly. The prototype study presented here implements straightforward and unobtrusive construction techniques that ensure the preservation of wall materials for easy reuse in future building projects.

The wall for this category was constructed using readily available and common materials such as 2x4 and 2x6 lumber wood, concrete masonry units (CMU), and ratchet straps for the column and beam structure. After thoroughly testing various binding methods for the wood members, the students ultimately selected ratchet straps for their strength and simplicity. The lumber wood was bundled together and secured with ratchet straps to form sturdy columns and beams, which were then sandwiched around the CMU with additional straps, which helped to stabilize with a minimal footprint (e.g., Fig 3).



Figure 3: Non-intrusive assembly connections using ratchet straps. (Author 2022)

This wall assembly system has been designed with versatility and practicality in mind. By utilizing the quick and non-invasive assembly method, it can be assembled with minimal labor and used as modular partitions in emergency shelters. The incorporation of insulation and cladding was investigated to augment the versatility

of a modular divider. A multi-layered exterior, consisting of a thermal blanket, tarpaulin, and wire mesh, was suspended and clapped to the beam structure. The wire mesh layer provided a versatile surface for hanging multiple cladding options, and the students opted for a collection of gutter covers due to their affordability and the presence of holes that facilitated attachment to the mesh. The gutter covers were assembled with cable ties for seamless installation and disassembly.

The wall system is equipped with several essential features, including weatherproofing, soundproofing, insulation, and solar-powered lighting, making it a comprehensive solution for a range of temporary housing needs. By leveraging the benefits of this design, this construction method can provide quick and effective shelter solutions in times of emergency and crisis as well as easily used for other construction in a new condition. In order to embrace material circularity, the wall units were disassembled after installation and either rerouted back to the fabrication lab or donated to the local Habitat for Humanity, a philanthropic organization that supplies building material stores (e.g., Fig 4).



Figure 4: The assembled wall structure and their components after disassembly. (Author 2022)

2.2 Creative reuse (upcycling)

One of the study areas focused on utilizing non-building materials to evaluate their feasibility. The course addressed the pressing issue of repurposing commonly discarded recycling materials in daily life, such as paper, paper, clothing, and aluminum. One student group delved into the innovative realm of plastic reuse in construction, with the aim of curbing the wastefulness of discarding materials into the recycling process, which demands a significant input of energy to purify, melt, and reduce plastic. Despite the generation of 51 million tons of plastic waste in the United States, a mere 5% was recycled (Greenpeace 2022). The low recycling rate can be attributed to numerous causes, including the non-recyclability of many plastic types and the environmental impact of recycling processes. Nevertheless, numerous examples of architecture have utilized plastic waste as building envelopes. For instance, architectural projects such as the Bima Microlibrary in Indonesia showcase an innovative solution through upcycling – a total of 1,872 ice cream buckets were transformed into an expressive facade and provided an ambient lighting environment within the interior space.

Students with an interest in utilizing plastic byproducts sought out readily accessible facade materials in their community that could provide shading and allow natural light to pass through. The primary focus of the research was the utilization of half-gallon milk jugs made of high-density polyethylene (HDPE). Students collected milk jugs from individual households and a local recycling center to test and build different prototypes. Being a thin and pliable plastic, HDPE offers a range of design possibilities beyond its original form. The plastic can be easily altered through cutting at various angles, leading to interesting formal manipulation and various openings. Six different cutting strategies were implemented by using three types of custom jigs, which allowed students to alter different brands and imperfect qualities of milk jugs into a consistent angle and dimensions (e.g., Fig 5). The different cut types create different possibilities of patterns, lighting, and visibility, such as opaque, translucent, and transparent conditions, functioning as a wall divider and veiled curtain at the same time.

The project developed into a lightweight wall partition that can be effortlessly suspended from any ceiling using cables and C-Clamps. The partition comprises a wooden modular frame that securely holds 60 milk jugs, which are held in place through a tension system woven with a fishing line through pre-punctured holes. The arrangement of the different cut types was carefully considered to determine the location of apertures, obstruct views, and create different lighting qualities. The final design was tested in a library setting, showcasing its ability to define space effectively (e.g., Fig 6). However, this versatile panel system can also be implemented in a range of interior settings, from large open areas such as offices or event spaces to create private areas.



Figure 5: Process of plastic collection, sorting, washing, and fabrication. (Author 2022)



Figure 6: Reused plastic wall installation suspended under a library staircase. (Author 2022)

Another student group reenvisioned the use of fabric waste in the context of creative reuse in architecture, specifically as an alternative to traditional scaffolding and formwork materials made from steel and heavy-duty plastic. With over 60% of used clothing ending up in landfills, textile waste has become a pressing environmental issue. Inspired by the low-tech suspended fabric mold developed by Lilienthal in the late 19th century (e.g., Fig 7), the team sought to incorporate this principle into their design. The technique leverages the interplay between the self-weight of the casting mixture and the pattern of the clothing without the need for a negative mold. To bring this concept to life, the team decided to sew the clothing waste into a quilt which would then serve as a mold for concrete panels (e.g., Fig 7).

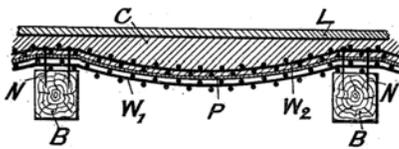


Figure 7: Fireproof ceiling patented by Lilienthal using hanging fabric mold (US Patent Office 1899); and fabric mold using clothing waste. (Author 2022)

The quilted formwork acted as a “skin” for each concrete panel, and the variability in the clothing types and patterns contributed to the distinct texture and form of the wall structure. For instance, shirts featuring vinyl heat transfer prints create a reflected image of the pattern in the concrete, while the thick, overlapping stitches on jeans create an imprint that clearly resembles pockets and belt loops. The variations in the elasticity of the materials result in an uneven thickness of the wall, imbuing it with a third-dimensional quality that is unattainable through conventional precast concrete methods (e.g., Fig 8). The panels can easily be fitted with apertures by incorporating sleeve and pant leg segments into the quilt, which protrude from the formwork.



Figure 8: Precast concrete panel from fabric waste formwork. (Author 2022)

2.3 Reclaimed building materials

There is a wealth of resources readily available in areas where projects are being demolished or materials are being discarded, such as factories or areas undergoing redevelopment. Reclaimed wood, versatile in its application, can be employed in a wide range of projects. Utilizing reclaimed wood offers a multitude of benefits for those seeking to use locally sourced materials, minimize transportation and processing costs, reduce carbon footprint, and incorporate a sustainable material while still enhancing the aesthetic quality.

The process of reclaiming and repurposing wood requires some effort prior to use. It is ideal for sourcing the wood before it reaches the landfill, and this can be achieved by searching demolition and renovation sites, shipyards, warehouses, etc. To classify the wood as high-quality reclaimed wood, it must undergo a series of processes, including the removal of nails and bolts, drying and stabilization, and smoothing of the rough exterior. If the wood is consistently sized, digital workflows can be utilized to input the measurements and determine potential design systems based on its shape and form, either parametrically or non-parametrically.

A team of two students delved into the exploration of using reclaimed wood to design a wooden facade for exterior screening (e.g., Fig 9). The reclaimed wood was sourced from torn-down barns situated within a 75-mile radius of the campus to reduce the carbon footprint in transport. The screening system was designed to offer versatility in regard to aperture adjustment, scalar growth, and density customization through the use of tensile connections. This facade system would be well-suited for a range of projects, particularly in the realm of adaptive reuse. For example, the tensile facade could be suspended from an existing building, adapting to its existing apertures, thereby providing the opportunity to alter the facade's appearance while preserving the existing building structure.



Figure 9: Wooden screen system using reclaimed wood. (Student: Anna Hartley and Jada Rezac 2022)

3. TOWARDS NEW MATERIALITY

3.1 Ecological tectonics

As Antoine Picon suggests, architecture is a supremely material art (Picon 2020). This simple definition raises the question of what artistic techniques are relevant in today's material world and how they impact the creative process, potentially leading to a transformative shift in our very perception of art. While architecture is a material practice, the continuous evolution of homogenized materials and techniques in architecture has diminished the prominence of materials, obscuring their inherent materiality. To overcome the reliance on carbon-intensive material products made from concrete, steel, and aluminum, the interrogation of a new family

of materials with a comprehension of tectonics is imperative. The utilization of reusable materials can establish a sustainable cycle that embraces both the old and the new. As this paper highlights, reusable materials can take on various forms and serve a multitude of purposes, fostering material-focused construction and materiality stemming from material ethics and care.

For ecological tectonics to become widespread, a commitment and practice of understanding the material's technical characteristics, including its structural behavior, variable texture, and adaptability at multiple scales, is essential. Although some of the wall studies have unfinished qualities, they offer students insight into the continual latent tectonic possibilities. For instance, the fabric waste formwork can be explored further with alternative casting materials such as rammed earth and hempcrete, and by examining the rigidity, elasticity, and stitching pattern of clothing to achieve various geometric and structural capacities. Also, nonstandard forms and dimensions of reclaimed materials can be efficiently managed through computational methods such as 3D scanning and machine learning optimization. These inquiries can bridge the current disconnect between the potential risk of using new material pallets and current construction techniques. Ecological tectonics can also impart a clear narrative aspect to the wider audience, aligning with moralistic design intent and promoting openness and accountability in both the material management and execution phases.

3.2 Emerging resources

One of the biggest obstacles for circular construction is the procurement reutilization of materials and components and ensuring their accessibility. However, a number of entities and initiatives in Western Europe have set a commendable precedent by laying the groundwork for enhanced accessibility of reusable materials. For instance, Rotor Deconstruction² is an online inventory offering access to over 3,000 meticulously dismantled, cleaned, and cataloged salvaged building components such as furniture, lighting fixtures, doors, and tiles. This platform is designed to support building owners, contractors, and architects in their pursuit of second-hand materials. Similarly, Opalis³ facilitates the identification of professional dealers, including private individuals or small contractors, of salvaged building materials, enabling users to locate sources based on the type of materials they need and their geographical location through mapping interface technology.

Furthermore, efforts have been initiated to provide technical support and foster computational advancements for improved digital evaluation, work processes, and tools for reclamation. For instance, Building Information Modeling (BIM) has been adopted in substantial development practices to examine materials in the recoverable dismantling of structures, such as the Aspern Seestadt in Vienna. Other endeavors, such as ReCapture⁴, have embarked on utilizing drone and laser scanning technology to catalog building components and evaluate their suitability for reuse. As more resources and methods become accessible, they can be seamlessly incorporated into both the architectural profession and education.

3.3 Lessons and observations

The students were driven to engage in critical thought regarding contemporary building practices and material culture, with the potential to become practitioners in reducing environmental impact. The creation of full-scale prototypes transformed learning into a more inclusive and cooperative experience. Hence, architecture design education must consistently challenge itself to uncover novel prospects in sustainable materials and devise innovative ways to align building construction with more equitable outcomes.

The selection of materials holds significant importance as it imposes distinct limitations. The process of analyzing and cataloging reusable materials has proven to be both demanding and exhaustive, particularly in terms of locating suitable reclaimed wood with uniformity. Furthermore, the caliber of upcycled and salvaged materials cannot be compared to manufactured ones. When obtaining a substantial quantity of unconventional materials, it is crucial to take into account the imperfections arising from the recycling and deconstruction processes. A pedagogical setting may focus on hybrid construction techniques that blend unconventional and conventional materials to optimize time and labor, thereby examining the structural strength and pertinent details.

CONCLUSION

The concept of a circular economy is not novel, and environmentalists have espoused the reduce, reuse, and recycle ethos since the 1970s (Goldberg 2020). However, the recent prevalence of building technology and a machine-driven approach to construction has resulted in a narrow focus on the end product of architecture, neglecting the sourcing, transportation, and disposal of materials. Today, the pressing ecological and sustainability issues hold an urgent place for action in both building practices and architectural education. Overcoming our dependence on virgin materials and combating the perception of obsolescence is imperative. The utilization of obsolete materials creates a multitude of previously undiscovered challenges and impediments, which can only be conquered through persistent effort and hands-on experience. The educational setting and student projects highlighted in this paper demonstrate how architectural education is

embracing the lifecycle of materials through a bottom-up design process that explores the constructability of reusing and repurposing materials. While these studies are in an imperfect state of progress, they raise important considerations regarding materiality and tectonics, uncovering the untapped potential of discarded materials to add depth and creativity to architectural designs.

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I would like to extend my admiration toward the seminar students who embodied a relentless passion and unwavering dedication to the concept of material circularity. Their belief in this principle is a testament to their commitment to shaping a better and sustainable future.

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Housing and Concrete, a Design Build Studio

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ABSTRACT: *The need for affordable housing has never been greater: Populations are fluctuating, cost of living is increasing and new typologies for live - work options are needed. This paper will discuss the framework and findings from a design build studio that developed and tested strategies to address these issues using precast concrete as a construction system. The paper will discuss the learning objectives, outcome and challenges of the studio that students selected as an option studio in their 4th year of NJIT's B Arch program. The studio investigated the possibilities of precast concrete construction methods, ideas for new strategies for mass customization, construction and assembly processes that make the use of concrete more efficient and therefore more environmentally and financially sustainable. To do that the studio teamed up with the Precast Concrete Institute PCI, High Concrete Group, BLDGUP a local developer, and NJIT's Concrete Industry Management Program CIM.*

KEYWORDS: Housing, Precast Concrete, Design Build

INTRODUCTION

In 2022, an estimated 420,000 new rental apartments were built in the United States, the highest amount for new multifamily construction in a half-century. The standard construction system for low rise housing in dense urban areas in the US is five wood-frame stories atop one concrete podium, also referred to by the industry as 5-over-1s. Optimizing 5-over-1s towards budgetary constraints from developers, density and zoning requests by cities led to a specific type of building that looks similar across the US to a degree that one would not be able to tell in what city a building is by just looking at the building itself. A specific construction standard of wood framing, very common across the country and a lack of experimentation and exploration of different construction techniques also contributed to such monotony.

The studio investigated precast concrete as an alternative to the typical wood-frame stories atop one concrete podium because of its advantages in performance and cost of construction. Precast concrete is a more fire resistant, durable and robust construction system for housing. It has a better acoustic performance, reducing sound reduction and lowering sound transmissions between dwelling units and external noise such as traffic. Compared to lightweight construction precast concrete also provides a higher level of internal temperature stability. As a solid construction material, it contributes to thermal comfort by absorbing and storing heat and radiating it back during cooler periods. If designed correctly with an effective use of solar control and ventilation, building with precast concrete can help minimize the need for air conditioning.

Compared to cast in place concrete, precast concrete has a series of advantages in the production and in the construction process: Panels can be produced faster and cleaner in a factory. Produced in a controlled environment the production is weather independent and independent to unique site constraints, which allows for the production to be optimized to save time and labor. An optimized process in a controlled environment also allows for better quality. The production in an ideal climatic condition of a controlled indoor environment can also speed up the curing process of concrete. On site the typical erection of a 5-story housing project is 10 weeks, which saves time and reduces construction cost. Once assembled on site wall surfaces do not have to be finished, concrete can be exposed, and the use of exterior insulated sandwich panels save time in the construction process and reduces the number of trades that would typically be involved in the construction of a multi layered façade. Walls can be used structurally, which can save on material and cost over alternative construction methods that are made up of columns and beams as a primary structure and wall panels as a secondary structure.

1. STUDIO FRAMEWORK

Instead of trying to build the prototypes and simulate an industrial construction process in the backyard of the architecture school this studio moved all the production to the industry. Instead of creating a make-believe environment the production of the students' projects was fully integrated into the production process of a precast concrete plant. This created a unique opportunity for students to collaborate with industry partners, learn about material, learn how to coordinate and meet schedules, learn about workflows and learn about the production of building components in a hands-on way.

The studio focused on the development of precast concrete assembly strategies and facade systems for micro housing. The semester was divided into three parts of about four weeks each: 1) Case study analysis and

schematic design, 2) Assembly processes and 3) the design and construction of a prototype for a façade panel. During the remaining two weeks students were asked to document all parts of the studio and synthesize and revise their projects. The studio took advantage of the location in the New York Metro area by starting off with field trips to recently completed micro housing projects and discussions with the local developer BLDGUP that is specialized in micro housing projects. Selecting an infill condition as site for the studio allowed to quickly develop a schematic design at the beginning of the semester and to develop projects in more detail. Beside the design of the project students were also asked to create assembly diagrams to discuss the construction process and estimate the construction time and cost. During this time students were connected to engineers at High Concrete, a local precast concrete plant for feedback. In the third part of the studio students collaborated very closely with engineers at the High Concrete Plant to design and build a prototype of façade panels of their projects.

2. CASE STUDY ANALYSIS



Figure 1: Wohnregal by FAR. Source: (David von Becker 2020)

The studio started by analyzing a wide range of case studies for five to eight story precast concrete housing projects. The projects were grouped into three different categories: column beam systems, panel systems and mixed construction systems. An example of a case study for a column beam system is the Wohnregal, a six-story housing block in Berlin, Germany. The project is using a precast concrete system to create an environment that can be highly customized. Instead of structural walls the project was constructed from precast pillars and TT beams that are supporting precast concrete slabs. Celebrating typical precast concrete details, the goal of the project was to create wide-open rooms. A span of 42 feet allowed for a maximum of transparency and flexibility to insert drywalls and divide the space according to individual lifestyles.

Very different applications for precast concrete are jail and prison cells in correctional facilities in the US. Because of the spatial requirements of small spaces panel systems are commonly used. They are built from precast concrete because of its durability, strength, and fire resistance. There are two different techniques used to build jail cells from precast concrete: Wall and floor panels and modular construction, where the entire cell is assembled from panels off site in a factory and brought to the site as a module. Both techniques can be customized to meet specific requirements to include built in beds, toilets and sinks. Differentiating between load bearing panels, sheer wall panels and non-load bearing panels allows to construct the entire building without any columns or beams.

Most precast concrete housing projects are a combination between column beam systems and panel systems. Typically, columns and transfer beams are used for the first floor to accommodate for programs that require larger spaces such as stores, restaurants or lobbies and panel systems are used for apartments because of the shorter span. An example for such a mixed construction system is the eight-story student housing project

currently under construction at the edge of NJIT's campus in Newark. Columns and transfer beams were used in the first floor of the project to respond to the required long spans to accommodate for parking, a student lounge and stores. The upper floors of the apartments were assembled as a column free load bearing panel system. Since the project was in the middle of construction during the semester of the studio, students could follow the process of assembly. Since High Concrete was the company that built the project students also had access to detail drawings of the project which helped to understand typical construction methods with precast concrete early in the semester.

Students compared different case studies and discussed possible advantages and disadvantages of using different precast concrete construction systems. An advantage for a panel system for example is cost, a disadvantage is the limited size for windows and flexibility in geometric complexity. An advantage of a beam column construction is the flexibility of floorplans, a disadvantage is cost. The advantage of mixed construction is the flexibility to respond to different program types. The disadvantage is cost.

3. ASSEMBLY PROCESS

Since one of the main goals of the project was to decrease the cost of housing students tested the three different strategies and different combinations of these strategies against the micro housing program. In the discussions with engineers from High Concrete student developed strategies to respond to the challenges of structure, spatial quality, speed of construction and cost efficiency.

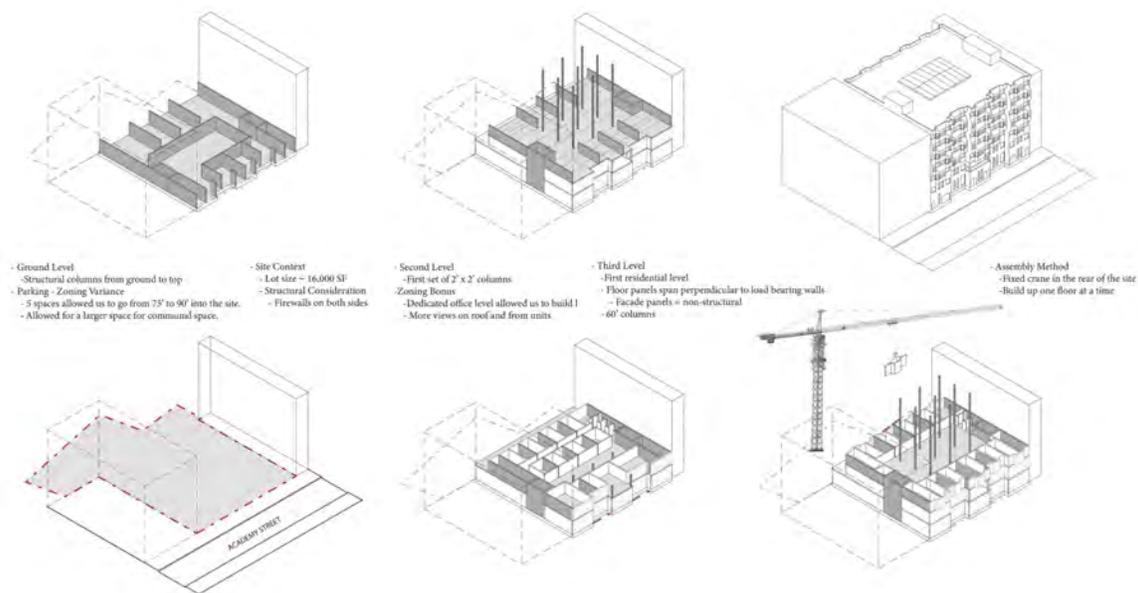


Figure 2: Project by Samantha Volpicella and Abdurahman Oudeh. Source: (NJIT 2022)

One example of responding to these challenges can be discussed in the project titled "Townhouse" by Samantha Volpicella and Abdurahman Oudeh. The team of students were interested in a façade that is more complex with large windows, which made it impossible to build the façade as load bearing precast panel structure. The student team responded by rotating the span of the ceiling and using every second interior wall between the micro units as load bearing walls. The façade was broken down into horizontal panels that span the length of each section of the total of five sections of the building. Tying the complex façade panels into the interior walls allowed for a complex façade with large bay windows, which created a unique spatial quality for the micro units. The team also aligned the load bearing walls with the walls of the first floor which saved cost as no transfer beams or columns were needed. Strategically cutting openings into the load bearing in the first floor allowed for programs such as a cafe that required more square feet. The façade was divided into five vertical sections to appear as five separate buildings. The prefabricated façade panel spanned the entire width of a section. This allowed for a design that responded to the characteristics of historic townhouses nearby. Leaving a large atrium in the middle of the building spatially connected all the residents into one community. The atrium was occupied by common functions such as shared office spaces, lounges, a fitness center and other amenities.

In a series of axonometric drawings students were asked to visualize the assembly process of the building. During a series of reviews, students and engineers discussed different strategies for panel sizes, the location

of the crane and the sequence and speed of the construction. In the case of Samantha and Abdurahman's project one crane was used to assemble the project layer by layer with the façade panels being the last components that would be brought to the site. Based on the feedback of the Up to 40 hollow core floor panels could be assembled on a single day. For the more complex façade panels 10-15 panels could be assembled per day which would allow for the entire building to be assembled on site in less than 12 weeks.

4. FAÇADE PROTOTYPE

Currently 30% or all housing projects in the US are precast concrete, most of them in states with tornados and hurricanes. Also, there are clear benefits for precast concrete for low-rise housing such as fewer labor costs and shorter construction time the default for 5-over-1s is wood-frame stories atop one concrete podium. This may have to do with the appearance of a precast concrete façade versus traditional finishes and historic associations and tradition. Precast concrete is often associated with prison architecture, student dormitories and post-war housing in Europe, that had to be erected fast and cheap after the world war. All this resulted into an unnecessary stigma being attached to precast concrete. Especially during the design of the façade students used the plasticity of the concrete to develop and test new aesthetic characteristics for housing projects that would replace current associations of precast concrete with new associations such as possibilities for a new lifestyle or performance benefits of precast concrete as a construction system.

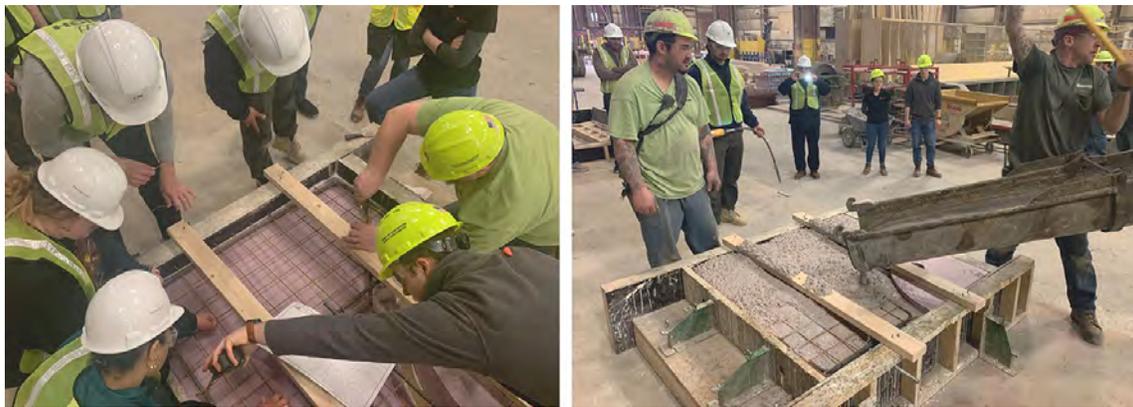


Figure 3: Production of Prototypes at High Concrete Group. Source: (Gernot Riether 2022)

Each student team had to build a real scale prototype of their façade system. Casting small scale models and creating a full-scale prototype student learned how to operate within the limitations of horizontally casted panels. At the same time the design of bay windows, a folded façade and extrusions showed how such limitations can be challenged and resolved. Student teams were responsible to build the form liner of the mold. The other components of the mold were built by High Concrete, the reinforcement was designed by High Concrete engineers. This required close coordination and effective communication between the students and our industry partner and the engineers. Deadlines were set at the beginning of the semester that allowed for error. Student teams were introduced to High Concrete's engineers at the beginning of the semester which started a conversation between student teams and our industry partner that lasted for the entire semester. Two months into the semester students finalized the design of the mold leaving one month for the production of the mold components. The drive from the architecture school to the concrete plant in Denver, Pennsylvania was 2.5 hours one way. To be able to produce the molds at the plant during studio time required good coordination and planning with the courses students had before the studio in order to leave early but also using the time there in the most efficient way possible. The studio did two trips: One to cast the panel and one to document the final piece.

In the case of Ella Martz and Karly Savinon's project the windowsill was extruded into a narrow spatial condition, which created a double curved surface on the exterior of the building. The team laminated panels of foam and used CNC to create the mold of the double curved surface. Also, the project took advantage of the plasticity of concrete as a material, it raised the question of using an alternative material for the mold that could be recycled.

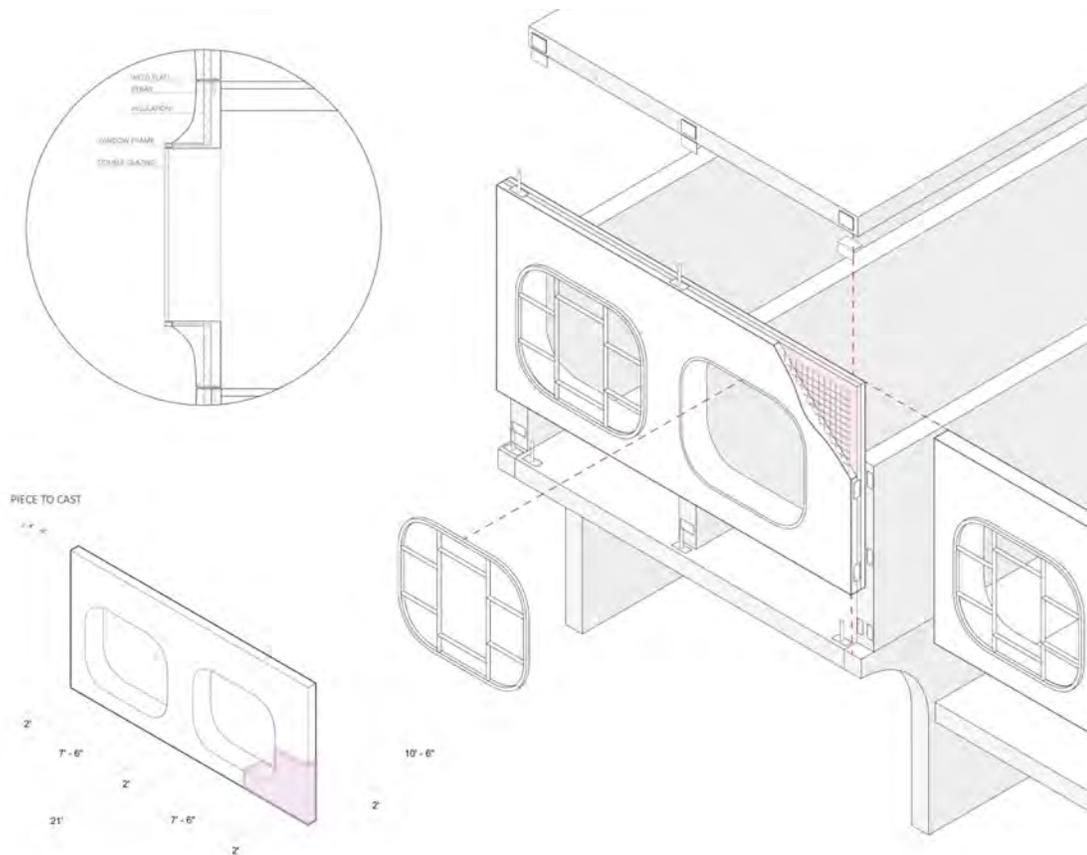


Figure 4: Project by Ella Martz and Karly Savinon. Source: (NJIT 2022)

While students built the form liner, the part of the mold that defined the double curved surface, High concrete produced the frame of the mold and prepared the reinforcement and connection details. Every change in the design had to be coordinated. Students learned how to effectively communicate with the fabricator with shop drawings. When students brought their component of the mold to the precast concrete plant everything had to match perfectly. Within two hours at the precast concrete plant the molds were assembled and the concrete cast.

Details were also added to allow for the prototype to be lifted from the mold. Students used smaller models to find the center of gravity of their prototype and tested with strings attached to small scale models of how one would lift and assemble the component with a construction crane. A week after students casted their prototypes students traveled back to High Concrete to see the final result. The casts were taken out of the mold, finished with a light sandblasting and exhibited at the exterior showroom at High Concrete.

5. FINAL REVIEW

The students' presentations of all three parts, the case study analysis and schematic design, assembly processes and the design and construction of the prototype. This allowed for a great discussion between architects, the developer, representatives from the precast concrete industry and engineers about advantages and disadvantages of precast concrete as a construction system for housing in comparison to other construction systems. Beside the possibility for students to be in the center of that discussion the review also presented a possible model for an architecture school to act as a platform for debates between investors, industry and architecture and a platform for research.

With the Precast Concrete Institute, PCI we also established a "People's Choice Award" of the best project from the PCI design build studio which provided the opportunity for students to travel to the annual PCI Mid-Atlantic Summer Membership Meeting in Williamsburg, Virginia, where the students from the best team presented the studio to the PCI industry and found a new network within the construction industry.

CONCLUSION

This paper presented a framework for a design build studio to design and test prefabricated concrete construction systems for micro housing. It discussed examples for strategies to use precast concrete construction to make housing more financially and environmentally sustainable. Developing real scale prototypes for façade systems and working closely with the Precast Concrete Institute and the Concrete Industry Management Program students were able to identify challenges and solutions and at the same time learned about construction systems and gained a hands-on experience of the production of precast concrete building components. Students also learned how to communicate ideas effectively and to develop solutions as a team member with industry partners and engineers. The focus of the studio was on the development of precast concrete assembly strategies and facade systems for micro housing. Further explorations will compare the building performance of precast concrete housing with conventional construction techniques in more detail.

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Guest reviewers: Andrew John Wit, Tyler School of Art + Architecture, Temple University; Michael Gibson, Kansas State University; James Kerestes, Ball State University.

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The Use of Wood Better the Relationship Between People and Places

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ABSTRACT: Wood is a very versatile building material. For centuries it has been used in construction. The use of wood declined as the use of reinforced concrete increased. Wood is a renewable material capable of storing CO₂, which is helpful for the struggle against climate change. Thus, starting from proper forest management, it is possible to have a building material that suits indoor climate conditions, allowing the improvement of structural response, good thermal and acoustic insulation, excellent olfactory perception, and easy humidity control. This versatility makes it a great material to ensure the well-being and comfort of the user. Well-being and comfort are people's perceptions of their environmental conditions. People's expectations and experiences are vital to the success of bio-economy business strategies, even if the inclusion of the human dimension is often not considered in the resolution of problems relating to housing. The focus of this paper is the encouragement of using wood, notably engineered woods like cross-laminated timber (CLT), glued laminated timber (glulam), nail laminated timber (NLT) and dowel laminated timber (DLT), because it favors the relationship between people and spaces, and it guarantees an excellent response in structural terms. This triggers a virtuous mechanism that enhances the entire wood supply chain that starts from forest management and reaches the benefits of the user both in the residential dimension and in the global space.

KEYWORDS: comfort indoor, wood, CLT, indoor environmental quality, bio-economy.

INTRODUCTION

The use of wood better the relationship between people and places: as a building material, it reduces the stress of occupants and is perceived as natural and warm (Frontczak et al., 2012); as interior finishes, it positively influences the comfort evaluation of space (Watchman et al., 2017). Despite the consumer's great importance, wood's effects on occupants' comfort have been rarely documented in built environments. The definition of internal comfort has an interdisciplinary nature that encompasses the psychology, physiology, and thermal-physics of buildings (Legros et al., 2020; Tian et al., 2018). An optimal quantity of wood in interior environments may exist because natural materials, such as stone, brick, and wood, convince the observer of their authenticity related to their age and history. In contrast, synthetic materials do not convey their essence or age to the observer. Well-being and comfort are people's perceptions of the environmental conditions they find themselves. People's expectations and experiences are vital to the success of bio-economy business strategies (Toppinen et al. 2018; Caru A. and Cova B. 2007), but the inclusion of the human dimension is often not considered in the resolution of problems relating to housing (Gram-Hanssen, 2014). People base their choices on social, cultural, economic, and psychological aspects (Wilk, 2002) in addition to aesthetics, well-being, and respect for the environment (Gold & Rubik, 2009; Hakala et al., 2015; Larasatie et al., 2018; Roos & Hugosson, 2008) but rarely on technical ones. Today, wood is again appreciated thanks to its natural features and the capacity to store CO₂. Wood could be a building material since it promotes the improvement of the structural response of buildings reducing the weight of the structure, has good thermal properties and allows satisfactory olfactory perception and easy control of humidity. The encouragement of using wood, and in particular, engineered wood like cross-laminated timber (CLT), favors the relationship between people and spaces and, at the same time, guarantees an excellent response in structural terms and better comfort to users. Its use triggers a virtuous mechanism that enhances the entire wood supply chain that, starts from forest management and reaches the benefits of the user both in the residential dimension and in the global space.

1. INDOOR COMFORT

Well-being and comfort are people's perceptions of the environmental conditions in which they are. Objective and subjective factors influence these perceptions and produce a reaction in the organism. Comfort is a subject that has been much studied in recent decades, considering the effect that it can have on human health (Baloch et al. 2020). However, its interdisciplinary nature creates a lack of a general definition.

One of the main parameters that deeply influences comfort is the thermal condition of an environment. Measurable and objective parameters define indoor thermal comfort:

- Air temperature. The optimal ranges vary from 19 °C to 22 °C in winter and from 24 °C to 26 °C in summer. It is preferable to have a homogeneous temperature in all the rooms.
- Air humidity. The optimal relative humidity values in a domestic environment should be between 40% and 50% in winter and between 50% and 60% in summer (UNI/TS 11300-1, 2014). Too dry environments damage the protective mucous membranes of the respiratory system, while those that are too wet favor the proliferation of viruses, bacteria and moulds.
- Air speed. The air currents, both hot and cold, generate physical intolerance. The air velocity in a house should be 0.01- 0.1 m/s in winter and 0.1-0.2 m/s in summer.
- Operating temperature (T_{op}), defined in ISO 7726 (ISO 7726, 1998). It considers the thermal exchanges between the human body and the surrounding environment by convection and radiation. It is the uniform temperature of an imaginary black envelope with which an occupant would exchange the same amount of heat as the actual room at an uneven temperature. It is determined by equation (1):

$$T_{op} = \frac{h_r * T_{mr} + h_c * T_{air}}{h_r + h_c} \quad (1)$$

where

- h_r is the coefficient of radiation heat exchange
- h_c is the coefficient of convective heat exchange
- T_{mr} is the average radiant temperature
- T_{air} is the air temperature.

Thus, the temperature perceived by the occupant depends on the air temperature and the surrounding surface temperatures.

The indoor environmental quality is also affected by the following:

- Air quality. It is determined by the presence or not of various physical, chemical, and biological contaminants. When these pollutants are present in significant quantity, the body reacts with symptoms of the respiratory tract, but also with other types of somatic pathologies, such as eye irritation and allergies.
- Olfactory perception. It can be associated with a pleasant or unpleasant smell. The sense of smell often determines decisions and behaviours. Olfactory perception can improve or worsen our well-being in an environment.
- Visual perception. It can blend the boundaries between indoor and outdoor spaces, between materials inside a built environment and its relationship to the materials in the landscape outside.

In addition:

- The optimal condition of visual comfort is obtained with natural light, but in the absence of this, it is good to maintain an adequate brightness resulting from more points of light in each room, to improve visual well-being. In a dwelling, visual comfort is given by points of light distribution, colour rendering, light shades, distribution of shadows, light direction, luminance distribution, and limitation of glare.

Moreover, the high visual relationship between the interior and the exterior is a condition that optimizes visual comfort.

- Sound/acoustic comfort depends on both internal and external sound sources. In a house, a good level of sound intensity is around 50 dB and can be achieved with efficient sound insulation.

2. THE ADVANTAGES OF USING WOOD

Until a few years ago, making a home comfortable was synonymous with higher energy expenses due to air conditioning and electrical devices, but today the concept of living comfort goes hand in hand with energy saving (Legros et al., 2020). This is mainly due to the materials used and new construction techniques. The construction sector increasingly uses low-CO₂ materials, such as materials of biological origin (wood, engineering wood, cork, straw, hemp, sheep's wool, etc.). Wooden houses, built with cutting-edge methods, tend to optimize the characteristics of environmental comfort thanks to the properties of the natural material used. Furthermore, automated and management systems, able to reduce energy consumption by monitoring the internal conditions, such as controlled mechanical ventilation, home automation systems, etc. can further improve living comfort.

Wood is the most used material for prefabricated houses and can ensure a high level of living comfort thanks to its innate characteristics. Its low thermal conductivity reduces the heat exchange between conditioned/non-conditioned spaces at different temperatures and retains heat inside the building (Ni et al., 2022) favoring thermal comfort conditions. It is an acoustic insulation that protects the house from unpleasant external noise even if timber structures, by their natural flexibility, tend to be characterized by low-frequency noise, which reduces occupant comfort (Gibson et al., 2022; van Damme et al., 2007). Ad hoc solutions are needed to reach the benchmarks set by the standards to ensure adequate living comfort. Since it is a hygroscopic material (Fig. 1), it naturally regulates the level of internal humidity (Ojanen 2014), improving well-being conditions. Moreover, olfactory perception can be improved, through correct and effective ventilation, both natural and mechanical, and by installing an air exchange system.



Figure 1: Example of hygroscopic effect: shrinking cracks caused by water leaks.

2.1 User satisfaction thanks to the wooden constructions

Several studies have been carried out to determine user satisfaction. In France (Legros et al., 2020), and in Canada (Rice et al., 2007), many people claim that perceived comfort is better inside a wooden room than in a plasterboard one. In fact, rooms made of wood are often evaluated better subjectively than objectively. The comfort temperature for the occupants is affected by the microclimate and some personal factors such as age and gender. On the other hand, the microclimate in a room of a building is also influenced by the materials of the walls. Different materials produce diverse internal temperatures (Hermawan, Prianto, and Setyowati 2020), but age and gender (De Simone & Fajilla, 2019) affect comfort perception. Moreover, considering the air quality, especially in old buildings, an abundance of pathogens and dangerous pollutants (Fürhapper et al., 2019; Pop et al., 2019) may be present.

Another problem related to wood is the growth of microorganisms and fungi. Solid wood buildings can present microbial charge by direct dust deposition due to a complex combination of local environmental conditions (Huniadi et al., 2019; Stenson et al., 2019). Old buildings must be monitored to minimize health risks and optimize maintenance costs, especially if they are historical and of tourist interest. Indoor air quality (IAQ) has become an important research topic in construction. Pollutants are harmful to human health and particularly dangerous for the most vulnerable, such as older people and children. Monitoring and controlling the internal microclimate and air quality through heating-ventilation-lighting are crucial (Marcu et al., 2021).

3. BIOECONOMY RELATED TO WOOD INDUSTRIES

The European Union's Bioeconomy Strategy (2018) promotes labels on wood materials to reduce carbon dioxide emissions in the construction sector, thus enabling the transition to a sustainable bioeconomy. The EU's goal towards a biobased circular economy promotes low-land-use construction and the use of recyclable materials and innovative and sustainable technologies. So starting from wood, it is possible to achieve these goals. Wood, by its nature, has characteristics that are often framed as a defect, such as a knot, ring shake, grain and shrinkage slot. The negative characteristics of wood are overcome through engineered wood products which are typically made up of wooden layers glued together or nailed, and they can be used both for new multi-storey wooden buildings (MSWB) and for the improvement of the overall response of existing structures (Frunzio et al., 2021; Frunzio & di Gennaro, 2018; IZZI et al., 2018; Sun et al., 2020). In Europe, interventions in existing buildings are necessary to renew their formal, structural, and technological aspects and preserve land consumption. (Frunzio et al., 2022; Pohoryles et al., 2020; Rinaldi et al., 2021). An example of engineering wood is Cross Laminated Timber (CLT). It consists of laminated wood arranged in cross layers. The solid wood use is typically softwood, but many researchers push to use local wood (softwood and hardwood) to improve the local short wood supply chain although of regulatory limitations on the use of some wood essences (Frunzio et al., 2021; Rinaldi et al., 2021). For example, Italy pushes to use chestnut and beech (Fig.2).



Figure 2: Examples of: a) *Castanea sativa* (chestnut), b) *Fagus* (beech).

Consumer acceptance of new bio-based products plays a key role in the transition to the forest bioeconomy (Kylkilähti et al., 2020). The MSWB represent a modern business opportunity based on biological material for the realization of low-CO₂ urban housing.

However, there is limited knowledge of consumers' different perceptions of wood as an urban building material. Despite the policy's success in supporting the spread of MSWB, cultural acceptance of MSWB has yet to be determined (Vainio et al., 2019). In addition, it must be taken into account that the environmental considerations of consumers are intertwined with the social, cultural, economic and psychological aspects of consumption (Wilk, 2002). Research into consumer perceptions of housing is necessary to fill these multidimensional aspects even if today, the inclusion of the human dimension, as perceptions and experiences of residents, is often not considered in the resolution of problems related to housing (Gram-Hanssen, 2014). Understanding people's expectations and experiences is vital to the success of business strategies driven by the bioeconomy (Caru A. & Cova B., 2007; Toppinen et al., 2018). In particular, there is limited knowledge about how consumers perceive the use of wood in MSWB. Consumer perception literature on timber as a building material is evolving. Wood can arouse both positive and negative perceptions among consumers. Literature suggests that "soft" factors, such as aesthetics, well-being, and respect for the environment, are features used to evaluate wooden-framed houses among German consumers (Gold & Rubik, 2009). Also, other studies document that consumers are inclined to value wood as a building material, especially considering features such as aesthetic beauty and a comfortable environment (Larasatie et al., 2018). Young people appreciate the wooden interior's aesthetics but also perceive wood as expensive and wonder if wood products are environmentally sustainable (Hakala et al., 2015; Roos & Hugosson, 2008). Overall, concerns

about earthquake safety or resistance are common findings in past studies. But, subjects who were previously familiar with wooden buildings were less likely to consider them susceptible to fire or consider their maintenance too expensive (Kylkilahti et al., 2020). For instance, in Finland, students' perceptions of MSWB are related to their familiarity with wooden residential buildings.

Moreover, the aesthetic appearance of MSWB is appreciated above all by thrifty and responsible consumers. At the same time, comfort, respect for the environment and durability of MSWB are important for consumers who identify themselves as "thoughtful spenders". So, many studies suggest that familiarity with the use of wood in homes, both for young environmentally conscious and "hedonistic" consumers, can contribute to a successful bio-economy in the urban context.

4. CONCLUSION

The encouragement of using wood and engineered woods like CLT, NLT, DLT and glulam better the relationship between people and spaces. It blends the boundaries between indoor and outdoor spaces and connects materials inside a built environment and those in the outdoor landscape. It is a flywheel for the entire wood supply chain. Good management of forests allows for high-quality structural wood. Thanks to their choice, the users obtain a twofold benefit: in the residential dimension, they ensure greater comfort in the global space, reducing their carbon footprint.

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Agricultural Waste Fiber in "An Economy That is Restorative and Regenerative by Design"

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ABSTRACT: This project investigates the use of grass fibers and how they can be used in "an economy that is restorative and regenerative by design", this is the definition the Ellen MacArthur foundation uses to define a Circular Economy. From an initial investigation by a graphic designer into the use of grass fibers for paper making a collaborative research initiative was established to analyze the properties of several grasses to better understand their structural strength and hydrophobic characteristics. Working with undergraduate research assistance from material science and fine and applied arts several perennial grasses and agricultural "waste" fibers were systematically studied. Initially meadow grasses were analyzed for their potential as an annual source of fiber for paper production as opposed to the clear-cut felling of trees for pulp. Following a couple of seasons of hands-on experimentation, the research became a more rigorous form of enquiry in which 10 plant types were studied down to the scale of a micron. In the process several preliminary findings related to tensile strength and hydrophobicity were discovered.

In 2017 another form of inquiry was initiated to see if various grass fibers could be used in three dimensional constructs. This research focused on three grasses for the following reasons: corn stover, due to its ubiquity across the region in which the research was being conducted, miscanthus because it's a high yielding perennial rhizomic plant with a high lignin content, and the hurd from hemp because it has been used in wall construction since antiquity and provides a good base case for comparative analysis. In 2018, with the assistance of an undergraduate student and assistant professor in the department of Material Science and Engineering, the thermal resistance properties of these three different grasses were analyzed using the flat plate method. The results were very similar for the three grasses tested, with both miscanthus and corn stover slightly outperforming hemp with an average conductivity of 0.1 W/mK or an R value of 1.3 per inch.

In the spring of 2019, a three-foot tall mockup wall was constructed in the context of a graduate seminar class. The grass fibers which were milled to a somewhat uniform dimension, were mixed with hydrated and hydraulic lime, and tamped down into wooden formwork. Over time the lime binder hardens preventing the fiber from being affected by mold or insect attack.

In the summer of 2019, a Master of Architecture Research Assistant was appointed to develop construction drawings for permit approval to build two 14 ft. tall experimental walls. Over the following three months, with the help of two more research assistance, the two walls were constructed. Each wall contains three different mixes: hempcrete, a corn stover-lime mix, and a miscanthus-lime mix. The current phase of the research involves the analysis of the walls using thermal humidity sensors and thermal imaging. Research is also underway to replace the lime that is in the mix with a geopolymer material with better thermal and structural properties as well as a lower carbon footprint.

KEYWORDS: Thermal Performance, Miscanthus, Hemp, Circular Economy,

INTRODUCTION

This paper presents the findings of an investigation into agricultural "waste" fibers and how they can be used in "an economy that is restorative and regenerative by design", this is the definition the Ellen MacArthur foundation uses to define a Circular Economy.

In 2012, with a desire to investigate if a more interconnected form of food production could be fostered in the industrialized agricultural landscape of America's mid-west, research got underway to see if mono-crop cultivation could be replaced with a fruit bearing perennial woody poly culture, interspersed with grazing crops and harvested meadow grasses. Within this more diverse landscape additional research opportunities opened. The meadow grasses were analyzed for their potential use as an annual source of fiber for paper production in contrast to clear-cut felling of trees for pulp. In the early years of the research several different native and forage grasses were explored to understand their properties and potential for use in paper manufacture. Following a couple of seasons of hands-on experimentation, the research became a more rigorous form of enquiry in which 10 plant types were studied down to the scale of a micron. In the process several preliminary findings related to tensile strength and hydrophobicity were discovered.

In 2017 another form of inquiry was initiated to see if various grass fibers could be used in three dimensional constructs. This research focused on three grasses for the following reasons: corn stover (from *Zea mays*), due to its ubiquity across the Midwest, Giant Miscanthus (*Miscanthus x giganteus*) because it is a high yielding

perennial rhizomic plant, and the hurd from industrial hemp (*Cannabis sativa*) because it has been used in wall construction since antiquity and provides a good base case for comparative analysis.

1. METHODS

The research into the use of grass fibers in three dimensional constructs was carried out in an incremental manner. Initially a comparison was made of the plant fibers themselves. This was followed by experiments with the fibers in conjunction with a proprietary lime binder. Once the behavior of the different mixtures was understood the research moved on to determining the thermal conductivity of the different mixes by utilizing a fin equation. Once the conductivity, and subsequent thermal resistance had been determined, a small mockup wall was constructed. Following the construction of the mockup wall two demonstration walls measuring approximately 10ft wide and 14ft tall were constructed. Once the walls were completed thermal imaging was used to determine if actual performance matched with assumptions that could be drawn from the earlier conductivity testing.

1.1 Grass fiber analysis

No specific testing was carried out to determine the essential components of the plant fibers used in the conductivity studies, the mockup wall, or the demonstration walls, however data from peer-reviewed literature points to some general composition traits, with some variation based on where the plants were grown, in which soils, and when they were harvested. All three plant types are composed of cellulose, hemicellulose, woody lignin, extractables and ash. The approximate percentages of cellulose in each plant fiber are as follows: 39% for miscanthus, 41% for corn stover, and 44% for hemp hurds. The percentage of hemicellulose in each plant fiber are as follows: 19% for miscanthus, 31% for corn stover, and 25 to 33% for hemp hurds. The content of woody lignin in the three samples is probably the most varied and could possibly be of greatest concern. For hemp and miscanthus the range is from 19 to 24% while in corn stover it only accounts for approximately 6%. What corn stover lacks in lignin it makes up in extractables that account for 17% as opposed to only 0.3 - 4% for miscanthus and hemp. The final component ash ranges from 1% for Hemp, 3% for miscanthus and 4% for corn stover.

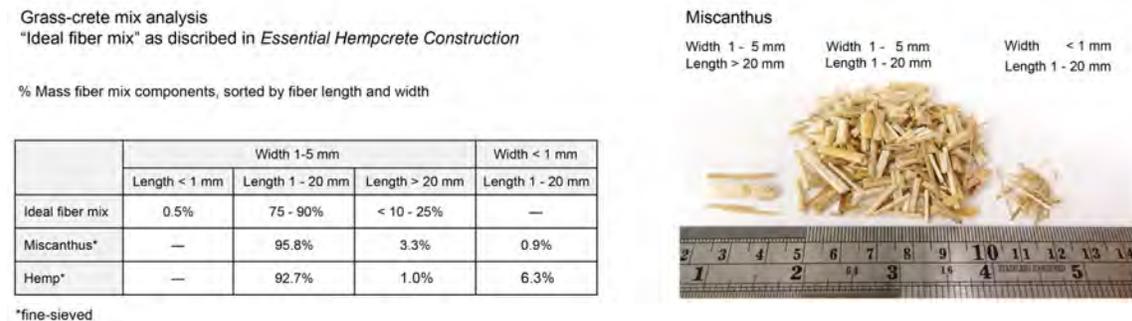


Figure 1: Fiber mix analysis. Source: (Lauren Kovanko 2018)

Although no testing of the essential components of the different plants was carried out, an analysis of the different sizes of material in each mix of chopped fiber was made. (see Fig. 1) This research was started before the 2018 United States Farm Bill removed industrial hemp, with THC content of less than 0.3%, from the list of Schedule 1 controlled substances, thus making it an ordinary agricultural commodity again, as it was in the 1950's. With the prohibition in place sourcing locally grown hemp was a challenge. Since 2018 more US farmers have experimented with growing hemp but many still face the challenge of decortication and potentially separating 5 different commodities from the plant including seeds, bast fiber and hurds. For this research hemp hurds were imported from Europe where large processing plants have long been established. That said when it came to harvesting corn stover and miscanthus, the two plants we were most interested in researching as alternatives to hemp, machines readily available to any arable farmer could be used. (see Fig. 2). In the case of the corn stover, which is essentially a waste product of corn production, the combined harvester was set to cut higher than usual, leaving stalks of corn sticking approximately 2ft out of the ground. A second pass through the field with a different machine was then required to chop and collect the stover before being stored in super sacks to dry before being run through a hammer mill to provide a material with fibers close to the range described as ideal in the book *Essential Hempcrete Construction* (Magwood, 2016). The harvesting of the miscanthus was more straight forward, and since miscanthus is a perennial grass, a machine only need pass through the field once a year at harvest time to collect the fiber. The machine and processes are like those shown in figure 2, however miscanthus can be allowed to dry in the field prior to harvest, it can also be chopped finer at harvest time requiring only a small amount of sieving before use.

Therefore, from the perspective of smallest carbon footprint of the three grasses studied miscanthus would be best due to the minimal amount of mechanical power needed to process the material prior to use, and in this case the material traveled less than a mile from where it was harvested to where it eventually became part of the demonstration walls.



Figure 2: Harvesting corn stover. Source: (Author 2019)

1.2 Behavior of material

One of the behavioral nuances of hempcrete is its ability to store a great deal of moisture because of the porous structure in the hurds; “the moisture is adsorbed onto the large internal surface area of the plant fibers and absorbed into the cellular structure. This storage capacity is very helpful in allowing the material to take on moisture when it exists and to release it when conditions allow” (Magwood 2016. p6) Historically these types of materials have been used in what has been described as “breathable construction”; vapor permeable would be a better descriptive term, as when trying to maintain a desirable interior temperature uncontrolled air flow through a wall assembly is never a good thing. That said before these purported vapor permeable traits can be put to the test some familiarity and mastery is required to judge how much moisture in the form of water should be added to the mix of fiber, and lime binder. The recommended mix ratio is 4:1:1. Four parts fiber, one part lime binder and one part water per volume. In practice however, we found that the fiber from each type of grass would absorb water at different rates. Corn stover, probably due to its differences in essential components, would absorb more water than the other two grasses so we had to be careful that we did not add too much water to the mix. The initial samples made for the thermal conductivity tests did not have sufficient water and soon became crumbly during testing. Mixing small quantities is also more difficult to get consistency correct than larger batches. With practice we were able to mix the different types of fiber to similar consistency; something like the consistency of oatmeal. The accepted test for assessing a mix of fiber, lime and water is using gloved hands to form a ball. “If the ball can be squeezed into a coherent shape and maintains its integrity, the water ratio is in the right range” (Magwood 2016. p62) (see Fig. 3)



Figure 3: Fiber composition and behavior. Source: (Lauren Kovanko 2018)

1.3 Thermal conductivity/resistance

A guarded hot plate (GHP) apparatus was designed to measure the effective thermal conductivity of cast “grasscrete” samples. The primary thermophysical principle that this apparatus exploits is Fourier’s law, which shows that heat flux (heat transfer rate per unit area perpendicular in units of W/m^2) is proportional to the spatial gradient of temperature (in units of $^{\circ}C/m$) with the proportionality constant being thermal conductivity k . The GHP directs heat unidirectionally by contacting a patch heater to one side of a given sample while

contacting its other side with an ice bath. All other surfaces were insulated from the surrounding environment. Provided that heat loss through the surrounding insulation is insignificant, the one-dimensional form of Fourier's law can be used to determine thermal conductivity. This law can be expressed by the following equation: $q_x'' = -k_{xx}\partial T/\partial x$, in which q_x'' is the component of heat flux perpendicular to the heater, k_{xx} is the sample's thermal conductivity in the direction perpendicular to the heater's plane, T is temperature, and x is position.

$$k = \frac{P_e \cdot L}{A_c(T_H - T_C)} \quad (\text{Eq. 1})$$

Equation 1 is another way of expressing Fourier's law in which T_H is the temperature of the heater, T_C is the temperature of the ice bath, P_e is the known electrical power applied to the heater, A_c is the cross-sectional area of the sample, and L is the thickness of the sample. In our experiments the six samples tested each had $A_c=11.8$ inches (300mm) x 11.8 inches (300mm) and $L=1.57$ inches (40mm). These sample dimensions, along with the dimensions of the GHP and the type/size of insulation, were chosen to minimize heat loss from the apparatus.

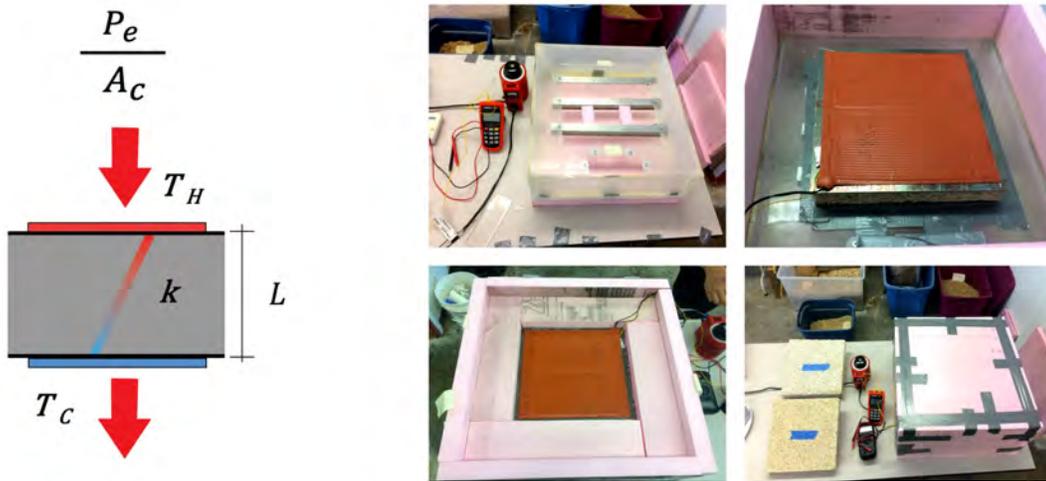


Figure 4: Thermal Resistance Testing Set-up. Source: (Kyle Smith and Author 2018)

To assure the validity of Equation 1 a quasi-one-dimensional model, a 'fin equation' (Bergman, Lavine, Incropera, and Dewitt, 2018), was used to account for potential heat loss from the sides of the sample. Using this approach, the following expression for the fraction of lost power was obtained as δ :

$$\delta \equiv \frac{P_{e,actual} - P_{e,ideal}}{P_{e,ideal}} = \left[m^* \frac{\left(\cosh(m^*) - \frac{T_C - T_\infty}{T_H - T_\infty} \right)}{\sinh(m^*) \left(1 - \frac{T_C - T_\infty}{T_H - T_\infty} \right)} - 1 \right] \times 100\% \quad (\text{Eq. 2})$$

Here, T_∞ is the temperature of the surroundings to which heat loss occurs and $m^* = \sqrt{4GsL^2/kA_c}$ is a non-dimensional parameter that depends on side length of the sample s 11.8 inches (300mm) and the net thermal conductance G (in units of W/m^2-K) through peripheral insulation and air beside the sample. For $T_C=0^\circ C$, $T_H=167^\circ F$ ($75^\circ C$), and $T_\infty=68^\circ F$ ($20^\circ C$), m^* must be less than 0.224 for the fraction of lost power to be less than 1%. Consequently, for a given conductance, thermal conductivity, sample cross-section, and sample side length, sample thickness must exceed a threshold value to assure heat loss of less than 1%: $L < 0.1\sqrt{kA_c/Gs}$.

Each sample was a mix of one of the three grasses being studied plus a lime binder. Small batches were mixed by hand with the addition of water and set in molds to dry for approximately two weeks before testing began. Six samples were created to see if particle size had an impact on thermal performance. Number 2 and 4 meshes were used to create a fine and a course mix sample for each of the three grasses being studied. Temperature was measured by securing thermocouple wires to steel plates on either side of the sample and connecting them to a thermoelectrical thermometer to record the temperatures on either side of the sample in $^\circ C$. Each sample was tested three times with a gap of approximately 4 days before a test was repeated with the same sample. Each test took approximately twelve hours to approach steady state. The final heater temperature applied to each sample was typically 158-176 $^\circ F$ (70-80 $^\circ C$) as shown in Fig. 5.

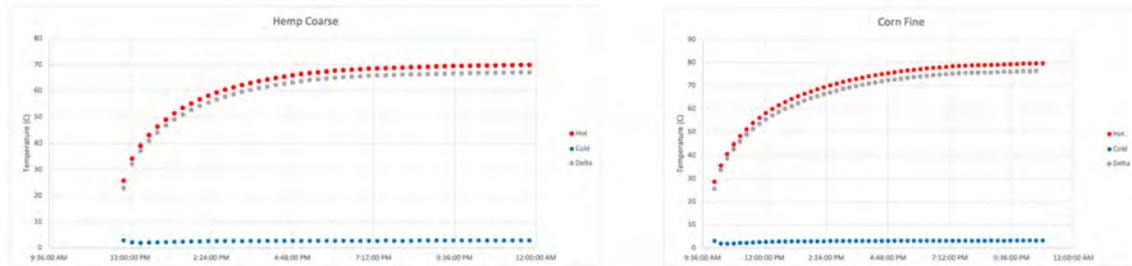


Figure 5: Temperature plots of hemp and corn samples. Source: (Cheng-Shen Shiang 2018)

Once three tests had been carried out on each sample the average thermal conductivity of each sample was calculated, this value was then converted into a unit more commonly used in construction: an R value. The outcome of the tests will be elaborated on in the results section of this paper, however, in brief no significant difference was detected between fine or coarse samples. Each of the three grasses performed very similarly with both miscanthus and corn stover slightly outperforming hemp with an average conductivity of 0.1 W/mK or an R value of 1.3 per inch.

1.4 Mockup and demonstration wall

Following the completion of the thermal analysis work began on a mockup wall. The wall was constructed in a seminar class to help understand what details would be needed when building larger demonstration walls. The mockup wall also provided an opportunity to mix larger volumes of material and gain experience in getting the mix consistency correct and develop the skills of tamping the material in movable formwork. It was envisioned that the first demonstration walls would be part of a retrofit of a small shed that needed repair on campus. With this in mind the mockup wall was built to reflect the construction of that building; 2x4 inch studs at 2ft on center sheathed with 0.75 inch boards. Inside of that envelope a 0.5 inch air cavity was created to allow the “grasscrete” materials to “breathe”. The corner section of the mockup was filled with hempcrete, in the middle section a corn stover-lime binder mix was used, miscanthus and lime binder was used in the final section. A 0.5 inch plaster coating was applied to the inside surface. The most significant lesson learnt from building the wall was that working with “grasscrete” is labor intensive and time consuming. It was initially thought that the mockup wall would have only taken three or four seminar sessions to complete. As things turned out it took most of the semester to complete, soon after that campus authorities decided the small, shed structure should not be saved but demolished instead.



Figure 6: Mockup wall construction. Source: (Author 2019)

Although the opportunity to renovate a dilapidated shed did not come to fruition, towards the end of 2019 a more attractive prospect was presented to our research team. The farm manager, at a research facility focused on the use of miscanthus as a biofuel, approached us with the proposition that plans be developed to enclose one bay of an existing pole barn structure measuring 60ft by 40ft. Each demonstration wall would be approximately 10ft wide and 14ft tall. As this would essentially be new construction, we had the opportunity to develop our construction details further. The only given constraint was the outside of the wall had to match with the existing metal panels that clad the rest of the pole barn. The site was not particularly well drained, so a generous concrete upstand was installed to ensure the bottom of the walls never got damp. Between the structural poles 2x4 inch horizontal girts were installed for the vertical metal panels to be attached to, on the outside of the girts a moisture barrier, house wrap, was installed, typical agricultural building construction. Inward of the girts 0.5 inch Blue Ridge Premium Insulating Sheathing was installed, manufactured from

recovered and recycled wood fibers this breathable sheathing was selected because of its vapor permeable characteristics which would allow any moisture in the wall to be able to migrate to the exterior of the assembly by passing through this sheathing to the air cavity created by the girts and the corrugation in the metal panels. Inward of the fiberboard 2x6 studs were set out on 2ft centers to provide something for the movable formwork to be screwed to. An improvement, that was not done in the mockup wall, was to cover the studs with a layer of "grasscrete" helping prevent thermal bridging through the assembly but also providing a more cohesive surface to plaster once the walls had been cast in place. A 30-gallon cement mortar pan mixer was purchased to allow for large batches of grass fiber, lime binder and water to be mixed. In a typical work session of approximately 3 hours the wall, which was 9 inches thick would grow by approximately 16 inches in height. The slow progress was in due in part to the team getting familiar with the process, and having to mix three different types of mixes in each wall: Hempcrete, "concrete" and "miscanthuscrete". Each wall took approximately twenty-five hours to cast including the time it took to raise the formwork between sessions, most of the time two people were working on the casting, one mixing the other on scaffolding tamping the material into the formwork. The team learnt to plaster for the first time and managed to apply a 0.75 inch plaster finish to both walls in three long days (approx. 30 hrs total).



Figure 7: Mockup wall construction. Source: (Luis Felipe Flores Garzon and Author 2019)

2. RESULTS

The results from the investigation are as follows: As previously stated the thermal resistance testing provided very similar results for the three grass mixes that were studied. Figure 8 shows the results of the tests carried out on the course mix samples, as this was the type of mix which was eventually used in the demonstration walls. Thermal imaging of the demonstration walls was carried out once the walls were complete, plastered and allowed to dry. Thermal imaging photographs were taken on January 24th 2022 when outside temperatures were 28°F (-2.2 °C). The spot reading on the inside of the demonstration wall, which did not show much variation across its surface, read 55.6°F (13.1°C) see Fig 9. On January 31st 2023, six temperature and relative humidity sensors were set into the wall, two in each mix. Sensors were set in two locations, one near the back of the wall, 8 inch (203mm) in from the surface, the other set of sensors were positioned toward the middle of the wall, 4 inches in from the surface, inside and outside temperature and relative humidity data was also collected. Preliminary data was collected 1st February 2023 at 9.45am when the outside temperature was 18°F (-7.7 °C) and the interior temperature was 60°F (15.5°C). Although not conclusive, preliminary results clearly show the demonstration wall working as an insulator to the outside climate (see Fig 10)

Material	Test #	Conductivity K (W/mK)	Avg K	RSI per meter (mk/W)	Avg Rsi	R per inch (ft ² f ^h /BTU ^h in)	Avg R
Hemp Coarse	9	0.1290	0.1214	7.7518	8.2575	1.1215	1.1946
	15	0.1206		8.2932		1.1998	
	21	0.1146		8.7273		1.2626	
Corn Coarse	4	0.1110	0.1089	9.0069	9.1874	1.3030	1.3291
	10	0.1095		9.1299		1.3208	
	16	0.1061		9.4252		1.3635	
Miscanthus Coarse	5	0.1101	0.1108	9.0807	9.0397	1.3137	1.3078
	11	0.1164		8.5885		1.2425	
	17	0.1058		9.4499		1.3671	

Figure 8: Thermal resistance testing results. Source: (Cheng-Shen Shiang and Author 2018)

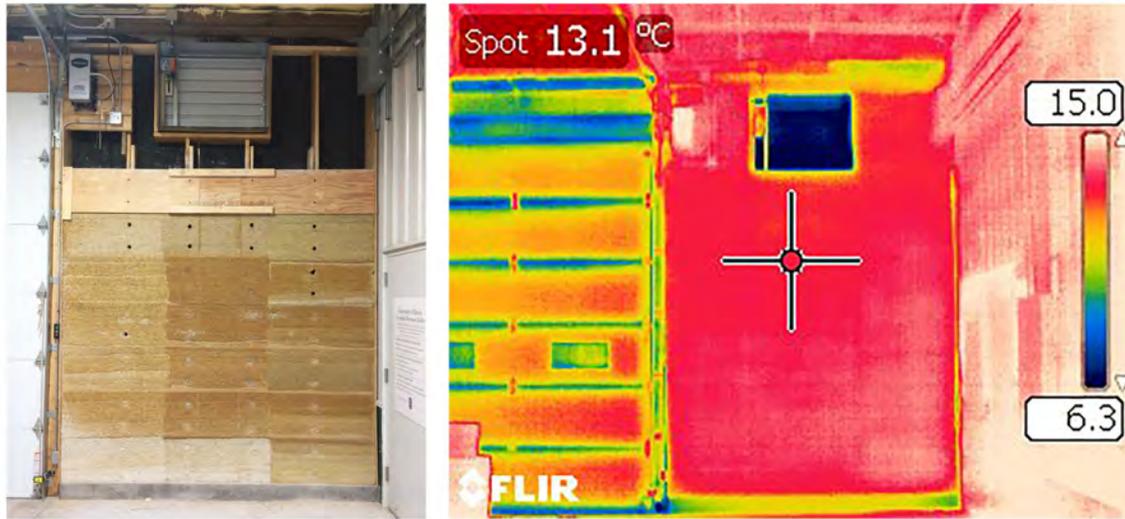


Figure 9: Demonstration wall near completion and thermal image after completion. Source: (Author and Yun Kyu Yi 2020)

2/1/2023 9.45am	Hemp	Miscanthus	Corn Stover	2/2/2023 3.45pm	Hemp	Miscanthus	Corn Stover
Outside	18.1°F (-7.7°C)	18.1°F (-7.7°C)	18.1°F (-7.7°C)	Outside	43°F (6.1°C)	43°F (6.1°C)	43°F (6.1°C)
Back of Wall	34.5°F (1.4°C)	33.3°F (0.7°C)	31.9°F (-0.08°C)	Back of Wall	41.0°F (5°C)	40.2°F (4.6°C)	40.5°F (4.7°C)
Middle of Wall	43.5°F (6.4°C)	-	-	Middle of Wall	47.3°F (8.5°C)	-	-
Interior	60°F (15.5°C)	60°F (15.5°C)	60°F (15.5°C)	Interior	60°F (15.5°C)	60°F (15.5°C)	60°F (15.5°C)

Figure 10: Preliminary in-wall sensor data. Source: (Author 2023)

CONCLUSION

The research to see if grasses, other than hemp, can be used as insulation materials in a wall assembly has been proven viable. In this study Giant Miscanthus (*Miscanthus x giganteus*), because of its essential components being very similar to hemp hurd, proved to be the most promising grass as an alternative to hemp. Giant Miscanthus also has the added advantages of being a perennial rhizomic plant that can dry in the field and requires only one mechanical process at harvest time to render the fiber ready for use as an insulation material in a wall assembly.

Corn stover also has its potential and further investigation may be needed. The material used in the demonstration wall may have been ground too fine in the hammer mill, or its essential components are not suitable for the application that was being tested. It was observed that the material would take on more water than the other two grasses, and when tamped into place it would compress more than the “hempcrete” and “miscanthuscrete”. It was also observed that as the material dried out horizontal cracks would form, cracks that had to be dug out and filled before the plaster finish was applied. It was initially intended that both the east and west demonstration walls would have the same samples in each, however, following the completion of the east wall it was decided not to use corn stover on its own in the second wall. Instead, the mixes that were used (right to left, see Fig 10) were hempcrete, “miscanthuscrete” and an even mix of corn stover and miscanthus with the addition of lime binder and water. It was noted that this mix with the combination of two grasses was easy to work and did not crack while drying out.

The preliminary data collected from sensors in one of the demonstration walls prove the “grasscrete” mixes are acting as insulators to the exterior climate. Further refinement of this instrumentation is required before

the data can be used to build a WUFI (heat and moisture transiency) simulation of the demonstration wall assembly. However, by looking at the data collected at 3.45pm on 2/2/2023 there appears to be a time lag or thermal flywheel affect taking place, something that has been observed in similar constructions of this nature (Evrard, A., and De Herde, A 2005). If this is the case it will be very interesting to “move” the WUFI model to different climate zones to see where an assembly like this would perform best, locations with a significant diurnal swing would be likely candidates for further investigation. A further line of enquiry that is also in its early stage is the replacement of the lime binder with a binder with a lower carbon footprint and higher structural performance. The material under investigation is a geopolymer binder; a ceramic that sets at room temperature. From initial studies this material is promising and could lead to other, more time efficient methods of construction, and thus address the labor-intensive challenges of this form of construction.

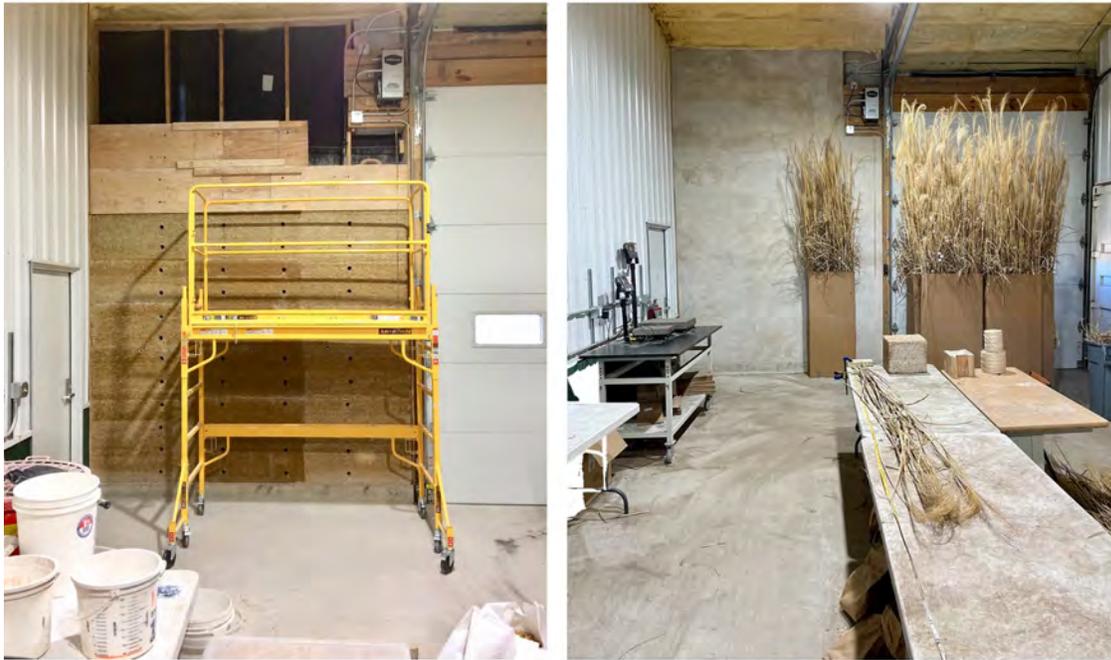


Figure 11: East demonstration wall under construction and complete. Source: (Author 2023)

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COMPLEXITY

The theories that seek to clarify the relationship between people and places. These include, among others, historical, archival, ethnographical, experimental, simulational, survey, mapping, statistical, and qualitative analysis methods

Framing a Tectonics of Place: The Arizona School

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ABSTRACT: *This paper will present a framework for studying how the best architecture of this region – including the work of the so-called Arizona School – has been, and continues to be, influenced by the tectonics of place: thoughtful in the use of local labor and techniques, creatively exploiting materials and architectural detailing, and informed by a varied and unique cultural history; all in response to a harsh and relentless (yet beautiful!) environment.*

KEYWORDS: Architectural Tectonics, Arizona Architecture, Arizona School, Critical Regionalism, Place

INTRODUCTION

In the winter of 1928, Frank Lloyd Wright made his first pilgrimage to Arizona to consult on the design of Albert Chase McArthur's Arizona Biltmore Hotel and was captivated by the natural beauty of the (mostly) unspoiled grandeur of the Sonoran Desert. He made several more trips to the Phoenix area in the following decade to live, work, and recuperate, eventually constructing Taliesin West in the early 1940s. This western edition of the Taliesin compound echoed the qualities of the desert. The materiality of the concrete walls, redwood frames, and "luminous canvas" panels provided a protected oasis perfectly situated to survive the ever-present harshness of the desert environment (Levine 1999).

Sixty years later, journalist Lawrence Cheek wrote an article for *Architecture* entitled "The Making of the Arizona School." In this text, Cheek ruminates on the past and current states of the built environment of Arizona. He speaks of the philosophies of Wright and their similarity to those of the indigenous peoples who have inhabited the region for centuries, focusing on the establishment of a graceful relationship between building and landscape that has been carried on by a lineage of Arizona architects. Cheek (2002) postulated that these influential individuals contributed to the emergence of an Arizona School of architecture "that now persists in the work of a scattering of modernists" practicing their craft in the heat and sun of the Sonoran Desert.¹ One of these architects, Jack DeBartolo 3 of DeBartolo Architects in Phoenix (2021), argues:

Place is the most influential element in our work. ... [P]eople change, criteria change. Places, however, tend to be pretty consistent. We ... think it's important that we respond to climate and to culture and to all the other facets of place. This is not just a philosophical attitude. The architect has a responsibility – a moral mandate – to respond to place. It's an irresponsible act to ignore the place of the work and to somehow think that you can – through cleverness, or through a material approach, or through some technological advantage – overwhelm or overcome the realities of place.

The logic of place, however, is complex, defined not only by the surrounding context, but also by cultural traditions of making, building, and living; political and societal influences; the systems at work within the ground; and the environmental impacts of the yearly climactic cycles. Place is not just a point on a map, and it is not simply scenographic; it is a composite environment, a quantitative and qualitative totality which cannot be reduced to any singular property (Norberg-Schulz 1976). Place accounts for the realities of the present, but it also refers to the traditions of the past and anticipates future trajectories. Place is messy; it is a complex endeavor that holds significant sway over what and how we build, what we build with, the temporal expectations of construction, and the connectivity of architecture, and in turn people, to its/their surroundings.

This research reflects on the proposition of an Arizona School, making the argument that, unlike other named Schools of architectural thought, it is not a stylistic or intellectual construct, but, instead, a tectonic one that specifically grounds the best work of the Sonoran Desert in the natural characteristics of this environment.² Informed by interviews with dozens of Arizona practitioners, this avenue of inquiry positions place as the foundational tectonic catalyst of architecture, informed by a lexicon of characteristics that shape the relationships built between people and place and, in this particular case, between architecture and the characteristics of the Sonoran Desert.

1. ARCHITECTURAL TECTONICS

1.1 Tectonic origins

In the mid-1800s, tectonic theory developed in Germany as a response to contemporary architectural practice. Neoclassicism, amongst other styles, was building a strong following in architectural circles and aesthetic appearance carried great weight in the evaluation of the built environment. Tectonic theory, championed by Gottfried Semper and Karl Bötticher amongst others, challenged the predominant assumption that what lay below the surface of a building was secondary to its ornamented cladding. It sought exterior expression for the mechanics that facilitate the development of our spaces of inhabitation. In this era, tectonics involved

building a relationship between the underlying technical necessity of architecture and its outward expression in the building's artform. As such, this theory began as one of ornamentation and was often disconnected from any notion of place. Many of Semper's and Bötticher's ideas were bound to their adoration of the ancient civilizations of Greece and Rome, creating a situation where architectural principles were not tied to one's own place, but instead to a place located remotely via distance, culture, and time.

1.2 Contemporary manifestation

Over a century and a half has passed since Semper and Bötticher wrote their manifestos on architectural tectonics. Cultural change and technological advancement have necessitated a constant evolution of the built environment, shifting the theoretical underpinnings of architectural tectonics as well. Its soul, however, remains: the belief that the construction of architecture – the ontological core of the built environment – is worthy of being expressed in the design of architectural space. Definitions of tectonics written around the turn of the last century illuminate the changes that have occurred in its contemporary interpretation:

The concern of tectonics is threefold. First, the finite nature and formal properties of constructional materials, be those timber, brick, stone, steel, etc. Second, the procedures of jointing, which is the way that elements of construction are put together. Third, the visual statics of form, that is the way by which the eye is satisfied about stability, unity and balance and their variations or opposites (Porphyrios 2002, 135-6).

Contemporary thought has shifted the definition to put more emphasis on the "revealed ligaments of the construction" (Frampton 1998) not just through representational means, but through their literal revealing. Tectonics is still concerned with the outward presence of a building, but more so with regards to the overall understanding of stability and balance than the surface application of ornament. The focus has also shifted to understanding the constructional logic of a building and the use of detailing and materiality to convey the qualities of the architecture and its spaces. Additionally, the historicism that grounded the early iterations of tectonic theory have all but disappeared, allowing a wide range of factors to exert a more significant influence over the reading of tectonic architecture.

Tectonic theory is integrative and its evolution over time means that no single definition exists that is inclusive of all its various interpretations. Within the context of this study, however, the exploration of tectonics in architecture is centered on understanding how the ways we construct impact the resulting spatial experiences. Per the late architect and educator Carles Vallhonrat (1988, 135):

Above all, we cannot build without the sense that the way we build is an active ingredient of the compositional strategies by which we try to achieve the ideal, or the idea of bound, sequential, and delineated spaces.

1.3 Tectonics and place

There are three primary realms of influence place has on architectural tectonics: the ground, the culture, and the environment. Buildings must deliver load to the ground thanks to the ever-present force of gravity on this planet. The significance of that intersection is often determined by the relative permanence of a structure. Regardless, though, weight must eventually return to the ground and the means employed to do so have a significant influence on the tectonic presence of architecture and the sense of stability that is critical to the development of that presence. We are hardwired to innately understand gravity's pull to earth and, as such, we read stability in the world around us as well. The plane of the ground – flat or sloped, rough or smooth – is, quite literally, foundational to our basic understanding of the tectonics of building.

The marking of the earth is the beginning of our taking possession of the land. Those who see the ground as a malleable substance that will change and develop with the integration of architecture will treat it differently than those who see it as a condition to be preserved. The second architect may find an ideal construction that integrates with the existing landscape, deriving a concept from the resulting relationship. The first architect, however, is more likely to start with a concept and derive a means to support it through the physical manipulation of the place, potentially creating conflicts between technology and topography (Berlanda 2014). The results of this conflict between the realities of the ground and human intent for the built environment occur often, sometimes resulting in the development of placeless architecture. The tectonics of place rallies against the spirit of universalism that facilitates the building of the same product anywhere.

Along with the ground, environmental conditions – heat, light, wind, weather, disasters – comprise the fundamental characteristics of place, which necessitate certain responses from our built environment to ensure that human comfort and safety are maintained. These factors were early components of tectonic theory, especially in the work of Semper who identified that cultures in warmer climates developed different building typologies than cultures living in cooler climates. Technological progress, however, has prompted some to ignore traditional practices in favor of technologies such as air conditioning which can be seen as "the main antagonist of rooted culture" when used "irrespective of the local climatic conditions which have a capacity to express the specific place and the seasonal variations of its climate." (Frampton 1998, 30) In fact, it can be

argued that evolutionary changes to tectonic theory have allowed not just gravity, but also climactic forces to contribute to the expression of a project and inform the underlying realities of architecture in a meaningful way.

Materials also play a key role in building a tectonic relationship between architecture and place. Vernacular buildings have material responses that are closely tied to both performance and availability: locally sourced, more familiar to the local labor force, and more resilient in the face of the regional climate. Semper linked the material language of architectural tectonics to the tectonics of craft – enclosure and textiles, framework and carpentry, earthwork and masonry, and the hearth and metallurgy and ceramics. Within these associations, he builds connections between materials and culture, effectively tying craft and architecture into the larger narrative of place. Additionally, materials can carry with them deeper meaning and, at times, both a lengthy history within a particular place and an evolutionary trajectory to come. While our current global society has allowed for an incredibly diverse knowledgebase to proliferate across the planet, it is our responsibility to ensure that while this diversity is opening possibilities, it is also acting in response to contextual conditions.

Building a relationship between place and current societal values is an emphasis of the theory of critical regionalism first proposed by Alex Tzonis and Liane Lefaivre and later developed by Kenneth Frampton. In the words of Arizona architect and educator John Meunier (2021):

Critical regionalism focuses on two things very well. The first is that we need to create buildings that are of our time, reflect the values of our time, and represent the aesthetics of our time. Hence the term critical. The second is that we need to do buildings that respond and contribute to the place where they are.

The goal is to create architecture that is respectful to the history of a place without nostalgically recreating vernacular imagery. In fact, tectonically centered architecture does not favor a particular architectural style; instead, it finds synergy in the “constantly evolving interplay of three converging vectors, the topos, the typos, and the tectonic” (Frampton 2001) or the place, the people, and the ways in which we construct spaces for their engagement.

2. PLACE

2.1 The Sonoran Desert

Deserts are most often defined first by their extreme aridity, but, in contrast to the prototypical image, when rains come, water “furiously pours from the sky” creating ephemeral pools and streams that momentarily replenish the desert and its inhabitants (Magrane and Cokinos 2016). The Southwest United States hosts four deserts: the Great Basin Desert, the Mojave Desert, the Chihuahuan Desert, and the Sonoran Desert. The Sonoran Desert, which exists primarily in Arizona and northern Mexico, is currently divided into six sub-biomes based primarily on the different types of flora that inhabit each, two of which – the Lower Colorado River Valley and Arizona Upland – are found in Arizona where the winters are mostly mild allowing for considerable biodiversity in what is considered the lushest desert in the world (Magrane and Cokinos 2016).³

Survival in the Sonoran Desert means adapting to an extreme environment and conforming to “Liebig’s law of the minimum, which simply states that the growth of a plant varies with the nutrients (including water) it is provided, and when the plant is deprived of nutrients, it cuts back.” (Shoumatoff 1999, 57) This reality does not mean, however, that life is struggling to survive in the Sonoran Desert. The flora and fauna there have adapted to live in this environment, evolving to integrate with the place to the point where many species require the arid environment for survival. Rather than the Sonoran Desert being a place of competition for scarce resources, it is often a place for mutualism to develop, a condition where interactivity between species benefits both equally, promoting a stronger ecosystem (Dimmitt, Wentworth Comus, and Brewer 2015).

Humans have lived in the Sonoran Desert for around 13,000 years. The first major civilization to thrive in the region was the Hohokam, who had their height in the 1300s and 1400s CE. Despite continual inhabitation since that point, the fact remains that of all the biodiversity in the region, it is humans who “are among the most poorly equipped animals for dealing with desiccating heat.” (Shoumatoff 1999, 65) In order to survive there, we need to carefully study the strategies that have proven successful for those best suited for the Sonoran Desert and use that knowledge gained to overcome our poorly adapted physiological makeup. We also must not abuse the very place we wish to inhabit as the greatest challenges to the Sonoran Desert are all man-made: global warming, habitat destruction, drought, and extreme wildfires. Our interventions must, now and into the future, be more respectful of place than the majority of what has been built there in the past.

2.2 Characteristics of a Place

Hassan Fathy (1986, xx), the late Egyptian architect, spoke extensively in his writings about the need to develop “an intimate knowledge of how to live in harmony with the local environment.” To effectively respond to this charge, however, we must be keenly aware of the characteristics of the place we are developing. Some of these characteristics are foundational elements of the natural environment – light, heat, water, earth, and air. In Fathy’s model, all other characteristics – the flora and fauna, the culture and spirit, the materials and

techniques used to build – respond to these natural characteristics, which exist virtually anywhere in one configuration or another. The following sections will briefly illuminate how these characteristics manifest within this particular place – the Sonoran Desert region of Arizona – and will provide concrete examples of their influence on the tectonic makeup of a handful of regional projects designed with a responsive attitude.

2.3 Light

Light defines our world and the shape and form of the objects in it. “Shadow is light’s counterpart” and it is “the gradation between lit surfaces and surfaces in shadow which supplies information about the three-dimensional form of a body.” (von Meiss 2014, 125) Light in the Sonoran Desert is a truly phenomenal force and can primarily be noted for its intensity, falling “fierce and hot as a rain of meteors ... the one supreme beauty to which all things pay allegiance.” (van Dyke 1918, 4) During the day, the brightness washes out character and color, but when the sun shifts low on the horizon, you can begin to understand the richness of the desert environment. The intensity of the sun in the region eliminates the need for substantial amounts of glass to achieve appropriate lighting within a building and reflected light is tremendously important because it has lost its intensity and a lot of its radiant heat and damaging infra-red and ultra-violet rays (Meunier 2021). Perhaps more so than in any other climactic region, understanding the path of the sun and shaping a building around that path are essential for designing responsibly.

Shadows in the desert are equally as intense; crisp and clean, almost as if they were cut by a razor blade (Weber 2021). “Desert light magnifies any little imperfection in a surface,” (Trzebiatowski 2021) allowing facility to play a crucial role in the expression of a project. These shadows stand in stark contrast to the ethereal qualities of the light of the sunrise and the sunset which shift the intensity, the color, and the value of the light considerably. As we consider light as a characteristic of place that can significantly alter the tectonic makeup of architecture, how does the best work of this region receive, resist, reflect, refract, exploit, or embrace desert light? How can the intensity of the light be handled as one shifts from outside to inside and back? What roles can shadow and shade play in the development of space in the desert as well as in the definition of form, detail, and tectonic expression?

One project that explores the use of shadow play is Temple Kol Ami [Scottsdale, 1994, Figure 1]. Will Bruder designed irregularity into the masonry walls by creatively misusing the methods of construction. He directed the contractor to “add a half-inch to the normative guide width dimension for a CMU wall” and when the blocks were dropped, if they landed between the strings, they were not to be adjusted (Weber 2021). The resulting walls have a texture that changes continually with the light, allowing for a play of shadow on the façade that varies throughout the day and throughout the year. In the Arroyo Residence [Tucson, 1990], Les Wallach was interested in managing the intense glare of the desert sun. Building on lessons learned from Judith Chafee about the use of a “big hat” to shade a project, a roof about three times the size of the house extends outward to capture exterior space. Along the southern exposure, the roof is specifically perforated to create a transition of light when looking from the dark spaces of the interior to the intensely bright exterior (Wallach 2021).



Figure 1 (left): A masonry wall at Temple Kol Ami by Will Bruder (Author, 2022); Figure 2 (right): The Prayer Pavilion of Light by DeBartolo Architects (Author, 2022)

2.4 Heat

With the light of the sun, comes its heat. While the control of light in architecture can impact human comfort, the control of heat through architecture can be responsible for maintaining human life. Phoenix, sitting at the northern end of the Sonoran Desert, has the hottest summer temperatures of any city in the Northern Hemisphere and, at an average daily high temperature of above 87°F, is one of the hottest cities on the planet

(Gammage 2016). Although the introduction of the home use air conditioning unit after World War II transformed the desert southwest into a place that could provide “comfortable” year-round living, responsible architects, and in turn responsible architecture, should rely on passive strategies to start the process of shaping comfortable space in Arizona, often through the adaption of time-tested, traditional practices. “You can tune the walls in a building...using different amounts of insulation based on orientation. Mass walls can absorb the heat, passing it through and releasing it in the building overnight.” (Wallach 2021)

The temperature of the southwest is significant, but it is also rising, especially in the cities, where the high temperatures have risen ten to fifteen degrees in the past several decades (Sydnor 2021). These rising temperatures, while partially due to climate change, are also a symptom of more immediate human-induced conditions such as the heat island effect and increased humidity caused by the addition of so many sources of open water. However, while it is assumed (correctly) that the Sonoran Desert region of Arizona is hot and relatively arid, intense heat does not always define the region. Outside of the summer months, the Sonoran Desert has a milder climate that encourages outdoor living. As we consider heat as an influence on the tectonic makeup of architecture in the Sonoran Desert, we must understand how a project resists and otherwise handles the intense heat of the desert, but also adapts to the yearly and daily shifting of temperature. How can performance carry equal weight to aesthetics in order to avoid “building the equivalent of the Farnsworth House in the desert”? (Wallach 2021)

With the Prayer Pavilion of Light [Phoenix, 2007, Figure 2], DeBartolo Architects explored, instead, if it would be possible to responsibly develop a glass box in the desert, one designed to resist heat infiltration. The enclosure of the building is composed of two glazing layers separated by a five-foot thermal chimney space. The interior skin is triple glazed while the exterior skin is laminated, fritted glass with a film in the center that shades the interior skin. The resulting construct provides light infiltration while mitigating the heat of the desert during the summer months (DeBartolo 2022). The Vali Homes Prototype project [Phoenix, 2014] provided coLab Studio with an opportunity to explore passively bringing better heat management to a prototypical single-family residence. The cladding mimics the vertical vents of a saguaro cactus, allowing moisture to breathe out, and a gap between the exterior metal siding and underlying layers allows thermal venting, also reducing heat gain. The 12-inch-thick, double stud walls are filled with 100% recycled cellulose for an R-value of 42. Additionally, EPS insulation around the edges of the slab allows the shaded ground to act as a heat sink and cool the house naturally (LeFevre 2019).

2.5 Water

Life on earth is water centric. Water is a critical component for sustaining life and a catalyst for human settlement patterns. It is also a universal symbol for life, rebirth, tranquility, peace, reflection, and power. The Turkish playwright Mehmet Murat Ildan wrote, “In the empire of desert, water is the king and shadow is the queen.” [3] Historian Thomas E. Sheridan (2012, 5) believes that a better metaphor in the American West might be “that of a feudal society of competing warlords held together by a weak king” who can deliver the precious resource of water. In the Sonoran Desert, “[t]he absence of water has largely determined the behavior and morphology of not only individual species... but entire cultures.” (Shoumatoff 1999, 9)

The state of water in the Sonoran Desert, however, has shifted dramatically with the influx of human settlement over the past 200 years. “A century or two back, water... in these deserts was no rarity.” (Cheek 2000) The aquifers lay close to the surface and the Santa Cruz River in Tucson and the Salt River in Phoenix were active waterways. The current condition, however, involves moving water to the people using massive infrastructural conveyance systems – the Salt River Project and the Central Arizona Project – that Marc Reisner refers to in his book *Cadillac Desert* as “a palpable mirage as incongruous a spectacle as any on earth: a man-made river flowing uphill in a place of almost no rain.” This “replumbing of Arizona” has allowed the metro areas of the region to exist, but the potential for cotton fields and golf courses has silenced many natural systems that depend on rivers for their lifecycles (Gammage 2016). Combined with dwindling resources, Arizona now has “an existential crisis of water, which they seem perilously oblivious to” (Kroloff 2021) at times.

While the organization of water resources is a guiding force in Arizona, the poetics and tectonic impacts of water in the desert are most often rooted in its delivery from above. The monsoon rains are fierce, but fleeting. A brief deluge of water transitions the desert to a world of torrid washes and roadways for the inundation of surface water seeking a home. Rainstorms in the desert are majestic events that bring additional resources to be coveted and, if possible, stored for later use. How can a project be tectonically configured to capture, store, and disburse water? How can architecture provide shelter from the driving monsoon rain? How can water be used to responsibly hydrate the dry air? How can we use wastewater productively? How can architecture “make sacred and visible the path of ephemeral water,” (Ten Eyck 2022) putting it front and center for all to see?

Marlene Imirzian shaped the Bob and Renee Parsons Leadership Center [Phoenix, 2017, Figure 3] – a camp facility for the Girl Scouts of America – around water in a variety of ways. Initially, Imirzian worked with landscape architect Christy Ten Eyck and civil engineer Leslie Kland to analyze the watershed of the hillside on which the center is located. Ultimately, the watershed was restored and protected by raising the entire complex off the ground, separating natural processes below from the camp’s activities above. The Center is also designed around clusters of cabins, each designed to collect water using a sculpted roof that channels it to tanks for reuse, visibly demonstrating the principles of responsible management to the campers (Imirzian 2021).



Figure 3 (left): The cabins and main walk of the Bob and Renee Parsons Leadership Center by Marlene Imirzian (Author, 2022); Figure 4 (right): The entry court of the Arabian Library by Richârd Kennedy Architects (Author, 2022)

2.6 Ground

As was mentioned above, the ground is, has been, and will continue to be the literal foundation of architecture. “The act of grounding – of fastening what we build to the earth – separates architecture from other acts of design.” (Kieran and Timberlake 2008, 57) The ground, however, is not a static, uniform mass. It is, instead, a palimpsest of layers that are unique to a particular place, a stratification of different natural and, sometimes, man-made substances. As was true with water, the cultural interpretations of the ground are also important as it serves as a symbol of fertility, growth, strength, stability, the afterlife, and timelessness for many. The ground can also be read either as a surface – one separating above from below, as is often the case when referring to topographical shifting of its topmost plane – or as a mass – acknowledging the strata, built up over ages, as a primary building material instead of an abstraction. Regardless of the interpretation, the building and the ground must engage in a negotiation, an “unavoidable encounter [that] constitutes an integral part of the design and is intimately connected to the attitude one holds with regard to the site and with the relationship between artefact and nature.” (Berlanda 2014, [1]) A building can occupy a site in three primary configurations: in the ground, on the ground, or above the ground. While most buildings start with an excavation to establish appropriate structural foundations, tectonic engagement with the ground can extend beyond issues of stability to the deeper meanings of the earth discussed above.

The landforms of the Sonoran Desert – rugged mountains, intimate canyons, wind sculpted dunes, winding arroyos, and vast expanses of open space – are varied and bold. The soils in the desert also range extensively, from expansive clay to rock-hard granite to caliche, a soil that is cemented together by calcium carbonate. At the surface, parts of the “desert floor [are] made up of cryptobiotic crusts that take centuries to regenerate when they’ve been damaged or disturbed.” (Winters 2021) In other parts of the desert, desert varnish, a thin coating of clay, iron, and manganese, is baked onto the surface of stone in the arid environment. Because of these conditions and others, scars on the Sonoran Desert’s surface – large or small – take an enormous amount of time to heal, requiring careful and thoughtful architectural engagement. Some projects touch the ground lightly to protect the desert floor and minimize impact, but there are valuable reasons to embed a building into the ground in the desert as well: thermal regulation and a reprieve from the desert heat. How else can a building take advantage of, burrow into, hover above, mimic, or otherwise respect the terrain? How else can it use the ground for protection or refuge? How can architecture be tectonically inspired by the colors, the textures, and the forms of the desert’s landscape?

The Arabian Library [Scottsdale, 2007, Figure 4] by Richârd Kennedy Architects takes its formal and tectonic inspiration from one of the most iconic landmarks of Arizona: Antelope Canyon. The building welcomes visitors through an entry sequence of tilted, corten steel clad walls reminiscent of the wind and water eroded slot

canyon. The building can be read as a geological outcropping, supported by a canted steel structure that is expressed throughout the building. Will Bruder's Deer Valley Rock Art Center [Phoenix, 1994] also draws inspiration from the ground. The building is situated across the primary relief outlet of Adobe Dam, intimately nestled up against the massive, man-made landform and serving as a bridge for visitors to view the petroglyphs that dot the adjacent hillside. The building is composed of tilt-up concrete panels encrusted with copper slag – a waste product of copper mining – serving both as a link to the history of mining in Arizona as well as to the concept of the desert varnish that made the creation of the petroglyphs possible via etching into the patina.

2.7 Air

Above the ground is a space filled with a mixture of gases essential for sustaining life on earth. It reaches upwards towards the atmosphere, which wraps and protects the planet. The desert air, according to John van Dyke (1918), is typically dry, thin, and clear – perhaps not quite as much in the current era – but often picks up particles of dust and sand. With particles in hand, wind, while often providing relief from the heat, can take on another role, that of the sculptor. “Granite and porphyry cannot withstand them, and in time they even cut through the glassy surface of lava. Their wear is not here nor there, but all over, everywhere. The edge of the wind is always against the stone.” In the desert, the earth is shaped by the movement of the air.

Gazing upwards, the sky – open and dematerialized, a symbol of freedom, lightness, vastness, and, to some, a spiritual home – sits in opposition to the solidity of the ground. The sky is the upper threshold of our existence on this planet and brings to us both our weather and a significant experiential component of our lives. In the Sonoran Desert, the sky serves as a vast canvas, exquisitely painted each day. The makeup of the air at a given place and given time has a significant impact on our impression of that sky, its coloring, and the particularly significant weather events it carries through the desert during the monsoon, events that bring with them the promise of renewal. How can a project tectonically relate to the vast expanse of the desert sky, the sunrise, the sunset, the weather, and the quality of the air? How can architecture redirect the movement of the air to help create comfortable spaces throughout the year in the Sonoran Desert?

Casa Caldera [Rural Southern Arizona, 2015] by DUST Architects is designed for providing this redirection. It is a three-bar scheme with the central bar serving as an open-air channel, typical of the zaguan typology found in Mexican architecture. Providing inside/outside connectivity and a sheltered patio, this central space, along with specifically located operable windows, is also aligned to channel cooling winds through the building during the warmest parts of the year, allowing the building to be fine-tuned by the occupants throughout the day (Hayes and Robles 2021). In the Palo Verde Library and Maryvale Community Center [Phoenix, 2006], Wendell Burnette drew from the qualities of the desert light and the color of the sky, referring specifically to the writings of John van Dyke in his writings on the project. The building is clad with a skin that absorbs the light of the desert sky, changing in tone and color throughout the day as the sky transforms from sunrise on the entry façade of the building through the warmth of the colors of sunset. This strategy is also reminiscent of the early tectonic theories of ornamentation, with the expression on the cladding here telling the story of the forces acting on the building rather than those acting from within.

CONCLUSION

“The Arizona School is a group of architects united in their pursuit of an appropriate modern architecture for desert inhabitation – one that is sensitive to the physical, technological, and cultural characteristics of life in an arid climate.” (Kroloff 2021)

As a part of this research, interviews were conducted with over fifty architects and other design professionals who have engaged significantly with the practice of architecture in Arizona. These interviews produced a wide variety of thoughts on the validity and composition of the Arizona School. Some architects who were a part of the original article believed it to be an accurate construct, others felt it to be a far looser association than had been described by the authors. Some architects felt their association with the School was constraining and had distanced themselves from it; others held a deep appreciation for their inclusion. Some interviewees felt that the selection of architects in the article was not inclusive enough at the time, and others acknowledged that the School would be much more extensive today with the significant rise in the overall quantity of quality firms that had taken up residence in Arizona in the past two decades. There was also sentiment expressed in some of the interviews about the appropriation of an Arizona School image by agents of mass production, reducing it to a material appearance of weathering steel and rammed earth – a style – without the associated intent or deeper meaning. Despite the lack of a singular voice, there was a clear sentiment expressed within the architecture community that there is an undercurrent of connectivity in the best architecture in Arizona that centers on a respect, if not reverence, for the desert. The relationship that has been developed goes beyond an image; it strikes at the heart of building, through the tectonic development of architecture, a meaningful, experiential, and sustainable relationship between the desert and the people who call it home.

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END NOTE

- ¹The term Arizona School was first coined by architect, educator, and writer Reed Kroloff, who was serving as the editor of *Architecture* at the time this article was published. He contributed significantly to the conceptual framework of this argument in its original configuration.
- ²While this research engages with both the natural and the cultural characteristics of place, this paper focuses only on presenting the natural characteristics of the Sonoran Desert and their connection to the best architecture of the region.
- ³This quote was mentioned by Brian Farling in my interview with him. (Farling and Farling 2021)

A Tale of Three Stones

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ABSTRACT: *Architects are often disconnected from the labor, sources, and processes used to produce the materials they select. In his recent book Unless, Kiel Moe confronts this disconnect by demonstrating the vast “terrestrial” nature (environmental, social, economic, political) of building through his description of Mies van der Rohe’s Seagram Building. This paper builds on Moe’s argument through considering another project by Mies: the Barcelona Pavilion. The Pavilion is a compelling case study for considering terrestrial building because of its complicated history: it was temporarily constructed for the International Exposition in Barcelona in 1929 and painstakingly reconstructed in 1986. This process, particularly the reconstruction, placed a unique emphasis on the material selections.*

This paper considers the selection of the stone used for cladding the wall at the heart of the Pavilion in three different iterations: the original, the reconstruction, and a speculative, contemporary version designed by the author. Given that a full terrestrial account of the Barcelona Pavilion would merit another book-length project like Moe’s, this paper focuses instead on what this material selection reveals about the discipline’s often unstated values. An unyielding commitment to luxurious, unique materials, privileging aesthetic and experiential considerations, provides a significant barrier to answering Moe’s call to realize the terrestrial impact of our building practices and address their significant contribution to climate change.

KEYWORDS: Barcelona Pavilion, terrestrial, contingency, literal

INTRODUCTION

The impact of the coronavirus pandemic in causing product shortages has highlighted the interconnectedness and extensive range of our supply chains. While this general reality has become part of the public’s consciousness to a greater degree, we simply cannot access the specific origin stories of even the most basic consumer goods. This is even more complex for architecture, a conglomeration of thousands of individual products, so we are completely ignorant of much of the materials, labor, sources, and processes used in its construction.

Kiel Moe’s recent book *Unless* seeks to address this disconnect and demystify the vast, “terrestrial” nature (environmental, social, economic, political) of building through his description of Mies van der Rohe’s Seagram Building. Moe is not simply calling out the inefficiencies, wastefulness, and contradictions of one building; rather, through providing a fresh look at an incredibly well-known building, he reveals the widespread lack of emphasis on construction ecology in existing scholarship about the Seagram Building. In lieu of continued preoccupations with architecture’s autonomy and “parochial” theoretical discourse, Moe calls for more “radically literal” (Moe 2020, 44) descriptions of buildings, “deep discussions of—and enchantment with—architecture’s formation” (44). In *Unless*, this discussion spans an overwhelming scale, from the geological formation of what is now Manhattan to the plight of laborers in the Chuquicamata copper mines in Chile. Even so, Moe admits that a full terrestrial account of the (or any) building is impossible (Moe 2020).

Of course, the Seagram Building has occupied a hallowed place in the canon of architectural history. Given the reality of climate change in our current moment, however, Moe calls the discipline to account for massive blind spots in assigning masterpiece status. He discusses the global impact of the building, emphasizing “how nature and society mix specifically through the procedures and processes of architecture” (Moe 2020, 30). Moe argues that it is no longer tenable for us to award and laud a project for exhibiting narrowly defined design excellence without considering the massive amount of resources used in its production (Moe 2020).

Along the way, Moe’s literal, terrestrial account methodically unravels accepted understandings of the Seagram Building, noting inherent contradictions between the building itself and the story created around the building. Despite claims of its being a “monument to standardization” (Moe 2020, 279), Moe reveals the Seagram Building as “a trophy” of “idiosyncratic manual craftsmanship” (280). Even its distinctive “bronze” envelope isn’t actually bronze; it’s brass hand-oiled with a special dye. Moe’s deep research into the material realities of the Seagram Building corrects several inaccuracies in other scholars’ descriptions of the building that use its details towards different ends.

Moe’s passionate appeals in *Unless* do not need to be seen as “cancelling” a masterpiece, but rather as a call to take seriously the power of the stories that the discipline tells itself about past significant works. A more complete, literal description would correct the factual inaccuracies in previous scholarly interpretations, as well as acknowledge the ecological impact of the work. Responding to *Unless*’s call for re-evaluating the discipline’s values, this paper will use Moe’s terrestrial framework to discuss another project by Mies: the

Barcelona Pavilion. In some ways, the Pavilion is an even more compelling case study for considering terrestrial building because of its complicated history: it was temporarily constructed for the International Exposition in Barcelona in 1929 and painstakingly reconstructed in 1986. The reconstruction offered a second chance to execute the “same” building, and analyzing the decisions made during the process can be instructive for the discipline today.

Given that an extensive terrestrial account of the Barcelona Pavilion would merit another book-length effort, this paper has deliberately narrowed its focus to material selection, and one material in particular. Perhaps most notably, the reconstruction architects, in what they described as “the most novelesque episode in the entire process of reconstructing the Pavilion” (de Sola-Morales, Cirici, and Ramos 1993, 33), went to great lengths to find a suitable source for the onyx doré, the precious stone used for cladding the wall at the heart of the Pavilion. Their extensive search ultimately led to an abandoned mine in Algeria. This paper considers the selection of this particular stone for the Barcelona Pavilion in three different iterations: the original, the reconstruction, and a speculative, contemporary version designed by this author.

While so much has been written about the Barcelona Pavilion, focusing on a terrestrial account of the Barcelona Pavilion can provide insights into the discipline’s myopic focus. To do so, the author purposely relied only on existing scholarship to construct an account of the material selection of the onyx doré. The following narratives piece together relevant fragments from a survey of many sources discussing the building (both the original and the reconstruction) over the last 94 years. Placing the material selection at the center adds another narrative arc for the Barcelona Pavilion; a story of waste, excess, opportunism, pragmatic capitulation, compromise, and somewhat arbitrary decisions begins to emerge, a far cry from the idealized canonical interpretations. This, then, is a tale of three stones.



Figure 1: Left - 1929 Pavilion (Source: Berliner Bild Bericht). Middle - 1986 Reconstruction (Source: Fundació Mies van der Rohe). Right - 2021 Re-design (Source: Author)

1. STONE 1

In the midst of designing the German exhibitions for the 1929 International Exposition, Mies van der Rohe and Lilly Reich were contracted to design a German pavilion, a key opportunity to provide an image of the young Weimar Republic.¹ The very process for this important commission was incredibly rushed. Initially, there were no plans for a German pavilion, but realizing that other nations like France were going to be building national pavilions, Germany decided to do so as well with only nine months remaining before the expo’s start. While design appeared to begin after Mies and Lilly’s visit to Barcelona on September 19th, the final site was confirmed in late November. A contract was signed on November 12, 1929, with the opening set for May 29, 1929, leaving only six months to design and build the pavilion.

A Plasticine model was used for early studies and a series of surviving sketches and floor plans document the harried evolution of the design. Most notably documenting the selection of the materials is a curious, seemingly unfinished perspective drawing. This drawing, attributed to both Mies and a member of his design team, Sergius Ruegenberg,² shows the interior space that was designated as the “throne room.” Here King Alfonso XIII and Queen Victoria Eugenia of Spain would sign a golden book in a ceremony to open the pavilion (de Sola-Morales, Cirici, and Ramos 1993). During the design process, Mies remarked that a wall must mark this location (Cohen 2007). The surface of this wall is a blank plane, completely unrendered, while the other materials in the view are rendered in graphite with a high level of detail. The drawing depicts the unique textures of the green Tinian and Alpine marbles, shadows emphasizing the slender cruciform columns, and the combinations of reflections between glass, travertine, water, and a sculpture.

This “free-standing wall,” as Mies referred to it, carried significant conceptual weight in the evolution of the design. Facing the significant limitations of a very tight schedule, Mies recalled the process for sourcing this material:

We had very little time. It was deep in the winter. You cannot move marble from the quarry in the winter because it is still wet inside and it would freeze to pieces. You had to find a piece of material which is dry. We had to go and look around in huge depots. There I found an onyx block (Neumann 2020, 75).³

Mies found this onyx block approximately 300 kilometers from his office in Berlin at a stone supplier in Hamburg in the winter of 1928. Unsatisfied with other samples he urged the supplier's staff, "Come on boys, don't you have something else, something truly beautiful?" (Filler 1986, 219). The onyx doré they presented in response was considered "one of the world's rarest and costliest marbles" (Hosey 2020, 240) and popular accounts indicate that this particular specimen came from a quarry in the Atlas Mountains of Morocco (de Sola-Morales, Cirici, and Ramos 1993). It was intended to be used for decorative vases on a Norddeutsche Lloyd oceanliner (Conroy 1979 and Cohen 2007).

Mies was the son of a stonemason, receiving training and working as a mason himself in his youth. He was immediately smitten with the onyx and wanted to assess its coloration and veining more clearly. Mies seemed to relish the opportunity to demonstrate his expertise as he later recalled the process at the marble distributor: [He directed the staff] Give me a hammer and I will show you how we used to do this at home. They finally brought me a hammer and were very curious if I would really strike a corner off the block. I hit it very hard and off came a slice, the size of my hand, very thin, and I said go and quickly polish it, so I can see it. We then decided to use it, figured out the quantities, and then bought the material (Neumann 2020, 81). Clearly satisfied with this "truly beautiful" material, he impulsively purchased it using his own funds.

With the stone now sourced, Mies adjusted the design of the pavilion to accommodate it. The previously un-rendered surface in the perspective would now bear this beautiful material. Based on the limitations of the stone, Mies set the overall height of the pavilion at twice the height of the onyx block: 3.1 meters. It's worth noting that for a pavilion that faced tight budget constraints, requiring some of the outer walls to even receive a faux finish on their back sides in lieu of stone cladding, the onyx alone represented 20% of the entire construction cost of the building (de Sola-Morales, Cirici, and Ramos 1993).

Given the specific veining of the material, Mies choose to deviate from the double diamond bookmatching used elsewhere and simply used a random match. Each side of the wall was made of four massive slabs, 235cm by 155cm and 3cm thick, with two solid caps on each end. To emphasize the freestanding nature of the wall and to allow for disassembly after its temporary use, the stone was mounted to a steel frame with open butt joints between them. Although the building is an image of a roof plane supported by the eight columns, additional structural support was integrated into the walls as well.

While many have speculated later that the distinctive golden tone of the onyx was intentionally paired with a black velour carpet and a red velvet curtain to represent the three colors of the German flag, this is not likely. The colors are not experienced in the correct order, and politically, there was a lack of consensus about whether to use the original German flag or the newly introduced flag of the Weimar Republic; this reality resulted in both flags being flown in front of the pavilion, causing confusion for many visitors (Neumann 2020).

On Monday morning, May 27, 1927, the pavilion remained unfinished but was complete enough to host the opening ceremonies. At the ceremony, King Alfonso XIII remarked that he "... had driven by the pavilion every day for the past week, waiting for it to be finished" (Neumann 2020, 114). He snarkily suggested "the Germans had delayed the opening of the pavilion on purpose, in order to show off their uncanny technical and improvisational skills to a world audience" (114). As originally intended, the pavilion was not meant to be a permanent structure. After unsuccessful attempts to sell the structure, after only ten months the building was disassembled and the stone shipped back to Hamburg in March 1930 to be used in government building projects (129). In late June, Sasha Stone documented the project in 13 photographs, which he sold to Berliner Bild-Bericht.

Contrary to the dominant narrative, the onyx doré at the original Barcelona Pavilion tells an alternate story of opportunism and contingency. The very selection of the stone was driven by the constraints of the schedule and natural forces, limited by the seasonal impact of extracting stone during cold weather. Hardly a predetermined material selection, the type of stone was a result of chance, of Mies being at the supplier at the right time, having the appropriate technical expertise to make an impulse purchase. While the proportions are seen as a critical aspect of the success of the design, Mies chose to adjust the designed height in response to the dimensions of the newfound material. Regardless of its golden tone recalling German colors, the material is spatially displaced; extracted from northern Africa, transported to Hamburg, and installed in Barcelona. It is not a German material; ironically, Mies rejected a German stone because it was not "noble" enough (Hosey 2018). While much has been written about the preciousness of the materials, Mies seems to undermine his own emphasis on the material selection, stating,

I think that the Barcelona Pavilion, if I would have built it in brick, it would be as good a building. I am quite sure it would not have been as successful as marble, but that has nothing to do with the idea (Neumann 2020, 76).

In summary, Lance Hosey described the built reality of the original as “a pasteboard illusion” (Hosey 2018, 233): rushed, over budget, and unfinished.

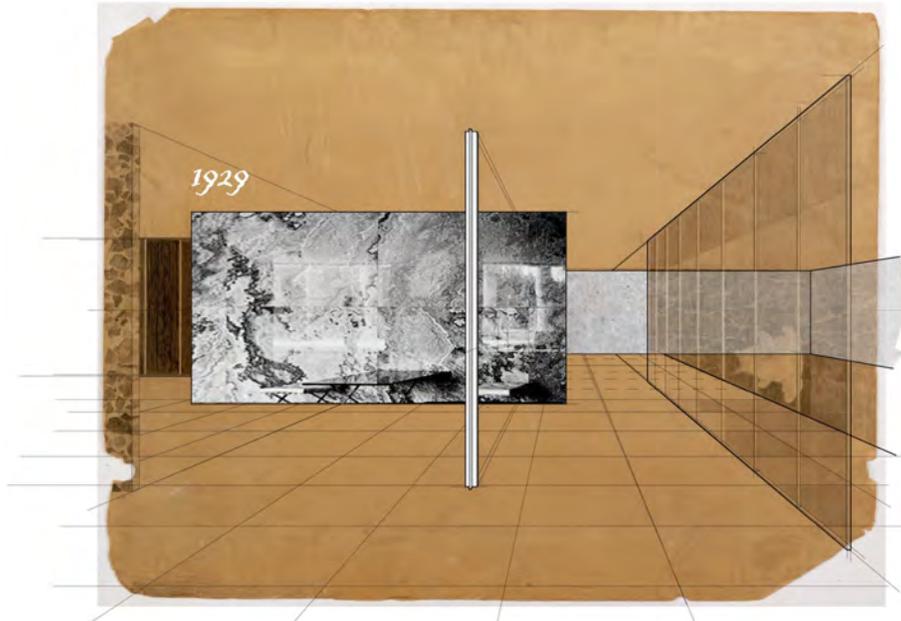


Figure 2: Original perspective drawing with 'Stone 1' material selection added. Source: (Author 2021)

2. STONE 2

Of course, the Barcelona Pavilion is such a unique case from a terrestrial perspective because of its reconstruction later in 1986. During the decades after the building's disassembly, Stone's photos were published and distributed widely and came to be the primary representations of the building. With few commentators actually visiting the building in person, it primarily existed as a set of images, which were used for subsequent critique, analysis, and interpretation. Many key commentators during this time based their arguments on inaccuracies about the actual construction of the building and historians have rigorously identified these inconsistencies. In one notable example, Philip Johnson touted the building's “expert craftsmanship” (Hosey 2020, 232), while the process and its execution noted above casts serious doubt on the correspondence with reality of that assessment.

When it was determined that the building would be reconstructed, the team of architects Ignasi de Sola-Morales, Cristian Cirici, and Fernando Ramos had an incredibly challenging task in deciding how to execute the reconstruction. Inherent to the process was an opportunity for the project to recalibrate and reconsider some decisions in executing the work.

In response to the significance of the project, and likely anticipating critique, the designers clearly outlined their approach to the reconstruction. They believed their role was not to simply rebuild the structure as it was built in 1929, but rather “...to carry through to its conclusion an idea with regard to which we had an abundance of information and the support of an architectural logic that was beyond all doubt” (de Sola-Morales i Rubio, Cirici, and Ramos 1993, 32). The reconstruction team explicitly chose to focus on what they believed was the original architectural idea, not an exact reproduction of a building they saw as tainted by its contingencies and limitations. In their assessment, these contingencies meant that “the physical execution of the building, for reasons of economy, haste or simple technological limitations, did not always come up to the level of its ideal character before, during and after its construction” (de Sola-Morales i Rubio, Cirici, and Ramos 1993, 29). To be fair, they also addressed the need for the building to now serve as a permanent structure, which required more robust solutions for technical issues (Cirici, Ramos, and de Sola-Morales i Rubio 1986).

Regarding the material selection, the design team assessed that the original's contribution was not in the newness of its materials, but their application: “the audacious manner of their combination and the technically radical way they were used for large surfaces and simple, elemental geometric forms” (de Sola-Morales i Rubio, Cirici, and Ramos 1993, 14). This ethos would guide their process in sourcing materials for the

reconstruction. For the onyx doré especially, the designers portrayed an almost nostalgic, whimsical attitude about the process to source a replacement. They seemed to assume without question that their task was to produce an exact replica of the onyx doré, arguably the most important material of the whole pavilion. However, stone is a natural material and replicating the exact texture, color, and veining of the original was utterly impossible.

Recognizing this limitation, they concluded, ...our task as reconstructors was equally divided between a faithful adherence to the colour, texture and shine of the material and our creative capacity to act as architects interpreting what was, in our judgment, Mies' intention at the moment of choosing the material, the cut and the finish. This tension between imitation and invention was what marked out our work as being not a mere process of restitution but a genuine project (de Sola-Morales i Rubio, Cirici, and Ramos 1993, 33).

Although it was purchased from a supplier in Hamburg, the original stone was believed to be from a quarry in Morocco. In "the most novelesque episode in the entire process of reconstructing the Pavilion," finding an exact match for the size, proportions, and physical characteristics of the stone were viewed as an absolute requirement, such that no suitable replacements were available. Holding to this inflexibility, the team searched onyx quarries in Israel, Egypt, Brazil, Pakistan, and Morocco. The fruitlessness of their search "...led [them] to the conclusion that the onyx used by Mies must have come, virtually beyond all doubt, from one of the quarries in the Oran region of Algeria" (de Sola-Morales i Rubio, Cirici, and Ramos 1993, 13). During their extensive travels, Fernando Ramos and marble expert Jordi Marques discovered a large block of onyx at an entrance to the abandoned quarry of Bou-Hanifia and convinced the owners to reopen it and extract the material (de Sola-Morales i Rubio, Cirici, and Ramos 1993). Ultimately, the determination was made that using a material from the same location would have to suffice.

With the material now sourced, the reconstruction team refined the anchor design, working to develop a system of anchors made by Frimeda (a German company) with input from Mecanotubos (a Spanish company). The panels were attached similarly to a steel frame, with the panel locations adjusted to give precise 5mm joints (de Sola-Morales i Rubio, Cirici, and Ramos 1993).

In the reconstruction, the onyx pieces were arrayed in a distinctive pattern to produce a symmetry about the four panels, reproducing the double diamond bookmatching of the other stone walls evident in the photographs. The design team does not explain their justification for the deviation from the random pattern of the 1929 version, but they were likely inspired by the green Alpine marble configuration (Neumann 2020). This effect, specific to their selected stone and not present in the original pavilion, created a kaleidoscopic effect with the veining and reflections giving a three-dimensional depth to the material and the plane it defines (Quetglas 2001). Interestingly, Martin Filler found it to be "an acceptable—though far from perfect—specimen, less translucent and more purplish" (Filler 1986, 219), critiquing the differences in the stone even though his analysis of the original was based on its black and white photography.

Despite the strength of their convictions that the logic was "beyond all doubt," the designers conceded that the process of the original building was so challenged by schedule and budget constraints that no record (drawings or photographs) definitively showed how the building was intended to be (de Sola-Morales i Rubio, Cirici, and Ramos 1993). It is worth noting that the architects chose to build the idealized, perfected vision of the building that had emerged through the critical response to the project based on the photographs, not the actual construction. This reality reveals the power of the stories that we weave around the buildings we create. While one can certainly argue for the building as an expression of an idea, one can equally present it as a temporary structure complicated by budget and schedule issues resulting in technical and aesthetic failures.

In this regard, it is less significant to determine whether the 1986 building is a reproduction, recreation, replica, fake, simulacra, etc.⁴ Instead, it is more instructive to consider how the overall approach to the reconstruction reveals the discipline's often unstated values. Why would the architects go to such great lengths to try to replicate an incredibly rare material that is impossible to replicate exactly? That this decision seems like an uncritical default reveals significant resistance to Moe's argument for a terrestrial account of our beloved icons. Imagine the carbon footprint of this one decision. And consider that in light of the fact that Mies selected the original material as a "ready-made" material from a range of available options, and adjusted the height and proportions of the pavilion to fit it. Without the original onyx, Hosey sums up the pavilion as "a reliquary with the wrong relic" (Hosey 2018, 243).

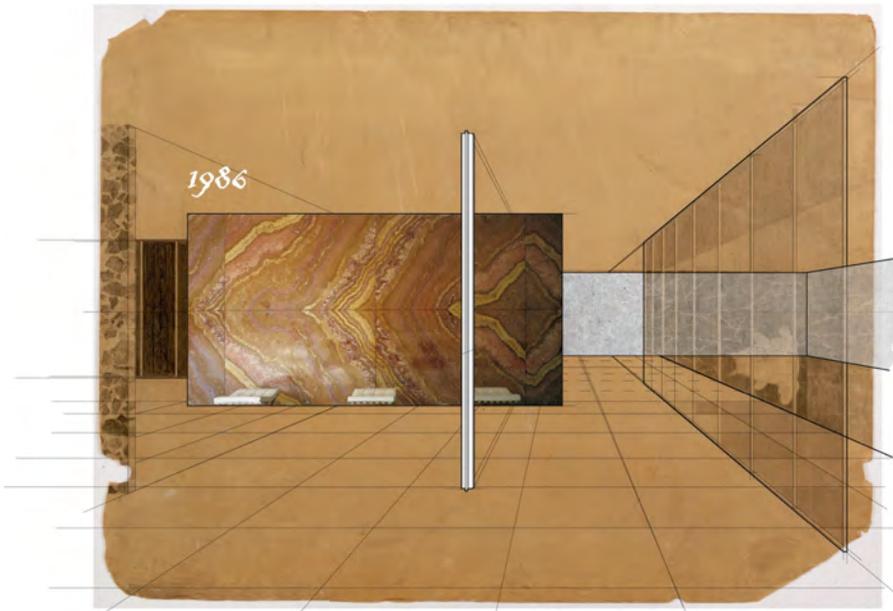


Figure 3: Original perspective drawing with 'Stone 2' material selection added. Source: (Author 2021)

3. STONE 3

Since redesigning the Barcelona Pavilion can be an opportunity to recalibrate some of the decisions made in the building's execution, this author created a speculative design for a third iteration of the pavilion using only standard details and materials in an intentional provocation. As an alternative to the pure, idealized version built in 1986, this re-design embraces the reality of the budget-challenged, improvisational, contingent process of the original. It also takes seriously Mies's own admission that the success of the design did not rely solely on the selection of ultra-precious materials. For example, custom framing systems were exchanged for aluminum storefront systems, and, like the original, the design was adjusted to incorporate the material and system selections.

Within this speculative design process, the designer visited the nearby Lowe's store to select a material for the throne room wall. Directly on axis with the main entry is Kitchen Design Services, showcasing the available material possibilities for countertops: quartz, stone, solid surface, butcher block, and laminate. Within the displays, there are 6" square samples of each option, all pre-polished. Although they sometimes run out of brochures, ample information is available on the web. Instead of a global search to try to match a completely unique color, texture, and veining, this material selection sought to approximate the stone's finish in the two previous iterations using readily-available options.

Each Lowe's store offers a limited selection of a private label manufacturer's total offerings depending on the region it is located in. Upon review of the available options at store #241, the architect selected quartz produced by Allen + Roth due to its consistency and relative approximation of the color and texture of onyx. Fortuitously, these slabs standardly come in the same 3cm thickness utilized in both the original and the 1986 reconstruction. The options are organized by different levels of cost—A through E—clearly outlined in the product display, with the designation clearly labeled on each 6" square sample. The selected option, Brockeye, is in category C so its material cost is estimated at \$91/SF. The total material cost for this cladding would be about \$35,000, far less than the cost of onyx. There would likely be an upcharge to produce the dimensions of the original slabs since they exceed the standard dimensions for countertop depths. Noting this limitation, additional joints were added to the design of the wall to accommodate the standard.

Global industries and supply chains are optimized to produce this type of predictability and accessibility, of which Mies could only dream in 1929. Yet, many in the discipline of architecture would balk at the suggestion of cladding Mies's masterpiece with a manufactured stone from Lowe's commonly used in suburban kitchens across the US. Despite its easy availability, when it comes to determining the source of the material, it gets considerably more difficult. Allen & Roth's countertops are marketed by Sage Surfaces and sold exclusively at Lowe's. Sage Surfaces is located in Magnolia, Texas. From there, it is unclear where the countertops are actually manufactured or where the material is sourced from.

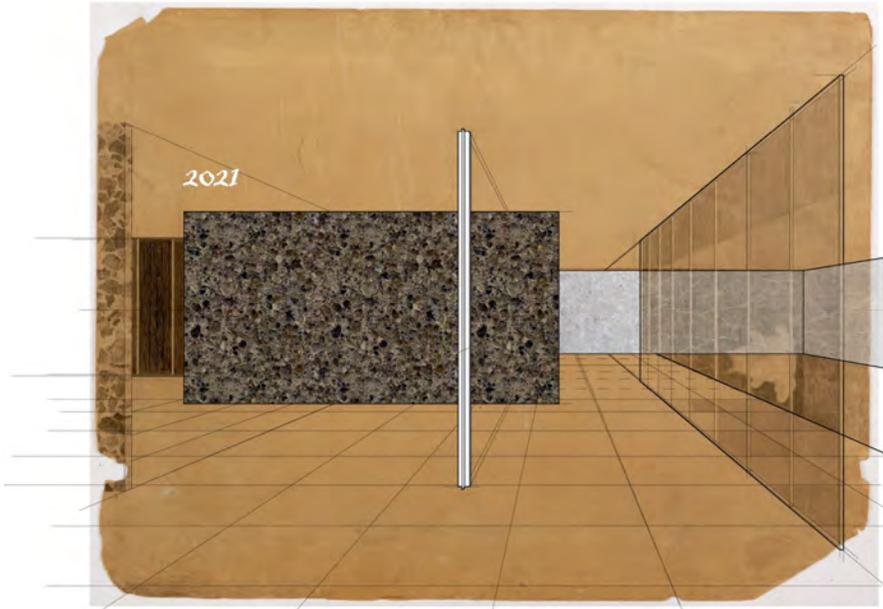


Figure 4: Original perspective drawing with 'Stone 3' material selection added. Source: (Author 2021)

4. TERRESTRIAL ACCOUNTS

The existing literature concerning the selection of the onyx material leaves significant gaps from a terrestrial perspective. Despite surveying many key accounts of the building to reconstruct the narratives above, the information and details related to a literal description of the building's construction ecology are few and far between. This information and these details were simply not emphasized or deemed significant in light of other considerations of the building's discursive value.

As shown in Moe's efforts with the Seagram Building, extensive research is needed to fill in those gaps. For example, what was the impact of shipping the original onyx along the many steps on its journey from Algeria to Hamburg to Barcelona and back to Hamburg? What about the resources consumed for the design team to travel to remote quarries, to extract the new stone, dress it and transport it to Barcelona for installation? Where did the source material for the manufactured quartz come from and what was the process to produce and distribute it? What about the steel framework and anchoring system? And the labor involved with all of these steps – was it ethical and safe? It is worth reiterating that this discussion is limited here to a single material for the building. Given the model of Moe's study, we can anticipate the vast resources needed to produce even this small, unconditioned structure. As a discipline, we can then extrapolate that these considerations affect every single building, as indeed, "every building is a terrestrial event" (Moe 2020).

What the Barcelona Pavilion demonstrates even more clearly, however, is the significant disciplinary resistance that is likely in considering architecture as a terrestrial event through its impact on the earth. What is it about the discipline that valorizes perfection at all costs? In the intervening years between the original and the reconstruction, commentators collectively constructed a perfected image of the building from those original black and white images. To do so, even notable figures like Robin Evans, K. Michael Hays, and Philip Johnson made significant factual errors in describing the literal qualities of the building.

These literal descriptions of the Seagram Building and the Barcelona Pavilion show that the myths and fictions the discipline creates around our buildings achieve more agency than the reality of the buildings themselves. Instead of centering the story around creative problem solving that resolved competing formal, technical, budgetary, and schedule demands to produce an iconic building, the Barcelona Pavilion's canonical accounts deny this contingency. When these details are acknowledged, they are typically minimized. Despite the impending crisis of climate change, if the Barcelona Pavilion were reconstructed today, do we actually expect a different approach to its material selection? Or would its architects go to ridiculous lengths to source the onyx again due to privileging aesthetic and symbolic concerns above the literal and terrestrial realities of material selections? How do we (as a society and as a discipline) decide when one building is significant enough to disregard the extreme wastefulness of its material selection?

While Moe's *Unless* is timely and compelling, we see in this discussion of the Barcelona Pavilion two critical impediments to incorporating the book's concepts into disciplinary discourse. First, massive amounts of historical research are required to fill in the gaps adequately to create a terrestrial account of the discipline's canon. Second, shifting the entire value system of the discipline away from the rejection of contingency and the privileging of the perfect, idealized version of architecture will be even more challenging. These gaps between what the building actually is and what we say it is, reveal many of the inherent contradictions in the discipline. While there are many forces that perpetuate the detrimental environmental impact of our buildings, they can often allow us to shift blame to external forces rather than looking inward. To answer Moe's call seriously, the discipline itself must significantly reassess its values and act on them. This reality has implications for all of us, academics and practitioners alike.

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ENDNOTES

- ¹Both Hosey and Neumann, among others, emphasize the unique political context for their discussions of the project.
- ²For example, Luscombe credits Mies with her extensive analysis of the drawing, while Neumann credits Ruegenberg. Regardless of who actually created it, this drawing's importance is evident through photographs showing its prominent display on the wall behind the team working on the project.
- ³While the actual sources of these direct quotations from Mies are other places, I am citing the secondary sources in which they were referenced because this is the way that I first encountered this information. This demonstrates the layered quality of scholarship on the Pavilion with multiple commentators referencing the source material in their own discussion.
- ⁴"The 1986 Pavilion has been described as reconstruction, replica, reproduction, copy, genuine copy, interpretation, reinterpretation, duplicate, facsimile, re-building, re-creation, incarnation, reincarnation, clone, and Phoenix – to mention just a few terms" (Capdevila-Werning 2016, 203).

The Restoration of Santa Maria delle Grazie: The New Life of an Ancient Church

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ABSTRACT: *Europe is rich in monumental buildings that characterise the lives of small, medium and large communities. These elements strongly typify territories they insist on and often represent their symbols. These buildings' value is not only defined by their historical nature. Like a magnifying glass, the studies of such types of structures allow us to scrutinise arts, technologies and construction techniques. Often, intervening to restore them instead of erecting new buildings represents an opportunity for the entire community to retrace the history of master artisans and architects of distant epochs. Restoration, therefore, represents a moment of cultural deepening and enrichment of society as a whole. The case study presented in this paper is an example of this approach. In addition to the political will to return a historical monument to a small community, the restoration work created a symbiosis between ancient construction techniques and new technologies, giving the building a new life.*

Carrying out structural investigations on various portions of the structure after an in-depth historical study, technicians tried to investigate the story and the mechanical behaviour of materials.

The masonries were reinforced with widespread interventions using the FRCM (Fiber-Reinforced Cementitious Matrix) technique. The monumental complex has numerous buttresses and arches, all reinforced with diffuse and punctual interventions to ensure their consolidation and structural improvement. Floors have been reinforced, and the roof was entirely rebuilt. In addition to the reinforcement goal, these interventions have boosted the box-like behaviour.

"The Santa Maria delle Grazie" monument is also the subject of an experimental monitoring campaign that involves the use of fibre optic sensors integrated within the cement matrix to consolidate the wall faces.

The building presented in this paper represents an enlightened example where technological innovations have made it possible to realise a project path catalysing effectiveness in both architectural and structural terms

KEYWORDS: Masonry restoration, Structural Analysis, Cultural Heritage, Structural Health Monitoring

INTRODUCTION

Europe is rich in monumental buildings that characterise the lives of small, medium and large communities. These elements strongly typify territories they insist on and often represent their symbols. Cultural heritage offers people a link to social values, beliefs, religions and customs, which enables them to identify with other populations of similar backgrounds while gaining a sense of unity and belonging.

A better understanding of previous generations and history that has characterised them up to today allows them to obtain their identity (Rouhi et al. 2022; Guadagnuolo et al. 2020). Their link with the past reflects in their present, leading to the future.

The monumental buildings' value is not only defined by their historical nature. Like a magnifying glass, the studies of such types of structures allow us to scrutinise arts, technologies and construction techniques (Frunzio and Di Gennaro 2018). Recovering historic sites and buildings is an opportunity for communities to strengthen their identity and affirm the link with their historical and cultural roots. Therefore, the renewed functionality of the buildings is not a mere rebirth of ancient remains but an absolute path of knowledge and revitalisation of what has often been lost (Frunzio et al. 2022). Intervening to restore monuments instead of erecting new buildings allows for retracing the history of master artisans and architects of distant epochs. Restoration, therefore, represents a moment of cultural deepening and enrichment of society as a whole (Elliotis 2022; Gunes et al. 2021).

There are many methodologies of approach and intervention for cultural heritage buildings. The case study presented in this article represents a transversal approach between the desire to preserve and revive what was with the creation of something new wholly detached from the original building.

1. THE MONUMENTAL SITE OF SANTA MARIA DELLE GRAZIE

The municipality of Barano d'Ischia is in the southeastern part of the island of Ischia near the city of Naples in the south of Italy. Its territory develops in length, starting from the Maronti beach towards the interior of the island until it reaches the municipality of Ischia with which it borders (Figure 1). From a geomorphological point of view, the city presents many hills with a marked agricultural configuration and numerous quarries. The formation of which is linked to landslides that have occurred over time. The first certain news that we have of the settlement dates back to the Greeks, who built a nymphaeum next to the source of Nitrodi, which they entrusted to the protection of the nymphs and Apollo. The vocation of the municipality is mainly of an agricultural and touristic nature. Most of the territory is cultivated with vines, and wine is among the most marketed products on the whole island, while the thermal springs, together with the beauties of the coast, attract large numbers of tourists. The complex annexed to the former Church of Santa Maria delle Grazie is located on via Duca degli Abruzzi, a panoramic road that leads from the city centre to the mouth of the Arso crater.



Figure 1: Site localization (Source: Authors 2022)

The complex of buildings is a construction whose original intended use was religious—built at the behest of the Baldino family, who lived in the annex behind the church. The Church of S. Maria delle Grazie was founded by Gioacchino Baldino between 1830 and 1835: the official nature of the testamentary deed, in which he claims to have built it "with the sweat of his brow", categorically denies the hypothesis of a dating around the middle of the eighteenth century (1740), supported by Onofrio Buonocore and Filomena Sardella in their texts (Buonocore 1930; Sardella 1985), and which was also supported by traditional knowledge "oral" of the same descendants of the family, Mrs Aniello and Raffaella Baldino. It was probably the direct observation of the decorative parts of the building, attributable to a late Baroque style, that allowed erroneous information to be handed down for so many years.

The Chapel and the Sacristy placed next to it are undoubtedly contemporary; the only elements presumably added later, due to the noticeable formal differences with the rest, are the coffered ceiling placed under the roof slab and the wooden choir loft with the helical access staircase (D'Ascia 1867).

In 1883 the Chapel, like the entire building of which it is part, was damaged by the disastrous earthquake that struck Casamicciola Terme. No restoration work is documented, at least until 1889, moreover: the brothers Vincenzo, Gaspare, and Mattia Baldino, in a letter to the Episcopal Curia of Ischia written in that year, state that they have not yet carried out suitable restoration work because they lacked sufficient funds. However, it is considered probable that a consolidation intervention, albeit minimal, was carried out in the following years, just as it is not possible to attribute to that seismic event the instability that still today interests the artefact. It was certainly open to worship until the first decades of the twentieth century, as the local elders recall, and as can be read from the archival documents, which make the closure of the church coincide with the death of R.do Mattia Baldino, which took place in 1920.

In the first decades of the last century, the transfer of family residence to another municipality on the island, in addition to the continuous hereditary disputes that developed within the family, led to the progressive abandonment of the complex.

The lack of maintenance over the course of several decades is certainly the main cause of the strong deterioration in progress. For example, the fall of roof tiles and purlins and their accumulation on the underlying wooden floor caused them to break through in the long run, which involved the coffered ceiling itself. In 1992 the last heirs, Aniello and Raffaella Baldino, sold the entire complex, including the Chapel, to the Municipality of Barano.

1.1 Initial conditions of the structure

The building is a masonry structure consisting of a ground floor which develops at a positive level of about 70 centimetres with respect to the street level and two other levels below. The structure is made of Arso lava stone, and lime mortar, with some parts arranged in regular blocks and others chaotically. The horizontals were made up of stone barrels, cross vaults, and wooden floors.

The state of the structure was very poor, and the whole complex was almost completely obstructed by weeds, which had grown freely over the years of neglect (Figure 2). It was clearly and evidently affected by widespread instability and collapses that did not allow entry for a complete and exhaustive analysis of the actual general conditions in the first stage of the study.



Figure 2: State of the structure before restoration (Source: Authors 2020)

Following the cleaning and safety measures, it was possible to enter all the rooms carrying out all the investigations, analyses, surveys and tests to complete the knowledge path. Both structures, masonry and vaults and elements such as mortar and the remains of original paints are investigated too.

The ground floor, occupied by the church with a rectangular apse called body A, is entirely devoid of a roof affected by a generalised collapse or completed forcibly in the safety phase. The wall structures are intact and protected by a finishing layer fresco painted plaster and enriched with various mouldings. The church's facade is almost entirely devoid of the plaster finish layer, and the entrance door initially walled up was opened with the loss of the portal, already seriously damaged by time.

Behind the church, in the block called B, there were residential areas of which today, almost exclusively the perimeter walls remain, having collapsed or demolished for safety purposes. They are exposed to atmospheric agents and affected by widespread collapses and a deep and generalised crack pattern. The first basement floor is located about three meters below road level. The side bordering the road is blind, while the other three sides open freely onto the surrounding landscape. There were mainly service areas on this floor, such as rooms, vats for vinification, kitchens and washrooms. The east and south sides were open onto panoramic balconies and loggias, which are partly collapsing. Vaults, as in the case of body B, are completely collapsed. Masonries are also affected by severe cracking phenomena, in some cases linked to the movements triggered by the collapse of the vaults, which have caused the floor's loss of cohesion and rigidity, effectively disconnecting the masonry connected to them. In the portions of plaster still intact, some traces of stucco decoration remain, but most of them are detached or affected by the attack of mould and weeds. The flatbreads on the internal and external openings are made of wood and report severe damage and sagging.

The second floor below the street, located at an altitude of about 6.50 meters lower than the street level, houses five adjoining cellar rooms, open only on the east side. The first two rooms are completely uncovered and open to the sky. The last three rooms, to the north, retain the roof vaults and the wall structures without a structural crack pattern, however seriously damaged by water infiltration and by the action of the vegetation that has developed there. Facing this last level, there is a large garden.

2. PROJECT PHILOSOPHY

The restoration project follows a route made of conservative strategies combined with breaking choices. While acting with respect to the original shapes and material for the church, arches, vaults and roof, a critical reconstruction will concern the parts that collapsed or are in an advanced state of decay parts . In these portions of the building, the residual original traces do not allow for a faithful reconstruction, therefore. The synergistic work put in place has led to choices that are both respectful of the static and architectural and historical needs and of the present materials, giving life to a new tailor-made project for the monument (Mancini 2021) (Figure 3).



Figure 3: Project rendering (Source: Mancini 2021)

The renovated architectural organism, not emptied of its primitive character, will be used for accommodation and cultural activities. Therefore, a complete redefinition of both horizontal and vertical internal spaces was carried out to allow better usability of the environments and better accessibility of all the areas covered by the intervention. To this end, multipurpose rooms have been provided for cultural, congress, educational and exhibition activities, as well as a series of meeting spaces such as bars and restaurants. The design choices are also dictated by the need to make the architectural complex compatible with the new intended use and compliant with Italian technical regulations regarding accessibility, safety and fire prevention. The plant and functional adaptation will also be carried out concerning the intended use.

In general, the built heritage, due to the values it represents and the role it plays in the life of the communities, can be considered a common asset whose use can represent a reason for union and socio-cultural identity. The built cultural heritage constitutes a fundamental resource for territorial systems and local communities to preserve their evolutionary possibilities and for development purposes. From this point of view, safeguarding cultural resources, such as the monument analysed in this work, must translate into the search for a balance between conservative and transformative demands. The aim is, therefore, to preserve the building and, at the same time, satisfy the functional needs. In this process, the heritage's ability to evolve takes on the character of an added value since it allows the full potential of the existing to be exploited through contemporary and relevant forms of use for the population.

3. TECHNICAL SOLUTIONS FOR THE RESTORATION

The restoration strategies aim to reconfigure the building respecting its original shapes apart from the reconstruction of the collapsed and huge deteriorated portions, which will be reconstituted differently. Space has been given to reversible interventions regarding the monumental asset where possible. Furthermore, the structural aspects are aimed at not substantially modifying the static structure of the building, avoiding the onset of stress states significantly different from those to which the structural system is "accustomed".

The structural consolidation intervention was tackled to improve both the static and seismic capacity of the building. It is, therefore, possible to identify two levels of intervention, the first aimed at building on a global scale and the second at the mechanisms of local influence.

The first level involved a widespread consolidation of the masonry in terms of increasing in-plane and out-of-plane strength by plating with the FRCM technique performed with basalt meshes and inorganic matrix. The box-like behaviour has been improved by connecting masonry hammers and angles and inserting cross-link chains.

To preserve the memory of the original collapsed roof, the new structure retraces the ancient one by using the same timber essence and static scheme. This choice allows the structure to keep a similar load distribution (Frunzio and Di Gennaro 2018). That could have happened for different positioning of trusses or considering static schemes not adherent to the original ones. A steel housing cap for the truss heads and plates for installing transverse steel chains is arranged. Thanks to this system of chains, the reduction of the thrusts of the truss and the seismic improvement of the entire structure will be guaranteed at the same time since the box-like behaviour of the masonry is favoured. The key-plate of the chains will be incorporated undercut, thus resulting in utterly invisible from the outside. The insertion of head braces in the initial and final spans also conveys the improvement of the seismic behaviour of the roof.

The execution of timber roof rebuilding has generated quite a few problems due to the need to mobilise significant elements with trucks of considerable size compared to the small streets of the village of Barano. The wooden components were factory pre-assembled and positioned at the work site with skill thanks to the high competence of the workers of the company carrying out the work (Figure 4).

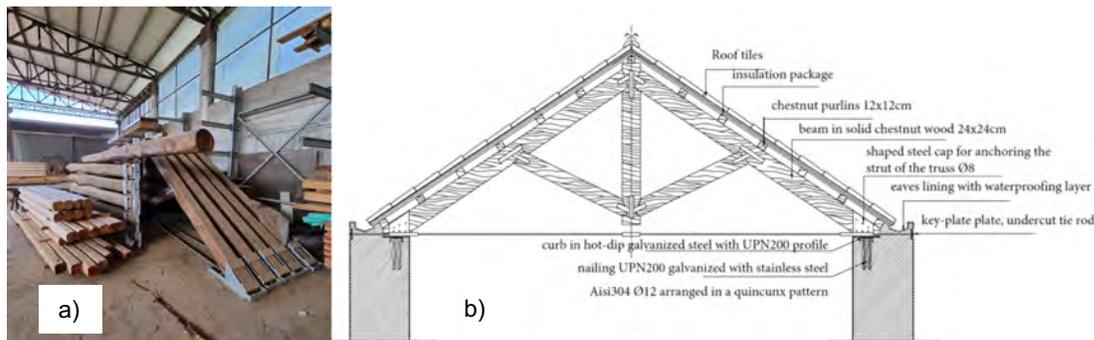


Figure 4: Timber trusses. a) Factory storage b) cross-section picture (Source: Authors 2022)

The "umbrella-knot", situated on the roof in correspondence with the passage between the apse and central nave, represents a little prodigy of the workers and is constituted by seven beams in one point converging. The figure below shows the rebuilt roof (Figure 5).

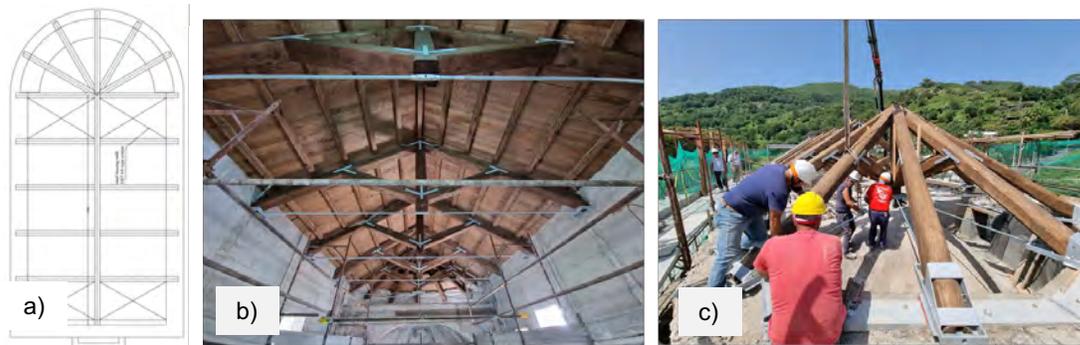


Figure 5: Timber roof structure. a) Roof scheme b) Central nave rood c) "umbrella-knot" (Source: Authors 2022)

As explained before, the building presents vaults and a plane floor. While the first ones showed a good state of conservation, the second ones mostly collapsed.

Stripes of PBO (Polybenzoxazole) fibre in an inorganic matrix realise the intrados strengthening of arches and vaults. Such intervention ensures protection for the opening of injuries and plastic hinges.

The original collapsed timber floors have been rebuilt with new floors with steel beams and a thin slab with a corrugated sheet and reinforced concrete. This choice is mainly due to the need for a structure with high load-bearing performance with an unload-bearing system of discrete type or a system where the load transfer to the masonry happens with punctual (discrete) elements such as a beam. That avoids an excess of stiffening of the floor and consequently increased bending actions on masonry walls.

The rebuilding of flatbeds requested particular attention. In the original configuration, they were simple timber solid plates of chestnut able to unload upper loads to the masonry silelights. To preserve the aesthetical aspects of doorways, ensuring better structural behaviour, an architrave with double steel beams inserted in the masonry with solid chestnut timber boards below has been realised (Figure 6). The right transfer between architrave and masonry is guaranteed by bearing in solid bricks.

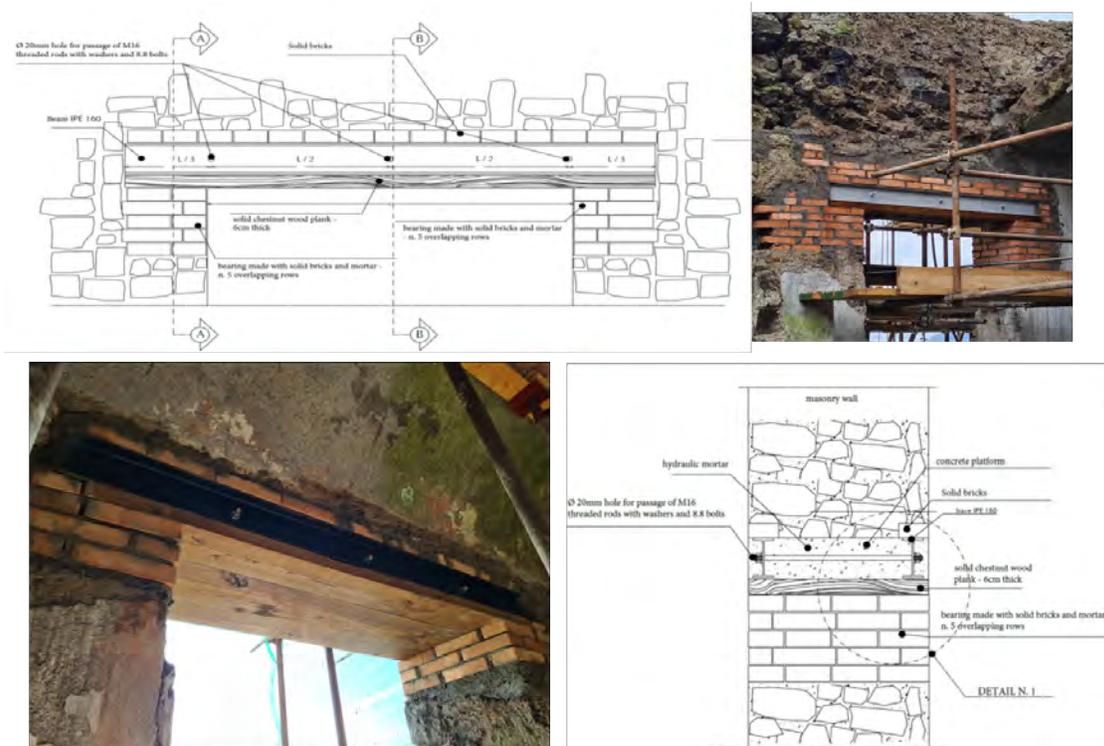


Figure 6: Rebuilt architrave (Source: Mancini 2021, Authors 2022)

The deep ageing state and the collapse of some parts of the original building determined the presence of unstable elements and portions of masonry for which unique solutions have been adopted.

In general, works that involve ancient structure requests an artisanal approach where solutions sometimes have to be found on-site rather than in the conventional workplaces of architects and engineers. That is because cultural heritage often regards buildings with features unknown in advance that trivially don't have right angles and vertical or straight surfaces.... The intervention reported below is an example of this approach born from the in-depth observation on site of the problem encountered in a masonry part at risk of collapse and for whose conservation an ad hoc solution was studied.

The intervention in detail referred to a temporary consolidation with steel beam and PBO strips in a cementitious matrix to avoid collapse preserving the masonry until the stabilising elements such as transverse walls and floors had been built (Figure 7) (Babaeidarabad et al. 2014).



Figure 7: Securing unstable Eastern masonry edge (Source: Authors 2022)

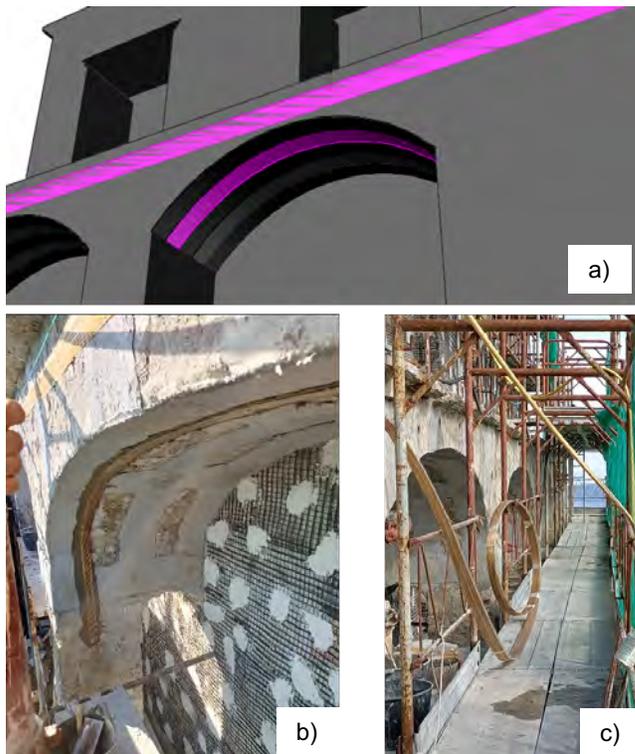


Figure 8: NSHT transducer a) intrados of arch installation b) façade installation (Source: Authors 2022)

Thanks to the synergy between the executing company, the Department of Engineering and the Department of Architectural and Industrial Design of the University of Campania Luigi Vanvitelli, the building site hosts an

experimental campaign related to a distributed optical fibre sensor for Structural Health Monitoring (R. Zona et al. 2022).

The patented transducer NSHT (Olivares et al. 2020), which core is an optical sensor based on the scattering of Brillouin phenomena (Minutolo et al. 2020; Di Gennaro et al. 2022; Renato Zona et al. 2020), has been installed on the arcade of the Southwest front of the building to monitoring any movements due to the single instrumented arch or else of the entire arcade.

The realisation of the prototype of NSTH is the first for structural use and involves the PBO fibre to ensure the compatibility of the modulus of elasticity between the transducer and masonry. Installation is shown in the following picture (Figure 8).

To date, a couple of measures have been performed, and no significant strain varying has been detected compared to zero detection. It is expected to complete the load test on the single instrumented arch to trial the transducer's functioning more specifically. The test will also investigate the strain distribution between the loaded instrumented arch and adjacent ones.

CONCLUSION

In this paper, the case study of the restoration of Santa Maria delle Grazie is presented. The building is an enlightened example of restoration work where technological innovations have made it possible to realise a project path catalysing effectiveness in both architectural and structural terms. The work aims to narrate a story in a way that transcends the mere architectural and technological aspects. That is because, working on cultural heritage, every element must merge with the other, sometimes passing through the human heritage that resides in the knowledge of handed-down techniques. Today restoration works are still ongoing, and the community of Barano is waiting to reappropriate this building intended to host multipurpose spaces for cultural, congress, educational, exhibitions and a series of meeting spaces such as bars and restaurants.

The technical solutions presented are the fruit of the combined experience of the designer, the executing company and the municipal administration, which have also allowed the implementation of an experimental campaign to test an innovative technique for Structural Health monitoring involving an optical fibre sensor.

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Avoiding the Imperialist Agenda when Designing for the Developing World

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ABSTRACT: *Overly technical modes of sustainable development can reinforce power dynamics implicit in imperialism. In response, this research explores a low-tech, accessible approach to sustainable innovation in developing regions, working at the material scale, so that local can control their own spatial and aesthetic autonomy. This paper will share the results from a review of public health, building science, and architectural literature exploring the role that unintentionally imperialist pedagogies play as tools for western exploitation in developing regions. Building off of this evidence base, this paper will close with examples of anti-imperialist workflows in architectural education, exploring the synergies between public health, material science, and design. These student-led innovations suggest opportunities for developing novel partnerships that integrate topics that tend to be studied separately and leverage the imperative to respond to the health effects of climate change with methods that advance human health and equity concurrently.*

KEYWORDS: Pedagogy, sustainability, anti-imperialism, developing countries, rural Africa.

INTRODUCTION

The effects of a rapidly changing climate are disproportionately impacting regions based on both climate and economic status. Studies indicate that climate change impacts will dramatically increase vulnerabilities in rural communities where those living off the land are at increasing risk from extreme weather events such as heat waves, famine and drought. In fact, it is expected that a 2°C-temperature rise would reduce world GDP by 1% globally (Stern 2007), but would cause a disproportionate 4-5% decrease in developing countries (Bierbaum and Zoellick 2009). According to the United Nations, the most significant population growth is expected to occur in tropical regions of Asia and Africa (Hoekstra and Molnar 2010), which have historically lagged in wealth and resources (Sachs 2001). Compounding the issue, more than 80% of the world is at risk from at least one mosquito-borne disease, and malaria is a leading cause of death in the developing world (WHO). However, most research in this field addresses this public health crisis in the form of pesticides, chemical interventions and genetically modified mosquitos with little consideration for the role of the built environment, particularly in limited resource settings. While this phenomenon presents a unique opportunity for the overlap between architecture and public health, this paper explores a pedagogical approach to housing, health, and environmental design in rural Africa while trying to avoid an imperialist agenda.

1. BACKGROUND

Development is a crucial facet of a region's economic, social, and political growth, but most importantly for individual human growth. According to United Nations Development Program's (UNDP) annual Human Development Report (HDR), human development is defined as, "expansion of people's freedoms to live long, healthy and creative lives; to advance other goals they have reason to value; and to engage actively in shaping development equitably and sustainably on a shared planet" (United Nations 2022). Implicit in this definition is the capacity to make personal democratic choices. However, development of certain regions often involves substantial support from industrialized, wealthy countries. Despite best intentions, this support can operate as a means of political, social, cultural, economic, and educational influence (Browne 2006; Xue et al. 2019). Though this aid can be benign, there is often a hidden agenda rooted in imperialism that creates trust issues and inhibits developmental autonomy in a region.

In order to reduce opposition from local people and foster development it is important to inculcate public engagement (Devine-Wright 2011). Conflicts and opposition can arise from feelings of powerlessness and lack of transparency on the decision-making process (Sturzaker and Verdini 2017). For this reason, public engagement becomes crucial to gain trust for smoother execution of development projects.

The local communities thus fear these encroaching forces that try to colonize the world under the name of "development". In the post colonialist world, with globalization, developing countries like China and India have been faced with internationalization (Chang 2010). Urbanization in India, for example, is heavily influenced by modern ideologies due to influence from the Western architects. The architecture is more global than local

and the developing countries like India struggle to keep up with the rapid pace of globalization. While this phenomenon is often most evident at the large scale of urban development, it is also a condition that we must be acutely aware of as we design from outside, from a position of privilege and power.

1.1 Technology & Imperialism

The technology-centric approach to urban development as the dominant model of innovation in industrialized countries has led to expansive ecological degradation and exclusion from sustainable technologies in low-resource settings. At an international economic policy meeting in 1995, Thabo Mbeki, the vice president of South Africa, told world leaders that the majority of the world's population had yet to make their first telephone call (Braa 1996), despite its invention over 100 years prior. Meanwhile, millions of Americans already had personal computers in their homes. With such a significant gap between first and third-world countries, developers often expect local communities to appreciate high-tech solutions. However, as buildings become more technologically complex, users must rely on professionals with specialized knowledge to design, manufacture and manage these increasingly complex environments. Instead, simple, accessible strategies should take the place of overly sophisticated and mechanically-driven designs to make high performance building design accessible to those with the greatest need.

Though there is an increasing emphasis on user-centered design methodologies in practice, this approach is often top-down, meaning that the process is driven by 'experts' and end-users have little opportunity for involvement in the innovation process. However, a truly bottom-up approach would recognize different forms of knowledge to democratize the innovation process, allowing end users to also become innovators. The maker movement, for example, has been cited as 'the new Industrial Revolution' (Anderson 2012) for its ability to foster bottom-up design to productively disrupt mainstream innovation systems dominated by disciplinary experts and open the door to a new era of participatory design and sustainable consumption (Davies 2003). What is needed is not high-tech, but "appropriate" technology that merges traditional knowledge with advanced technologies that can be controlled and maintained by the local communities (Murphy et al. 2009). It is clear that high-tech modes of sustainable development reinforce the power dynamics implicit in imperialism. In response, this research explores a low-tech, accessible approach to sustainable innovation in developing regions, working at the material scale so that local residents can have control their spatial and aesthetic autonomy.

1.2 Architectural Education

Within early level architectural design education, work flows are tending toward digital means (Özkar 2007) and media-driven, production-based representation (Canizaro 2012) as well as emphasis on technological competence (Cheung 2012). However, this global trend in education appears to neglect the transfer of experiential knowledge and indigenous practices that seek to address similar issues in an analog way. Instead, institutional models are becoming more like mature enterprises in the business world where capital and influence are dominating the primary idea of literacy and growth (Christensen and Eyring 2011). Globally, higher education often reflects a shift from public good to private profit. On one hand, it promotes information globalization and education equity while on other hand it may be discerned as an instrument that perpetuates colonization related to profit generation, reliance on market transactions, and power related to discourse (Reyes and Segal 2019).

Decolonizing education is not just about supporting indigenous people and decolonizing aboriginal education, it is about changing the whole education system to make it more accepting to worldviews and nourishing the common agenda of learning. It is about rethinking the curriculum, rejecting Western pedagogy as normative, and adopting new ways of knowledge production, transfer and intake. Changing direction is required for achieving these larger goals. Student led initiatives and academic involvement in research need to be promoted to achieve educational development. Internationalization and colonization have had tremendous impacts on regional educational systems as well. Countries often tend to analyze their own education systems and draw flaws and deficits in them. What decides that, is the spirit behind exercising the change. To imitate western countries and their high-tech systems, developing countries often neglect the merits of their own resources and indigenous practices. Colonization by western education pedagogies can be further demonstrated by the following cases:

The case of Africa: "Africanisation" is a process that called for including African perspectives into the post colonized African world that was influenced by European colonization (Makgoba 1997).

The case of Hong Kong: Higher Education Policies in Hong Kong have been influenced by market ideologies and three major sections of education: teaching research and management have been influenced by the global wave of "corporate managerialism" (Mok and Lee 2000).

The case of Korea: The civil exam system that was existing in pre-colonial Korea was reformed after being colonized by Japan in 1910 and focus shifted to expanding the use of Japanese language in schools (Hong and Paik 2018).

The case of Canada: The impacts of colonization of educational institutions in Canada can be seen in residential schooling. The current Canadian education system favors ethnocentric ideologies and Eurocentric frameworks that marginalizes indigenous Canadian people (Semple 2020).

The case of India and Nigeria: In early 1900 school children in India and Nigeria were reading English literature as a result of British colonial rule (Elder 1971).

Architectural education has also been a subject to colonialism. The architectural pedagogical approaches are the ones that have a direct impact on the students and the architectural values that they adopt. In Africa students were treated as 'blank slates' that were subjected to approaches from European or North America, disregarding their previous individual life experiences (Olweny 2020). In Northern Canada colonization in architecture education is evident by the Euro-Western practices adopted over indigenous human centric approaches (Semple 2020). While these may seem like obvious examples, the notion of imperialism permeates many aspects of the education experience.

Architecture is a distinct, creative field that overlaps with various other disciplines like art, science, dance, etc. The pedagogical approaches must therefore focus on balancing student design and socio-behavioral aspects. In other words, the curriculum should be structured to make the students better designers as well as better global citizens. The curriculum of architectural education needs an overall reformation which rejects the colonial adulterated practices that are not applicable in that given regional setting and promotes indigenous methods that serve the environment and culture of that region. Architectural education must be cross disciplinary in order for the students to have a holistic knowledge of the human aspects of architecture and not just the technical realities of construction. There is a lot to learn beyond the four walls of the classrooms, may it be architecture or any other discipline. This paper will address the way that the use of design thinking in material science can be used as a tool to support developing communities while avoiding the imperialist pedagogies.

2. METHODS

This next section will describe a graduate level topical (elective) design studio offered by the University of North Carolina at Charlotte School of Architecture in the Fall of 2021.

2.1 Protective Atmospheres

Indoor air can build up high levels of moisture, disease, odor, gases, dust and other respiratory contaminants which can more easily dissipate in fully-outdoor conditions. Though contaminants can be mitigated by advanced mechanical systems, this is typically supported by the consumption of fossil-fuels to provide an air quality that is still inferior to outdoor air. Though a building with 'breathable' qualities may alleviate some of the respiratory concerns and reduce energy consumption, it is no silver bullet. In fact, breathable buildings present their own set of issues, particularly in tropical regions with a high prevalence of vector-borne diseases. This research studio addressed the tremendous need for low-cost, accessible domiciles that are culturally responsive, thermally comfortable and exhibit a high level of functionality from the standpoint of respiratory and vector-borne disease prevention.

Recent efforts to make a house more "protective" from vector-borne diseases often lead to dwellings that have reduced air transmission and provide substandard air quality and interior comfort. In response, this course linked human comfort and mosquito protection as part of a singular design proposition, dispelling the notion that protective, low-energy and comfortable buildings must be sealed, airtight enclosures that isolate the occupant from the outdoors and much of the social life of the community that occurs there.

Because the project site was located in rural Tanzania, a region that not a single student in the class had been to, we had to be particularly cautious of an imperialist approach to design. Additionally, residents are often skeptical of substantial interventions to their built environment, particularly those that affect their housing. Despite best intentions, outside developers often rely on the regional aesthetic, while overtly vernacular styles may reinstate stigmas of poverty in communities that seek modern buildings. In preliminary research, we found that Tanzanian residents would prefer to live in modern brick houses (that may take many years to build), rather than 'cheap' but fully protected wooden homes. While this project actively pursued solutions to address human health, energy consumption and constructability, we were also sensitive to the needs of the community. In response, this project built on the notion of public interest design and the role of community members as

local experts and critical decision makers, demanding a strong service component to be addressed through multidisciplinary collaboration and shareholder involvement.

2.2 The Humble Brick

Though many modern buildings can be high-tech and mechanically complex, rural communities often have limited resources for building materials. The brick is the most used building material in the world – in fact, one third of the world’s population lives in buildings which are totally or partially made from earth (Barnaure et al. 2021). In addition to its low cost and accessibility, earthen construction has significant performative qualities, including thermal, fire and insect resistance, durability and low maintenance as well as its ability for reuse and recycling. By studying the material aspects in tandem with the synergistic relationships of heat, energy, emissions, water, information and resources that make up a city’s public services, this humble building material has the potential to become a greater part of the urban resiliency strategy, while also limiting biases toward from Western influence. Architecture students designed innovative ways to reconceive modular materials that challenge existing norms of construction, thermal comfort and vector control.

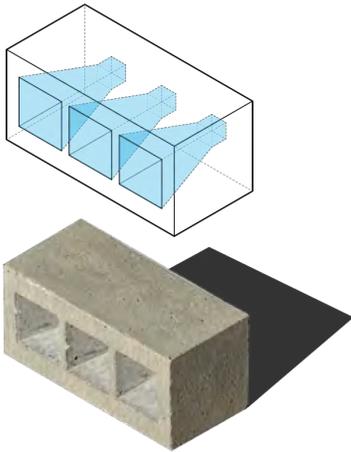


Figure 1: 'Venturi Block' by Nathan Smith, 2021.



Figure 2: (left) 'Porotherm Block' by Vamsi Kamatham, 2021 (right) 'Water Collecting' by Sarika Merchant, 2021

Shown in Figure 1, Nathan Smith developed the 'Venturi Block', which used the principles of the venturi effect to create a cooling effect while also increasing airflow to a level that is difficult for mosquitos to fly. Shown in Figure 2, Vamsi Kamatham and Sarika Merchant designed blocks with vertical cavities to move air and water respectively. The students were encouraged to work in concrete and at full scale to replicate real-world conditions. Using the principles learned at the material scale (the block), combined with the site research from the beginning of the semester, students developed strategies for protective housing in rural Tanzania using the parti diagram from their blocks to translate the design principles from the material scale to the scale of the domicile, community or infrastructure. Students considered their modules as a 'system', which was prepared for a common purpose and described a set of rules and organizational strategies. Students continued exploring the material, constructability, and thermal performance qualities of the blocks / modular units at the domestic scale. Students also explored (in detail) how the building came together as well as how it behaves to keep occupants thermally comfortable and protected from mosquitoes. However, students were never asked to lay out particular spaces beyond the major functions of cooking and sleeping to avoid Western bias. Instead, students were most concerned with the constructability and tectonic innovations inspired by their block strategy. Students were asked to establish a clear direction for the kind of protective atmospheres that addressed critical principles of thermal comfort, protection from mosquitoes and resilience in a changing climate. This, of course, is difficult to capture in measured drawings. Therefore, other forms of visualization were needed in order to convey their approach to place-making, in articulating an authentic sense of place, and in providing the residents of Ifakara (or other rural Tanzanian communities) with a sense of refuge. Prototypical designs addressed several needs, including the ability to:

1. protect from mosquitos and other public health risks;
2. provide thermally comfortable environments without access to energy;
3. leverage existing skills while adding innovative methods and techniques;
4. increase resilience to economic and ecological challenges.

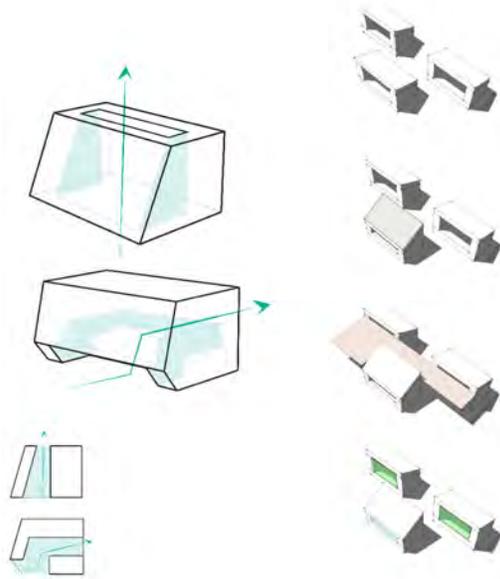


Figure 3: Schematic diagrams by Vamsi Kamatham, 2021



Figure 4: Interior (top) and exterior (bottom) renderings by Vamsi Kamatham, 2021

According to graduate student Vamsi Krishna Kamatham, whose project is shown in Figures 3 and 4, the term 'porotherm' was used to describe its porosity and desired thermal characteristics. The primary objective was to provide air movement through the brick system, while also achieving a certain level of privacy so that it can be used as external wall system. The main idea is to accommodate the all three key features: to promote air circulation through the brick, to protect the wall system from sun (i.e., minimizing solar heat transfer through conduction, convection, and radiation), and thirdly to accommodate a certain level of privacy (i.e., privacy protected jali screen). The angular face is used to protect the brick from climatic and privacy point of views. A recess is provided underneath to let the brick breathe and have a continuous flow of air, so that thermal comfort is achieved. In scaling the ideas of the module to the full house design, Kamatham utilized three primary keywords: collecting, connecting, and regulating. Similarly, the house layout was composed of three individual units with the concept of incremental development. The form of the individual units was inspired from actual brick geometry and properties. The individual units were arranged in a way to take the advantage of prevailing wind. The middle unit (gathering space) is emphasized, so that the maximum wind movement is created by framing the wind with the help of other two units. The corridor space acts as connector, which binds all three units together and the middle block further opens to the corridor space by creating a transition zone, which is peri-domestic in nature.



Figure 5: Exterior Rendering by Matt Panko, 2021



Figure 6: Interior Rendering by Matt Panko, 2021

Similar to Smith's 'Venturi Block' shown above, graduate student Matt Panko worked under the assumption that mosquitos have difficulty flying at increased levels of air speed, shown in Figures 5 and 6 above. However, Panko didn't actually utilize a novel block design, instead manipulating the stack pattern to increase air flow from cross ventilation but maintaining the structural integrity of the masonry wall. His project served to improve thermal comfort and reduce mosquito intrusion by increasing air flow. The central living air is more open, with a solar-powered ceiling fan, and the perimeter sleeping rooms are more enclosed and protective from mosquitoes which are more likely to bite at night.

CONCLUSION

While focused on one country terribly afflicted by mosquito-borne disease, the intention was that strategies embedded in the initial and subsequent prototype designs would be translatable to other communities in developing, tropical climates. Through interdisciplinary research, design and fabrication processes, students explored ecological, cultural, and thermodynamic issues that frame modern housing typologies in rural Tanzania. Particular emphasis was paid to sophisticated and thoughtful applications of conventional construction techniques and affordable, low-tech building materials as opposed to building layout, which would be overly subject to Western influence. By working at the material scale (the block), we believe that this approach is a way to serve those most in need without inflicting one's own views and reinstating an imperialist agenda.

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Performative Periodic Tessellations: A Study of Parametric, Light-Responsive Façade Systems in the Museum Setting

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ABSTRACT: This paper reports on the design and development of responsive façade systems as exemplar case studies for museum applications. Real-time visual outputs generated by physical models and computational simulation engines inform the design and analysis of performative periodic tessellations (PPT) leading to enhanced building–environment interactions. In this paper, different skin tessellation approaches are investigated to regulate solar gain, improve visual experience, and optimize view within the context of museums which can also be applied to other settings. Systematic generation and simulation of responsive façade systems are developed along with a parametric analysis of various tessellation techniques. The final results demonstrate a comparative study between two design iterations through a mixed methodology using physical and digital models where both qualitative and quantitative approaches inform the design, selection, and optimization of shading devices.

KEYWORDS: Parametric, Tessellation, Computational Design, Façade, Museum

1. INTRODUCTION

Museum architecture has always been a significant source of attention aiming at improving museums' public role, educational impacts, and their interaction with the urban context. The controlled use of daylight in museums, along with its therapeutic and energy-saving qualities, can enhance the user experience and foster the link between the outdoor environment and the artwork and its surrounding atmosphere (Hudson 2008 and Soleimani 2013). Furthermore, the experience of an artwork is inseparable from the spatial dimension of the museum setting. In particular, the design of daylight openings in the museum is an integral part of the museum experience. As Louis Kahn noted, "no space is really an architectural space unless it has natural light" (Loud 1989). Nonetheless, allowing daylight in museums has always been a challenge for architects since excessive natural light can damage the artworks and cause a visual disturbance in museums. However, by regulating and filtering natural light in museums, the viewing of artworks and the museum experience of visitors can be enhanced significantly.

1.1 Background

The concept of 'light informing museum spaces' has been well-explored in different architects' work overtime. For one, Renzo Piano has his way of designing art spaces with light. "Every time you take a new job, the one thing that's constant is the magic of light," Piano says. "But everything else is different—the direction of the sun, the energy consumed, the people you are working with" (Keegan 2008). In general, there are two main approaches to enlighten museum spaces and the artwork inside: a poetic approach that uses diffused daylight to paint the space and artwork, and an artificial approach that uses electric lighting to create a high contrast between the artwork and its immediate surrounding. Renzo Piano's museums in Atlanta, Dallas, New York, Los Angeles, and Chicago built upon the first approach using diffused natural light to fill the space. For example, the High Museum's roof in Atlanta is composed of 1,000 egg-crate-like skylights resembling a field of sunflowers where the flowers gain light from the north in contrary to a real sunflower, which looks for light from the south (Fig. 1).

In another example, the Broad Museum in Los Angeles was designed by Diller Scofidio + Renfro in a way to minimize the use of electric lighting during the year (Heyler 2015). The building benefits from a parametric 'veil' as a light filtration device allowing diffused natural light into the galleries in a controlled manner (Fig. 2).



Figure 1: The High Museum of Art Expansion, Atlanta, Architect: Renzo Piano.¹

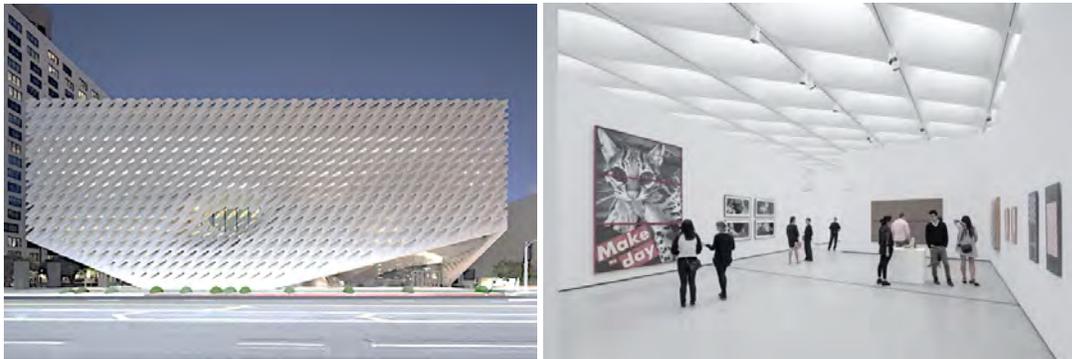


Figure 2: The Broad Museum, Los Angeles, Architects: Diller Scofidio + Renfro.²

1.2 Tessellations

One of the efficient strategies recently being used to enhance the daylight experience in museums is through the use of tessellation techniques. Tessellations are generated by several polygons stacked together to infinitely fill a surface area while leaving no gaps in-between the shapes (Pearce 1990). In general, tessellation techniques can be put into two main categories including periodic and quasi-periodic tessellations. Periodic tessellations are comprised of a “repeating unit” and a “repetitive structure.” Figure 3 illustrates different shapes of repeating units depending on the net type of the repetitive structure e.g., parallelogram, rectangle, square, and hexagonal (Abas and Salman 1994). Quasi-periodic tessellations, on the other hand, are comprised of a limited number of shapes that stack together to fill the surface area in a non-periodic way. This paper focuses on periodic tessellations informed by parametric, solar analyses. The proposed PPTs are tested based on the level of responsiveness to daylight variations and the level of exposure to sunlight in the museum setting (Pottmann et al. 2007 and Woodbury 2010).

1.3 Research Question

Building upon the concept of daylight integration in the museum setting, we argue that museums can further benefit from introducing parametric logics in the design of their building envelopes. Through design-based explorations, this paper investigates the application of two PPTs' various configurations in the museum setting while answering the question of “How can Performative Periodic Tessellations (PPT) enhance the museum experience through the use of diffused daylight in a controlled way?”

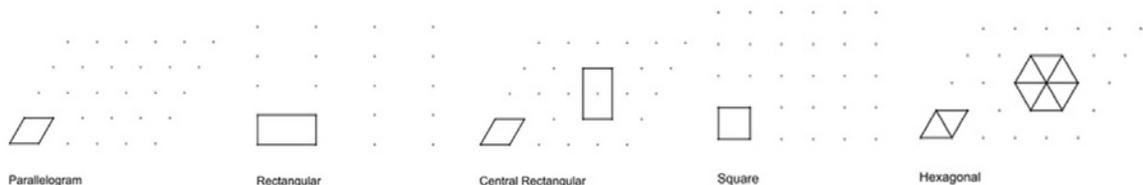


Figure 3: Five Net Types. Source: (Authors 2022)

1.4 Research Methodology

The research utilizes a sequential mixed-method approach to first develop performative periodic tessellations, and then conduct analysis to assess the performance of the proposed tessellations.

In the first phase of this research, various configurations of the two PPTs were designed and developed through extensive mathematical and geometric explorations. The parallelogram net type inspired both tessellation processes (Soleimani 2019).

In phase two, a mixed methodology guided the analysis and assessment of the two PPTs' configurations in the museum setting. First, we studied how a repetitive integration of various configurations of each PPT may regulate solar gain and museum experience. This part was conducted through digital modeling techniques and computational simulation—the assessment involved rating of various parameters through a Likert scale (Table 1 & 2). Afterward, we studied how a parametric logic—through curve attractors—can parametrically inform the design of one PPT including various configurations of each module in one design. This part was assessed through the making of physical models to further understand how a parametric logic can regulate shadow patterns and solar gain inside the museum setting.

2 DESIGN PROCESS

This section discusses the design process of two types of performative periodic tessellations: the diamond- and conifer-shaped iterations.

2.1 Performative Periotic Tessellation #1

An extended diamond-shaped module was designed to offer multiple configurations for different orientations; the embedded flaps within the module allow for more control over the amount of solar gain/exposure as desired inside the building. Figure 4 shows the tessellation process of PPT #1 as well as various configurations of the façade system in response to sunlight.

Since the proposed façade is facing the south, the horizontal configuration was selected over the vertical module. The geometric development and the analytical evaluation of the façade system suggest a sophisticated set of performance-driven skin configurations as a result of a computational dialogue between parametric modeling and daylight optimization. Based on the radiation maps, generated by Rhino's DIVA in Grasshopper (Fig. 4: TOP-RIGHT), four configurations were generated to allow various amounts of natural light inside the building (Fig. 4: BOTTOM-RIGHT). Configuration #1, with fully closed flaps, allows for no light to travel through the surface; Configuration #2 uses flaps at a 30-degree angle with minimal light transmission; Configuration #3 uses 60-degree flaps to allow moderate light transmission; and Configuration #4, with fully open flaps, allows for maximum solar gain. These four configurations can be further optimized by defining a parametric logic such as lines or points attractors in response to the radiation maps (Fig. 4: MIDDLE-RIGHT).

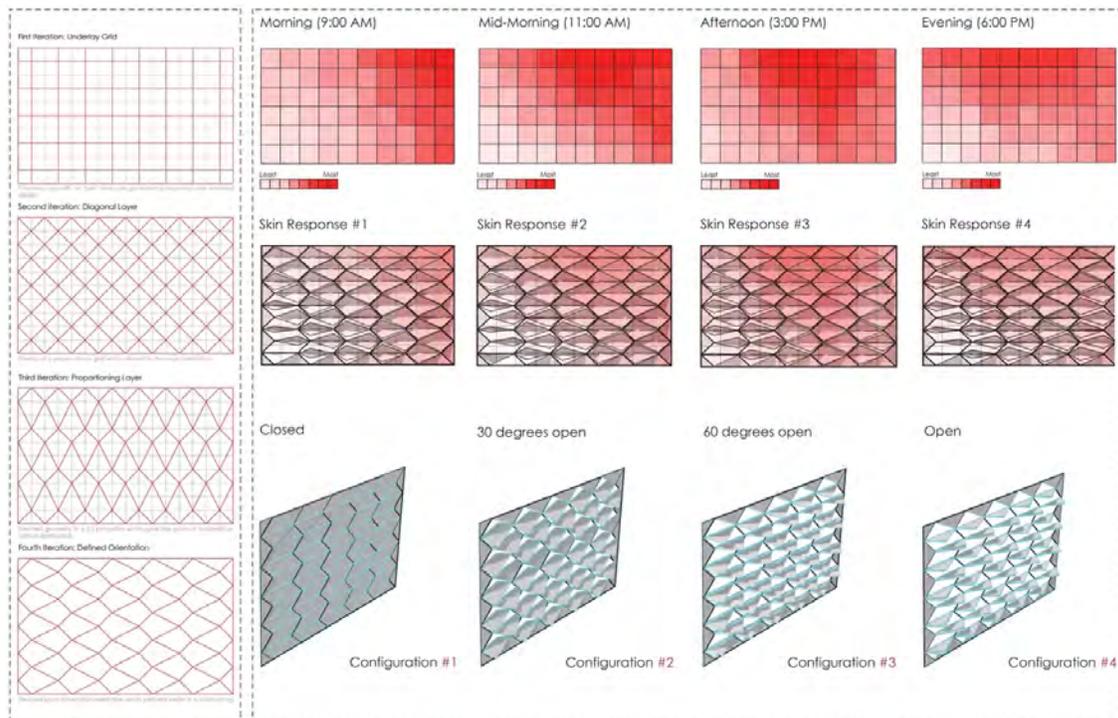


Figure 4: Tessellation process of PPT #1 (LEFT) and different configurations of PPT #1 in response to sunlight variations (RIGHT). Source: (Authors 2022)

2.2 Performative Periotic Tessellation #2

PPT #2 was inspired by the conifer cone shape. A square module was designed with two flaps, which resemble cone scales. The flaps offer various configurations for different orientations. Figure 5 shows four different configurations of the module as well as the tessellation patterns ranging from a fully closed to an open iteration.

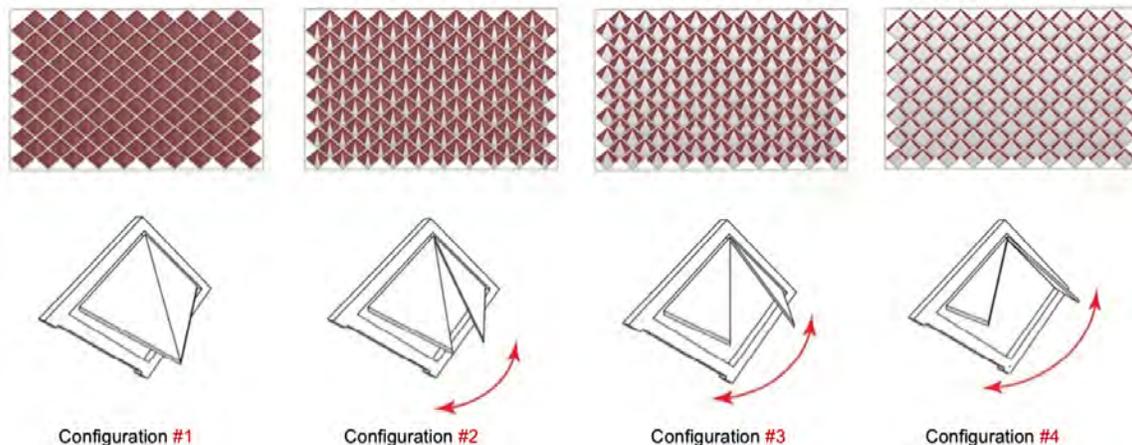


Figure 5: Different configurations of PPT #2 in response to sunlight variations. Source: (Authors 2022)

3 PPT ASSESSMENT

The proposed analytical approach can be applied to the design and assessment of various tessellations in order to measure different PPTs' performance levels qualitatively and quantitatively.

3.1 Qualitative Approach

Each PPT's configuration was evaluated based on Liljefors' "seven visual and perceptual factors" (Liljefors 2005) employing a five-point Likert scale for a qualitative assessment of the following factors (Iordanidou 2017) in a 25'wx10'dx15'h darkroom utilized with a south-oriented PPT at a time. The authors were the primary participants to study each iteration based on Liljefors' factors.

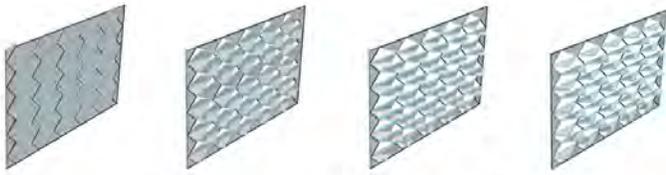
- Light Level: the level of brightness in the room
- Light Distribution: the level of light uniformity throughout the space
- Glare: the level of glare if it occurs inside the room
- Shadows: the level of disturbance if shadows appear inside the room
- Reflections: the level of disturbance if reflections occur inside the room
- Transparency: the amount of transparency connecting inside to outside
- Exterior View: the existence of outdoor view

Additionally, the qualitative approach benefited from the making of both physical and digital models of the PPTs. Digital models were built in Rhinoceros (Rhino). Grasshopper's DIVA plugin was used as the simulation engine for conducting radiation, reflection, and shadow analyses (Fig. 4: TOP)—aluminum with medium reflectivity was selected as the primary material. Two matrices of the findings were developed to assess repetitive PPTs' various configurations based on the seven factors suggesting the strengths and weaknesses of each configuration (Table 1 and 2).

The comparative study of the two PPTs suggests that symmetrical daylight modules, i.e., PPT #2's configurations, allow for better control of natural light transmission as well as offering more uniform light distribution inside the museum. Additionally, the orientation of the aperture flaps can play a key role in the amount of reflection inside the museum. The PPT #1 configurations 2, 3, and 4 allow for light penetration from the top of the modules which can result in undesired reflections/glare inside the space; however, the PPT #2 configurations have a better performance due to the way they block the south light coming from the top of each module.

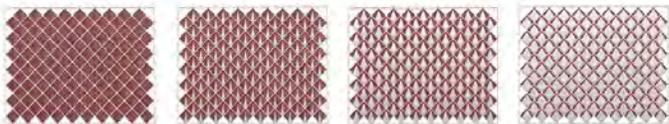
Based on what we learned about the weaknesses and strengths of different modules, two designs were developed for each PPT, where various configurations of one PPT informed one parametric design (Fig. 6 and 7). For both iterations, the daylight modules gradually open from one side to the other. Physical models were built and placed on a heliodon for daylight analysis.

Table 1: Assessment matrix evaluating PPT #1's four configurations' performance level based on Liljefors' seven visual and perceptual factors using a 5-point Likert scale.



	CONFIGURATION #1	CONFIGURATION #2	CONFIGURATION #3	CONFIGURATION #4
Light Level (Dark–Bright)	0 out of 5	1 out of 5	2 out of 5	3 out of 5
Light Distribution (Uniform–Varied)	0 out of 5	0.5 out of 5	1 out of 5	2 out of 5
Glare (Invisible–Disturbing)	0 out of 5	0 out of 5	0.5 out of 5	0.5 out of 5
Shadows (Soft–Hard)	0 out of 5	3 out of 5	4 out of 5	4 out of 5
Reflections (Diffuse–Strong)	0 out of 5	2 out of 5	3 out of 5	3 out of 5
Transparency (Invisible–Visible)	0 out of 5	1 out of 5	2 out of 5	3 out of 5
Exterior View (Isolated–Open)	0 out of 5	0.5 out of 5	1 out of 5	2 out of 5

Table 2: Assessment matrix evaluating PPT #2's four configurations' performance level based on Liljefors' seven visual and perceptual factors using a 5-point Likert scale.



	CONFIGURATION #1	CONFIGURATION #2	CONFIGURATION #3	CONFIGURATION #4
Light Level (Dark–Bright)	0 out of 5	1 out of 5	2 out of 5	3 out of 5
Light Distribution (Uniform–Varied)	0 out of 5	0.5 out of 5	1 out of 5	2 out of 5
Glare (Invisible–Disturbing)	0 out of 5	0 out of 5	0.5 out of 5	0.5 out of 5
Shadows (Soft–Hard)	0 out of 5	2 out of 5	3 out of 5	4 out of 5
Reflections (Diffuse–Strong)	0 out of 5	0 out of 5	0.5 out of 5	1 out of 5
Transparency (Invisible–Visible)	0 out of 5	1 out of 5	2 out of 5	3 out of 5
Exterior View (Isolated–Open)	0 out of 5	0.5 out of 5	1 out of 5	2 out of 5



Figure 6: PPT #1: Qualitative assessment of Liljefors' Visual and Perceptual Factors through physical model making. Source: (Authors 2022)

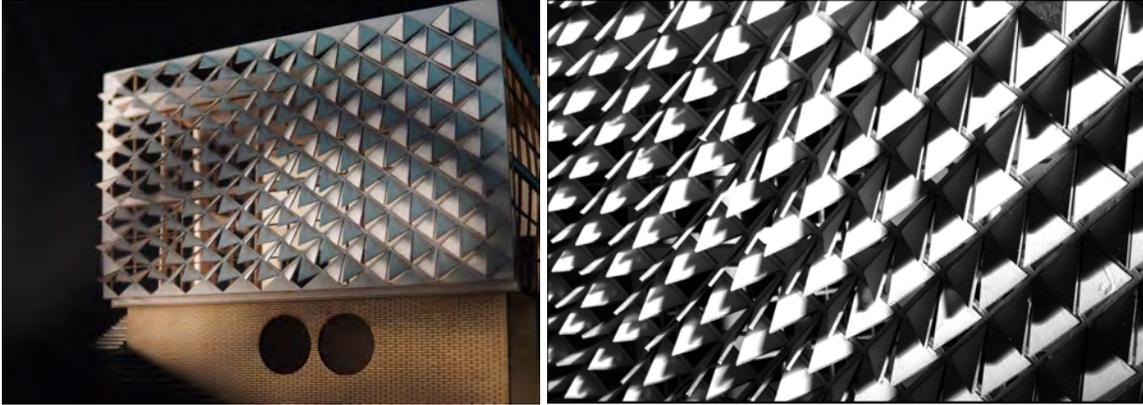


Figure 7: PPT #2: Qualitative assessment of Liljefors' Visual and Perceptual Factors through physical model making. Source: (Authors 2022)

The results suggest that although parametric models offer less uniform light distribution throughout the space, they offer varied lighting qualities in museum/gallery spaces which have a direct correlation with visitors' level of engagement as they explore different parts of the museum.

3.2 Quantitative Approach

A comparative study of the two PPTs was conducted to assess the efficiency of the daylight modules with regard to natural light transmission through each PPT. In each configuration, the Projection Factor (PF) was computed through the ratio of the horizontal depth of the repeating unit divided by the height of the vertical fenestration (Fig. 8 and 9).

PF = A / B PF: projection factor
 A: horizontal depth of shading device
 B: height of vertical fenestration

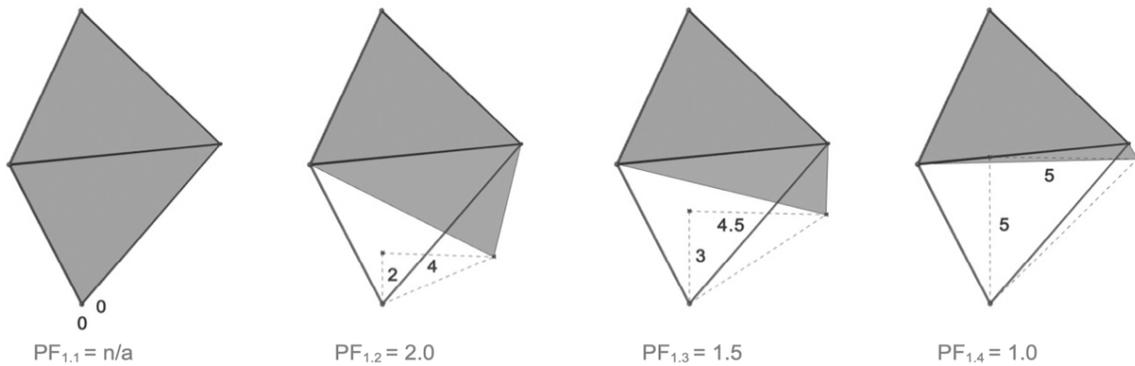


Figure 8: Computed projection factors for PPT #1's module configurations assuming the top flap at the fully closed condition. Source: (Authors 2022)

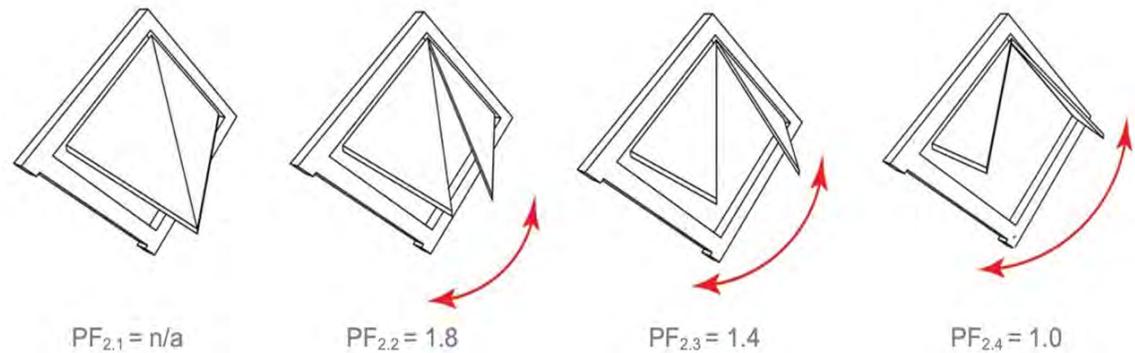


Figure 9: Computed projection factors for PPT #2's module configurations. Source: (Authors 2022)

CONCLUSION

"I think we're all realizing that the idea of a museum as a place of galleries with storage in the basement is outmoded. Museums are about bringing art and people together. The means by which you can do that are anchored in the exposition and exhibition of a work of art but go far beyond that. You have to engage them in any way possible," says Aaron Betsky, the director of the Netherlands Architecture Institute (Betsky 2011).

The concept of daylighting in architecture has been well-explored since early constructions in history. The most important aspect of daylighting is its uniqueness where it changes every second in intensity, temperature, color rendering index, and the direction of radiance. This characteristic of daylight makes it an ever-changing phenomenon inside the building, which complicates the design of daylight apertures and shading devices. At the same time, it opens an opportunity for an investigation of geometries that respond to such dynamic physical conditions.

Nature utilizes tessellated structures as an efficient strategy to optimize performance at various scales. These structures are flexible enough to morph their physico-geometric characteristics (Pearce 1990) to offer a wide range of solutions that better suit the surrounding physical conditions. The parametrization of such structures thus provides the ability to investigate the whole spectrum of possible solutions in a performatively informed way, and on a single repetitive unit level. Inspired by that, in the museum setting where controlled daylight is desired, performative periodic tessellations can inform the design of shading devices for better control light transmission.

In this paper, we introduced how daylight can be integrated into museum settings where the interplay of controlled natural light in the museum space can foster the visitors' experience. This study, in particular, targeted museum settings; however, this research-based design approach can be applied to various building typologies with different desired daylight qualities that better suit the functionality of each building. For the larger Computer Aided Architectural Design (CAAD) community, the parametric approach that was introduced in the paper can showcase a forward-thinking process where the qualitative and quantitative investigations are enhanced through the power of computation.

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END NOTE

¹<https://www.pinterest.co.uk/pin/555772410242401051>

²<https://dsrny.com/project/the-broad>



CONSTRAINTS

The range of techniques on gathering, assessing, interpreting, and comparatively evaluating relevant information for inquiry, education, and methodologies.

Techne: Teaching Iterative Tectonics to Architecture Students

Eric Weber

University of Arizona, Tucson, Arizona

ABSTRACT: A work of architecture is made of numerous components and learning how to use these elements to communicate ideas gives designers agency to enrich their work. Becoming engaged in how buildings are made and exploring how to assemble materials is a critical opportunity for architecture students, one that might help them to develop a tectonic language informed by critical exploration. Nathaniel Coleman articulates the opportunity and concomitant challenges: "Architecture is not as nuanced as language; its elements are expressively more limited but potentially more immediately powerful. Architectural elements including materials, details, and forms constitute a series of hieroglyphic characters available for a kind of physical writing that through use speaks directly to the body. More explicit links between architecture and language could take shape at those junctures where material and form analogize some describable social idea. Here, social is intended to encompass individual and group experiences of being in the world, individually or collectively, from the uprightness of a body to the character of a community. The difficulty modernist architecture has in locating points of intersection with language arises, at least in part, from the tension between exaggerated individual artistic expression in one direction and trivial practice in the other, with both dominated by a more than less universal building industry that demands standardization."

The University of Arizona School of Architecture created a course called Techne to provide second year students the skills needed to support their studio education. The course was intended to integrate digital modeling, shop skills, photography and image management, and other skills. In the current incarnation, we were given the opportunity to focus the skills training on improving students' ability to use material exploration as an iterative tool that could inform learning digital tools, and to help students to learn to move between digital production and physical fabrication, leading students to learn tectonics through the creation of both physical constructions and digital analogs.

*Teaching tectonics is a process, one that requires the instructor to focus on the methods of fabrication and construction at the beginning of any project. Formal exploration, the normative approach of most design courses needs to follow considerations of material assemblies. This does not preclude formal innovation, but it is essential to foreground the materials and methods of construction. As Edward Ford states in *The Architectural Detail*:*

My sense is not that joints are necessary for construction, but that they are necessary for coherence, for architectural meaning to occur, even if jointlessness is technically feasible. It is clear that long before the modern era, the understanding of the parts of a building and their constructional relationship was a key to a larger understanding of the building as a manifestation of ideas. The assembly of parts in precarious equilibrium can be understood as a parallel for another system: a social order, a political order, a philosophical order, a natural order.¹

KEYWORDS: teaching, pedagogy, hands-on learning, tectonics

THESIS

A work of architecture is made of numerous components and learning how to use these pieces to communicate ideas gives designers agency to make their work better. By learning more about how buildings are made, and how they can be constructed, architects can create more design opportunities. Becoming engaged in how buildings are made and exploring how to assemble materials is a critical opportunity for architecture students, one that might help them to develop a tectonic language informed by critical exploration. Nathaniel Coleman articulates the opportunity and concomitant challenges:

Architecture is not as nuanced as language; its elements are expressively more limited but potentially more immediately powerful. Architectural elements including materials, details, and forms constitute a series of hieroglyphic characters available for a kind of physical writing that through use speaks directly to the body. More explicit links between architecture and language could take shape at those junctures where material and form analogize some describable social idea. Here, social is intended to encompass individual and group experiences of being in the world, individually or collectively, from the uprightness of a body to the character of a community. The difficulty modernist architecture has in locating points of intersection with language arises, at least in part, from the tension between exaggerated individual artistic expression in one direction and trivial practice in the other, with both dominated by a more than less universal building industry that demands standardization.¹

How might we teach students to understand tectonics, and how to value it as integral to the design process? It is precisely this tension between the polarities of standardization and artistic expression that we intend to explore. Much of the agency architects have begins with developing a critical response to these competing

imperatives. We have developed projects to show students that they can design and make many more things than they think, and these opportunities can help students to create compelling architectural interventions. The iterative processes we created helped students to understand the development of tectonic principles.

CONTEXT

The University of Arizona School of Architecture created a course called *Techne* to provide second year students the skills needed to support their studio education. The course was intended to integrate digital 3D modeling training, shop skills, photography and digital image management, and other techniques. In the current incarnation, we were given the opportunity to focus the pedagogy on improving students' ability to use material exploration as an iterative process that could inform learning digital tools, and to help students to learn to move between digital production and physical fabrication, leading students to learn tectonics through the creation of both physical constructions and digital analogs.

Teaching tectonics is a process, one that requires the instructor to focus on the methods of fabrication and construction at the beginning of any project. Formal exploration, the normative approach of most design courses needs to follow considerations of material assemblies. This does not preclude formal innovation, but it is essential to foreground the materials and methods of construction. As Edward Ford states in *The Architectural Detail*:

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Design build is a well-established pedagogy for teaching tectonics. While the details differ considerably from one university program to the next, design build studios typically design small projects (very often a small house), and then build the project themselves, sometimes with a few key subcontractors depending on local regulations. Students learn everything from creating construction documents to nailing wood framing members together, but the most important lesson is how to understand the complex order of operations and interrelationships that make up every architectural project. This process is extremely valuable to the student's education, but it is limited in its application due to logistical challenges, not the least of which is that students often need to learn the basics of design and construction before undertaking a design build project. This usually results in these studios being scheduled near the end of a school's curriculum. As an academic engaged in design build projects for the past decade, the author is keenly aware of these limitations. How might we begin teaching students these fundamentals using hands-on techniques earlier in their education? Kenneth Frampton illustrates a potential approach:

The one tends towards light and the other towards dark. These gravitational opposites, the immateriality of the frame and the materiality of the mass, may be said to symbolize the two cosmological opposites to which they aspire: the sky and the earth. Semper's emphasis on the joint implies that fundamental syntactical transition may be expressed as one passes from the stereotomic base to the tectonic frame, and that such transitions constitute the very essence of architecture. They are the dominant constituents whereby one culture of building differentiates itself from the next. There is a spiritual value residing in the particularities of a given joint, in the "thingness" of the constructed object, so much so that the generic joint becomes a point of ontological condensation rather than mere connection. We need only think of the work of Carlo Scarpa to touch on a contemporary manifestation of this attribute.²

We began to think about the fundamental differences between cast and tectonic materials in the models the students might make, and how this informs students' thought processes. Frampton's articulation of the fundamental difference between stereotomic and tectonic elements formed the generative pedagogy that developed into our approach to teaching second year students. In addition, a fundamental questioning of typical architectural practice—design then fabricate precisely to match—became a key component of the pedagogy as it was developed.

Scarpa's re-working of the conventions of drawing might encourage us to similarly position a way of thinking and constructing that also breaks out of the rigid confines of representation. This might be akin to sketching with material—working at full scale, responding to the conditions, resistances, and tolerances of actual materials, searching for the latent and serendipitous rather than being bound by an abstract set of explicit instructions. Must a constructed architectural artifact always be the material consequence of a pre-determined idea—fixed and delineated by someone and then constructed by someone else—or can the act of making itself be generative, exploiting the dense, fertile ground of difference that Evans is implying and that Scarpa demonstrates in his drawings? I propose a way of building that uses the transitive power of iterative prototyping to advance the tectonic qualities in the work. This is not simply to say that the architects' involvement in the work is any guarantee of success—only to suggest that the gap between the abstraction of drawing and the constructed outcome has been neglected as a source of inspiration and meaning. A robust period of material and assembly explorations, full-scale prototyping, testing for fit on site, all

combined with simultaneous refinements and modifications, constitute a significant part of a holistic and empathetic design process that has somehow disappeared in the work of most architects.³

METHODOLOGY

Techne begins with students learning how to use the shop by making a series of predetermined wood block shapes, which are used to create simple, speculative massing model arrangements. Students developed design skills, utilized narrative, two-dimensional computer drawing, photography, and sketch overlays as design and representation tools.

The students were tasked with composing eye-level photographs, which are used to describe verbal prompts. These prompts serve as context to inform Photoshop texture mapping exercises. Students were asked to create an Open Courtyard, Terrace with Access, a Series of Multi-Level Units with 3, 5, and 7 blocks, and an Open category, totaling 10 models. Students then created their first Rhino 3D models based on the block massing assignment.

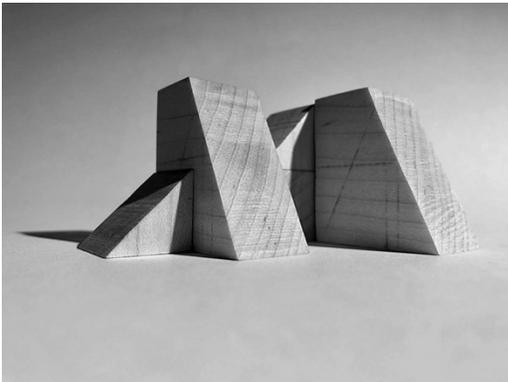


Figure 1: Wood Block Massing Model. Source: (Anthony Rascon, Student 2021)



Figure 2: Photoshop Material Study. Source: (Anthony Rascon, Student 2021)

The objectives of this assignment were to develop representational skills in physical prototyping, digital drawing (using Rhino 2D), as well as design skill in abstraction and observation. Students learned basics of 2D drafting, liveweights, layers and printing, and demonstrated ability to document their projects using architectural conventions. They also learned how to photograph architectural models to communicate ideas regarding proportion, daylight/shadow, and to convey narrative ideas. They also began speculating about how materials might be used early in the design process, by applying texture maps to their massing models via Photoshop, allowing rapid exploration.

In the next phase, the class began creating small cast explorations using rigid insulation foam as form work. These gradually increased in size and complexity, ultimately leading to a full-scale detail component cast using concrete with reinforcing rods and conventional plywood formwork.

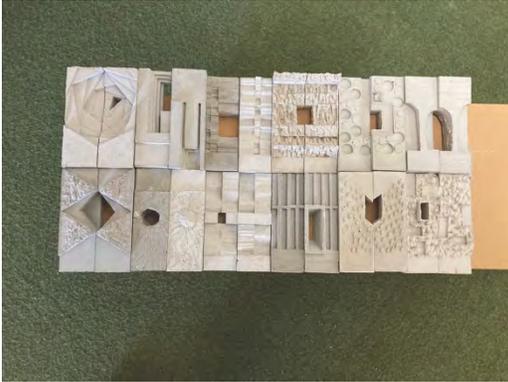


Figure 4: Preliminary Cast Material Studies: Surface+Opening. Source: (Author 2021)

Students developed their designs through experimentation and iteration, using digital and physical modeling to create modular cast models that explored surface textures and openings within the surface. These explorations included fundamental principles of architecture to include repetition, solid/void, contrast between surface textures, and numerous other potential discoveries. The objectives of this assignment were to develop representational skills in physical prototyping. Students learned how to make well-crafted models and developed understanding of the value of iteration. Many cast elements required refinement, but open-ended experimentation resulted in numerous discoveries. They also learned the reflexive relationship between physical and digital modeling and utilized these skills to inform the creation of the cast modules. The process of making, reconsidering, and re-making led to highly refined results, often with unexpected outcomes students would not have achieved otherwise.

Parallel to the increasing casting scale, students were expected to carefully photograph their projects. One of these photos was developed into a photomontage that shows shade, plants, and the addition of a framed opening to result in the appearance of a completed building. Creating this composite image was a somewhat convoluted process, but one that taught students a number of skills that they might not have explored otherwise. Incorporation of the plant and plant shadow in particular were steps that gave students the opportunity to develop skills with wider opportunities for further development.



Figure 6: Surface+Opening Composite Photomontage. Source: (Alexio Mora, Student 2021)

The first step was taking photos of distinctive native Sonora desert plants, and then using Photoshop to carefully crop out and isolate the plant profile. The cropping border was then transferred to Rhinoceros as a continuous, closed polyline, where it served as a laser cutting profile. These profiles were cut from thin chipboard, and then used to cast the desired shadows onto the concrete cast models, which were then photographed, making sure the profiles were not visible in the photo. The final step was to insert the cropped plant photo as a layer into the cast project photo, carefully aligning the image to the shadow, creating a convincing composited image. Creating the appearance of a window was fairly straightforward by comparison, students were shown how to add a gradient across a specific area, then added another layer with an outdoor scene which is made transparent. Once these two layers are superimposed, it gives a reasonable impression of glass reflections. These techniques can be implemented quickly, providing a more realistic impression for the overall composition than one might be achieved with rendering software, especially regarding the textural richness of the cast components.

The projects are intended to help students to explore material culture, and to lower barriers to entry and iteration. Our pedagogy actively encourages iteration, by teaching students to play with materials to see what they can do. Engaging students in the essential value of iteration was a focus of the work throughout, but we made this explicit in the second semester. The second semester focused on assemblage of framed, tectonic elements, in Frampton's terminology, in contrast to the stereotomics of the fall course.

In the Spring semester, the first assignment required students to duplicate the construction of a wood 2x4 framed wall assembly exactly as prototyped by the instructors. The purpose was to start with a measurable, verifiable project; students would either build theirs correctly or not. It was important that students could not explain away something that was not square and true. Objective criteria were intended to demonstrate to the students that this was achievable, even with beginner's skill levels. The project also required paying attention to the order of assembly.

The next step was to use standard 1x2 furring members to develop a horizontal composition spanning across the frame wall. Student teams were required to use either 4'-0" or 2'-8" lengths and spacing between members were required to be increments of the actual 3/4 or 1-1/2" dimensions of the nominal 1x2 members. Students attached the members with a brad nailer, allowing quick attachment as well as removal as required. They were allowed to place the furring members with either the long or short dimension placed vertically. While the number of constraints might seem to severely limit opportunities for creative expression, the resulting projects prove otherwise.



Figure 8: Cladding-Layering Iteration 1 Examples. Source: (Author 2022)

We deliberately set up many constraints in the exercise, trying to create as limiting an approach as possible. Despite this, each project became vastly different from each other.

“Design depends largely on constraints.”⁴ Charles Eames' dictum explicitly informed our pedagogy and was critical to student success. It is precisely the degree of constraint that helps designers to understand the nature of a design problem. The more constraints, the clearer the solution.

The students were required to create Rhino models of their work, which were used as part of the next iteration of the project. Part Two required the students to create a 16" framed corner section and add it to the existing frame, and then explore how the students' compositions might “wrap” around the corner. Exploring how materials transition from one geometry to another is an essential part of the art of building, so students were confronted with the opportunity to create their own point of view on how to articulate the corner condition in their projects.

For this part of the project, students were given the same 4' and 2'-8" length requirements, and students were expected to add a second layer to their screen assembly. The implication was that this layer would be primarily vertical, but this was not explicitly stated. Because all the teams had some of their horizontal members in different orientations, the surface was not flat, which affected the resulting compositions. Another detail that became quite significant in some students' projects was that in adding the second layer to the project, we gave the students the option to use either brad nails as they used for the first layer, or countersunk black oxide coated wood screws, which create opportunities to provide a highly visible method of attachment in contrast to the nearly invisible brad nails. This contrast was used to contribute another ordering layer in some projects.



Figure 9: Cladding-Layering Iteration 2 Examples. Source: (Author 2022)

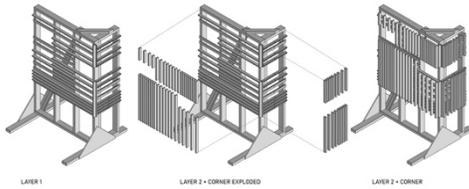


Figure 10: Cladding-Layering Process Drawing. Source: (Emme Mooday, Damien Narum-Brelay, Andrew Rodriguez, Linea Skura, Student Team 2022)



Figure 11: Cladding-Layering Iteration 2 examples, one with screws creating an ordering system, one without visible screws. Source: (Author 2022)

Interestingly, many of the students seemed resistant to actively engaging the corner, especially with layer two. Specifically, they resisted creating another, fully developed second layer, but when they began utilizing iterative rhino model studies and sketches, they began to become more engaged with the opportunities this project presented. While some students seemed to resist the iterative process initially, they eventually embraced the challenge, and their work developed significantly. Several teams embraced unexpected, accidental discoveries that occurred due to lack of experience in assembly processes. These in turn informed their computer models in a reciprocal relationship that improved the design process. In Figure 9 above, the students inadvertently attached the angled components at the bottom first, resulting in these parts rotating at an unintended angle. This unexpected discovery resulted in a more interesting relationship of parts, something that likely would not have happened if the project would have been designed entirely via computer, and then fabricated exactly per the preconceived design.

Part 3 of the project required students to create a framed opening. The shape was initially defined by existing frame member locations; students were told not to cut any of the primary structural frame members. Students were given one piece of 24-gauge steel, 12x48" with which to create the frame; the material could be cut, folded, and attached as necessary to create the framed opening. Depth and height were not constrained, except by material quantity.

Students were provided cardboard which they used to mock up their solutions, while simultaneously working on 3D computer models. Each student team member developed one option, and then the team compared

design ideas to determine how to proceed with the group solution. Later, they developed laser cut templates using chipboard; the laser cut patterns were derived from the students' Rhino models. The shop's laser cutter has a 32" maximum size, so students were required to use maximum pattern sizes of 16"Wx32"H. Creating laser cut components facilitates students in developing an understanding of how the components fit together before creating the steel parts, a common practice in industry. Students learned to consider the assembly and attachment methods as integral to their design processes. The teams began to realize that there were numerous opportunities to extend their design ideas by taking advantage of the panel joinery and fasteners to emphasize their project's area of focus. There were several examples that demonstrated a further layer of communication through the fact that the project was made from multiple pieces. This recognition allowed for another layer of design ideas and a means of communication of these ideas. Many teams overlapped their pieces with assembly tabs on the outside of the box, to make sure the interior of the box was clear of visual distraction. Some teams also made mounting tabs that attached their boxes to the frame, keeping fasteners out of the interiors. One team went further, designing their assembly so fasteners would be invisible from inside and outside of the opening projection, resulting in a complex assembly process, but one that enriched the design development. These seemingly simple decisions are just a few demonstrations of the fundamentals of tectonic expression.



Figure 18: Frame-Opening Final Assembly with Expressed Fasteners. Source: (Author 2022)



Figure 19: Revised first semester final project demonstrating tectonic/stereotomic interrelationship. Source: (Author 2022)

RESULTS

The second iteration of the Fall course incorporated an early exploration of tectonic assemblies to form a counterpoint to the stereotomic/cast projects. After teaching the course sequence the first time, we determined that finding a way to create an explicit bridge between the first semester's focus on stereotomics and the Spring's tectonic emphasis was appropriate. With this in mind, we developed a short exercise using the students' previous castings as the site of additional exploration. The students were tasked with using small basswood members in two sizes to create a spatial assemblage to create pattern and shade in contrast to the cast elements; the students were expected to clamp, wrap, cantilever, and intersect their castings in unexpected ways due to the need to respond to the existing context, as seen in Figure 19 above. This results in many interesting relationships because the intersections weren't pre-planned. Students then re-made the casting to respond to the intersections between cast and tectonic elements. This process resulted in students creating richly expressive projects, and prepared them for the larger, more complex tectonic assemblages that followed.

The way we approached *Techne* is an argument in favor of Edward Ford's "The Detail as Join," one of the philosophical constructs articulated in his book *The Architectural Detail*. By intentionally making the students create the project in discrete phases, it required students to carefully consider the existing context, and respond to the actual parts that were present. This approach made it challenging for students to think about the project as a whole, and instead meant that students had to think about the specific components within their projects. This created numerous unexpected and challenging conditions, which in turn created opportunities for the students to further articulate their tectonic ideas.

Students have learned a number of technical skills and received essential reinforcement of the importance of foregrounding the means and methods of assembly to architectural production. They have also demonstrated the importance of working between digital and physical iteration, as experimentation is beneficial in both realms. The studio faculty have taken advantage of the students' newfound abilities, most directly with their facility in creating cast models. It remains to be seen whether their other skills will be integrated into studio teaching.

CONCLUSION

Whether it was a moldy melon leading to the discovery of penicillin, or Marcel Duchamp's "Large Glass" being inadvertently cracked during transportation to an exhibit, accidental discoveries have a celebrated history of transformation in the arts and sciences. The accident can be more informative and interesting than the intention. Because computer input is determinate by design, it is at times challenging for architecture students who use conventional digital design tools to make unexpected discoveries as they work. One would have to find ways to subvert this tendency, an interesting possibility for faculty with greater digital design expertise to explore.

Hands-on, skills-based teaching has set *Techne* students up for success in future classes, especially the design-build studio. Having said that, even if students never create another physical prototype again, they will have learned the value of iteration and moving between different modes of representation, skills that will serve them well as they continue their architectural education. The methods of teaching demonstrated here can be readily applied in other programs, although the biggest challenge will likely be getting the class itself approved as separate course sequence. Many faculties may think these skills could be incorporated into their regular studio sequence, but without a formalized pedagogy that makes room for focused, skills-based learning, it would be challenging to integrate the lessons demonstrated in this paper into a cohesive and effective experience for the students.

ACKNOWLEDGEMENT

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END NOTE

¹Edward R. Ford. *The Architectural Detail*. (New York: Princeton Architectural Press, 2011), 226.

²Kenneth Frampton. "Rappel a L'Ordre, the Case for the Tectonic." In *Theorizing a New Agenda for Architecture: An Anthology of Architectural Theory 1965-1995*, ed. by Kate Nesbitt. (New York, Princeton Architectural Press, 1996), 522.

³Terry Boling. "Embodied Making: Designing at Full Scale." In *Designbuild Education*, ed. by Chad Kraus. (New York: Taylor & Francis, 2017), 141-2.

⁴Charles Eames, in conversation with Madame L. Amic. "What is your Definition of Design?" Musée des Arts Décoratifs, Palais du Louvre, 1969. <https://www.vitra.com/en-us/magazine/details/what-is-your-definition-of-design-monsieur-eames>. Accessed May 15, 2022.

Matter, Making, and Testing: Designing with Next Generation Precast Concrete

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ABSTRACT: *Precast concrete panel design, fabrication, and assembly are the subject of a seminar being conducted at the University of Pennsylvania's Stuart Weitzman School of Design over the last four academic years. This seminar focuses on precast concrete and specifically its complex history, materiality – how it is manufactured and the logistics of its assembly - and cultural affects through both its traditional uses within the constructed urban environment as well as new approaches to building typologies such as housing. Through a strategic partnership with the Precast/Prestressed Concrete Institute (PCI) and Northeast Precast, based in Vineland, New Jersey, students have gained access to places where precast concrete is made, formed, and put into action. The seminar has yielded unique opportunities for collaboration, where student teams work directly with project managers and engineers in the design and fabrication of formwork and work with these experts at the precast plant in the actualization of panels. The collaboration, however, is not one-way, as students engage in three-dimensional design software and imagine creative production techniques to develop their panels, finding ways of transmitting their goals electronically to the plant experts. The resultant workflow utilizes advanced Building Information Modeling (BIM) and direct-to-fabrication schemas. Students are present at the facility and participate in the fabrication and assembly of formwork, as well as the pouring of one panel. Unique to the seminar is the production of full size, as opposed to scaled, panels that address multiple formal and performance characteristics present in precast panel design. A primary interest of the seminar is to address the need in design and construction to limit material waste, supporting a more sustainable mode of both design and object production. Students are constrained materially to (2) 5'x10' stainless steel sheets they may use to construct a single formwork that must be re-used to produce two discrete 4'x8' precast panels. The process yields a two-way workflow between students and the precast project managers and engineers and allows for a bi-directional knowledge exchange, making the production process instructional for all parties as well as fun. This paper will address the educational objectives of the seminar, as well as introduce a case study produced by students in the fall 2021 semester. That project further explores surface and formal variation across the two panels by inserting voids into the formwork and varying the material expression in different zones of each panel.*

KEYWORDS: Precast Concrete, Education, Density, Building Information Modeling, Digital Workflows, Sustainability, Collaboration, Shop Drawings

1. CONCRETE AND PROCESS



Figure 1: Examples of panels produced in Matter, Making, and Testing, the seminar was held in the fall semesters of 2019 through 2022 and was each time enrolled by twenty (20) graduate students.

1.1 Precast Pedagogy

Introducing architecture students to material assemblies is a complex pedagogical endeavor. Such an introduction to materials, and more specifically construction technologies, should be grounded in history, environmental circumstance, as well as best practices in order to facilitate a more comprehensive understanding leading to a sound approach and selection process for future practitioners. Concrete, and especially precast concrete, has a rich history that includes its use as a simply composed mortar in antiquity, through the more chemistry- and engineering-grounded formations in the 19th and 20th centuries. The repurposing of post-war factory space in the mid-20th century led to the rise of modern precast technology, adding prefabrication and modularity to the positive criteria the material has accrued in its use.

That the material is plastic, that is, moldable to any form is topical to the educational objectives of many architecture schools and assists in the challenges of introducing concrete as a form- and performance-driven construction technology that continues to find worth in the 21st century. Taking advantage of this opportunity, at the University of Pennsylvania we have introduced a seminar in design and technology that engages the history and use of the material as well as giving students the opportunity to fabricate and pour precast panels by working directly with a local producer. Titled Matter, Making, and Testing: Designing with Next Generation Precast Concrete, the seminar has been held for the past four academic years and continues to be a popular course among the student body. Students generally enroll in their second or third and final year of their graduate studies, however, first year students have also been admitted to the course. The seminar was conceived with and enjoys the support of Northeast Precast, located in Vineland, New Jersey. Through this collaboration, we have had the opportunity to study the material historically, conceptually, and physically through a panel design and casting process undertaken with the precast sponsor. These efforts have also just been awarded funding over the next four (4) years through the Precast/Prestressed Concrete Institute.

1.2 Seminar Learning Objectives

The seminar has been conceived with three (3) distinct components which are equally divided in course delivery. Through the course of the semester, participating students build knowledge and content through:

1.2.1 Lectures on the History and Technology of Precast Concrete

A history of reinforced concrete from the turn of the 20th century, and more specifically the rise of precast in the 1950's as part of an offsite, factory-based movement within the construction industry, are explored. Specifically, concrete's relationship with both modernity and nature are considered. As both a material and construction technology, it is equally a product of advancements in the engineering and chemistry of 19th and 20th centuries – becoming synonymous with new architecture and various utopian movements; as well as a result of simple and time-tested labor operations requiring no special knowledge or expertise. A goal of precast construction was the use of tools, machinery, and other equipment, ideally automated, in the production of standard, interchangeable parts and products; this promised a restructuring of entire conventional construction processes.

At the beginning of the 20th century, the material was chosen by Thomas Edison as a solution for worker housing in the steel towns emerging in the Midwest including in Gary, Indiana, where a series of single-family concrete houses were produced with reusable steel forms. Edison patented a process in which a concrete house could be formed with a single pour. The prototype was designed by New York architects Mann & MacNeille in 1909. The fact that Edison chose them for the house prototype is telling, as his concept was most broadly explored in the 1910's in Gary, Indiana, which was a company town with concrete worker houses planned and constructed by the United States Steel Company, which was formed in 1901 when JP Morgan and Andrew Carnegie merged their steel interests. In 1913, Walter Gropius published, in the German magazine *Deutscher Werkbund*, images of large reinforced concrete grain elevators from the United States, captivating European architects and ushering in a 20-year period associating the material with modernity. While some architects and inventors in the US and Europe, including Le Corbusier, further explored the material as a solution for houses and housing, the trajectory of the material would be for more industrial and large-scale uses, including roadway and infrastructure construction.

The association with these projects further separated the material from housing, and the 1960's and 70's saw a conscious move away from the material's use in housing, with modular housing solutions being proposed in either timber or steel. There was one notable experiment, however, completed in 1975 in Jersey City. Summit Plaza, which provided 486 affordable and precast concrete housing units in several multifamily building configurations across a 6.35-acre site. The dwelling units were built by a now defunct company called Shelly Systems and was commissioned by the Department of Housing and Urban Development (HUD) at one of nine (9) sites developed country wide. The project was part of a HUD initiative called Operation Breakthrough, a three-phase demonstration project that tested innovative building materials and construction methods with the goal of removing obstacles to large-scale affordable housing production in the United States, bringing quality

housing to all income groups. Operation Breakthrough ultimately worked with 22 system producers that provided some 2,900 housing units, all delivered using off-site construction methods. The selected producers utilized housing systems ranging from precast concrete- or wood-framed modules to units constructed largely of plastic or metal, supplied by companies including Alcoa, Levitt Technologies, General Electric, and Republic Steel. Some systems were already in production when selected, while others were new and untested.

Lectures also engage contemporary issues including sustainability, carbon entrapment, and concrete's relationship to ecology; and are supplemented through a variety of readings.

1.2.2 Introduction of Novel Precast Precedents

Building precedents are introduced throughout the seminar that range in scale from houses to larger buildings of various typologies. Case studies have included the Church of Notre Dame du Raincy (1922-23) by August Perret, the Rudin House in Leymen (1996-97) by Herzog & de Meuron, The Perot Museum of Nature and Science (2012) by Morphosis, and Steven Holl's Rubenstein Commons at Princeton (2022), as well as work by the instructor. The precedents are paired with weekly readings that introduce both concepts surrounding the buildings themselves as well as the design workflow that produced them. Projects are selected not only for their cultural and technical novelty, but for the unique and increasingly digital and collaborative processes that led to their formation. For these case studies, student groups organize brief presentations following a lecture that links the building/precedent to a weekly reading. It is expected student teams understand both the architectural and technological significance of each case study, as well as the design and collaboration workflows entailing their production. The case studies also offer the students an opportunity to study the three-dimensional modeling of panels ahead of their own panel design. Several of the case studies were produced by the precast concrete company giving the students access to production and logistics data, and supply shop drawings for those projects.

1.2.3 Group Collaboration / Development of Digital Content / Mock-ups

Students are ultimately responsible for a precast mock-up that is produced in collaboration with and at the facilities of Northeast Precast. Working in teams of three (3), students work collaboratively to produce all virtual information required to realize the precast mock-up at full scale, as well as a panel schema with joint patterning and formwork images that will position the mock-up within both larger and more local scales. Final seminar deliverables are the mock-up panel itself, produced in conjunction with Northeast Precast, as well as documentation including shop drawings and other studies that express the mock-up production process and simulations that study panelization and structural feasibility. During the seminar's two scheduled workshops at the precast plant, students have access to the sponsor's various CNC capabilities, including a plasma cutter, multi-axis routers, and wire-based foam cutters, and a full metal fabrication shop. Formwork material had generally been either coated $\frac{3}{4}$ " plywood, or milled high-density foam, or a hybrid of both. Students have also explored Autodesk's Structural Precast Extension for Revit as a basis for shared documentation.

The ability for students to engage the precast team and facilities has ensured consistent interest and participation in the seminar and to date, some ninety (90) students have had the opportunity to interact in various ways with the precast sponsor. The primary deliverable of the seminar has been a full-scale panel, and the constraints applied to this work have varied by semester. In the fall of 2019, the initial semester the seminar was offered, students worked to produce a 4'-0" x 8'-0" flat panel that specifically dealt with issues of formal variation, aperture, and insulative performance, as well as lightness. In most cases, panels were imagined as an architectural façade component, so students developed concepts that addressed aperture and cladding.

Based on the initial success of the fall 2019 work, the fall 2020 course introduced a more specific construction constraint – the corner. Instead of one 4'-0" x 8'-0" panel, students were given the task of designing two (2) 3'-0" x 6'-0" panels and were asked to consider their joint and design a corner – an architectural condition that is specifically topical to precast concrete design that also has a rich architectural history in terms of both construction and detail approaches. In this instance, one precast precedent was removed from the course so that a student team could study the history of the corner instead. This work was presented to the group in class prior to the commencement of the panel design process.

In 2021, the course was reimagined again, taking advantage of a new CNC plasma cutter installed at the precast plant. In that instance, student teams were given two (2) $\frac{1}{8}$ " thick 5'-0" x 10'-0" sheets of steel. This flat stock would be utilized as the primary material in the production of panel formwork. Student teams were permitted to use CNC-cut foam inserts in some instances, but the goal of the exercise is to introduce reusability of the formwork as a material engagement and management strategy. Foam inserts would allow a certain amount of difference in panels cast from the same formwork, a response to the formally ambitious panels previously produced in the course utilizing coated plywood, a material that is usually discarded after a single

use. To prove reusability in this exercise, Northeast Precast agreed to produce two (2) panels per team, each poured from the same formwork. A requirement of inter-lock was given that would allow students to vary the formwork with the foam inserts.

1.3 Workflow

The specific workflow utilized by the students in each semester varied by team and goal(s) of each panel. In some instances, a portion of a building already designed by a student or team was selected for further development and panelization, and in others, panels were developed specifically for the course. This phase of the work commenced with a visit to the precast plant which included presentations regarding various capacities of the company including insulated sandwich panels, Superior Wall-type panels, as well as specialty and architectural precast. Students were asked to consider each of these as criteria for the design of their own panels. Following the plant tour, students were initially tasked with imagine the positive form of their panel designs using modeling software. These models, as well as their surrounding negative geometry – an initial attempt at formwork - were transmitted to Project Managers (PMs) selected by Northeast Precast to work with each student team. The file data, sent as raw geometry and initially unformatted, was viewed in a 3D environment and commented on by the team at Northeast Precast. Around this time, lectures focused on the production of shop drawings, with examples of two- and three-dimensional graphics shared with the students. Once the PMs and students arrived at a final design that met size and shape capacities available, students embarked on rationalizing their work into a series of shop tickets that specified reinforcing bar size, layout, and location within panel thickness, as well as the location of any anchors and lifting hooks for eventual stripping. It was an important goal of the course for the students to imagine a comprehensive design, fabrication, and stripping process, so the utilization of components for the lifting and setting of the panels were understood as an integral part of the panel conception.

2. STUDENT'S PERSPECTIVE ON SEMINAR

2.1 Case Study Project

The fall 2021 course ultimately brought objectives from previous seminars together with the key object of a reusable formwork. In addition to this set of course criteria, teams implemented their own series of design goals and rule sets that helped guide the formation and development of their panels throughout the duration of the semester. The student team of Riley Engelberger, Lisa Knust, Madison Tousaw, and Lauren Hanson built upon the specification of a reusable formwork and the effect this would have on panel variability from a single form. For the course, the team produced two 4' x 8' precast concrete panels that are unique from one another, join at a 90° corner and introduce two possible finishes in a precast setting – sandblasted and revealed aggregate (fig. 2).

2.2 Design Team Goals and Approach to Initial Digital Geometry

The student team started with the joint condition and pursued a design that could accommodate a 90° corner. This is complex given course constraints permitted the production of a single formwork. To achieve a second panel that would notch into the first at the corner, it would have to rotate in one plane at 180° and in another plane at 90° (fig. 3). Had the geometry of the notches at the corner been horizontal rather than diagonal, the panels could simply slide into each other. The team desired a more complex joint, and the notches occur at a diagonal, which ensured the two panels would fit together, allowing the joint edge to be mirrored along the vertical axis, with the top half being the negative of the bottom half. Because of the diagonal the second panel had to be installed from above the first and slid down into the notch. As long as these parameters were adhered to, the design of this joint could have many alternative expressions. Secondary to the notching is a faceting of the corner in order to lessen the harsh 90° that would otherwise exist. Once this corner was resolved, the design of the faces of the panels were explored (fig. 4).

The team used curved form profiles developed in previous work while reimagining and implementing these elements under new constraints, which turned out to be so great that the curves altogether were re-worked into straight lines that were only slightly curved at each turn, responding naturally to the bend radius of the machine that would bend the 1/8" thick stainless steel sheet material used to create the formwork. The larger radius curves in the initial design option (fig. 5) would have been faceted to meet the constraints of the production method and directions received from our project managers at Northeast Precast. Because of this, the team chose to pursue the second design option, which did not require to facet larger radii curves and would lead to a cleaner final set of panels. There was some design disappointment in losing the original curves, but the team learned an important lesson — that they must sometimes alter design intent in order to meet the constraints and requirements of the fabrication process. Though a simpler option was engaged, there were still important fabrication considerations, as the bent profile could not be achieved in a single sheet, but rather multiple cuts that would then have to be welded together (fig. 6). Of course, these were obstacles that would ultimately be tackled by the Northeast Precast fabricator, but it was important that the team considered the welds for the sake of design and fabrication efficiency.

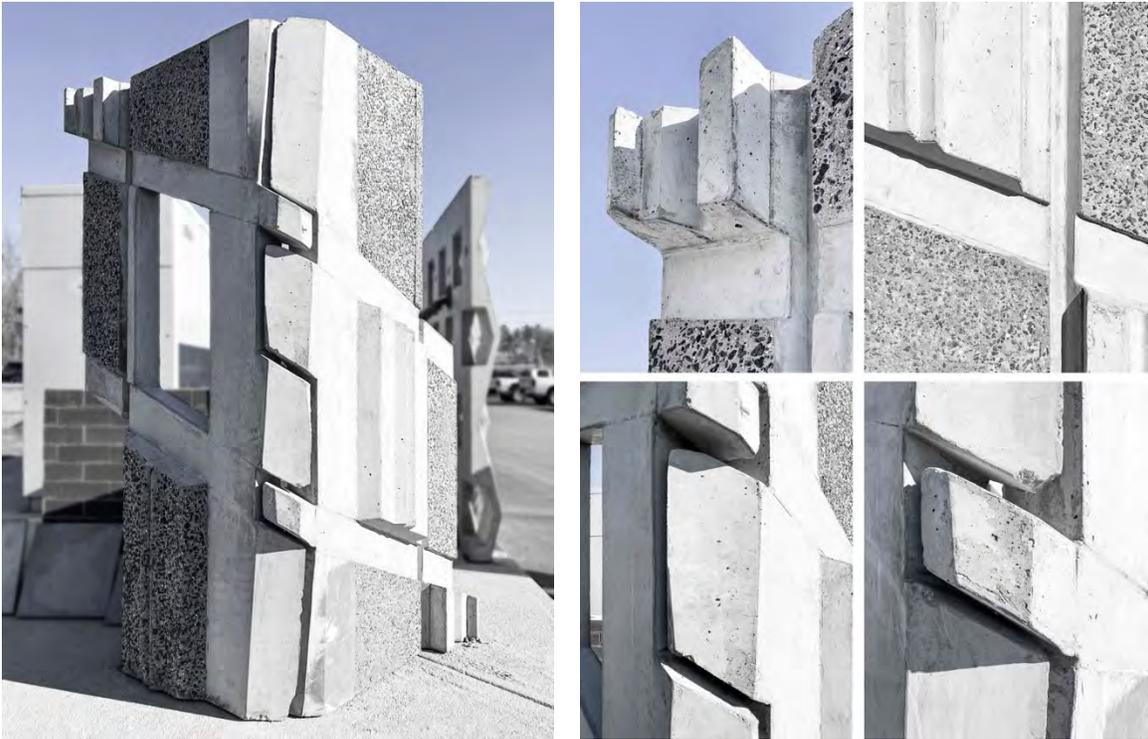


Figure 2: Final unique precast panels from single form at 90° corner and details of corner joint, extruded profiles, & sandblasted and revealed aggregate finishes.

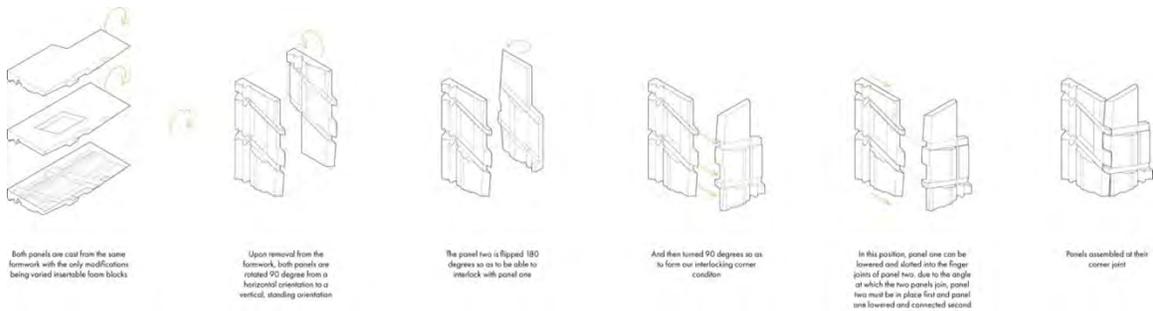


Figure 3: A step-by-step process of casting, removal, and joining the corner panels. This diagram helps to further illustrate the necessary rotation of each panel to ensure that the corner notches will properly interlock.



Figure 4: Screenshot images of a digital model were exchanged digitally, allowing team members to draw on top of the images and suggest new design potentials. These images specifically show the progression of the joint condition including diagonal notch, facet, and idea for faces.

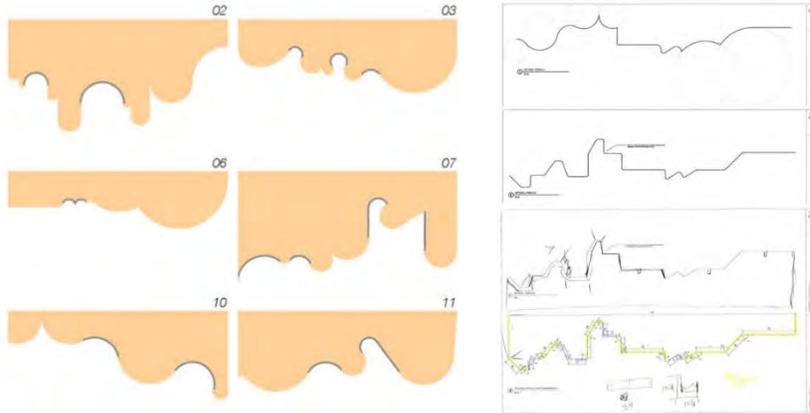


Figure 5 (left): The profile catalogue, left, highlights a selection of referenced profiles that were refined and modified for use on the panel façade.

Figure 6 (right): The shop drawings on the right show how these profiles were translated for our design and underwent a series of modifications to work with the constraints of casting with concrete.

2.3 Translating Digital Intent to Documentation for Physical Production

Initial translation between digital and physical production dealt primarily with the negative – that is, the formwork that needed to be produced in order for the two panels to be poured. This presented many challenges, not least the limit that each group received (2) 5'x10'x1/8" stainless steel sheets to be used to fabricate the formwork. The need for a waffle support grid was initially unknown, and as can be seen in fig. 7, accounts for approximately 50% of the total allowance of stainless-steel, however per conversations with project managers at Northeast Precast, it was clear that the grid, spaced at 12" increments, was necessary to support the weight of both the form placed within it and the subsequent 1,500 lbs of concrete poured into the form. Beyond material restrictions, the team also had to consider the simple nature of translating something from a 3-D model, and bring surfaces with no inherent thickness, into dimensional reality. The geometry was complex, with small ledges and other parts that were difficult to make thick. If the team had foreseen these difficulties while working on the design, it likely would have led to a different set of panels. One aspect of this that had been on our minds while designing was the need for slightly canted surfaces in order to prevent the panels from getting stuck in the form as it was being extracted. If we had been less prepared for this, it would have led to a lot of time spent later on remedying this potential problem.

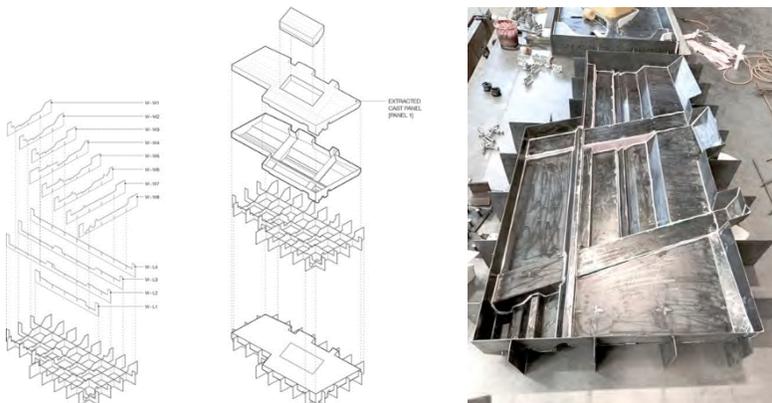


Figure 7: An exploded kit of parts breaks down the design elements, from the assembly of the waffle frame, to how the formwork sits within the waffle structure and where foam block outs are inserted. The finalized formwork was constructed from plasma-cut pieces of stainless steel, bent, and welded together. Seams were caulked for clean edge conditions.

The most satisfying part of the experience for the team, beside the reveal of the final concrete panels, was traveling to Northeast Precast to finish fabrication prior to pouring the concrete. Work at the plant involves assembling rebar lattices per shop drawings that had been prepared for the panels, as well as laying out rebar, CNC-foam block outs, pin anchors, embed plates and other various hardware required for the successful extraction and subsequent erection of the panels. The drawing phase that led up to this final fabrication and assembly day involved much back and forth between the student team and project managers at Northeast Precast to ensure everything was formatted and notated to their standards. Beyond preparation of the drawing

files, teams were responsible for preparing fabrication files for the plasma cutter to cut the stainless-steel sheets as well as instructional files to digitally describe how each plasma cut piece had to be folded – including the location, degree, and direction of each fold. While tedious, it is clear that the preparation of these drawings and digital files were most responsible for successful execution of the fabrication and construction of the panels. As can be seen in figure 8, a clearly drawn and notated set of shop drawings made for easy work when the time came to physically lay out all the elements that went into the final concrete panels that are eventually hidden from view.



Figure 8: Shop drawings proved integral to the fabrication process. Physical assembly and orientation of rebar were nearly identical to shop drawings, as well as placement of foam block outs, pin anchors, and applied retardants.

2.4 Possibilities for Individual Panel Variation and Architectural Implementation

The formwork that was fabricated for the two panels slightly constrained the total number of unique panel options that student designs allowed for given the allowable stainless-steel sheet use from Northeast Precast. Had more material been allotted, the formwork fabricated could be used to create an immense number of unique panels given that there are 9 zones of the panel that can take 3 forms – extruded profile, flat, or void (fig. 9). Each zone may be partially or fully blocked off with theoretically re-usable stainless-steel pieces, which in our fabrication process was accomplished with CNC-milled expanded polystyrene (EPS) foam due to the constraint on the amount of stainless-steel sheet we could use. Beyond this, for the profiled and flat options, each could either be sandblasted or aggregate finished, increasing variability even more.

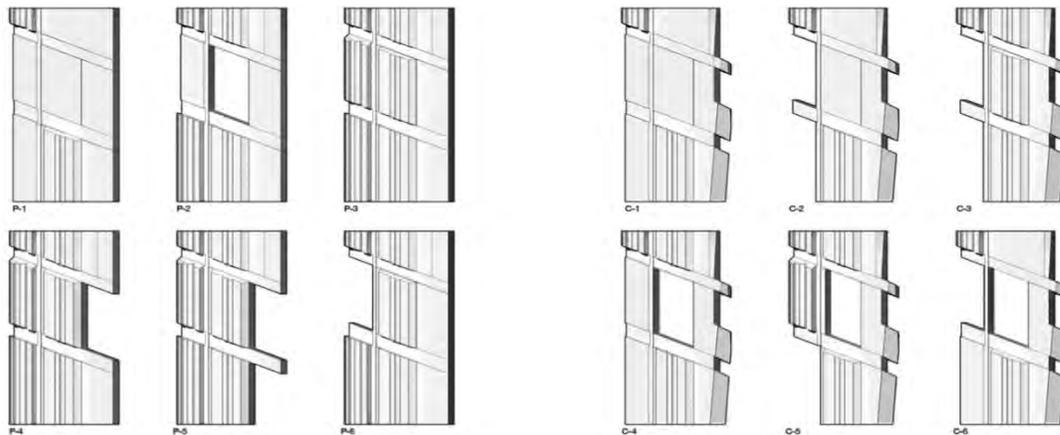


Figure 9: The specific multi zone-based design of the panel façade was a critical component to producing design variability. These zones offer the potential for both flat and articulated faces, as well as openings for fenestration and corner conditions, offering greater architectural interest.

Throughout the project, the team imagined and worked to design these panels such that there would be variation when applied as façade panels. The variation in panels allows for different types of openings to occur in the building allowing for natural light, and creates a highly expressive, and while static, constantly shifting façade due to its play on light. The extruded profiles cast deep shadows that alter its expression throughout the day. It should be noted that for the duration of the course the panels were consistently thought to be the size they were fabricated (4'x8'), but there is of course possibility for a scaling of these panels to a much larger dimension, as we saw first-hand being produced at Northeast Precast. These panels could be increased in size and possibly used on much larger buildings with interesting architectural effect.

3. CONCLUSION

The seminar has proven that collaboration with material and fabrication companies, like Northeast Precast, provides opportunities unparalleled to those typically available in a solely educational setting. Most important is the ability to translate, at scale, something designed digitally to something physical. To successfully translate from digital to physical, the project demanded that we adhere to schedule, material budgets, and required constant back-and-forth communication and collaboration with our project managers at Northeast Precast. Producing these panels continues to be an immensely rewarding experience for both students and the precast company, and the lessons learned by each will certainly carry forward as they further engage the profession and find opportunities to bring material, and precast, solutions into their work.

The COTE Student Design Competition as a Vehicle for Integrative Architectural Education

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ABSTRACT: As the architectural profession becomes more complex, the education of a 21st-century architect requires integrative technological processes to prepare students to design more equitable, resilient, and environmentally responsive interventions. Interwoven design logics and innovative solutions are hallmarks of a holistic architectural design. The prompts that educators devise should encourage students to consider carbon emissions in response to our rapidly changing climate. The Committee on the Environment (COTE) Competition offers a vehicle for integrating these climate-critical issues. This paper will demonstrate how contemporary architectural curriculums can use the newly adapted AIA Framework for Design Excellence to frame larger discussions about the impact of architectural design on equity, ecosystems, water, economy, well-being, resources, adaptability, discovery, and integration. Using a collaborative and integrative approach by coupling a 6-credit graduate design studio with an adjacent 3-credit technology course, architectural ideation responds to the COTE Framework for Design Excellence through the design of a comprehensive building project. Using design methodologies and materialization strategies in relation to equity, and the environment, in the age of rapid climate change demands the need for resilient and innovative architectural solutions. While the COTE Top Ten could, and should, encompass good design at any size and scope, these coordinated studios sought to craft a specific relationship with indigenous cultures and ecologies of a specific place. Our experience shows that crafting finely tuned design prompts can offer an efficient and effective vehicle for entering the design problem with maximum effect. During the past two years, we have coordinated these studios with indigenous tribes to design cultural and environmental centers, allowing the graduate students to specify exact programmatic definitions for their interventions.

Collaboration is an essential component of the architectural profession. As part of this complex and comprehensive studio with a laundry list of requirements, we have instigated teams for this studio project to allow students to hone their designs through constant negotiation with their partner(s) while allowing for increased output throughout the 16-week semester. This inherent complexity of the competition and a client's 'real world' constraints necessitates an architectural response beyond mere formal manipulations. While students are encouraged to submit their work to the final competition, the course is more than just the submission. By learning more about the past histories of the original inhabitants of the land we now occupy, students are confronted with how previous peoples utilized local resources and designed them in relation to distinct climates. Ultimately teaching the students the importance of design integration for an equitable and environmentally conscious future using the COTE competition has allowed a vehicle for cultural discussions to allow for a deeper understanding of place, people, and the power of the design profession for exacting change in our future world.

KEYWORDS: Design Competition, Integrative Studio, Environmental Awareness

INTRODUCTION

Architects play a crucial role in addressing the causes and effects of climate change by designing the built environment. The building industry accounts for nearly 40% of the total CO² emissions, and the global building floor area is expected to double by 2060 (GABC 2017). Innovative design thinking is key to producing architecture that meets human needs for both function and delight, adapts to climate change projections, continues to support the health and well-being of inhabitants despite natural and human-caused disasters, and minimizes contributions to further climate change through greenhouse gas emissions. Preparing architects to envision and create a climate-adaptive, resilient, and carbon-neutral future must be an essential component and driving force in contemporary design discourse.

Climate change is here. Our design education must adapt. While it could be argued that climate change has always been present, one only needs to read the recent headlines to know the rapidity of this anthropogenic climate change occurring now and that our actions are affecting the entire globe. The education of an architect in the 21st century needs to prepare students to design safer, more equitable, resilient, and sustainable built environments. Innovative and integrated solutions are hallmarks of architecture education, the discipline, and the profession. Architects today are responsible for the impact of their work on the natural world and public health, safety, and welfare. As professionals and designers of the built environment, we embrace these responsibilities and act ethically to accomplish them. As Dipesh Chakrabarty stated, "The future emerges directly from the objects we design" (Graham 2016, 23). We need to raise awareness and curiosity within today's design students to wrestle with the complex realities of design interventions in our world. "The image

of green supersedes the actual environmental performance of green – much the same way that the modernists' aspirations for buildings as efficient and hygienic machines became an alibi for adopting the look of the machine..." (Schafer and Lawrence 2011, 4).

1. COTE AND ENVIRONMENTAL DESIGN

1.1 Brief history of environmentally conscious design within the profession

While architectural design trends have evolved, it was a mere 30 years ago that the architecture profession began to formally recognize environmentally conscious architecture in design, founding The Committee of the Environment (COTE) in 1990. Of course, before air conditioning, when architecture was designed to work with a specific climate condition to be more sustainable, had been addressed previous to 1990 (Olygay 1963, Brundtland 1987, Barber 2020). The following year, the American Institute of Architects (AIA) held an exhibition on "Environmentally Conscious Architecture" and launched its Environmental Resource Guide" in 1992. At roughly the same time, the Building Research Establishment Environmental Assessment Method (BREEAM), based in the United Kingdom, began in 1990 to measure and recognize sustainable buildings. In 1994, the Leadership in Energy and Environmental Design (LEED) was created by the U.S. Building Council (USGBC) and most widely recognized in the United States. Other rating systems and protocols, such as Green Globes (1996), and these frameworks have evolved over the past thirty years. Initially focused on the building, many of these programs have created guidelines specific to interior design, existing buildings, and even sustainable sites and urban planning as they aim to take a holistic view of what sustainable design may mean to different subsets of the architecture and planning industry. The Living Building Challenge (LBC) was developed in 2006 as a benchmark for building standards that aimed to move the needle on environment design that not only does *less* harm but create positive change through ideas of regenerative, equitable, and ecologically sensitive design. Each guideline frames sustainable design principles through the lens of architectural building practices, also falling within the 2016 United Nations Sustainable Development Goals (SDGs) framework that demonstrates "our shared vision of humanity and a social contract" to fight inequality, climate change, poverty, and ecologies throughout the world as part of the 2030 Agenda (Ki-moon, 2015). As we approach the year 2030, the profession must make efforts to become more climatically responsive, ecologically attuned, and holistically enhance the lives of its users. Educators should introduce these metrics within our curriculum to recognize this impetus as more than a trend. Figure 01 relates the sustainable objectives of COTE, LEED, LBC, Green Globes, and BREEAM to demonstrate common language alignments while categories such as "beauty" from LBC and "economy" from COTE demonstrate some of the more noteworthy misalignments.



Figure 1: Alignments of several prominent professional sustainable building assessment tools. Source: (Author, 2023)

1.2 COTE international design competition

In 2015, the AIA launched the Top Ten for students with the Association for Collegiate Schools of Architecture (ACSA) to encourage faculty and schools to challenge students to submit projects that thoughtfully integrate architecture, landscape, and natural systems with technology as a design regime. Projects presenting a comprehensive and holistic approach to designing with nature to enhance existing environs. Utilizing the same AIA Framework for Design Excellence helps introduce students to the metrics while tapping into the wealth of information provided through the design guides and toolkits utilized by the architectural profession. Each year, this framework is utilized to create ACSA/ AIA COTE® Top Ten for Students International Student Competition. The competition is announced each summer, through the ACSA website, along with a copious amount of studio and design guides to assist in studio coordination, pacing and implementation.

The AIA COTE framework was initially the COTE Top Ten Measures and only used for 'Environmentally Conscious' architectural projects; for now, adopted as the basis of professional practice and awards across the AIA). The competition recognizes ten exceptional student design studio projects that integrate health, sustainability, and equity evaluated following the same categories that the professional AIA COTE® Top Ten Award for built work uses and the AIA Framework for Design Excellence, with each of the winning projects demonstrating innovative building technologies, design for equitable communities, as well as material, energy, and resource efficiency for the complete design solution. There are benefits to working within a professionally-accredited program, as it prepares students for the architecture practice. However, architecture school is also about speculating and developing personal voices and theoretical frameworks for the graduate. The assessment protocols within the academic and professional structures should complement more exploratory and innovative pedagogical modes. The diagram below illustrates intersections between the COTE/AIA agenda and the NAAB/SC.5 + SC.6 frameworks to demonstrate alignments and misalignments.

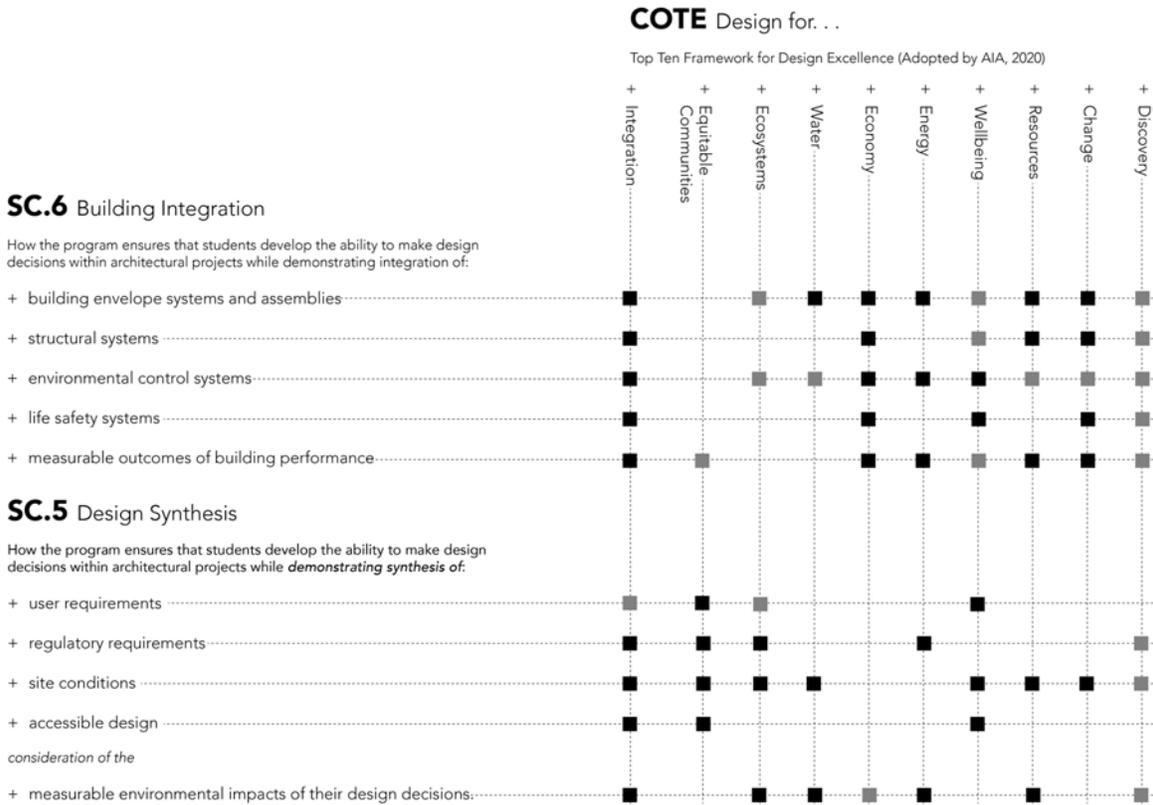


Figure 2: Matrix exploring specific line items of NAAB 2020 SC.5 + SC.6 in relation to the COTE Top Ten Framework for Design Excellence. Black squares are implicit, grey squares as potential overlaps, while no square has unclear or limited connections between the two assessment criteria frameworks. Source: (Author, 2023)

1.3 COTE top ten measures

The COTE Top Ten is a list of ten measures that exemplify design excellence within the project. The full list of measures includes Design for Integration, Design for Equitable Community, Design for Ecosystems, Design for Water, Design for Economy, Design for Energy, Design for Well-Being, Design for Resources, Design for Change and Design for Discovery. Professional and student projects submitted to the competition are evaluated on a broad and inclusive definition of quality design within any number of these areas. It is likely too difficult for a single project to tackle each one of these issues with equal weight, however depending on the program emphasis, scope and design narrative of the project, design solutions likely need to address several of these measures to be successful in the competition. One understated, or maybe understood, issue expressed within the AIA professional guidelines for submissions is an emphasis on aesthetics, in addition to notions of resilience, community connections and performance. Both within the professional interface and the student design competition, the framework is set up as a series of queries to initiate an investigation of how projects address the framework.

1.4 Design for integration

Within the studio, students are required to consider three of the topics in a tangible way, to direct their study. This is often addressed after their initial scheme ideations for their projects around week three. All students must address the first topic – Design for Integration, as the studio is an integrative design studio and a large component of the student learning objectives for the course and its NAAB requirements. Questions relating to the Design for Integration components connect to the larger narrative; What is the big idea? How does the project demonstrate the intersection of design excellence and sustainable performance? Performance is a key term here, as it necessitates qualitative desires grounded in quantitative metrics. The holistic concept identified through one of the following eight or nine metrics.

1.5 Design for equitable community and well-being

Architecture is about people. Design for equity is about extending architectural modes of exploration from a discreet building to an idea of its inextricable connection to the larger community and how it can positively provide more equitable opportunities to the underserved. This differs from the modernist ideal, as a building is separate from context and potentially serves a singular purpose and asks the designer to determine unique cultural and natural characteristics of a given region for their design. In a sense, the ability for the design prompt to occur within an academic context provides a great deal of flexibility in how this can be proposed to the studio. Additionally, questions about who the project is for can also be addressed. In the context of our fall 2022 studio, working directly with the Mescalero Apache and Kiowa tribes provided both a community connection and opened important dialogues and considerations of how architecture can have a greater meaning and purpose. Design for Well-Being can also be constructive here, as the design for people considers the comfort, health, and wellness of the inhabitants and visitors of the buildings. Metrics and imagery that can pertain to Well-Being would be interior perspectives, daylight analysis, views, and connections to the exterior environment. Design for Equitable Community would require consideration of the urban fabric, walkability, and existing transportation networks to allow access to the site, along with the purposeful design of the program to benefit the larger community.

1.6 Design for ecosystems and water

Eco-systematic thinking is relatively new in terms of Eurocentric design education, however, it may have stronger roots within indigenous groups. One example could be Angkor Wat, a Cambodian temple complex built from the 9th to the 15th century AD that incorporated hydraulic structures of dykes, basins, reservoirs, and canals to work within a specific ecology to preserve and complement the existing natural setting. Similarly, investigating how indigenous cultures of North America designed environmental mediations within their surroundings during the fall 2022 semester allowed students to reconsider their own context through different eyes to learn from the cultural significance of the natural world while designing for a specific native population and place. While the previous two measures focus on human health and equitable communities, this measure goes beyond the building to investigate how architectural design can protect and even benefit the larger ecosystem, watershed, and wildlife habitats in the presence of human development. This is a tall task; especially as architectural interventions have an extremely negative impact on the existing ecosystem and wildlife. This measure may preclude the use of a virgin site for development, instead moving prompts to consider urban infill, existing buildings, or brownfields as potential sites for intervention. Additionally, consideration of exterior walls, roofs, courtyards, and landscape features as areas that could create habitat that mutually benefit humans and the larger ecosystem. This larger site consideration and the conservation of water and protects and improves water quality.

1.7 Design for economy and energy

Design for Economy is not typically addressed within a design studio. We often eschew such strictures within academia, and maybe for good reason, as those constraints tend not to serve the exploration of design ideation. COTE offers this measure to consider affordable solutions around the true economy – from first to long-term operational costs while benefitting occupant health and productivity. This measure could be addressed using BIM tools to calculate the true costs of the design but also could incorporate seasonal adaptability of the interior and exterior environments to lower reliance on mechanical systems for thermal comfort and better connect buildings with their climate.

Design for Energy is one that is possibly the best studied, especially since the ubiquity of mechanical systems and building envelopes that have been the focus on architectural design for the past seventy years (Barber). Measurement tools such as Sefaira can calculate how a building's formal design, orientation and material conserves energy resources and reduces the carbon footprint while improving building performance and comfort. A sustainable design could aim to reduce the amount of conditioned space or integrate façade systems to lower thermal impacts of the surrounding environment while also anticipating future energy sources. Examples of how students used Environmental Impacts Analysis tools within the initial design phase to

determine more efficient massing and orientation strategies through comparative design, while investigating Energy Use Simulation to test different material strategies through several iterative studies (Figure 3).

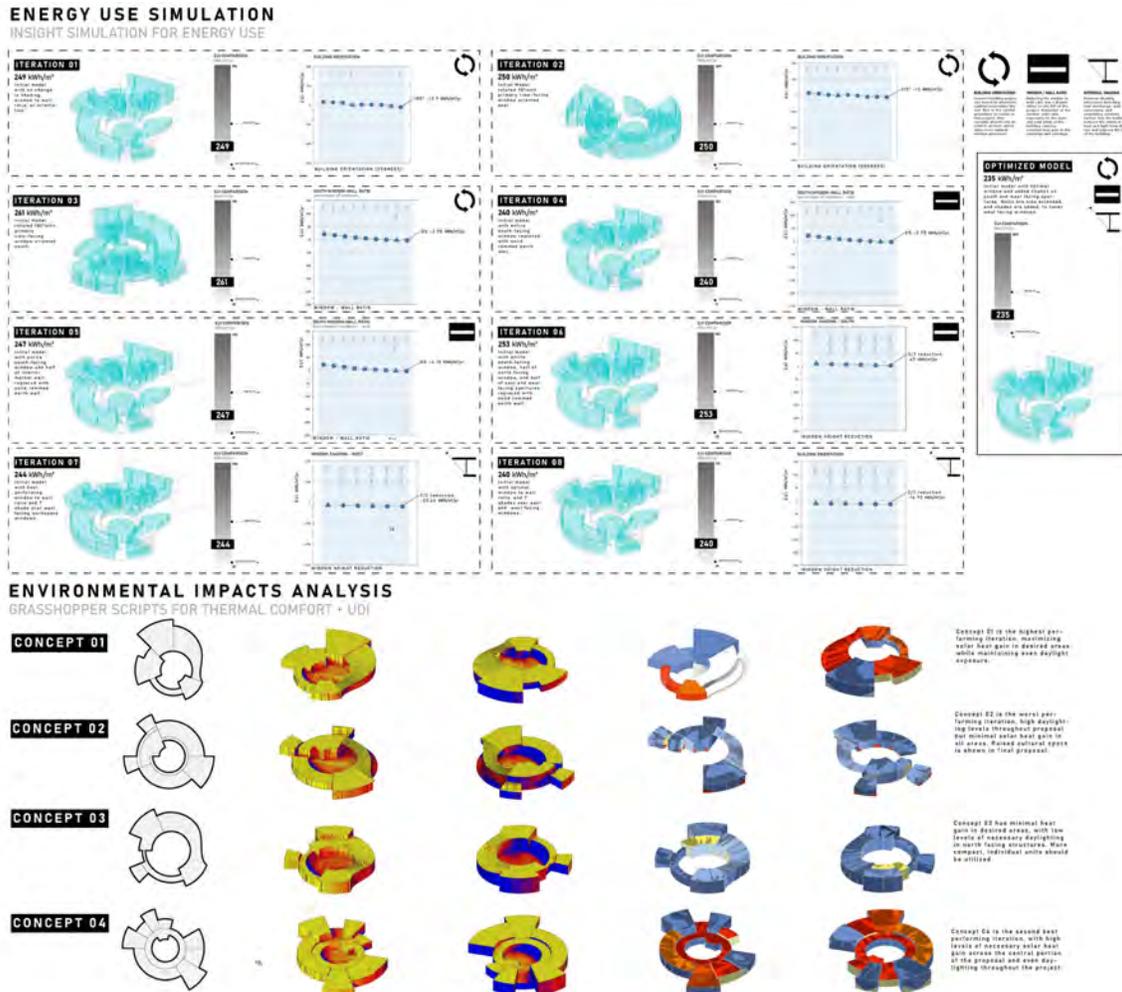


Figure 3: Using environmental analysis tools early in the process, students could revise and refine building orientation and volumetry to achieve energy use goals for their project. Source: (Tyler Glass + Matthew Stevens, Fall 2022)

1.8 Design for resources and change

These two aspects are incredibly important regarding sustainable practices. What we do with the finite materials on our planet, and how we might consider our designs to be adapted to future uses within a community. Design for Resources asks the students to make informed selections of materials and products that consider reducing life-cycle embodied carbon and other environmental impacts while enhancing building performance to prioritize occupant health and comfort. Employing Building Information Modeling (BIM) software tools within the latter stages of the design process in the studio course allows for further inspection of materials to calculate life cycle costs and embodied carbon analysis within the adjacent technology course. Design for Change anticipates adapting a building towards future uses, considerations of the oncoming climate change, and even resilience to anthropogenic (natural) disasters. While not specifically questioned within this framework, retrofitting existing building stock for future lives could also be investigated here. Several winners of past competitions delved into this typology. With the expectation of doubling our building stock within the next thirty years, consideration of dilapidated structures for the future would address both designs for resources and change.

1.9 Design for discovery

This measure is possibly a bit more difficult to design for, as it asks what the building or design process can present best practices for sustainable design as an evolution through documented performance and shared knowledge of lessons learned. This measure is most readily discussed through precedents as evidence of how buildings can be instructive for the students' designs. Potentially, more community or educational-type

facilities could teach users of the building about the power of architecture. Still, this measure might not be discovered until later in the design process. Along with the existing professional examples and toolkits that are readily available and open-sourced on the AIA Knowledge Community website, there are also copious examples of winning student projects over the past eight years. Also, on the ACSA website, there are several program guides available as teaching tools to equip both instructor and learner to the frameworks above, giving a design narrative, questions, and means and methods of addressing each of the ten areas, including suggested graphics, metrics, and sample strategies. Many of the slides are exemplary built projects and winning examples of how these areas are graphically and numerically diagrammed.

2. INTEGRATIVE CURRICULAS

2.1 Technology and design

A three-credit-hour advanced integrated building systems course aligns with this graduate design studio. During this course, professional projects garnering previous COTE recognition for environmental attunement are analyzed, documented, and presented to the entire cohort to share the lessons learned from the environmentally conscious design precedents. Throughout the design process, this supplementary course teaches building performance software that assists students in measuring their own design solutions throughout the design process to determine how their buildings compare with their intentions. Exercises are integrated throughout the semester as their designs grow in complexity. Initial studies on massing and orientation are coupled with energy analysis. Upon determination of initial material and organizational understandings, secondary studies on energy analysis and daylighting are introduced. Finally, once student ideations are codified, extensive structural and material analysis is linked with life-cycle analysis programs to determine the total environmental impact their designs have on the environment. At each iteration, students must compare their written design statements, often organized within the AIA Top Ten Framework for Design Excellence against their ideations' measurable outcomes. The ability to draw on multiple professors' expertise and connect these courses meaningfully during the semester leads to better understanding for the students and more comprehensive projects at the final review. Much like the profession, where consultants are brought in to advise and direct certain aspects of the design process, this adjacent course allows for a richer dialogue throughout the semester.

Many successful responses demonstrate design methodologies that display technical knowledge through the thoughtful integration of passive design strategies, material innovation, and active systems. Many other projects focus on low-carbon material strategies, hydrology, and ecological impacts of the built environment. The integration of these ideas is represented within graphs, data, and diagrams, along with renderings and written words to describe the methodologies deployed and the anticipated effects of the design solutions. Several projects, especially recently, have been specifically designed to enhance an existing community through adaptive reuse, urban infill, and re-using brownfield sites within the larger design strategy. This intelligent land use can positively affect site ecology and address social issues to impact health and wellness. While unable to determine with certainty, several projects seemed to link social and community issues with the overall design prompt. The opportunity here allows for a project to have a life beyond just the classroom and aim for a larger connection with the affected community. If designed correctly, the course could involve a real client group to find more specific data and human feedback on the student's designs. During this past semester, our studio worked with several federally recognized indigenous tribes to attune the students' projects to the needs of the specific community. On several instances throughout the semester, students learned the importance of cultural histories within the designs for their people. This is an important lesson that architectural design is not within a vacuum but needs to address the client's specific concerns. While this step of engagement is not necessary for a successful COTE studio, it provides a potential platform to further the Design for Equitable Community framework that can benefit the community through sharing the final projects.

2.2 NAAB and the profession

Within the longer NAAB descriptions, one can understand how a full COTE competition submission would ensure that students “understand the established and emerging systems, technologies, and assemblies of building construction, and the methods and criteria architects use to assess those technologies against the design, economics, and performance objectives of projects”, as described in SC.4 (NAAB 2020). Demonstrated performance metrics throughout the iterative process to determine the right sizing of a given building, attempts to achieve net zero through demonstrative diagrams and performance simulations during a rigorous design process. In SC.5 Design Synthesis, a COTE submission that begins with the ecology, climate, and specific site and addresses a specific population group would ultimately show a “synthesis of user requirements, regulatory requirements, site conditions, and accessible design, and consideration of the measurable environmental impacts of their design decisions” (ibid). Measuring the environmental impacts of an architecture designed under the AIA Framework for Design Excellence is essential for an integrated design project. Accessible design and regulatory requirements could be explored during the initial and thorough site analysis. Lastly, SC.6 Building Integration requires students to “develop the ability to make design decisions

within architectural projects while demonstrating integration of building envelope systems and assemblies, structural systems, environmental control systems, life safety systems, and the measurable outcomes of building performance.” (Ibid). Many of the requisite drawings for the competition entry include the analytical building section diagramming how external and internal environments are mediated and running these designs through evaluative software such as Insight, Sefaira, and LCA analysis software such as Tally or Athena.



Figure 2: Board 01 and 02 demonstrate the design project's comprehensive nature and integrative approach to environmental constraints and architectural response. Source: (Jared Tejada, Brandon Geiger, Fall 2021)

2.3 Criticisms and successes

The comprehensive nature of a studio that sets its sights on the COTE Student Competition can be both rigorous and rewarding. In addition to satisfying many of the NAAB criteria, the competition also prepares students for the profession with evidence of a collaborative design project that provides ample evidence of their understanding of the complexities of the architectural profession. Of course, students have struggled at various points within the semester. Initial hurdles are met when students consolidate initial ideations towards a collaborative narrative that they need to translate into a formal design strategy. Secondly, students must be flexible with their initial designs to allow for measurable, evidence-based design solutions to be synthesized into their design process. This may be the first time in their education that they must go beyond pure aesthetic, experiential and rule-of-thumb notions of iterative design strategies to rigorously test their designs in a measurable manner. Another issue is the scaling and curation of larger-scale drawings and physical models into the final dimensions required for the competition submittals. Several design exercises, such as wall sections, detail drawings, and physical fragment models to study specific moments within the comprehensive design project require large-scale outputs for design reviews to provide a beneficial critique. Best practices have been to use informal and in-class design reviews to operate in a more flexible manner using physical models, digital and printed mediums for discussion. In contrast, more formal mid-term and final reviews operate within the more spatially restrictive requirements provided by the competition.

Site selection and initial programmatic frameworks can help students jumpstart their design process, while providing room for dialogue and research to individualize student design solutions during the first half of the semester. Students learn about the difficulties and benefits of working with colleagues on design projects. A student's familiarity with BIM software allows for the many evidenced-based assignments within the adjacent course to be integrated within the design studio with ease. In surveying several students who successfully

completed this integrative project found that many highlighted this collaborative, sustainably focused studio project within their portfolio which allowed them to get jobs and do extremely well in professional firms, often leading design competitions within their offices.

CONCLUSION

Using varied interrogation modes, students must delve more deeply into a series of analytical exercises developed collaboratively to elicit thoughtful, comprehensive, and environmentally appropriate massing, orientation, and material strategies (Raab 2019). As this studio is the entry to the professional graduate program, students typically have an architectural undergraduate degree in architecture that prepares them for the rigors of the COTE Competition. While discreet exercises could address several components listed under NAAB's SC.5 and SC.6, NAAB 2020 requires synthetic integration of these elements within a comprehensive project. Utilizing the framework of the COTE and the structure of the ACSA/COTE Student Design Competition allows the combination of the NAAB criteria through a singular design project. Students benefit from the given competition framework, several years' worth of winning projects – both student-led and professional – and necessitates an integrative approach to complex issues. Professional education needs to prepare students to comprehend the complexities of current and future practices while speculating on the breadth of what health, safety, and welfare mean within contemporary society, and the COTE competition provides a curricular structure where students can understand the architectural profession in open dialogue with the bioclimatic, social, and ecological systems that surround us.

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From Integration to Embodiment: An Evolving Approach to Teaching Design and Building Technology

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ABSTRACT: This paper explores how an expanded notion of ‘embodiment’ can provide a conceptual and pedagogical framework for teaching the integration of building technology and design, particularly in the context of comprehensive studios in professional architectural programs. Drawing on the rich discourse around the term embodiment in the humanities, architectural theory, and contemporary sustainable design, we argue that our understanding of embodiment can be expanded to include notions of embodied practice, aesthetics, and knowledge. After outlining this conceptual framework, we go on to discuss specific pedagogical goals and share examples of assignments and student responses from recent iterations of the comprehensive studio at our university. We identify four areas of focus that support a more embodied approach to architectural education: 1) generative models, 2) the problem of the section, 3) assemblies of exchange, and 4) deep specifications. Reviewing each of these areas in terms of their potential to foster embodied forms of design, we outline a set of frameworks for future development of comprehensive building design sequences, and for architecture curriculum in general.

KEYWORDS: Design, pedagogy, embodiment, building technology

1. INTRODUCTION

The hiring of two new tenure track faculty members in the area of design and building technology in our department has become a catalyst for redesigning the comprehensive studio sequence and rethinking the relationship between design and building technology more generally. At the same time, the sudden transition to remote teaching in response to COVID continues to reverberate through the academy, spurring us to reconsider what was gained and what was lost during these disruptive years. Furthermore, the multiple crises facing the discipline – climate change, architecture’s role in perpetuating inequality both within the profession and through its output, and the ongoing disruptions of the digital age – demand new and more engaged frameworks for the conceptualization and practice of architecture and architectural education. These challenges become even more important in the context of building technology, where architecture makes its final affirmative transformation from ideas to materials. In response, our evolving approach to teaching design and building technology, most notable in the comprehensive studio sequence, embraces the reciprocal idea that technical considerations and constraints can be generative opportunities for design and that the technology of building can be understood as rich territory for creativity, expression, and meaning. To capture this, we propose adopting an expanded notion of ‘embodiment’ as the conceptual framework to understand architecture as a dynamic process situated within the nexus of material, energy, labor, capital, and culture.

There is a rich discourse related to the term embodiment in the humanities and social sciences. Broadly speaking, it refers to a shift in perspective from overly abstract, rational frameworks to more unmitigated, felt engagement with the material world in all its vibrancy and insistent material properties (Bennett 2010, Ingold 2007). In contemporary architectural discourse, this term has become most closely associated with the concepts of embodied energy and embodied carbon, concepts that refer to an accounting of the environmental impact that accrues in the processes of making a given building material or product. (Benjamin 2017, Moe 2021). While the idea of embodied energy and carbon is an important emerging framework, we argue that there is more to mined from the notion of embodiment in the context of teaching building technology and design.

Just as embodied energy opens the possibility of comprehending the multiplicity of energy expenditures contained within a building, an expanded notion of embodiment opens the possibility of comprehending the multiplicity of other relationships endemic to an architectural work. This includes understanding embodiment within the framework of aesthetics and knowledge, as well as an expanded understanding of embodied labor, embodied culture, and embodied building and form. It also offers a framework for thinking about the making of architecture through notions of embodied practice. Crucially, viewing architecture through the lens of embodiment compels us to see buildings not as static objects, but rather as conditioned artifacts situated in a complex set of relationships with history, culture, technology, materials, and processes of making. With respect to building technology and design, this compels us to see technical details and technical resolution of architecture as opportunities for further engagement with this embodied nature, rather than merely functional solutions.

2. EMBODIMENT IN CONTEMPORARY ARCHITECTURAL DISCOURSE

Writing nearly forty years ago, Alberto Perez-Gomez diagnosed what he saw as the shortcomings of then contemporary architectural education and practice as a problem of embodiment; namely a failure to recognize and appreciate the extent to which architecture is, fundamentally, a form of embodied knowledge and therefore, an embodied practice (Perez-Gomez 1987). For Perez-Gomez, architecture is necessarily an interdisciplinary endeavor that derives value and meaning in the contemporary era by adopting a critical stance towards culture, thereby generating knowledge. Knowledge (as opposed to mere data or information) is something that grows out of an active interaction with the material world. Architecture's engagement with knowledge is two-fold: first, it generates knowledge through its function as a creative practice, and second, it materializes this knowledge, embodies it within itself, within its material form. Through architecture, material is given meaning, and that meaning is in turn embodied in the physical form of the building. The technology the architect chooses becomes a critical hinge in this double articulation. Writing at the cusp of the digital revolution, Perez-Gomez pushed back against the premise that technological systems that seek to

“functionalize, control and manipulate variables in order to attain greater efficiency and economy...can easily be put to work in the name of humanist values...[rather] the self-referential values of the system (efficiency and economy) invariably dominate production” (ibid., 57).

Instead, Perez-Gomez implores:

“The architect's work confronts technology with desire and thus explores the true potential of new materials. It is by definition new because it is not preconceived; it is a discovery occurring at the intersection of the potential abstraction inherent in modern consciousness with the ground of figuration inherent in the human body itself” (ibid., 58).

Writing three decades after Perez-Gomez, Stephen Kieran similarly diagnosed what he saw as the shortcomings of so-called sustainable architecture as the lack of a robust environmental *aesthetic*. An environmental aesthetic is derived from direct engagement with the natural world, forging relationships that are essential, integrative, and not overly abstracted. Opposing this, Kieran identifies an “additive culture of innovation” (Kieran 2008, 244) where technical solutions, each responding to the problems created by the previous solution, accumulate within the built environment as an ever-expanding technical edifice, taking us, for instance, from the air conditioner to the hermetically sealed glass building to the high-performance envelope, and so on. While the resulting architecture might be “constructive, functional, and ethical” (ibid., 244) it lacks, in Kieran's mind, an *aesthetic* dimension. This results in an architecture that, despite our best intentions, is increasingly alienated from nature and natural systems, and perhaps more critically, undermines architecture's capacity to function as an aesthetic form and thus to “attract.” This is to say, it undermines the capacity of architecture to inspire, to express our collective stories and aspirations, and to render visible the potential and consequences of our actions, activities, and interventions in the material world. The role of architecture to communicate through an aesthetic means is for Kieran “always more potent than force” (ibid., 246), outstripping the benefits from any incremental innovation.

In relation to sustainable design principles, the term embodiment has become most closely associated with the concepts of embodied energy and embodied carbon. Embodied energy, along with operational energy, provide a framework for quantifying the total energy (and by proxy carbon impact) of a building over its lifespan. Embodied energy has gained focus as buildings and mechanical systems become increasingly efficient and as we become more attuned to the carbon impact of the global supply chain of building materials (McDade, 2018). While the conceptualization and implementation of approaches to quantifying embodied energy and carbon is of unquestionable importance, in recent years several architects and scholars have argued that notions of embodied energy should be expanded beyond the mere numerical calculation of energy and carbon to be a critical lens to understand the ways a building, and the material components of which it is made, are situated in the world through their making, use, and ultimate disposal (Andraos 2017, Benjamin 2017, Moe 2021). As Amale Andraos puts it,

“embodied energy renews architecture's commitment to an engaged worldliness – an engagement without which architecture loses its chance for reinvention, relevance, and even existence” (2017, 8).

To understand the embodied energy of a building compels an understanding of the building not as a singular object, but rather as a participant in an expanded, dynamic process. As Andraos further elaborates,

“embodied energy connects the smallest part of a building to territories of extraction, transformation, and transportation, rendering once and for all mute the possibility of architecture as an autonomous object. Instead, embodied energy reveals architecture's potential as a frame for registering multiple and overlapping scales of environment at once” (ibid., 9).

Taken together, the critical lens of embodied energy alongside an appreciation of embodied forms of knowledge and aesthetics, provide an expanded notion of embodiment within architecture; one that resituates architecture within an extended field and opens new readings of architecture and new opportunities for intervention. The existential crisis of climate change and broader recognition of human's planetary impact,

along with the recent, acute disruptions of COVID, have presented the opportunity to reformulate our relationship to the world. This entails a fundamental recalibration of our relationship to technology, one that engages technology not just as a sequential set of solutions (which it undoubtedly is) but also in its social and poetic dimension, and as a historically contingent framework that guides how we, as humans, situate ourselves in the world. This is to suggest that for architecture, perhaps the most important point of creative and expressive exploration is at the intersection of technology and design, for that is where perhaps most effectively, we can reconstitute our relationship to the natural world and to ourselves.

3. EMBODIMENT AND ARCHITECTURAL EDUCATION

This expanded notion of embodiment has become a critical and catalytic tool for examining the ways in which we teach the integration of building technology and design. Building on the work of educators who have developed pedagogy aimed at integrating building technology into the design process in a vital way (Armpriest 2017; Albright et al. 2019), our approach grows out of an ambition to foster a more sophisticated approach to sustainable design that incorporates the cultural and poetic dimensions while better accounting for the complex interrelationship between the built environment and the planet.

A key point of focus for this curricular development has been our comprehensive building design studio, which comprises of a two-course sequence over two semesters. The first, Graduate Design IV, engages students in the design of spatially and programmatically complex public building. The second, Integration Studio, engages students in further design development and technical resolution of the studio project and seeks to enable students to think through a fully integrated building solution from site to detail. Building on the theoretical framework provided in the previous section, we have identified four areas of focus in the continuing development of our comprehensive building design sequence: 1) generative models, 2) the problem of the section, 3) assemblies of exchange, and 4) deep specifications. Each of these categories articulate a set of goals, challenges, and problematizations that organize and motivate our pedagogy in relation to the comprehensive building design studio and in the teaching of building technology in general. They are outlined below, with student work provided to better illustrate our approach and goals.

3.1 Generative Modeling

At the core of an embodied practice is an emphasis on the development of generative models. A generative model is not a thing but an iterative process, an approach to making that draws out conceptual ideas, while imprinting material forms with meaning. It provides a framework for “thinking with our hands and our gestures” (Perez 1987, 58). As Mark Lee and Sharon Johnston recently observed, generative modeling should be iterative and engage “in-between conditions – between idea and building, material and immaterial, problem and solution” (2022, 57). As they further outline:

“A model is not simply a model. It never stands alone but is always part of a larger iterative set, whether the others are present or not. A collection of models is always greater than the single model because it is through the collection that *the model as an idea is measured against the model as a physical form.*” (ibid., 61, emphasis added).

Generative models grow out of a reciprocal process of material experimentation and critical evaluation, building an embodied knowledge progressively through the process. The advantage of founding a design process on generative models is two-fold: first, it foregrounds material practice at the outset, framing the design process in material articulation; and second, it fosters a mentality and a set of design frameworks that are assertively open-ended, and thus can adapt as the myriad constraints (structure, mechanical, code, constructability considerations, cost, user-requirements, etc.) are brought into the process. In other words, the goal of the studio is not to produce a form or idea, but rather a process. This notion of generative modeling represents an embodied form of practice, where architectural ideas emerge through the experimentation with actual, physical material forms, and thus these ideas are constructed as intrinsic to these forms (and vice-versa).

A useful point of reference for introducing students to the practice of generative modeling as an embodied practice is the artist Richard Serra and his Verb List (1967). Consisting of a handwritten list of actions (“to lift”, “to spatter”, etc.), the Verb List conceptualized an open-ended, but highly specific and deeply embodied form of practice that underpinned Serra’s formative early work. By applying a kind of creative combinatorics, Serra engaged a given material with a specific action of his body: lifting rubber, splattering lead, and so on. For Serra, the verbs are “actions to relate to oneself, material, place, and process” (MOMA, 2022); they are way to locate one’s creative process in relation to the physical world of action.



Figure 1. Graduate Design IV Student Work: Generative Models – from Concept to Façade Studies. Image by Erica DeWitt + Lincoln Nemetz-Carlson (2022)

In a recent iteration of the Graduate IV design studio, we used the Verb List as a point of departure for the design of a new building for the United States Mission to the United Nations in Geneva Switzerland. A particularly successful example of this approach can be found in a student project that took the action “to join” as a framework for thinking through their approach for integrating the diverse programmatic requirements. Starting with a simple idea of stacking different programmatic strata, their project evolved and grew more sophisticated as they embraced the idea of wood joinery as a conceptual and material framework to think through the complex requirements and ambitions of the project. Rather than static objects, these generative models operated as a set of material configurations that could be tested and explored to achieve different effects. At the same time, the students’ proposal began to take shape as a critical response to the US embassy building in Athens designed by Walter Gropius. The generative model became a tool for critically assessing the closed, introverted nature of the courtyard typology of the Athens’ building by enabling the students to unlock the courtyard with more nuanced, permeable boundaries. This idea extends from building massing to the details of a system of modular façade screening elements. The physical boundary of the building and the threshold between the exterior and the interior of the courtyard begins to function like a filter that integrates rather than an envelope that “systemically segregates” (Kieran 2008, 245). The proposal goes beyond the “functional fact of integration” (ibid., 245) and suggests an architecture that embodies a critical stance towards material, culture, history, and technical constraints. Understood within the broader pedagogical goals, this project illustrates an approach that engages material properties in the design at the outset while engaging these material systems as a set of possible configurations that help negotiate the space between architectural ideas and architectural form (Lee 2022).

3.2 The Problem of the Section

Writing at the cusp of the digital revolution in architecture, Perez-Gomez could be considered uniquely prescient in anticipating many of the challenges we face as a discipline and in design education. Chief among this is the tendency to conflate information with knowledge and to let fluency with information occlude the creation of true knowledge.

“Computers may indeed allow the architect to have at his or her fingertips all the information one needs [...] but the fundamental problem of meaningless will still prevail” (Perez-Gomez 1987, 57).

One place where we see this play out in contemporary design education (and practice) is in the section, particularly the conceptual discrepancy between a section that is constructed and a section that is derivative. The section is a unique, critical tool for creating architecture. More than any other analytical drawing type, it is the section that most provocatively engages the core functions of architecture.

“The architectural section is the key to architectural innovation [...] the section is the site where space, form, and material intersect with human experience, establishing most clearly the relationship of the body to the building” (Lewis, Tsuramaki, and Lewis 2016, 6).

The section is the tool that enables architects to think through these essential relationships, both conceptually and technically. As such, it is the critical framework where there is the greatest opportunity for the integration of the various functions, both practical and poetic, required of contemporary architecture. This is particularly true of sustainable architecture. There is a way of understanding the problem of sustainable architecture as a problem of the section: the section reveals materials and the relationships between them and, most critically, defines the relationship between the interior and exterior, the threshold between the building and the environment. This can be a practical question about the way a wall assembly manages environmental factors like heat, water, and light, but it can also be a conceptual question that directly targets the essential relationships between humans and their environment. It’s also the site that is most apt to respond to Kieran’s injunction to think about filters rather than envelopes. For Kieran, an environmental aesthetic depends on an embodied relationship with context and environment. This requires interrogating the separation between interior and exterior as a filter that “selectively integrates rather than systematically segregates” (Kieran, 245). The rich potential of the section is often lost when section drawings are merely derived from other sources (e.g. BIM models). It’s the difference between something found and something created, between information and knowledge. With this in mind, we have introduced a number of exercises to interrogate this discrepancy and help student develop an understanding of the constructed section as a critical, and potentially revelatory tool for architectural design both at the scale of details and the scale of buildings.

The first assignment in Graduate Design IV was an in-depth precedent analysis focused on section and exterior facade details. Instead of an outside-in approach to precedent analysis, this was an inside-out approach that privileged the façade as the critical lens for understanding a building as a whole. The goal was to ground students understanding of a precedent building through the section and set the stage for seeing technical details as a site for architectural meaning. In a precedent analysis assigned in Design IV studio, students were tasked with building three-dimensional, “bas relief” style section models. Starting with an existing section of their precedent, students had to build the section up from the two-dimensional space of the paper. The translation from drawing to model and the purposeful pace of physical modelling compelled a different level of engagement and understanding of the section. As before, it grounds students’ understanding of the building through the section and prioritizes the relationships embodied in the section as the critical architectural relationships.

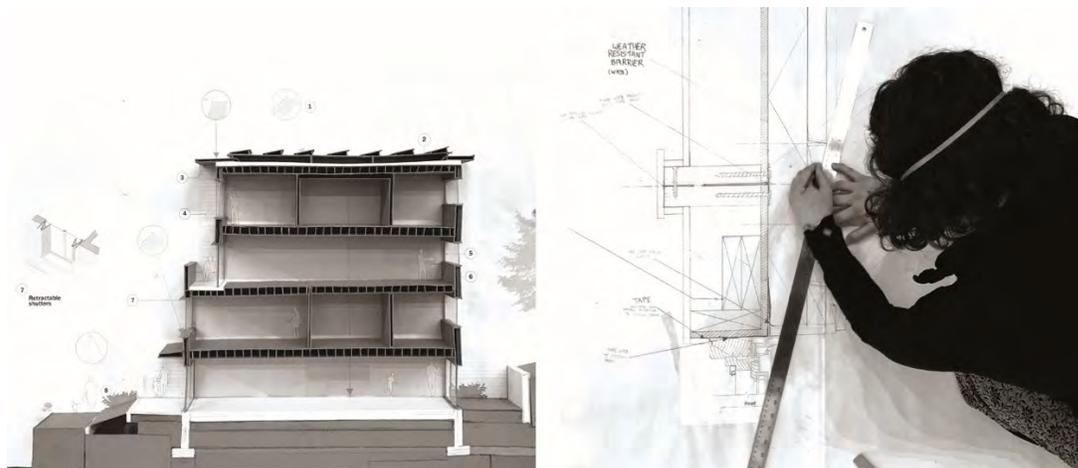


Figure 2. Design IV Student Work: “bas relief” section models. A student literally embodied in full scale sections

Continuing this trend at the scale of details, in an assignment titled “Section Forensics” in the Integration Studio, students were challenged to draw a full-scale section of an assigned building on campus. This required students to visit, observe, document, and finally deduce the composition of the wall section. The explicit goal was not for students to get it exactly “right”, but rather to construct a drawing that could be right. The assignment sought to build relationships between the physical, embodied world and the space of drawings, and to encourage the understanding of the section as a critical tool for investigation. In another course, this

assignment was inverted such that students hand drafted full-scale wall sections of proposed designs. As seen in Figure 2, the students were literally embodied within the space of the drawing. Taken together, this constellation of assignments is intended to engender an understanding of the section as a generative tool for the production of architectural meaning and embodied knowledge, rather than merely as a single, derivative artifact.

3.3 Assemblies of Exchange

Extending the exploration of the potential of the section to engage the threshold between the building and the environment, our approach to teaching building envelope design emphasizes the role of the building envelope not as a separator, but rather as a territory of exchange that negotiates the thermodynamic, atmospheric, biotic, and cultural environments inside and outside of the building (Kieran). Furthermore, the building envelope represents a site of technical and aesthetic intensification. When handled right, the conceptual and performative ambitions of a project can be fully embodied and an *aesthetic* – in Kieran’s sense of the word – can emerge; if not, these will inevitably be drowned out in a myriad of conflicting solutions and functionally expedient decisions. This becomes particularly evident in the context of high-performance building envelope systems, where the performative and technical criteria exponentiate and often overshadow the expressive opportunities of the envelope.

An engagement with building envelope design is incorporated throughout the comprehensive building design studio sequence – including an initial façade precedent analysis and a series of conceptual façade modeling exercises in the Graduate Design IV studio, as well as the development of a series of detailed envelope drawings in the Integration studio. A key part of this exploration, particularly in the later design development exercises include the use of multiple/hybrid drawings that combine orthographic views and/or 2d and 3d detail drawings. The intent of these drawings is to help the students interrogate the assemblies they are developing from multiple points of view and frames of reference and to understand these assemblies as robust systems of three-dimensional elements that must be assembled in a coherent way. We have found that these hybrid drawings, particularly the 3d “chunk” drawings done at the detail scale, help the students overcome the inherently abstract nature of detail drawings, and begin to engage the underlying material and geometric characteristics of the elements in their proposed assemblies.

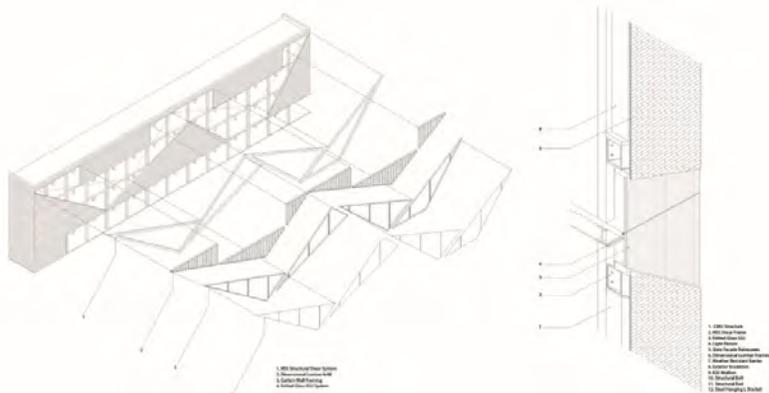


Figure 3. Integration Studio Student Work. Aerogel Façade Panels Image by Kamil Quinteros (2021)

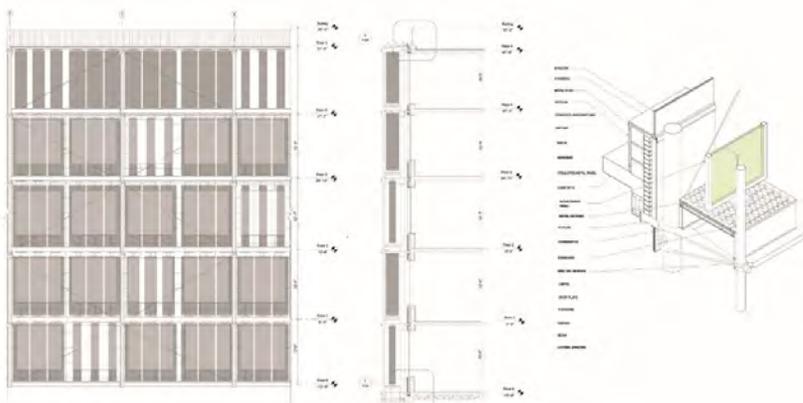


Figure 4. Integration Studio Student Work. Dynamic Algae Fin Façade System. Image by Carly Regalado (2021).

A recent iteration of the Integration Studio focused on the adaptive reuse of an existing academic building on campus. The existing building, constructed in the 1970's, was characterized by a monolithic, underperforming masonry façade with limited apertures. Responding to this existing façade, students developed proposals for the integration of high-performance façade systems as a key part of their overall design. Proposals included large-scale aerogel window inserts (Figure 3) and a system of movable fins that held algae growing containers (Figure 4). As the students developed their designs later in the comprehensive studio sequence, they were challenged to consider the limitations and potentials of the existing masonry façade. Rather than strip the building down to the structure, several students explored the potential to make more surgical interventions into this façade, opening questions about how to improve its thermal performance and introduce more apertures while respecting the constructive logic of the existing masonry system. The constraints and material realities of the existing building forced the students to address the building in a direct way, and the drawings became a framework to interrogate the conditions of the existing building, and to develop a set of strategies for integrating their proposed interventions into the façade. For the algae fin proposal, the student developed a scaffolding approach that created a steel superstructure that tied into the existing concrete structure that both supported the fins and provided lateral support lost through a series of window openings in the existing CMU walls. For the aerogel proposal, the student envisioned a system of steel frames that bridged across the large window penetrations. This student developed a large-scale axonometric drawing to determine which sections of CMU could be saved and used a set of 2d and 3d detail drawings to understand how the existing and new assemblies came together. This approach allowed students to gain a tangible, embodied understanding of the material systems at play, and to begin to manipulate them to achieve the effects they sought out in their designs.

3.4 Deep Specifications

Alongside these exercises, we are also exploring pedagogy to empower students to make informed choices about the materials and products they incorporate in a building. This involves an engagement with an expanded conception of specifications to think about both the performance of materials and systems on a building, as well the broader impact of these choices on the larger ecology of extraction, labor, and energy that is involved in its creation and ultimate disposal. Embodied energy provides a starting point for quantifying the environmental impact of different material choices, however, as Stephanie Carlisle has observed, these numbers, taken on face value, do not tell the full story. As she points out: “Embodied energy is a proxy, like transportation distance or recycled content – a stand-in for a host of relationships and end-point measures that are much more complex and meaningful. Clearly, all megajoules are *not* created equal” (Carlisle 2017, 166).

Life Cycle Assessment (LCA) provides a much broader analytical framework to track the processes and flows of material and energy in the production of a given product, pushing beyond information to generate knowledge about these materials and their history, supporting “deep thinking about materials and places” (Carlisle 2017, 174). And while the complexity of buildings makes LCA a challenging enterprise for architects, its deeper potential is made evident when we shift from an emphasis on determining an absolute quantification of environmental impact of a given set of materials or products, and instead employ LCA as a “means and method to explore a richer narrative about the full history of materials” (Carlisle 2017, 174), and as a “provocation rather than a solution” (Benjamin 2017, 15). Ultimately, as Carlisle reminds us: “A closer examination of materials does not limit design: it empowers and grounds creative practice” (Carlisle 2017, 174).

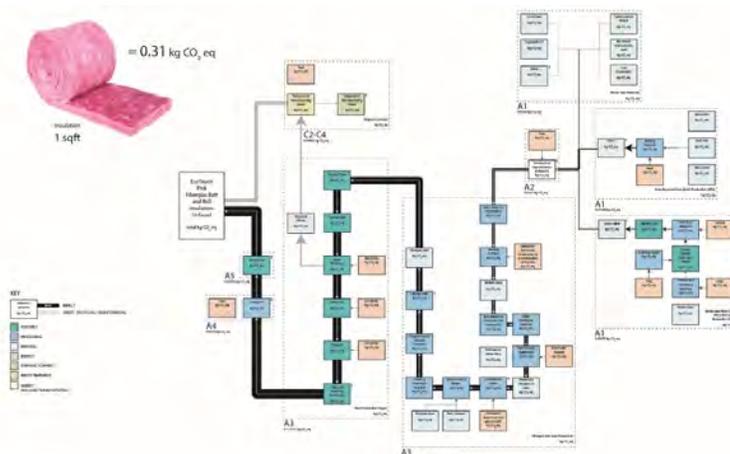


Figure 5. Carbon Mapping: Fiberglass Insulation. Image by Amanda Ferrante (Based on a diagram by Stephanie Carlisle)

Our approach to introducing students to specifications was informed by this approach to LCA and a diagram created by Stephanie Carlisle. Building on Carlisle's graphic language, students employed the analytical methodologies of LCA to develop and understand the ways the global warming potential (GWP) accrues in each product. Students were tasked to take one material in their building envelope assemblies and create a carbon map of its production, from raw materials to delivery on site. Using Environmental Product Declarations (EPD) for each product, students broke the production process into a series of life cycle phases, and then further broke these phases down into specific extraction, manufacturing, and transportation processes. Using GWP data gleaned from the EPD and further refined through additional research and educated guesses about the energy requirements of various processes, students were able to develop quite robust maps of their products and a strong intuitive understanding of the relative GWP contributions in the history of the products production (as illustrated by the line weights of the energy flow lines). This in turn, provided the students with a framework to think about ways in which they can intervene in these processes and expand the scope of design from building in isolation to a deeper understanding of how that building and its material systems operate in the world, and to extend their understanding their building designs as fully embodied forms in the world.

4. CONCLUSION

The four approaches outlined in this article represent a set of principles and frameworks for a pedagogy of embodiment that is still very much a work in progress. They have grown out of intuitive responses to a variety of challenges in the contemporary academy including broad disciplinary shifts in response to the ongoing digital revolution, mounting social, political and environmental crises. We view these approaches as tactics to help students engage in the increasing and unavoidable overlapping of technology, aesthetics, culture and nature, emboldening architecture in its historic role to give meaning to our material world. Ultimately, we view the turn towards embodiment and embodied forms of knowledge in an expanded sphere as a shift that engages architecture with the specific constraints and forces that face the discipline, but also with a much broader set of discourses, from the humanities to the sciences, that will ensure architecture's relevance in a rapidly changing, increasingly complex world.

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How much does your building (model) weigh? On heightening awareness of embodied carbon in the design studio

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ABSTRACT: *This paper describes an academic exercise of our own design, conducted in our graduate-level architectural design studio in a professional architecture degree program. We designed the exercise to highlight the importance of embodied carbon in architectural decision-making processes as taught in the studio context. We report on the background and our pedagogical approach, placing the work in a context of relevant literature. We describe the academic exercise and suggest questions for the next phases of our research work.*

KEYWORDS: embodied carbon, physical models, net-positive

INTRODUCTION

As educators in building design and construction, we aim to heighten our students' awareness of embodied carbon in their academic design-studio projects. In this context, we use the term embodied carbon to refer to the total carbon equivalent (CO₂e) associated with constructing and maintaining a building during production, construction, operation (except utilities), and demolition and disposal, i. e., life-cycle embodied carbon (Hu and Efram 2021; Spector et al 2021; Dewolf et al 2017). Specifically, as studio teachers in a professional school of architecture, our responsibilities include educating our students in the kinds of decision-making processes they are likely to encounter in professional practice. We are pedagogically interested in highlighting factors that can inform design decision-making processes, and specifically in the physical models students construct as part of those processes.

Our work is guided by our long-standing research interests in architectural studio pedagogy (Christenson and Srivastava 2005; Christenson and Aly-Ahmed 2007; Christenson and Barnhouse 2008; Christenson 2013; Srivastava, Christenson, and Atwood 2015; Christenson and Srivastava 2016; Christenson 2017; Srivastava and Christenson 2018; Srivastava 2020; Srivastava, Barton, and Christenson 2020; Christenson 2021). We also recognize that architecture students are expected to possess a growing and evolving set of knowledge, skills, theories, and analytic methods (Thompson and Soccio 2022; Khodeir and Nessim 2020; Mari et al 2019). They should also be proficient in working at various scales, from details to systems, and understand the complex factors that impact their readiness to join professional practice (Akimova et al 2021). Within this expansive context, our prior work has suggested the value of cooperative work structures in creating new knowledge within the architecture studio (Srivastava 2020).

These interests led us to design and implement the approach described in this paper: an extended exercise in which we asked our students to consider the weight of their physical models as proxy registers of embodied carbon in their evolving architectural design projects. While the work is at an early and speculative stage, we have preliminary indications of its promise for our next implementation.

1. BACKGROUND

1.1 Pedagogy of physical models in architecture

Briggs (1929) expressed a traditional assumption about architectural models when he insisted that models are valuable registers for posterity only to the extent that they enable us "to realize how an artist transmitted his [sic] ideas to those who were charged with carrying them out" (Briggs 1929: 174). In this view, models are primarily useful for communicating concepts to others and only secondarily as tools for the working-out of ideas. Contemporary literature has expanded this view to allow for recognizable and useful distinctions between different kinds or types of models and their respective roles in architectural pedagogy. For example, Nour Afify et al (2021) distinguish between "concept models," "schematic models," and "presentation/finished models," associating specific pedagogical expectations with a defined project timeline. Distinctions such as between "spatial models" and "structural models" (Dunn 2011) or between "sketch models" and "massing models" (Mills 2011) can help to clarify a particular model's focus, i. e., to the exclusion of issues deemed extraneous or distracting. Dunn (2011) also distinguishes between "descriptive," "projective," "evaluative" and "explorative" models, thus usefully identifying models with specific kinds of questions, echoing Echenique's (1970) categories of "descriptive," "predictive," "explorative," and "planning" models.

An alternative approach to categorizing architectural models is to de-emphasize distinctions between *types of models*, highlighting instead the *distinct uses which models are brought to serve* within extended design

decision-making processes. To illustrate this point, consider that any given physical model can be conceptually framed as both a tool for iterative development and as an artifact supporting public presentation, e. g., in cases when physical models resulting from iterative decision-making processes are exhibited publicly, or in cases when models constructed for presentation purposes are framed as momentary concretizations of ideas and concepts, as steps along the way toward something not yet fully defined. We might call these “provisionally final” models. In this way, it is possible to distinguish architectural models’ *epistemic* function (“what they are for”) from their representational nature (“what they are of”) (Gouvea and Passmore 2017; Cannaerts 2009). Similarly, Starkey (2007) differentiates between “building a model” and “modelling a building” (Starkey 2007: 239). While the former creates a speculative space for design research and materiality, the latter involves a scaled-down or full-scale representation of a building.

1.2 Physical models and embodied carbon

Frei Otto is recognized as a pioneer investigator of relationships between modelmaking and what we now refer to as “embodied carbon.” Although “embodied carbon” terminology was not available to Otto, his interests in pursuing lightweight, mobile structures clearly indicate his sympathy with contemporary aims to reduce embodied carbon through addressing material waste and inefficiencies (Whitehead 2021). Similarly, Gaudi’s approach to modelmaking (Tomlow 1989; Tomlow 2011), or that of Heinz Isler (Chilton and Chuang 2017), insofar as these approaches pursue formal and material optimization, are early examples of physical models as devices for material exploration and particularly material minimization in building and construction. Otto’s work in particular is remarkable for its transcendence of “purely physical haptics” in achieving results of political and cultural significance (Vrachliotis 2020: 15).

Questions of optimizing model weight or of maximizing material efficiency are commonly addressed in structural engineering pedagogy (Guerguis and Pitts 2021; Schmucker 1998). Transcending optimization as a sole criterion for success, engineering pedagogy also engages physical models in “playful” and generative situations (Vrontissi et al 2018: 1-2).

In the context of our studio, we positioned physical models as having several specific epistemic functions, the principal one of which was to support an iterative development of ideas and concepts. This aim is not necessarily directly connected to material efficiency. For this reason, we asked students to construct “Re-Use Strategy Models” in pursuit of identifying a specific strategy for re-using the existing building at the core of our studio. Re-Use Strategy Models are constructed from found or recycled materials, and are expected to be “sketch” or “pedagogical” models, as defined by Johnson (2007), meaning that they should “incorporate a subset of the [building’s] authoritative dimensions, or ... simplify the geometric forms in published drawings” (Johnson 2007: 2). To state this expectation differently: the Re-Use Strategy Model is constructed at a specific scale; it is a formal abstraction or simplification; it is speculative, even as it makes reference to the existing conditions. A student, in an early-semester conversation, aptly characterized our approach to the Re-Use Strategy Models as being concerned with “the “quantity(?) and quality of ideas rather than the quality of craft.”



Figure 1: Students collecting Re-Use Strategy Models, January 2023. Source: Author’s photo

Centrally to the question in this research, we also positioned physical models to increase student awareness of embodied carbon impact on design decisions.

1.3 Embodied carbon in digital models

With respect to their role in heightening awareness of embodied carbon, digital models are much more thoroughly explored in the literature than physical models. Pedagogies of building information modeling (BIM) and its connections to life-cycle analysis (LCA) are particularly prevalent in the literature (Farid Mohajer and Aksamija 2019), and BIM’s integration into the architectural discipline continues to open opportunities for

embodied-carbon analysis (Soust-Verdaguer et al 2017). Integrating LCA into pedagogy, supported by BIM, engages students with sustainability assessments, making it possible for them to routinely incorporate them in their decision-making processes (Gomes et al 2022). Tools such as EC3, Athena Impact Estimator and the Tally Carbon Calculator (Yan et al 2022; Cameron 2020) provide visualization methods for embodied carbon impacts. Furthermore, custom tools and particularly parametric methods can provide robust methods for querying digital models (Hollberg, Genova, and Habert 2020; Hollberg et al 2016).

2. THE STUDIO

The work we describe here concerns an architectural design studio which we co-taught in the spring semester of the second year in the three-year professional Master of Architecture (M. Arch.) program at the University of Minnesota. Considered as a semester-long experience, the studio introduces professional graduate students to the integration of architectural design, environmental technology, and high-performance regenerative practices.

2.1 Half-Semester Modules

The studio is organized into two half-semester modules, namely, “net positive design” and “integrated design.” “Net positive design,” the focus of the studio’s first half-term, relies on Mang and Reed’s (2015) definition of net positive, i. e., referring to “buildings that ‘add value’ to ecological systems and generate more than they need to fulfill their own needs” (Mang and Reed 2015: 7). Although students in the studio are free to make design decisions in pursuit of zero-energy use or positive energy production, the “net positive design” studio aims more broadly to engage approaches such as biophilia (Guzowski 2015, Guzowski 2021a, Guzowski 2021b, Guzowski 2022). “Integrated design,” the focus of the studio’s second half-term, is generally agreed to refer to the decision-making processes involved in integrating “building envelope systems and assemblies, structural systems, environmental control systems, life safety systems, and the measurable outcomes of building performance” (NAAB 2020).

In a typical year, the second-year M. Arch. students are organized into three or four sections of nine to 12 students, each section led by two instructors, one of whom is assigned to teach the first half of the semester (“net positive”) and the other to the second half (“integrated design”). While all of the second-year M. Arch. students share a common, aligned schedule (e. g., common lectures, consultant workshops, and energy modeling training), each of the studio sections addresses a unique project.

2.2 Our pedagogical approach

In spring of 2023, we co-taught a section of the net-positive and integrated design studio. Our section enrolled ten graduate students. In our studio section, we chose to position existing buildings as *congealed repositories of matter* (material) and *effort* (labor and energy). In this view, existing buildings are understood to be capable of operating as instruments of net positive impact, whereby matter and effort are fluidly coaxed into responsive, regenerative and resilient configurations. Processes of coaxing, so defined, necessarily involve second-guessing and hindsighting those decisions that led to the construction and operation of the building under study. Framed in this way, our approach aimed to engage students in understanding building science principles, systems, and performance frameworks. In this context, we framed a studio project to materially transform an existing (1936) three-story building in Minneapolis with the potential for a cold climate courtyard. We challenged our students, in addressing the existing building, to work within a range of operations within three strategic extremes: reincarnation (-100%), existing as-is (0), and reconfiguration (+100%), without adding either footprint or program. We positioned the program as transitory: while we left the question of program open, students could choose to work with the building’s existing use (university offices, classrooms, and study spaces) or propose new uses. We posited a new form of practice, where architects are commissioned to not add or subtract program but to reconfigure the existing for better performance. Performance, in this case, was defined qualitatively (enhancing experience, comfort, and function) and quantitatively (reducing footprint in terms of operational and embodied carbon).

Similarly to our past studios, we worked with our students to form *cooperative work structures*, trading drawings and models, teaching/learning concepts and skills (Srivastava and Christenson 2018). This approach is aimed at prompting operative questions such as: how do we foster and encourage the “shifting allegiances” to ideas and concepts that inevitably occur in the design studio in order to maximize learning (Srivastava 2020)? In addition to cooperative work structures, we proposed a combination-drawing and combination-making method of work and study, in which each student took ownership of a segment of the existing building, researching, observing and documenting understanding of the whole through an in-depth understanding of a part of the building. Students taught each other what they are learning from the deep examination of that one segment of building that they are working on. With this work method, we hoped to understand the relationship between work quality in the studio and wellness of the students in the studio. Could a cooperative work structure not just be a method to enhance learning (Srivastava 2020) but also improve wellness?

The Net Positive studio brief was originally proposed by our colleagues, Mary Guzowski and Richard Graves, based on Mang & Reed’s approach towards net positive, as buildings that add value to the ecological systems that they exist within (Mang & Reed 2015, Srivastava 2020). As such, the process of iteratively achieving modeled Net Zero performance based on Architecture 2030 goals, was only part of the pedagogical consideration of the studio. In our section, we developed the “net positive” consideration through random assignments of each of the the aspirational AIA Framework of Design Excellence, provisionally ten frameworks, one for each of our students. This assignment of one framework for each student also allowed us to further examine the potential of cooperative work. We asked the question, can depth emerge from the ability to focus on a single framework and can breadth emerge from the students teaching each other the framework that they were responsible for researching?

2.3 Description of the extended exercise

Within this overall context, we designed an exercise to highlight the presence of embodied carbon in student decision-making processes. Through this exercise we ask students to again examine questions that we had previously asked in a class called Architecture as a Catalyst through a full scale investigation of materiality (Srivastava 2023). Examples of questions included the following. How can we incorporate formal geometries that help reduce the amount of materials being used (Srivastava 2022)? How can we examine local material systems and minimize or make redundant energy-consuming systems (Maierhofer et al 2022, Srivastava 2022)? How can we change the composition of materials to include bio-based, responsive materials? How can we position the reuse of materials to promote local circularity without creating a waste-intensive system? How can we see local vernacular and craft cultures and practices irrespective of industry and potentially apply them to the building industry? However, in this studio we deliberately asked students to examine these questions through scaled representations as having a material effect on the architectural form and geometry, the quantified footprint of the structure as a whole and the potential experience and comfort of occupants. As part of the studio’s iterative design activity, we asked our students to construct physical models of their evolving design projects at various moments in the course. In our first attempt to initiate this exercise in the studio environment, five of our students completed full sets of models over a round of three iterations. We asked the students to weigh their models and report the results (Table 1).

Table 1: Average model weights, first three iterations.

	<i>Student 1</i>	<i>Student 2</i>	<i>Student 3</i>	<i>Student 4</i>	<i>Student 5</i>
Iteration 1: Average	15g	31g	25g	224g	43g
Iteration 2: Average	27g	37g	23g	241g	56g
Iteration 3: Average	46g	35g	11g	19g	68g

Following the initial implementation of the exercise, we asked students to respond to several questions, with responses ranked on a five-point scale, numbered 1 through 5, the extreme ends of which were labeled “strongly agree” (at 1), and “strongly disagree” (at 5). The questions and the most frequent responses, sorted in order from greatest agreement to least agreement, are included in Table 2.

Table 2: Survey questions.

Question	mode response (1 = strongly agree; 5 = strongly disagree)
Being asked to weigh my models increased my awareness of embodied carbon.	2
In the future, I am more likely to weigh my models as part of my design decision process.	2
I feel that there are important connections between model weights and the decisions I will make about building design.	2
The model-weighing exercise has helped me to understand the importance of material selections in design.	3
My understanding of embodied carbon improved as a result of the model-weighing exercise.	3
After weighing my models, I will be more conscious of my material choices for future models.	4
The model-weighing exercise helped me to understand the consequences of early-stage design decisions.	4

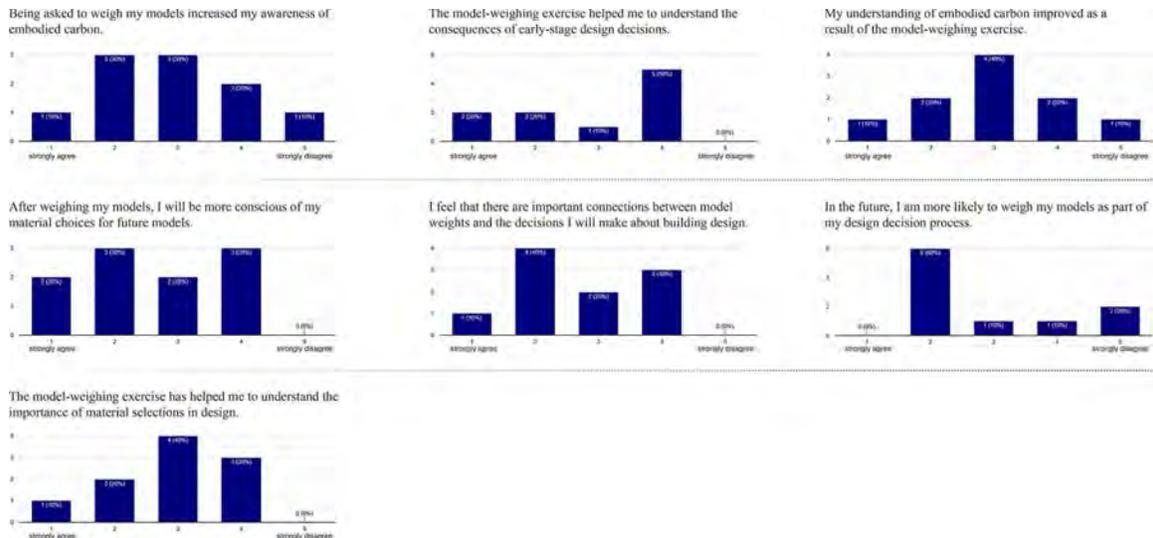


Figure 2: Summary of responses to survey questions.

Acknowledging the small sample size ($n=10$) and the likelihood of distorted results (e. g., due to central tendency bias, acquiescence bias, social desirability bias, etc.), we observe per Figure 2 that in general, the students were more likely to agree with the following statements: “Being asked to weigh my models increased my awareness of embodied carbon”; “In the future, I am more likely to weigh my models as part of my design decision process”; and “I feel that there are important connections between model weights and the decisions I will make about building design.” Students were least likely to agree with the following statements: “After weighing my models, I will be more conscious of my material choices for future models” and “The model-weighting exercise helped me to understand the consequences of early-stage design decisions.”

2.4 Opportunities for pedagogical development

As we look ahead to future implementations of the exercise, we acknowledge that our informal survey results are not yet sufficient to demonstrate that our strategies were effective in increasing awareness of resource usage in comparison to alternative methods, or even in comparison to a standard class baseline. The questions we asked in the survey could be too suggestive, and we suspect that a comparable outcome could arise even within a control group. In a situation such as a design studio, where the sample size is small, we expect that it could also be valuable to collect written or oral feedback from students, instead of depending solely on numerical data which may not be statistically meaningful. In the future, we will aim to obtain this kind of qualitative data in the hope that it will be more insightful as well as beneficial in terms of improving the approach.

We also aim to engage the exercise with greater rigor and specific constraints. For example, the materials used by students in their physical models varied, presumably corresponding to “real-life” materials with differing amounts of embodied carbon per unit weight. Thus, in the future, we will ask students to calculate both the total weight and the per-material weight of their finished models as well as any material acquired for the purpose of building models but ultimately not used (i. e., the “waste material”). We will ask our students to weigh (a) the model and (b) the waste material. The sum of these two quantities is (c) the total material weight. Finally, we will ask them to calculate the material efficiency (d) of the model by dividing the total weight (c) by the model weight (a). The calculations will be recorded and compared across student projects, and we will re-ask our survey questions, tabulating the results for comparison.

Fundamental to our ongoing development of this exercise is the decided ambiguity between (a) the open-ended conceptual development that the models are designed to support, and (b) their quantifiable weight. However, we feel that this kind of ambiguity is characteristic of architectural decision-making processes, and in the future, we intend to problematize it more openly and directly.

DISCUSSION

In a collaborative and iterative effort, we guided our students through a cyclical process of quantification and creation. Our pedagogical position is that this cyclical process is uniquely capable of providing prompts and provocations on the iterative development of architectural concepts. The purpose of this exercise is not to accurately measure the embodied carbon in the student models or design proposals they represent. Instead, our hope is that the exercise, once fully developed pedagogically, will raise students’ awareness and encourage them to consider possible impacts of their material choices. Beyond this, the exercise could prompt the students to recognize relationships between their model-making decisions and corresponding building

design decisions. In these ways, the exercise promises to provide a worthwhile provocation on what would otherwise be an unquantified pursuit of conceptual development.

Because we rely on model weight and material weight as proxies for embodied carbon, we are specifically exempting the students from directly analyzing the extent and impact of such factors as extraction, processing, transportation, and recycling of building materials. Nevertheless, we expect that students will as a result of the exercise begin to articulate and develop questions concerning the lifecycle of their model-building materials. Furthermore, that the student research will both prompt students to conduct research on the larger-scale question of (real) building materials, and that it will provide them with exposure to -- and experience with -- tools and methods for lifecycle analysis of their academic projects.

When Buckminster Fuller asked "How much does your building weigh," he provoked new ways of understanding decision processes in building design and construction (Zung 2001). We envision this exercise becoming a formalized part of our studio process, as a way to heighten student awareness of embodied carbon and to trigger questions about it, much in the same spirit. While Fuller's interests were driven by efficiency, ours are driven by the concerns identified earlier in this paper, specifically a concern for carbon emissions, contextualized by our expectation that cooperative work structures will improve work quality.

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Lessons from an Integrated Design Course

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ABSTRACT: *Integrated design is an activity that promises improved built outcomes by factoring technical and performance goals throughout the entire design process. It acknowledges that technical knowledge, typically provided by engineering consultants, is generally layered onto schematic design ideas. Often these specialists do not internalize the visions of architects and stubbornly assert themselves. Additionally, environmentally responsible architecture is best conceived of holistically, especially if passive design strategies are to offset mechanical and electrical solutions that are historically accepted as the appropriate way to solve for larger objectives of thermal and visual comfort.*

In architecture school, knowledge understood to be necessary to achieve integrated design has largely been relegated to technical courses executed in a lecture format. A benefit of utilizing a lecture format for these courses is that they are suitable to foregrounding and evaluating factual information. Drawbacks to relying on a lecture class format for technical subjects include large class sizes and limited opportunities for project work; factors that are compounded by limits of time in required courses for addressing technical knowledge. Challenges to integrating technical knowledge into studio courses includes the notion that foundational knowledge is best introduced outside of the studio, although some programs have incorporated engineers as studio consultants and studio instructors.

A premise of the experiment addressed in this paper is that architects are synthesizers of knowledge and better qualified than engineers at recognizing social, programmatic and visual factors as relate to design and building. In other words, the art of architecture cannot be separated from creating a material artifact. This means that effective architects are needed if integrated design is to be realized consistently and that relying on practice as the place where integrated design skills are introduced is not adequate. Another premise is that integrated design outcomes need to be assessed in relation to criteria unique to the project as well as criteria from outside such as code. Like architecture in general, there is no single litmus test for successful integrated design. In this light, integrated design is not achievable without a program tailored to the project and designers who value the expressive potential of design, building construction and building performance.

Given the opportunity of running an elective graduate research seminar, the author of this paper introduced a design problem for a small building (artist's studio) with the expectation that students could manage and recognized conflicts related to program objectives and technical factors. Key to this effort was forcing students to identify and acknowledge design criteria that they developed. Prior to engaging in design, students participated in discussions on readings related to integrated design theory. At the conclusion of the design process, students were tasked with reflecting on the theory and their experience balancing tensions between design criteria which were unique to each student. Challenges included showing students that art and construction realities are compatible.

KEYWORDS: Integrated, Sustainability, Goals, Criteria, Programming

1. INTRODUCTION

The challenge of preparing future architects to practice integrated design is in many ways similar to the challenge of preparing students for sustainable practice. Overlaps between the two contribute to a misunderstanding that they are the same, as are the fundamental competencies required for success. Both approaches require significant technical knowledge which has proven difficult to instill in school and require the ability to weigh the impacts of design well beyond building completion. Limits to both topics are imbedded in traditional curriculum structures and cultures that resist expansion of their scope in architecture schools. However, unlike sustainable design, design objectives includes specific environmental factors as represented in assessment programs such as LEED but are less tightly bound to them as other considerations can take priority and drive the design process. These can include a greater variety of design objectives, such as safety, durability and maintenance, but are often discounted in pursuit of goals that align with sustainability measures. Another major difference is that integrated design objectives, and the means to achieve them, have to be deliberately acknowledged and weighed against each other.

Currently, a comprehensive design studio, but not an integrated design course, is required at this author's school, so he took the opportunity of offering a graduate level elective seminar to address the subject directly. As a registered architect with significant practice experience and an academic who teaches technical courses in addition to design studio, the author decided to craft a course that combined theory with a design project meant to allow students to come to grips with issues fundamental to integrated design. Unlike integrated design case studies that typically involved complex mechanically driven environmental control solutions, a

small building problem was introduced to factor out mechanical systems that student were not facile with yet. The result was a hybrid course the spanned approaches used in studio and non-studio formats.

2. INTEGRATED DESIGN DEFINED

Integrated design is an activity that directly engages the fact that engineered building systems, especially mechanical, are such a large part of buildings that architects must be more proactive in making them part of well resolved buildings. It also acknowledges that quality design solutions involve more than system integration to encompass complex problems that are often cultural. These are problems that can't be exclusively understood and resolved through a lens that author Leonard Bachman categorizes in his book *Integrated Buildings: The Systems Basis of Architecture* as industrial (scientifically grounded). Integrated design promises more holistic outcomes by factoring technical and performance goals throughout the entire design process. It acknowledges that a better balance between the objective and technical parts of building knowledge need to align with the components of architecture culture that includes meaning.¹

Like sustainable design, building performance in integrated design is fundamental for success. One of the reasons is that managing and reducing reliance on engineered systems are intertwined with methods for making buildings. Another reason is that both require the architect to provide leadership on how questions of performance are solved, putting architects at odds with the prevalent culture in which engineered solutions are supplemental to architecture and often run counter to architectural objectives. Examples are the goals of utilizing passive thermal comfort and daylighting techniques in which investment in elements such as insulation, shading devices, venting and strategically placed windows can reduce mechanical systems size. Integrated design can also place value on expressive and experiential outcomes such as views, functional relationships and sense of place. Considering that it is difficult to optimize all goals, integrated design encourages compromise and negotiation.

3. PROBLEMS OF EDUCATION AND REPLICATION

Components of integrated design are baked into the DNA of design education but does not ensure efficacy in practice. Practitioners who find success can learn while doing after formal training provided they are persistent and effective learners and can work in situations that where their actions are appreciated. However, successes of some practitioners does not guarantee that the majority of practitioners are able to replicate those accomplishment. As is the case with celebrated designs and designers, the profession of architecture is content with success at the margins despite arguments for broad diffusion of well-integrated buildings. Rather than relying on the current cadre of architect practitioners, a better guarantee of capable integrated designers, is to prepare graduates in greater number that will be able to demonstrate success in practice scenarios big or small.

The subject of scale is one that challenges school culture as it is susceptible to an all-or-nothing approach in which students are expected to impress a design jury who have not observed the process the student engaged in. This experience is valuable in that it simulates the experience of selling a schematic design to a client, but it misses other opportunities for designers to establish expectations and educate owners. Design reviews are conducted in a context in which the simulated clients are more experienced designers who are unlikely to be swayed or informed by the student. In reality, success in an architecture project need not be compelling and combined with a dazzling presentation. Success can be measured statistically, experientially and ultimately should be measured over long durations.

Another issue with architecture school is that it centers on the design studio where students are immersed in the unique aspects of the design process while honing representation and presentation skills. Projects simulate actual building programs allowing students to build confidence and familiarity with practical factors while learning how to push the envelope on conventional solutions that in practice are constrained by regulations, financing and limits of client preconceptions. Educational content that is more closely related to fact than process are largely constrained to non-studio courses delivered in a lecture or seminar format. A result is that concrete knowledge is inconsistently applied in studio where practices approaches are ingrained, and design activity is largely absent from non-studio courses. The adoption of comprehensive studios have helped ground systems related knowledge in the studio sequence, although requiring students to incorporate mechanical systems into large building designs does not necessarily allow for alternative paths that deemphasizes normative engineering solutions. Language on integrated design in the most recent NAAB Conditions for Accreditation are distinct from definitions of design synthesis in the document and assessment structure. This can lead to misconceptions the two can be independent and bind notions of integrated design too bound to closely to engineered systems integration.

Resistance to incorporating concrete knowledge and real-world design constraints into design courses is a result of emphasis on soft skills, encouraging originally in studio and the notion that introducing practical

constraints will dampen fluid creativity. Thus, a significant amount of acclimation to practical concerns occurs in practice with some structure provided by the AXP apprentice program. Apprenticeship builds on knowledge instilled in school by situating in the realities of practice, but it does not introduce theoretical and technical knowledge consistently, or contribute to the development of design problem solving skills. This allocation of academic and practical learning has been maintained despite the erosion of architects' influence on the construction site, sustainability goals and other performance objectives that building owners desire. A downside of limited exposure to real-world factors, and performance objectives, in school is that architecture school graduates are ill prepared to achieve concrete sustainable and integrated design results if not closely associated with practitioners who can mentor them.

Sustainable design is largely tied to specific design outcomes that are measurable and can be managed with a standard scoring system as demonstrated with LEED and Passive House. An advantage of this is that designs can be shaped to meet scoring criteria reducing the necessity for specific programming goals in order to achieve certification. A standard scoring system for integrated design does not currently exist, and by definition defies existence. Parts of integrated design, such as sustainability, can be accommodated by a scoring template, or measured against existing benchmarks and regulations, but many accomplishments have to be measured against goals specific to the project. Identifying goals and metrics related to measuring success is largely up to the designer and project owners. This implies a programming process that is seldom rigorous in practice.

4. ASSIGNMENTS

The semester's activities were divided into three portions. First, prior to engaging in a design process, students read, assessed and discussed chapters of Leonard R Bachman's book *Integrated Buildings: The Systems Basis of Architecture*. Despite a paucity of books on integrated design, Bachman's framing of integrated design was not passively accepted, but rather scrutinized by the class in a seminar format. The thirteen enrolled students found the reading, much of it dense, interesting, especially when provoked by the instructor's personal views and experiences on practice and education. To provide additional context, students also read chapters from the author of this paper's book, *Constructing Building Enclosures: Architectural History, Technology and Poetics in the Postwar Era*, which highlighted collaborations between architects, engineers and builders. The aim in this case was to demonstrate that integrated design is best achieved when different parties in the design and construction process work collaboratively.

Central the course was creating a design problem (second part) that forced students to identify design goals on their own and to reflect on the impact of the goals on their designs. The site provided to the students was a lot near the school for which the author is designing an art gallery addition. Instead of a gallery addition, students were asked to design a free standing one-room artist's studio with fixed plan dimension at a specific point on the site. By limiting dimensions and location, students were given objective constraints that would prevent diversions such as creating geometrically complicated plans and volumes. By encouraging an open space, students would not be arranging rooms and could focus on space qualities.

Before designing, students were asked to develop their own project objectives, prioritize them and write them down so that they could be referenced through the design process. (Interestingly this is not done in studio courses and instead students are often asked to develop a concept that eludes specificity.) Objectives were to address qualities of outcomes which in practice could be qualitative, such as lumens, but in this case were qualitative since students were not familiar enough with qualitative goals such as insulation metrics. Instead, quantitative goals were baked into goals such as favoring daylighting over artificial lighting. During class working sessions and in individual crits, students were asked to refer to their goals. They were dissuaded from changing their goal, but were permitted to do so. Updating design goals was discouraged, but permitted as knowledge is gained through developing designs.



Figure 1: Digital Model Capture from Above. Source: (Author 2023)

Two reviews, a mid-project and a final, during the semester involved bringing in outside critics. Both critics were practicing architects who were teaching, or had taught, Materials & Methods at the school. Both were also grounded in the fundamentals of sustainable design. This, and the size of the building, made for and unusual discussions which included detailing and construction. During the reviews, students shared drawings of their designs and provided access to their digital models (Fig. 1). Colorful renders were not required and discouraged to focus students and critics on the material of the designs. The first act of each student when presenting their designs was to highlight their most important design objectives (Fig. 2).



Figure 2: Student Presentation Slide. Source: (Author 2023)

After the final review, students were tasked by the instructor to produce a report (third part) that reflected on the tensions, trade-offs and challenges encounters while designing. They were also asked to reference the readings introduced at the beginning of the semester. A reflective exercise was a deviation from the traditional end of project review in design studios after which feedback is limited when provided. Prompting reflection encouraged students to evaluate their process, and improve on it, as the goal of the design project as opposed to producing an impressive product. It was also a valuable opportunity to revisit the theoretical component of the course which is often perceived as supplemental to design.

5. PROJECT HIGHLIGHTS

Considering that the course did not have the duration and a complementary output expectation, of a design studio most of the students in the class were able to respond to the building program in a manner that was not too personal and respected the need to support various types of individuals. (Overly personally derived responses to program briefs are characteristic of most students design proposals from the perspective of the author.) With integrated design, impetus from the program lays at the opposite spectrum from external environment and site in terms of shaping designs. Program also introduces a human perspective that informs the dimension, layout and details of an interior environment.

Extra attention was placed on providing apertures that acknowledge views in addition to the daylighting (particular to art spaces) and the heating potential of the sun. The fact the site is located in one of the poorest areas of Philadelphia prompted issues of security and sense of safety. Since art studios accommodate different sized media, students were reminded that access and mounting options for work. This necessitated modelling different types of artwork such as sculptures. It also influenced the operation of doors by including overhead and sliders.

Wall construction, cladding and roofing became another area of unusual attention on contrast to typical design studio. This was especially true with storm water management as students were pushed to incorporate gutters and downspouts into their designs. In some cases, students incorporated water retention vessels which is particularly valuable in Philadelphia where an antiquated stormwater system is overburdened and there are too many impervious surfaces (Fig 3). With some encouragement, students came to see accommodation as an opportunity and not an obstacle to creativity.



Figure 3: Digital Model Capture. Source: (Author 2023)

6. CHALLENGES

Challenges in the course included limits on the amount of technical knowledge they brought to the course which reflected the curriculum. Most of the students had not taken Materials & Methods within a couple of years, and knowledge of basic construction was not reinforced in subsequent courses. Knowledge from their structural courses was either impractical, too abstract or focused on case-studies for large buildings. Knowledge of basic environmental control approaches were addressed in a required sophomore level course most of this cohort had completed, and the Environmental Control Systems course most of them had, difficult to relate to small buildings. These experiential factors contributed to inconsistencies in sustainably design knowledge. Students also had little to no experience researching materials and products as well as little experience detailing for design. Challenges also included showing students that art and construction realities are compatible and that large gestures were not necessary for good design. Some students overreached by attempting to design a novel assembly without an idea of what architects who established similar precedent were seeking and without an ability to follow through on their ideas.

7. CONCLUSION

As an elective course was implemented in the school for the first time, the class was well received. Students were engaged and demonstrated interest in the subject matter. They were able to produce design proposals that they were willing to invest in and present with confidence and candidness. Students were attentive at the reviews and engaged in productive dialogue. More importantly, the quality of their input suggested that they were grasping the subject at hand. When queered at the end of the semester, students found design a realistic building at a small scale satisfying. Some students shared that they wished there had the opportunity to design without being pushed toward the novel at the expense of solving complex problems. For the instructor, testing the premise of an integrated design course in the context of his program was an important way of learning what students are capable of and interested in. (The latter notion being particularly important if students are to internalize lessons and seek to build on them.) It was also an opportunity to reduce the scale of design project and reduce the tendency for heroic gestures as a proxy for resolved proposals.

Integrated design can be incorporated into a curriculum in multiple ways. Since concrete knowledge of construction systems and materials are important, it is necessary to acknowledge the subject in standard foundational building technology courses. This entails discussing how material and systems choices relate to design outcomes. Integrated design courses should be offered as electives and, if possible, required courses. They should include some basics of building programming if programming courses are not offered. Since non-studio courses do not have the schedule band-width of studio courses design problem, if utilized, must be streamlined and manageable. Traditional studio courses are the most desirable location for integrated design, provided related theory is present. Many comprehensive studio courses involve systems integration, but large scale project generally leave little room for producing and evaluating alternatives. Considering these challenges and achievements, there is significant work to be done to make integrated design a more robust and normative part of architecture curriculums.²

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ENDNOTES

¹ Leonard R Bachman, *Integrated Buildings: The Systems Basis of Architecture* (Wiley: Hoboken, 2003). p. 10.

² After multiple years of discussion at the authors institution about implementing a required integration course, a course is closer to becoming a reality despite related course content that is difficult to relinquish or reassign.

Design for industrialized construction in architecture education: a case study integrating dfma and digital twin in the design studio

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ABSTRACT: This case study aims to contribute to the adoption of Industrialized Construction (IC) principles into teaching. The paper presents the work done in a Master of Architecture studio conducted remotely. A pedagogical approach to introduce Design for Manufacturing and Assembly (DfMA) and Digital Twin concepts is presented. An analysis is conducted to evaluate the effectiveness in integrating IC principles into the design studio. The analysis framework uses the DfMA guidelines developed by the American Institute of Architects (AIA), the Royal Institute of British Architects' RIBA Plan of Work 2020, and the British Ministry of Housing's Modern Methods of Construction. The case study uses three phases in the design process, pre-design, design, and post-design, in its evaluation. The analysis results show that certain components of DfMA can successfully be integrated into a design studio framework. Although the structure of AIA and RIBA guidelines is followed, the order of the design process can vary according to the workflow designed by the students in the pre-design phase. The case study demonstrates a pervasive sense of social and ecological responsibility associated with the adoption of IC techniques in the design studio. There is an opportunity to expand the potential of IC practices by thinking beyond the design methodology. Findings suggest modularity as a social connector, which in turn, serves as a component towards a more cohesive built environment.

Keywords: Education, Industrialized Construction, Design for Manufacturing and Assembly, Digital Twin, Modular Architecture, Built Environment

INTRODUCTION

This paper presents a case study where a design studio explores two concepts of Industrialized Construction (IC): Design for Manufacturing and Assembly (DfMA) and the Digital Twin (DT). The case study involves a design studio conducted as a two-semester course conducted remotely during the 2020-2021 academic year. This was at a critical moment during the world pandemic when there was uncertainty as to the near future of the architecture professional landscape.

Industrialized Construction (IC) describes changes in the Architecture, Engineering, and Construction (AEC) industry driven by the automation and connectivity of industrial and manufacturing practices. There are various components to Industrialized construction, including DfMA for offsite construction and building delivery optimization, and DT for analysis, monitoring, and decision-making. DfMA combines techniques of Design for Manufacturing and Design for Assembly that have been utilized in other industries and applies them to the modularization and offsite production of building components. DfMA techniques focus on reducing the cost and time in the production of building components and are currently integrated into the building production process for residential construction and other parts of the industry where buildings can be easily modularized and mass-produced. Digital Twin refers to the data connection or monitoring of a physical building system using an intelligent virtual representation. DT leverages the technological advances in cloud-enabled tools and platforms for storing, sharing, and management of building information throughout the building lifecycle. It is a modeling strategy that enables project stakeholders to create a digital version of the real system to evaluate scenarios and collect data to make decisions.

CASE STUDY: STUDIO 812

The challenge of introducing IC concepts in the architecture design studio is centered on how to present this paradigm shift to novice designers, with varying levels of understanding of building assembly techniques and processes, and proficiency in computational design and Building Information Modeling (BIM). Eight projects were developed in an architecture design studio during the academic year from Fall 2020 to Spring 2021. The eight projects were designed by students studying in their last year of the Master of Architecture program. Having completed all requirements for the accredited professional degree, the design studios at that level of the program focus on special topics, in this case introducing students to industrialized construction concepts. The initial brief worked as a dynamic document providing an outline for the project. The class was conducted with a design research approach, where students reviewed precedents to become familiar with the state of

the art, developed a research proposal in which research questions are identified, and developed a design solution as a speculative project.

Research Proposal

In the first task of the studio, students were given lectures to introduce theoretical concepts and design computing workshops to level their technical skills. Students conducted precedent research to further familiarize themselves with the concepts of DfMA and DT. As part of the research students, students selected one or more architectural design precedents, “reverse engineer” the building systems, and develop a proposal for the building program for their project, and a preliminary prototype.

Design and Modeling

The second task of the project extends from the fall to the spring semesters and involves two design iterations. In the first iteration students focus on the modeling by selecting to emphasize a focus on the DfMA as a smart kit of parts, or DT as a tool for environmental analysis. In the second iteration, students are asked to reflect on the bigger challenges of social and environmental justice and use this lens to revise and develop their projects. This aspect was influenced by complementary lectures related to the current global challenges and issues, such as climate change and health.

FRAMEWORK FOR INDUSTRIALIZED CONSTRUCTION ANALYSIS

To evaluate the effectiveness of integrating industrialized construction principles in the design studio, two sets of documentations were used: the DfMA guidelines developed by the American Institute of Architects, AIA, and the Plan of Work guidelines offered by The Royal Institute of British Architects, RIBA. The Plan of Work recommends a complementary manuscript called MMC: Modern Methods of Construction developed by the British Ministry of Housing, Communities & Local Government Group. For the purposes of this study, it was considered that MMC forms part of RIBA’s guidelines.

Both AIA and RIBA guidelines are organized into three design phases: named pre-design, design, and post-design. Each phase is integrated by subphases to shift from traditional-design practices to industrialized-design practices. The guidelines agree that the pre-design phase can serve as a formal preparation in which the design team and the owner work together on a project’s brief. The importance of making the brief, relies on settling a strategy toward the usage of an industrialized construction method in the project. Details regarding the budget of the project, local permitting requirements, construction codes, manufacturer characteristics and initial design considerations must be established. When the pre-design phase is completed, the design phase is ready to put the brief into practice. Although AIA and RIBA differ in the quantity of subphases within each phase, the number depends on the coordination of all the parties involved in the manufacture and design processes. AIA suggests a design freeze subphase to accelerate the coordination and delivery of the project on-site. RIBA suggests that the conceptual design settling, assures that coordination. Once all the concerned parties have accomplished their coordination objectives and outcomes, the post-design phase can be started. This last phase includes the delivery, assembly and installation of the project or project’s components on-site.

Pre-design phase

The aims of the pre-design phase are: to establish the aims of the project itself, to settle the requirements of the client and to define the role of the design team in the project. The outcome of this phase is a strategic brief that includes the planning scheme to be developed in the design and post-design phases. This brief must serve as an agreement between the client and the design team of the project, and it is also an engagement plan with the industrialized construction methodology. In addition, the brief includes a workflow map as a guideline toward the design and post-design phases.

Design phase

The aim of the design phase is to evolve from the initial brief to the technical design, as well as coordinating the design under a ‘manufacturer thinking.’ According to AIA and RIBA, the design phase can consider the following general scenarios: designing for off-site pre-manufacturing, designing for near-site pre-manufacturing, and/or designing for a site-based process improvement. AIA and RIBA agree that the design phase is the longest phase of the IC methodology because it involves an integrated process compound by multiple design decisions. These decisions can be organized in different categories, AIA suggest two categories: the volumetric construction design and the non-volumetric construction design. While RIBA, suggests reviewing the MMC definition framework and its seven categories for manufacturing and assembly practices. The seven categories are: 3D primary structural systems, 2D primary structural systems, non-systemized primary structure, additive manufacturing, non-structural assemblies and sub-assemblies, improvements of traditional building products, and on site-process improvement.

Post-design phase

The post-design phase refers to the handover of the project. Thus, it requires the preparation and delivery of the project or the project's components on site. These include transportation, staging and assembly strategies. And also, a post-assembly vision of the performance of the project. RIBA suggests including post occupancy evaluation tactics, as well as providing formats and tools for keeping track of the building's performance regarding its operations and maintenance.

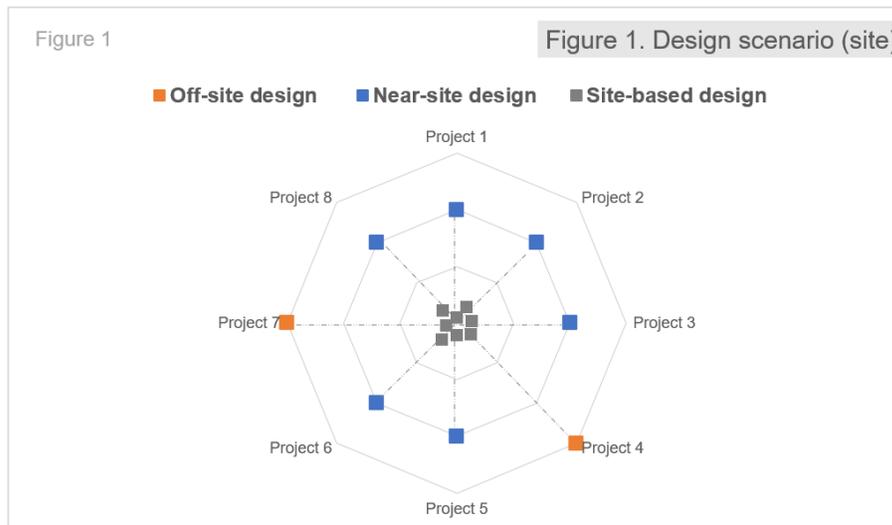
COMPARATIVE ANALYSIS

The 3 design phases are considered in the comparative analysis. The outcome of the 3 phases developed by each project is retrieved in the Studio 812 documentation available online¹. The results of the analysis can be classified in the following topics: site as design scenario (Figure 1), general design considerations and categories for design decisions (Figure 2), and subphases used in the design phase (Figure 3). This topic classification is obtained from comparing the modular approaches described in AIA and RIBA guidelines (refer to Figure 0 located in the appendix).

For the purposes of the case study evaluation, it is considered that to accomplish the pre-design phase, students should demonstrate engagement with a topic through research. Thus, each project considers a topic definition, historical precedents of the selected topic, and the translation of those precedents into a contemporary and industrialized context. The design phase is composed of an architectural proposal obtained from the theoretical framework of DfMA, digital twin, and design for modularity. For evaluating the general design considerations of the eight projects, the categories provided by AIA and RIBA's Modern Methods of Construction (MMC) were considered as complementary. For each guideline, the suggested categories are different; AIA focuses on assembly strategies, whilst MMC refers to the components of the project. Finally, the post-design phase is evaluated as a set of recommendations for manufacture, site preparation, and transport staging.

Site as a Design Scenario

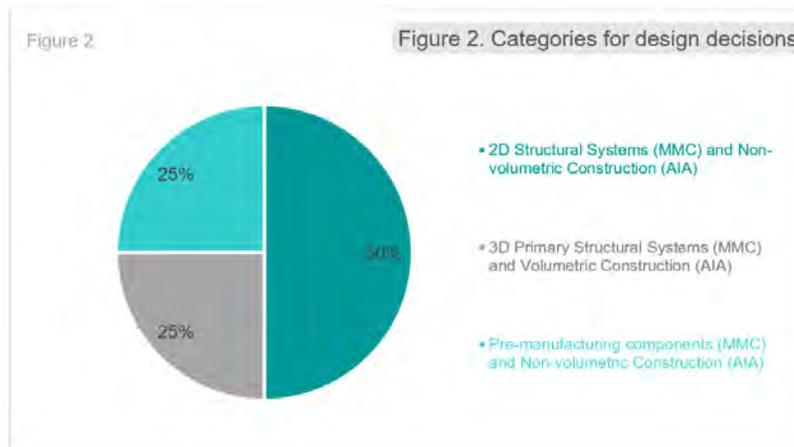
As it can be seen in Figure 1, six projects are influenced by a near-site design, while only two projects are shaped by an off-site design. There are no projects considering a 100% site-based design. However, the eight projects relied on traditional practices on site (to a certain extent) for specific moments in the construction of the project itself. For example, some of the projects considered foundations built on-site, carpentry work on-site, and colocation of building components on-site. This situation was part of the final discussions in the classroom because it supports the idea that automation does not necessarily "erase" human labor from construction practices. The discussion included the recognition of the possible design paths to study while implementing an industrialized construction methodology. It is considered that this is an asset for preparing professionals with deeper insights in IC.



Categories for design decisions

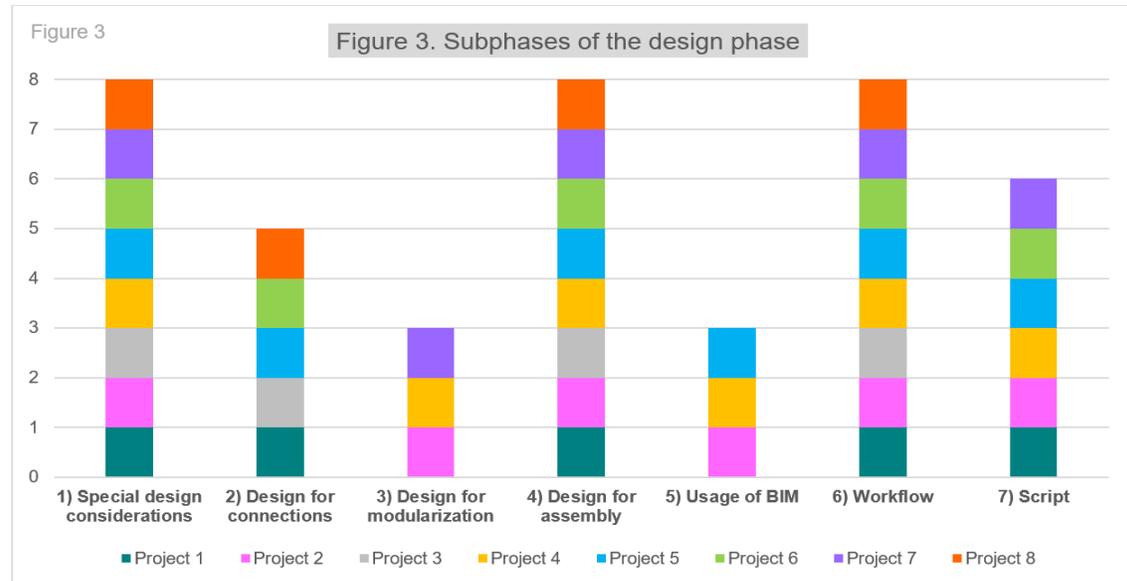
Each student selected the design topic to address in their project. Therefore, eight topics were developed under an industrialized construction methodology: Project 1 focused on Tectonic Aggregations for DfMA

Construction, Project 2 focused on Affordable Housing, Project 3 focused on Modular Systems with Bamboo, Project 4 focused on Design for Automation, Project 5 focused on DfMA for Residential Construction, Project 6 focused on Vernacular Architecture and Carbon Emissions, Project 7 focused on Modular Adaptation for Housing, and Project 8 focused on Harnessing the Wind in Buildings. The variety of topics addressed on each project, confirms the versatile character that the methodology can provide in architectural projects. The selected topics also demonstrate a strong sense of ecological, technological and social responsibility. Figure 2 shows a proposal to categorize the projects into three categories, which are: 2D Structural Systems (MMC) and Non-volumetric Construction (AIA), 3D Primary Structural Systems (MMC) and Volumetric Construction (AIA), and Pre-manufacturing components (MMC) and Non-volumetric Construction (AIA). These categories illustrate how AIA, RIBA, and MMC can contribute to classifying the implications of industrialized construction in architectural design. The projects demonstrate the application of industrialized construction practices. Pre fabrication, additive manufacturing, robotics, big data, and the internet of things, are evident tools of architectural design in the student projects.



Subphases of Design

This section of the evaluation includes seven aspects of the design subphases retrieved from the AIA and RIBA guidelines (refer to Figure 0 in the appendix to better visualize all subphases). The seven aspects are the following: 1) Special design considerations (geometric design, parametric tools and/or collaborating with the manufacturer), 2) Design for connections, 3) Design for modularization, 4) Design for assembly, 5) Usage of BIM, 6) Settling a workflow and 7) Creation of a script. Figure 3 shows how these aspects are integrated. All projects demonstrate special design considerations, design for assembly, and settling a workflow. The usage of BIM and Digital Twin were more difficult to integrate in the design process due to the lack of foundational knowledge in modeling and simulation. Designing for connections and modularization were also challenging aspects to achieve simultaneously. Projects focusing on design connections did not develop modularization strategies.



DISCUSSION

In this case study, all of the student projects successfully followed an industrialized construction process. The use of the AIA and RIBA guidelines, and the pre-design, design and post-design phases provided insightful evaluation of the case study's integration of Industrialized Construction concepts. This study recognizes the flexibility embedded in the AIA and RIBA guidelines. It was found that the order of the design process can vary according to the workflow developed by the students during the pre-design phase. In addition, the eight projects addressed a diverse range of topics that demonstrated the diverse character of industrialized construction practices. It was observed that the majority of the student projects adopted a near-site design scenario with hybrid design considerations. A situation that prompted class discussions regarding the importance of decision making in the design process and architectural solutions.

Although the majority of aspects in the design phase were adopted in the projects, the Digital Twin concept was more difficult to integrate due to the lack of foundational knowledge in modeling and simulation. Also, designing for connections and designing for modularization, were challenging aspects to achieve simultaneously. Another limitation is the post-design phase because the topics include a management vision. This suggests that additional lectures would have benefitted the studio, focusing on the characteristics of the post-design phase albeit at a theoretical level. To compensate for this aspect, complementary lectures related to the challenges of current global issues, such as climate change and health were given to the students. Thus, the final deliveries demonstrate a strong sense of social and ecological responsibility.

There is an opportunity to expand the potential of IC practices by thinking beyond the design methodology. Findings suggest modularity as a social connector, which in turn, serves as a component towards a more cohesive built environment. This study evidences the challenges of encompassing the post-design aspects into academic projects designed by students studying architecture. The present evaluation of the projects do not consider any post occupancy evaluation analysis. Instead, it considers a visualization of the assembly or delivery methods on-site only.

RECOMMENDATIONS FOR DESIGN PEDAGOGY

In this case study, students familiarize themselves with two Industrialized Construction concepts: Design for Manufacturing and Assembly and the Digital Twin. The evaluation of the design research pedagogy shows that it supports diversity of design explorations based on student interests. However, the analysis also points to the need for strengthening the technical skills of the students, before presenting them with the challenge of designing and modeling. The integration of IC concepts into a design studio was conducted in a senior design studio, with students in the Master of Architecture. More support is needed to prepare architecture students for Industrialized Construction practices.

Integrating IC in the Architecture studio sequence

Although the outcomes of this case-study show that the design studio remains central in design education as the environment where knowledge is integrated and synthesized, the integration of other perspectives would have enhanced the design research approach. For example the integration of Industrial design and Engineering design expertise would have benefitted modularization strategies explored in the course. These types of expertise can be integrated in a variety of ways, through lectures, external reviewers and guests, or

through co-teaching with other disciplines. We believe that a multidisciplinary design studio focused on IC practices is critically important in the architecture studio sequence. Architecture programs can generate a variety of interdisciplinary IC studios, based on the areas of focus and strength of each program.

Integration IC in the Building Technology sequence

IC is a fundamental transformation of how buildings are designed and produced. Therefore, a new curricular paradigm is needed to integrate computational design literacy and understanding of building systems. In general, students should be given more support in understanding and utilizing Building Information Modeling (BIM) and building simulation. This can be done by reconsidering the computer aided design as separate from the building technology in architectural design curricula. One is indeed a tool for the other. For example students learning about the use of 3D printing in architecture, should also be encouraged to consider the carbon footprint implications as well as energy use. These issues could be examined with a Digital Twin. We believe that an integrated approach to building technology is fundamental to Architecture Design Education. The Building Technology sequence of means and methods could integrate labs where digital modeling tools could be utilized for assignments and focusing on modeling, analysis, and decision-making.

CONCLUSIONS

This case study presented shows that it is possible to adopt an industrialized construction methodology in the classroom. The methodology observed in this study can be applied to both in-person and digital courses.

By applying a design research pedagogy, students can make decisions about the focus of their work and develop critical thinking about the integration of new technologies to impact larger questions at the intersection of design, justice, and ecology. This approach to introducing IC concepts fostered diversity of projects in the classroom. It can evolve from a pre-brief to the final delivery of the class. It also serves as the integral evidence of the class by retrieving all the projects developed in the classroom.

The guidelines from AIA and RIBA provide a framework to guide the evaluation of learning outcomes. The results of the analysis suggest that a new version of this course could be extended into the post-design phase by evaluating impact on labor reduction, productivity improvements on-site, manufacture and site preparation, and post-occupancy evaluation. The architectural projects developed under an innovative approach are a step forward for preparing young architects to apply IC methods in the practical field.

ACKNOWLEDGEMENTS

Thanks to Logan Brammeier, Charley DeVries, Robbie Edberg-Oostdik, Shawn Khokher, Andrew Klenke, Victor Renteria, Rebecca Twombly, and Tyson Washington for their work, dedication, enthusiasm, and resilience.

APPENDIX

Figure 0. Comparison of modular approaches described by AIA and RIBA guidelines.

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ADDITIONAL MATERIAL

1 The Studio 812 documentation is available in the following link: https://issuu.com/system812_dfma___digital_twin_-_pages

Teaching carbon responsibility to first year architecture and engineering design students

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ABSTRACT: *In architecture and engineering schools in the US, environmentally responsible building technologies are often taught in upper division curricula. This paper argues that environmental ethics and responsible material use should be foundational to architecture and engineering design education. The authors discuss a pedagogical framework developed for Cal Poly San Luis Obispo first year architecture and architectural engineering students for introducing carbon responsibility through an ethic of wood use where wood is locally sourced and kept in use through buildings and furniture products. Over the course of a term, students engaged with the full arc of the life cycle and use of wood in buildings. This involved planting trees, watching a milling demonstration using local urban wood, and designing an all-wood speculative project. The term culminated in the design and fabrication of a functional full-scale wood object, made of donated urban wood, which students constructed with minimal or no glue. Using local wood rather than Home Depot lumber for the 240-person studio saved over 1,000 kilograms (1.1 tons) of carbon dioxide emissions from transport.*

KEYWORDS: Foundation Design Pedagogy, Wood Structures, Carbon Sequestration, Urban Wood, Circularity

INTRODUCTION

This paper argues for an alternative pedagogical framework for foundation level architecture and engineering design students where material and ethical constraints guide learning objectives. Often in architecture and engineering curricula, building technology (and therefore environmental) concerns are introduced in upper division “support” courses such as Environmental Controls and Materials and Methods. In these scenarios, some first-year design studios abandon real-world constraints to allow formal freedom and design exploration. In contrast, the authors argue that teaching environmental and material constraints should be foundational. For this reason, they developed a core curriculum for first year architecture and engineering students in which assignments were driven by environmental ethics and material responsibility through a focus on wood. By constraining the material to wood and all-wood assemblies, the authors argue, students gained design sensibilities in parallel with an environmental ethic as a core principle of designing buildings today. The design studio’s focus on wood proves straightforward. Afforestation, reforestation, and forest stewardship are critical components of climate change mitigation and adaptation. (Griscom et. al. 2017, USGCRP 2019) Trees sequester carbon, but decomposing trees or chipping them releases carbon back into the atmosphere. When sustainably harvested, the best end-of-life use of trees are wood products including buildings and furniture, which enable continued carbon storage. (Sather and O’Connor 2010, MIT Climate Portal 2022) Given the urgency to address climate change caused by the built environment (GlobalABC 2021), the authors developed a curriculum to instill an ethic of wood use and stewardship. Through activities and projects, the curriculum aimed to teach students about the life cycle and benefits of using wood in building and structural design.

To push the agenda further, the design course emphasized the importance of *specifying local wood*. In *Wood Urbanism*, Jane Hutton describes that plantations provide one third of the world’s wood and that these plantations are often monocultures planted for maximum harvest and financial return. (Hutton 2020) Hutton goes on to explain the negative impacts of plantations, which are often planted where biodiverse forests once stood and provided livelihood and sustenance for indigenous and local peoples. The clearcutting practices used by plantation owners contributes to “land degradation, erosion, water pollution due to applied chemical fertilizer and pesticides, and drought.” (Hutton 2020) These practices have negatively transformed US forests. A University of Michigan study found that since 1600, 90% of the virgin forests have been cleared, despite that extensive clearcutting began only 50 years ago. (Buis 2019 and *ResEarth*) As a result, the pedagogical agenda described below sought to engender a deeper understanding about wood and where wood products come from. Through fruitful partnerships both on and off campus, the course provided learn-by-doing experiences involving planting trees locally and using local wood.

1. PURPOSE

The fall quarter of the first-year design curriculum focuses largely on abstract, compositional ideas. Previous iterations of the winter quarter curriculum sometimes became an extension of the fall quarter where assignments focused on formal output alongside digital and analog representation and skill-building. One

consequence of this curriculum is that it often generates a lot of non-recyclable and non-reusable waste. The 240 first-year students make significant contributions to the 7,000-pound dumpster container that awaits refuse at the end of each quarter. Recognizing the local and global real-world problem of curricular and building industry waste, the authors sought to develop a curriculum where the materials were recyclable or biodegradable, or even better, kept forever.

Driven by the need for waste reduction and carbon sequestration, the design course focused on an ethic of wood use as a multi-pronged objective where wood is locally sourced from a variety of species, wood is used in the design of buildings and furniture as much as possible, and wood is kept in use rather than discarded in a landfill. Over the course of the term, students engaged with the full arc of the life cycle and use of wood in buildings. The “wood studio” involved planting trees on campus, watching a milling demonstration using local urban wood, designing an all-wood speculative project, and designing and fabricating a functional full-scale wood object made of donated urban wood, which students constructed with minimal or no glue.

2. PEDAGOGICAL METHODS

The focus on environmental ethics and responsible material selection for the wood studio marks a significant shift from the pedagogical framework and abstract assignments that dominated the studio content in previous years. Whereas the primary learning objectives had been geared towards representation, beginning design, and skill-building, the learning objectives for the wood studio upheld the benefits of wood use and understanding wood sourcing and assemblies as the primary goals. Analog and digital skill building, and representation techniques were embedded in the course assignments, but were not the end in themselves. To demonstrate the shift in learning objectives, three previous assignments are compared to three of the main wood studio assignments: a precedent study, a speculative design project, and a woodshop demonstration project.

In previous years, the precedent assignments in the first-year studios have focused on small projects, such as houses or pavilions, with the primary goal of teaching the process of studying and explaining precedents in preparation for a design project. Previous deliverables included asking students to create slide presentations, printed boards, diagrams, and/or digital models of the buildings. For the wood studio, the focus centered on learning about wood structures, representing a more technical and tectonic approach. Students worked in pairs to investigate and understand wood projects and described these to the class through a verbal presentation and slides. Presentation content included a brief description of the architects and engineers, and information (as much as could be found) about the design process, construction, and wood material.

Students then worked individually to model a tectonic chunk of the wood project in McNeal’s Rhinoceros (Rhino). The purpose of digitally modeling a tectonic chunk was to learn about floor, ceiling, and wall wood assemblies including the hierarchy of structure and cladding. On a basic level, students gained an understanding of the relative sizes of wood members for different structural or cladding purposes. A secondary benefit of the modeling exercise was to further the students’ Rhino 3d modeling skills since they had only used Rhino in 2d in the previous term. The final output requested two side-by-side isometric views of the tectonic chunk. Well-executed examples demonstrate an understanding of wood systems including wall and floor or ceiling systems. (Figure 1) Students based the tectonic chunk model on 2d drawings imported into Rhino, which were then traced and modeled through extrusion and other techniques. When high resolution or detailed dimensions were not available, students worked with faculty to take their best guess based on typical lumber dimensions.

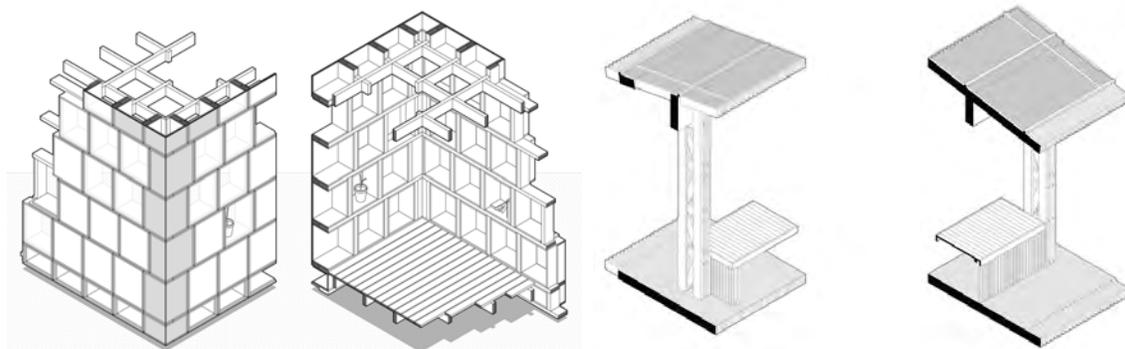


Figure 1: First Year students, Benoit Lepottier and Kelsey Howryla’s isometric drawings of a tectonic chunk of CLP Architectes’ Observatory Pavilion in Muttersholtz, France and Bornstein Lyckefors Arkitekter’s Kärda City Pavilion in Estonia. Sources: (Benoit Lepottier and Kelsey Howryla 2022)

Building on knowledge gained from the wood precedent assignment, the speculative design project assigned for the wood studio also marked a shift from previous speculative design projects assigned in first year. The basswood modeling project of years past had similar learning objectives including to “understand simple structural relationships” of the building site, which was a wood pier. For that assignment, students had worked in groups to analyze the existing structure alongside other environmental and historical data. They continued the group work to create speculative designs for wood structures sited on top of the pier; however, the wood materiality of the projects was permitted to play second seed to formal ambitions. In contrast, for the wood studio, each student developed a design for a 1,000 square-foot all-wood, open-air pavilion housing an arborist’s office and a presentation space sited in the campus arboretum. The arboretum site allowed for a discussion about the wood structure relative to the surrounding trees and the pavilion’s place in a cycle of life. Students were asked to base wood system designs on the library of tectonic chunks the students had modeled previously. Drawing directly from the precedents helped students to create hierarchies of structure and screening in their design proposals. Additionally, the brief specified that the pavilions should hover above the ground, supported by ground screws, to allow for flows of water, creatures, and plants and to have a light touch on the landscape. This provided an opportunity to teach about accessibility, and a 1:12 ramp was required as part of the design.

Two examples of the ways in which wood systems factored into the students’ design work are pavilions composed of similarly sized wood members to create shade canopies, support structures, and seating for visitors. (Figure 2) Accessible ramps are embedded in the wood decks, which were modeled using sheet material to save time. The final exhibition for the arboretum pavilion project included work from all 240 of the architecture and engineering first year students. (Figures 3 and 4).

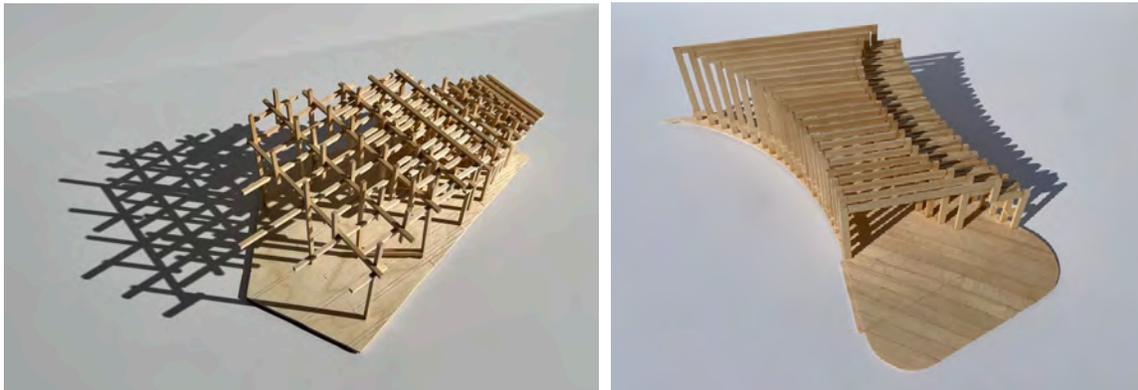
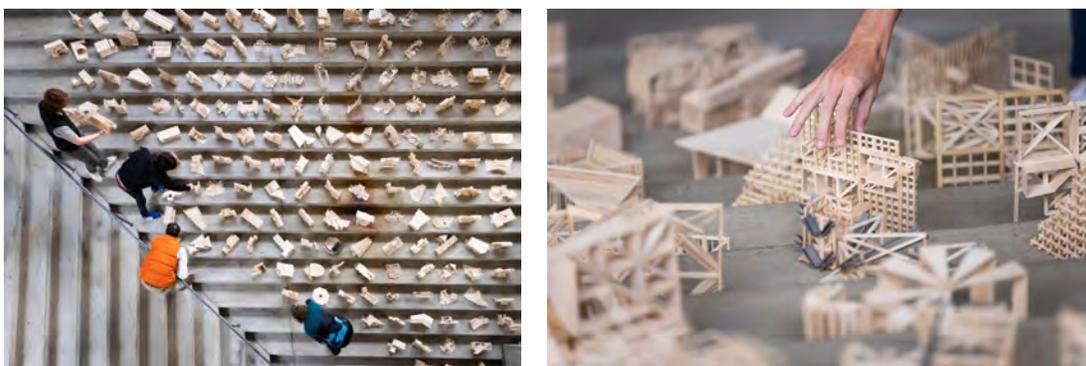


Figure 2: First Year students, Alex Jenkins and Jack Boennighausen’s speculative design for a wood pavilion for the campus arboretum. Source: (Alex Jenkins and Jack Boennighausen 2022)



Figures 3-4: Exhibition of basswood models of wood pavilions (and interior dividers). Source: (Joe Johnston, 2022)

Rather than ending the term through this speculative design project (as many design studios tend to do), the culminating project for the wood studio was a full-scale functional wood object. This contrasted with previous woodshop demonstration project assignments, which involved designing an abstract wood cube. Although the ethic of material use was part of the previous project brief—students were required to use 100% of the 4” wide, 4’-long board they were issued—the goal behind making a functional object was to encourage students to keep the objects in use. A partnership with a local urban wood forestry group, Deadwood Revival, who had recently been awarded a grant involving urban wood education and use, offered key contributions to the

pedagogical arc. They brought their portable Wood-Mizer LT15 sawmill to campus to demonstrate how urban wood is sawn into slabs (Figure 5), and they also generously donated 1,000 linear feet of urban wood for students' use in the final project.



Figure 5: A local urban forester provided a milling demonstration. Source: (Clare Olsen 2022)

For this culminating project, the local forestry company supplied students with 3"-thick boards from felled urban trees, sometimes with a raw edge. Receiving the material in this state helped students to understand the source of the wood, and the responsibility to keep wood in use for carbon sequestration. The project also facilitated development of woodshop skills (a parallel goal since woodshop training is part of the first-year curriculum). Students cut boards in half on the bandsaw, planed them, and used any number of shop tools to configure "something for storing." Building on the ethic of design for deconstruction, the project brief encouraged students to construct the functional wood object with minimal or no glue, using 1/4" wood dowels that were purchased in bulk and made available for the students in the woodshop. However, due to time constraints and the need to make simple joints, many students used wood dowels in conjunction with wood glue to make a durable, functional connection.

Two student work examples show storage objects that celebrate the wood's live edge. (Figure 6) Craft sensibilities are challenging to teach to a cohort of this scale. Faculty provided tips through a common hour, delivered by Keith Wiley, an expert wood craftsman, and one-on-one advice given by studio faculty and woodshop staff. Two three-hour sessions were blocked out for each studio and although many students were able to complete their project in that time, many students also visited the shop for additional work time.



Figure 6: The "something for storing" woodshop project made from donated local urban wood. (Source: Samhita Vallamreddy and Alex Jenkins 2022)

Towards the end of the term, the authors worked with the campus arborist, Matt Ritter, and team to provide volunteer opportunities to plant trees. Over the course of three days, 78 students and four faculty participated in digging holes, planting, staking, and watering trees. (Figure 7) Dr. Ritter explained to participants that the average American needs to plant about 80 trees per year to offset their annual carbon emissions. (Skonberg 2022) Although the group did not plant anywhere close to that number, more than 20 trees were placed in the

ground providing carbon draw-down, shade benefits, habitat creation, and beautification of the campus. Additionally, the planting events contributed to renewal of the university's Tree Campus USA certification.



Figure 7: Tree planting with the campus arborist, Matt Ritter. (Source: Clare Olsen 2022)

3. REFLECTION

The outcomes of the wood studio assignments and activities resonate in both pedagogical and climatological ways. One interesting result of the focus on wood as the sole material for the arboretum project is that the drawings, made in Rhino by modeling the building in three dimensions and then creating Make2d drawings, were highly articulated. Students were not permitted to use sheet material greater than 12" wide (and generally employed 2x's ranging from 2x2s through 2x12s). So this meant that the pavilion designs involved many members to create shading, screening, and a sense of privacy for the "private" component of the small program. The students were taught two methods of line weight hierarchy: near versus far, used for plans, sections, and elevations, and "spatial edge" (Ching and Juroszek), which were used for isometric drawings. Changing line weights in Rhino can be quite time consuming, but the density of linework and textures created "thick" atmospheric drawings that instilled pride in the achievement of creating drawings with a lot of content. To reduce the time and labor involved in making the pavilion models and drawings, the authors recommend including the allowance for sheet material for a portion—perhaps one third—of future iterations of the all-wood pavilion project.

Promoting craft sensibility in wood fabrication proved challenging in terms of numbers of students and time constraints, so students were encouraged to create simple designs. Yet asking students to create a functional object that they would want to keep instilled an importance of craft and an appreciation for the skills required in making wood furniture. This was the first time that the first-year students had been asked to make a functional object from wood, so it was notable that a handful of the cohort participated in the school's 19th annual furniture competition the following year. In the previous eighteen years of the competition, there had been very few second-year student entries. Only one of those received an Honorable Mention, and none had ever won a top tier monetized award. In Fall 2022, however, there were more second year entries than all previous eighteen years combined. Remarkably, out of the twelve top tier awards, three were won by second year students. In addition, one second year piece received a People's Choice award.

Another benefit of the use of local wood for the 240-student studio is that it resulted in climate benefits, even if simply looking at the fact that the school previously purchase wood from Home Depot for the woodshop demonstration project. The local Home Depot sources Weyerhaeuser wood from Oregon and Washington states, and although Weyerhaeuser practices sustainable forestry, the carbon emissions from trucking the lumber proves significant. The average semitruck gets approximately six miles per gallon. Given a 700-mile drive from Oregon, and 8.78 kilograms of carbon dioxide emitted per gallon (according to the *US Energy Information Association*), this means over 1,000 kilograms (1.1 tons) of carbon dioxide was averted by using locally sourced wood. According to Our World in Data, a U.S. resident emitted an average of 13,480 kilograms (14.86 tons) of carbon dioxide in 2021, so saving 1,000 kilograms is the equivalent of about .07 percent of what one US person generates in one year. (*Our World in Data 2022*)

CONCLUSION

The wood studio derived from a concern and responsibility to address carbon emissions and waste in the building industry and the obligation to respond to these issues through learning objectives in the first year of the curriculum for architecture and engineering students. Through local partnerships with urban wood foresters, the campus arborist, and the wood shop staff, the learn-by-doing experiences became more robust and more real. The large teaching team made use of precedent studies, speculative wood building design, and fabricating a functional wood object to teach students about basic means and methods of wood building and furniture design. Despite the practicality of these endeavours, the constraints on the assignments provided meaningful ways to engage form, representation, craft, and skill-building. The wood studio experiences and emphases on wood design and construction suggest that tackling vital concerns like environmental ethics and building industry responsibility can prove productive and fruitful for students at the start of their design education. To continue building on ethics as the foundation for design pedagogy, the next quarter in the sequence focuses on social ethics and community responsibility. A final project, which speculatively provides shelter and food security for the local unhoused community, will be piloted for the first time in Spring 2023. The quarter begins with students working in teams to design temporary full-scale structures, which they sleep in for two nights. Although this project has been integral to the pedagogy for decades, this is the first time in which the students will be asked to reflect on the act of sleeping outside to evoke empathy for those who sleep outside every day. At time of writing, the quarter has barely begun, so a future paper will report on the pedagogical methods and outcomes of this social justice framework for first year architecture and engineering design pedagogy.

ACKNOWLEDGEMENTS

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Direct Housing for Post-Disaster Recovery: Design and Logistics for Alternative Solutions

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ABSTRACT: *Considered a last resort in disaster recovery scenarios, direct-housing solutions are deployed only after other housing assistance options (such as rental assistance or temporary lodging) are exhausted. Their viability and effectiveness depend on a range of interrelated constraints, from unit costs to the logistics of storage, mobilization, and installation, and from their physical resilience to the seamlessness of their social integration. A particularly impactful constraint is the 18-month time limit placed on federal disaster housing assistance by the Stafford Act, which often results in abrupt and problematic transitions.*

In the United States, there is not a “one-size-fits-all” solution to post-disaster direct-housing systems, due to wide variations in disaster scenarios, logistical protocols, and the intent and timeline for the housing itself. Too often, the attributes that are desirable for direct temporary housing (speed and ease of delivery/setup, low labor and power requirements, etc.) are at odds with the durability, resiliency, energy performance, and even cultural expectations associated with permanent housing. Temporary MHUs of the past, such as those supplied by FEMA after Hurricane Katrina, are illustrative of these limitations. Alternative housing solutions that exhibit promising logistics attributes, such as rapid deployability, low cost, high modularity, etc., have potential to serve as adaptable solutions from temporary to permanent housing.

This paper presents in-progress research relating to alternative architectural solutions and production/delivery paradigms for flexible and adaptable post-disaster housing, ranging from volumetric modular to panelization to rapidly-assembled kit-of-parts systems. The paper concludes with a look at the current phase of this project, in which the effectiveness of recovery housing solutions is investigated through an integrated modeling and analysis framework for logistics planning and operations. This framework analyzes disaster housing solutions from a systematic perspective while drawing on converging research from multiple disciplines: architectural design, natural hazard and fragility analysis, and relief logistics network design and operations planning.

KEYWORDS: Disaster Recovery, Direct Housing, Adaptable

INTRODUCTION

In its 2016 report on the subject, the Congressional Budget Office (CBO) estimated that 1.2 million Americans live in locations at risk of substantial hurricane damage. It was stated at that time that hurricane damages cost government around \$28 billion per year, and that this number will rise from the effects of climate change (Congressional Budget Office 2016). Newer data continues to speak to increasing severity of natural disasters and the urgency of this threat. According to the NOAA’s National Centers for Environmental Information (NCEI), there were 18 separate billion-dollar weather and climate disasters across the United States within the 2022 calendar year, with hurricanes (including Fiona, Ian and Nicole) being the dominant source of destruction across the southeastern United States (NOAA 2023).

An interdisciplinary research team at Clemson University is currently in the midst of its third project in a series of studies relating to post-disaster relief and recovery. The work began in the 2018-19 academic year, as a team led by Industrial Engineering faculty and students developed a stochastic “look-ahead” approach for the optimization of hurricane relief logistics planning under uncertainty. The model aimed to minimize the total cost incurred in the logistics operations, which consist of transportation costs and social costs. That first study did not explicitly address housing, but focused on other relief materials. However, several key principles, including the notion of social deprivation costs for unmet demand, can be applied to direct-housing logistics. The second project in our sequence was aimed at studying a range of building solutions for post-disaster recovery, including direct-housing, which varied in their degree of prefabrication and in their methods of delivery and construction. These alternative design solutions and their associated data on costs, materials, dimensions, timetables, etc., would help provide case-studies for applying and testing an integrated housing design and logistics operations model, which is currently under development in the third project of our sequence. This paper will focus on the direct-housing design studies from project 2, and conclude with a look at the integrative modeling taking place in project 3. Throughout this work, our premise, which is supported by

the background research summarized in the next section, has been that recovery structures should ideally exhibit the following attributes:

Flexibility: a flexible supply chain system that is adaptive to disasters of various types, locations, and severity is the key to support a successful deployment of medical and/or housing solutions during disaster relief, leveraging limited manufacturing, energy supply and infrastructure capacities.

Modularity: modularity in design solutions for disaster relief is a key factor to ensure that building materials are packaged, delivered, and assembled in affected areas in a timely fashion.

Reliability: reliability and resiliency of design solutions is the key to offering different levels of safety and durability under various disaster scenarios.

Adaptability: the adaptability of design solutions is the key to sustainable long-term disaster planning, allowing temporary structures, such as housing or medical facilities constructed immediately after a disaster, to be converted into more permanent houses later on.

1. BACKGROUND: DIRECT HOUSING

When natural disasters such as hurricanes strike in the U.S, states like South Carolina turn to their Emergency Management protocols, including their Disaster Housing Plans. The SC Disaster Housing Plan, which was last updated in 2018, states that: “The State of South Carolina must be prepared to ensure housing for those whose homes are not safe and sanitary due to a natural or man-made disaster.” (SCEMD 2018). Additionally, it identifies concerns of chief importance when it comes to locations of emergency housing, indicating that: “Key to the recovery of the State is individuals returning to their jobs and communities as quickly as possible after an event. A vital part of this rapid recovery is ensuring people remain as close to their homes and communities as possible.” The express purpose of the SC Disaster Housing Plan is to “identify available resources for locating, securing, and funding housing for people affected by a disaster within the State” (SCEMD 2018). When the resources of a local jurisdiction are exceeded, the State steps in to assist, and when the State’s resources are exceeded, the State can request federal assistance. This disaster management hierarchy and approach is common across the U.S.

When it comes to post-disaster housing, there are several stages of need which must be addressed. The first, which occurs in the immediate aftermath of a disaster is the need for Emergency Sheltering. Mass sheltering, if needed, is often accomplished in designated community buildings, such as school gymnasias, churches, etc., and is often supported by non-profits such as the American Red Cross or the Salvation Army. The next stage of housing need is Transitional Sheltering, which “consists of lodging that is not an emergency mass care situation, where each individual has their own access to the housing unit.” It requires a Presidential Disaster Declaration for the affected area. The Disaster Housing plan goes on to say that: “If Emergency Shelters are overwhelmed or FEMA determines shelter residents and evacuees cannot return to their homes for an extended period of time, the State may request FEMA authorize eligible disaster survivors to receive TSA (Transitional Shelter Assistance)” (SCEMD 2018). Transitional sheltering generally takes the form of hotel or motel rooms.

The next stage of need, if a need persists, is called Intermediate Housing. “Intermediate Housing consists of providing safe, sanitary, and functional conditions for individuals within a reasonable distance to schools, businesses, and services” (SCEMD 2018). Intermediate Housing is again dependent on a Presidential Disaster Declaration, and the housing solutions can take two different forms. The first is rental units located within or close to the affected area. The second, which is a last resort measure, is called Direct Housing. “If FEMA, in conjunction with the State, determines that there may not be a sufficient supply of available rental units to meet disaster housing needs, FEMA will survey those applying for Housing Assistance to determine if a Direct Housing mission is appropriate” (SCEMD 2018). The SC Disaster Housing Plan goes on to say that “direct housing can take many forms, depending on the needs of the affected communities and the resources available.” In seeming contradiction, it also states that “the only type of currently approved FEMA direct housing is factory made housing including mobile homes.” And, finally, the plan reports the following concerning the locations / placement of FEMA-provided Direct Housing:

“The preferred method is to place housing units in locations where services and utilities are already established. This includes the placement of units on land owned by eligible applicants, and can also include utilizing existing manufactured housing parks and filling in vacant areas with disaster housing units given the appropriate infrastructure. This can be accomplished in as few as 24 hours and can remain operational for months. When those options are not available, or will not meet the needs of all affected people, FEMA may expand an existing mobile home park or create one to accommodate disaster housing” (SCEMD 2018).

The most well-known case of FEMA Direct Housing occurred in the aftermath of Hurricanes Katrina and Rita in 2005. In response to the devastation across the Gulf Coast Region, FEMA ultimately purchased 140,000 manufactured mobile homes and trailers for distribution. Shortly thereafter there were complaints about the construction of the homes, particularly the trailers. There were problems with formaldehyde levels from the off-gassing of the materials. The units also suffered from poor energy performance and a lack of durability and resiliency. It did not help that the transition to more permanent housing was complicated and delayed for many families. The FEMA trailers were never intended to be anything more than a temporary solution, but, in numerous cases, families lived in them for several years.

1.1 Flexible, expandable alternatives

In 2006, in conjunction with what it was learning after Hurricane Katrina, FEMA initiated the Alternative Housing Pilot Program (AHPP). It was aimed at identifying and evaluating better ways to directly house future disaster victims. Ultimately, FEMA provided over \$400 million to four Gulf Coast states (Alabama, Mississippi, Louisiana, and Texas) to develop a range of recovery housing prototypes whose construction technologies were being advanced in the private sector. These solutions included site-built construction, panelized construction, and offsite modular and manufactured housing (FEMA/AHPP 2008). One of the common threads among early projects funded by the AHPP was “expandability”, and the related notion of a temporary, deployed solution being adapted for long-term use. Such approaches have come to be referred to as “Temporary-to-Permanent” solutions. This idea is also reflected by concepts such as progressive shelters (“post disaster rapid household shelters planned and designed to be later upgraded to a more permanent status”) and core shelters (“post disaster household shelters planned and designed as permanent dwellings, to be the part of future permanent housing”), as defined by the International Federation of Red Cross and Red Crescent Societies (IFRC/RCS 2013).

One particularly compelling example of a temporary-to-permanent post-disaster housing framework is the RAPIDO program developed by Building Community Workshop, a Texas-based non-profit community design center. Developed in the wake of Hurricane Dolly in 2008, the Rapid Disaster Recovery Housing Program (nicknamed RAPIDO), aims to create a “bottom-up community-based approach that is centered on the families it intends to support” (Building Community Workshop 2015). The RAPIDO direct-housing solution consists of a core dwelling unit intended for rapid deployment and occupation. This core unit is designed to be easily and incrementally expandable, so as to grow into a long-term house if desired. The goal is to help close the physical, infrastructural and policy-related gaps that often plague the transition from short-term recovery housing to long-term recovery housing.

The RAPIDO core includes one bedroom, one bathroom, a small kitchen and an open dining/living space. In total, it is approximately 480 ft² in size (Building Community Workshop 2015). The unit is designed to be elevated above any flood waters, and its walls and lower roof are quickly assembled from prefabricated panels, each approximately 4ft by 10ft and constructed with in-line light wood framing. The panels include insulation, interior and exterior sheathing, and accessible raceways for electrical wiring. BC Workshop contracts with a network of different builders capable of providing these prefabricated panels. They are easy to erect and connect on site, which, in combination with the simplicity of the core unit design, makes for a fast and repeatable construction sequence. BC Workshop has been successful at finding funding and has been able to get numerous RAPIDO houses built, including in East Texas communities impacted by natural disasters.

Philosophically, the RAPIDO concept and its record of successful applications supports our team’s key objectives of Flexibility, Modularity, Reliability and Adaptability. These objectives are further supported by the parameters of the Stafford Disaster Relief and Emergency Assistance Act, which was initially passed in 1988 and is regularly updated (FEMA 2021). The Stafford Act currently limits federal emergency housing assistance (including Direct Housing) to a duration of 18 months from the time it is first awarded. Thus, individuals or families receiving Direct Housing are required to transition out by 18 months. An alternative would be a private purchase of the house, or donation through a buy-back program. The possibilities for adapting and expanding the provided housing units make it more feasible that affected persons, and/or supportive non-profits, might elect to purchase the houses for permanent settlement. If the houses have initially been located on sites close to the pre-existing neighborhoods of the displaced victims, then this whole scenario can promote broader community resilience – everything from keeping individuals employed to keeping children in their schools to keeping key social networks (churches, community organizations, etc.) intact.

2. DESIGN STUDIES FOR NOVEL APPROACHES

Our design studies for disaster recovery structures followed closely from the background research described above in Section 1.1. Moreover, each of our studies prioritized the use of prefabricated wood building systems, for reasons of weight, constructability, flexibility and low carbon footprint, among others. On one end of the spectrum, we looked at modular units with varying degrees of offsite completion. Offsite volumetric modular

construction holds the potential of being an especially fast solution for disaster recovery, particularly if units are built and stored in advance of disaster events as in the case of FEMA's standard approach. While fast to deploy, the modular approach does carry the most intensive demands for transportation and installation, in that it requires heavy moving equipment at all points between the factory and the building site. This approach also demands the greatest amount of space and volume for pre-deployment storage, supposing that units are planned and prepared in advance of a disaster.

On the other end of the spectrum, we studied an approach that would utilize a kit-of-parts system in which prefabricated components could ship in a condensed format (flat-packed on pallets, for example) and then be assembled on site. For this, we turned to a unique light framing system which has been under development at Clemson University since 2014. Compared with offsite-fabricated modular units, a kit-of-parts approach is necessarily more intensive and time consuming when it comes to onsite installation, though design measures can be taken to make assembly of the components easy and safe, like a puzzle, making it favorable for situations in which volunteer and/or low-skill laborers are in ready supply. This approach is also nimble to prepare, store and deploy, and could be useful for sites which may be hard to reach with tractor trailers. Each of the two methods (Modular and Kit-of-Parts) is summarized in the following sections, with the designs for core units and their expansions being illustrated therein.

In the middle, between the offsite modular approach and the kit-of-parts approach, is the panelized construction approach, utilizing some combinations of prefabricated wall, floor and roof panels, as exemplified by the RAPIDO concept from BC Workshop. RAPIDO, whose closed-panel, light wood construction supports reasonably fast project delivery and installation, and whose clever detailing, including accessible raceways for wiring, supports flexibility and expandability, has served as our consistent reference point for a panelized design.

2.1 Volumetric modular units

Supported through a grant from the USDA, and in partnership with the U.S. Forest Products Laboratory, our team's work on volumetric modular designs, actually began by studying the topic of deployable medical relief units for the rapid delivery of medical supplies and clinical care to areas whose hospital systems may be overwhelmed or out of reach. The premise was that these structures could be designed to be adaptable into housing units for use during the subsequent recovery phases. While this part of our study is not the subject of this present paper, it is worth noting that our research led us to the precedent of deployable medical modules from *Clinic in a Can*, a non-profit based in Kansas who retrofits steel shipping containers for use as off-grid-capable medical relief units (Clinic in a Can 2023).

With this example in mind, and considering the ease of transportation and the widespread familiarity with standard shipping container sizes, we elected to stay with ISO container dimensions as a parameter. Standard containers come in 20ft and 40ft lengths and are 8ft wide by 8'-6" tall. "High Cube" containers, which are also quite common, are a little bigger in cross-section at 8ft wide and 9'-6" tall. The additional ceiling height drove our team to utilize the "High Cube" dimensions for our basic modular unit. As in the example from *Clinic in a Can*, we considered the 20ft unit length to be the most versatile and nimble, and the majority of our work focused on this size. As an alternative to steel containers (whether new or recycled), our team based its designs for the 20ft x 8ft x 9.5ft modules on the use of mass timber panels, specifically cross-laminated timber (CLT) for a variety of reasons. These included: the natural insulating qualities of timber; the flat surfaces of CLT which enable the use of standard format rigid insulation; the fact that CLT presents a continuous structural substrate for mounting or attaching without blocking; the rigidity of the panels themselves which negates the need for space-consuming moment-framing; the ease of window and door openings without a need for engineered framing; the ability to expose the CLT as a finished surface; the fact that wood is a renewable, carbon-sequestering material; and the potential for reclaiming and reusing entire panels in the event the modular units are decommissioned or highly altered in the future.

For the potential of shipping supplies (medical or otherwise) in the units themselves, we considered one end wall of the unit to be open (or openable), just like a shipping container. Next, we located a single door within a larger opening in one side wall whose dimensions would match the unit's end opening, enabling two units to join in a T-shaped configuration, if desired. This is the sort of consideration that reflects the project goals of Modularity and Adaptability. The door and transom in the side opening would be installed within light framing used to infill the larger rough opening in the CLT. Similarly, the wall that infills the end-opening, plus any interior partition walls would be of light framing. This framing and finishing could be completed offsite by the modular manufacturer, or could be completed onsite after the units are placed, whether by stick framing or through the use of prefabricated infill panels that ship with the unit. Operable windows would be located in rough openings across from the single doors in order to enable cross-ventilation.

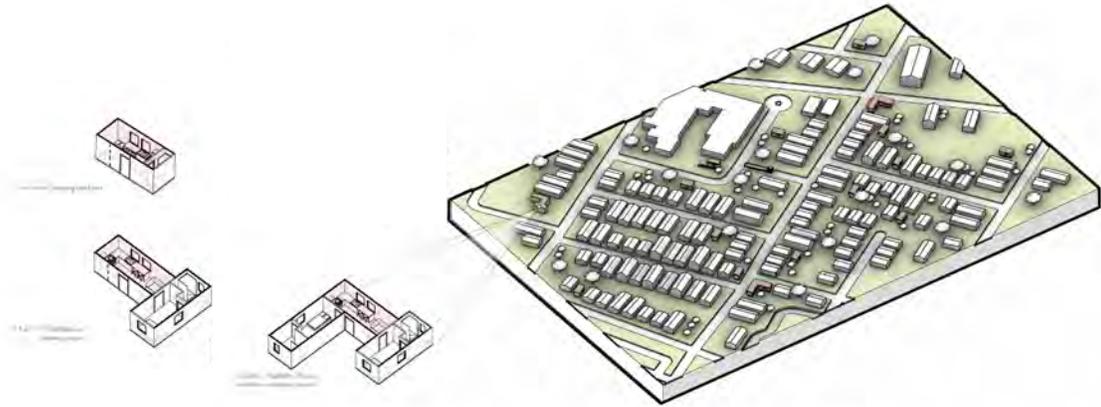


Figure 1: Core unit and expansion scenarios visualized within flood-prone Charleston, SC neighborhood. Illustration by: (Ryan Bing 2021)

From a structural standpoint, it was imperative that the timber units be able to be moved and stacked just like steel containers. With this in mind, our partners in Civil Engineering designed for the rigors of lifting and transporting, while even planning for payloads of medical supplies or units of blood. Using SPF V2M1.1 panels from Structurlam (a manufacturer based in British Columbia) as the initial basis of design for the CLT, the team concluded that 3-ply panels would be sufficient for walls, floor and roof. Later the team looked at 3-ply, Southern Pine SL-V3 panels from SmartLam’s factory in Alabama and drew the same conclusions. Outer laminations would run vertically in the wall panels, and would span in the short direction for roofs and floors. Structural analysis confirmed that the desired sizes and locations of the rough openings would be permissible.

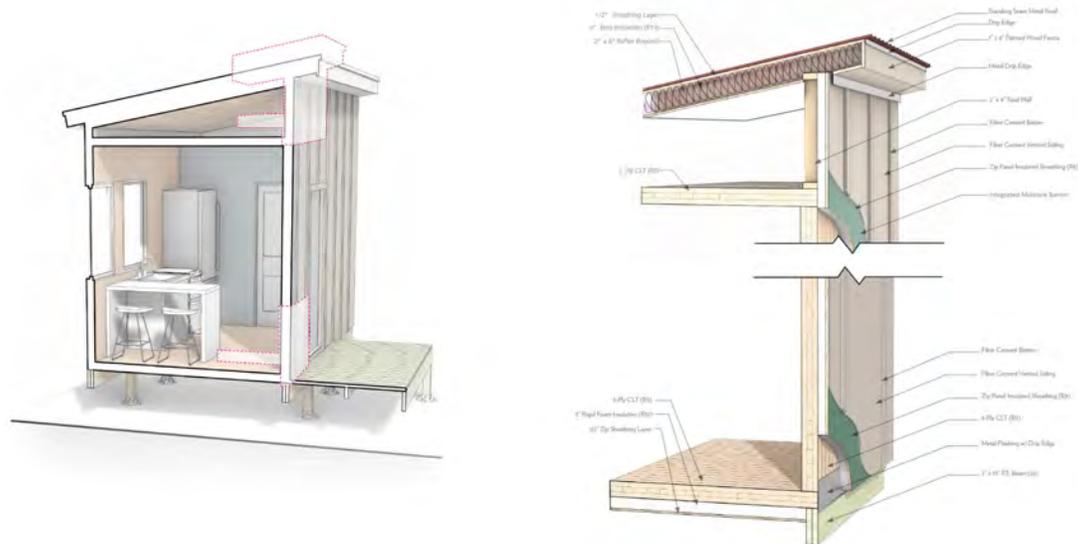


Figure 2: Cross-sections depicting unit finishes and on-site completion measures. Illustration by: (Ryan Bing 2021)

The units could either be shipped with a house-wrap preinstalled, later to receive rigid exterior insulation and finishes, or with a disposable weather-proof wrap, later to receive an insulated sheathing panel with integrated moisture barrier (and taped seams), plus finishes (e.g., Fig 2). Once onsite, units would be installed atop a raised substructure and reversible pin footings, offering resiliency, ventilation, and reusable foundation components. Other onsite work would include a pitched roof, which could be stick-built or assembled from prefab, light-wood framed panels. Roof designs could be tailored to suit the surrounding context or occupant preferences. Mechanical heating and cooling needs would be addressed by the inclusion of a multi-zone ductless mini-split system. These systems are compact and efficient, requiring only a small outdoor heat exchanger and wall-mounted interior units placed as needed. Like the examples from *Clinic in a Can*, the units could be powered by diesel generators, or, ideally, by integrated PV panels and onboard batteries for energy collection and storage. The ability to operate independently from the power grid is an important post-disaster consideration.

2.2 Kit-of-parts units

As an example kit-of-parts approach, our team turned to the “Sim[PLY]” framing system, which was first developed and utilized for Clemson’s entry in the 2015 Solar Decathlon Competition, and has been refined through several iterations and applications since. This system utilizes CNC-milled $\frac{3}{4}$ ”-thick plywood components which fit together like a puzzle and rely on a combination of unique wood-to-wood joints. It leverages the speed and accuracy of prefabrication for on-site assembly that is intuitive, safe, and quiet, without the need for heavy construction equipment, saws, nail guns, or other power tools. Walls, floors and roofs consist of built-up members (serving as studs, joists, and rafters/trusses, respectively), each featuring a plywood web and two plywood flanges (interior and exterior), and resulting in highly-insulated cavities. The flanges serve as strips through which to screw structural sheathing and interior finishes. Flanges and webs are joined by wood-to-wood tab and slot connections and secured by steel cable ties. Stud, joist and rafter webs are designed and milled for the rapid and integrated passage of MEP services.

During its development, the system’s structural performance has been tested through a series of coordinated ASTM test procedures. There were single-fastener tests to understand shear strength of the tab and slot joints, others to test screw withdrawal from the plywood flanges, and others to understand the tensile capacity of the cable ties. Full scale tests were performed on roof rafters (to test bending strength) and also on 8ftx8ft shear walls (to test racking strength and resistance to lateral deflections). Ultimately, the system was shown to be suitable for expected gravity loads and also suitable for seismic category D2 and wind speeds of up to 135mph.

In addition to its ease of assembly, the Sim[PLY] system is likewise easy to disassemble non-destructively. Once the steel cable ties are cut, the joints are reversible and pieces can be replaced or reconfigured. Using this logic, the frame can be designed with features that support the notion of adaptable and expandable structures. For example, door and window openings are designed to be interchangeable through the use of a removable sill and the joints in the studs that support these sills. Similarly, rafter components can be designed and milled with joints that accommodate future rafter extensions for roof additions.

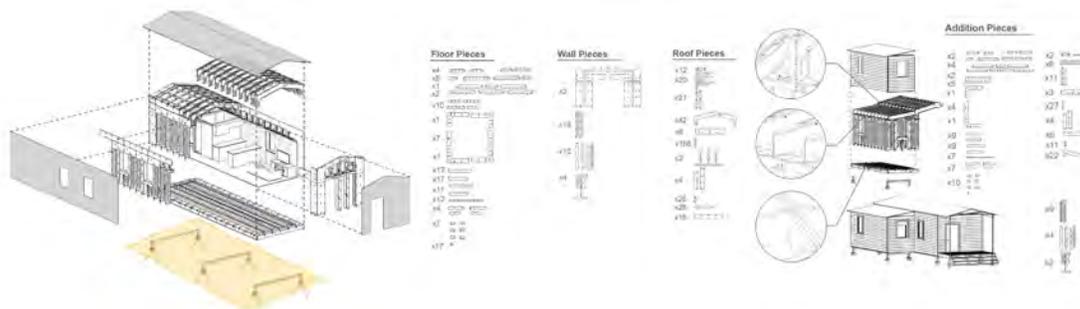


Figure 3: Core unit and bedroom addition utilizing Sim[PLY] framing system. Illustration by: (Daniel Mecca 2021)

As a starting point, and for the purpose of future comparison, the layout of the kit-of-parts core unit was designed in reference to BC Workshop’s 1-bed, 1-bath RAPIDO CORE. An optional 1-bed addition was also designed. The framing would be sheathed using structural sheathing with an integrated moisture barrier. Exterior cladding and interior finishes could be anything that the budget and conditions warrant, but systems that could be easily disassembled and reused would be ideal in the event that the housing units are eventually recovered and repurposed. For the interior of the housing unit there is the potential to use prefabricated bath and kitchen assemblies with a shared wet-wall, something we are still researching. This would provide a fast and integrated installation. Alternatively, the restroom walls (including the shared wet-wall) could be framed on site using Sim[PLY] components or conventional framing, and then plumbed and wired. Like the CLT modular solution (see Section 2.1), the Sim[PLY] solution utilizes an elevated undercarriage of beams (built-up from dimension lumber) and prefab pin footings. The porch and steps are likewise framed onsite.

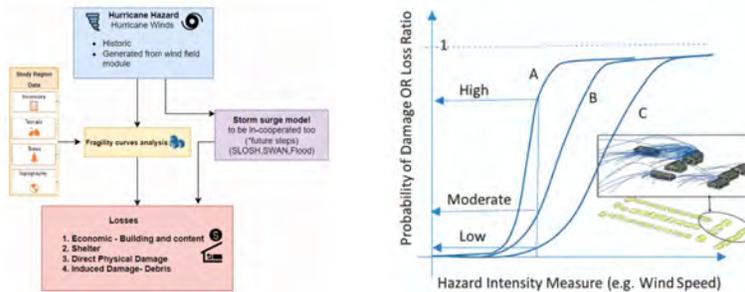
3. INTEGRATED DESIGN AND LOGISTICS MODELING

The third and current project in our sequence is being supported by NSF’s Disaster Resiliency Research Grants (DRRG) Program. Building upon the earlier logistics modeling from project 1, the main objective is to create an integrated modeling and analysis framework for disaster housing designs and logistics planning, including evaluating and enhancing their effectiveness in resilient hurricane response and recovery. The framework will integrate the physical resilience of disaster housing, the system resilience of the disaster housing supply chain and logistics network, and the operational resilience of robust and adaptive logistics operations under various hurricane scenarios. The team aims to analyze recovery housing solutions from a systematic perspective while drawing on converging research efforts from multiple disciplines: natural hazard and fragility analysis (in service of prefiguring demand for direct housing); relief logistics network design and

operations planning (in service of identifying supply); and architectural design. This work is ongoing, but the basic elements of each of these threads is described below.

3.1 Demand for Direct Housing Assistance

Three modules have been developed to estimate the housing assistance demand scenarios. Module One, the hurricane hazard module, quantifies hurricane hazards on a study domain (e.g. South Carolina) using simulated hurricane tracks based on historical observations. This study uses a stochastic simulation framework, which consists of several modules including a hurricane formation model, tracking model, intensity model, central pressure filling rate model, and wind field model. Module Two, the loss estimation module (e.g., Fig 4a), analyzes the hurricane hazard in order to calculate housing damage and monetary loss. The damage includes downtime for each building in the hurricane-affected region. Module 3, a fragility framework was developed to apply the risk to various residential buildings within the hurricane zone (e.g., Fig 4b). The study region data is taken from the FEMA inventory, which draws from the 2020 US census and the Nationwide Structure Inventory (NSI). The inventory includes data of the study domain such as tree parameters, building counts, populations, and building exposure values. Building fragility curves are used to predict damage and loss of residential buildings according to wind building classes (e.g. one-story wood building or multi-story apartment). Future work will integrate the three modules. The actual observed losses will be compared with the loss estimation results and the estimation framework will be recalibrated as necessary.



Figures 4a and 4b: Framework for hurricane hazard loss and damage estimates. Source: (Authors 2023) and Example damage fragility curves. Source: (Grayson et al. 2013)

3.2 Supply of direct housing assistance

The team is proposing an optimization model to capture the logistics process for transitional housing after a disaster. The model aims to address the logistical planning challenges brought by the gap between estimation and actual data. A regression-based forecasting model for the housing demand estimation has been created and is being calibrated using historical hurricane data and socioeconomic data. A two-stage optimization model has been built to capture the short-term logistics plan and address the housing demand uncertainty (e.g., Fig 5). The first stage corresponds to the preparation of disaster housing supplies prior to the realization of the housing demand, and the second stage corresponds to the operational decision making to address the housing demand that has been realized. To account for the extreme scenario of unexpectedly high demand, we consider two modalities for the operational decisions: a typical supply plan (based on the first-stage preparation only) and an emergency supply plan (which includes “emergency acquisition” decisions).

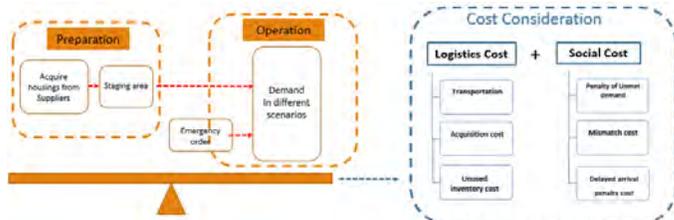


Figure 5: “Two stage optimization model” is the short-term logistics plan and cost consideration. Source: (Authors 2023)

3.3 Architectural designs as inputs

Drawing on case-studies (such as BC Workshop’s RAPIDO) and on the unit designs described in section 2, we aim to examine a set of alternative direct-housing designs across a range of prefabrication and delivery scenarios, all to address common needs and logistical concerns associated with post-disaster housing. This includes: cost of materials; logistics of storage and transport; speed of production and delivery; speed and ease of installation; required labor force; space, equipment and power required for on-site construction;

structural resiliency; and ease of adaptability and expandability. Data associated with this list of attributes, plus any others deemed important, will be coordinated with the hazard analysis and plugged into the optimization modeling described above. To date, we have gathered data on the conventional FEMA MHUs and trailers deployed after Hurricane Harvey in 2017. This serves as a baseline case and as an aid to refining the optimization model. Data for the RAPIDO unit (representing a panelized approach from a network of builders) has been obtained through communications with BC Workshop and through published reports, including the 2020 Disaster Recovery Alternative Housing Study commissioned by the Texas General Land Office (Hagerty Consulting 2020) – a study which again affirms the desire for “temp-to-perm” solutions.

Detailed fabrication costs and timelines on the Sim[PLY] framing system have been gathered over the course of past building projects, but will need updating for our proposed kit-of-parts recovery unit. The material costs for the plywood frame are tracked using the known sheet count derived from our nested cut files. Final decisions still need to be made on the sourcing of the interior elements. Finally, the team will decide whether to move forward with mass timber modular units. Up until this point, meaningful production data has been elusive because of a lack of modular builders working at the intersection of mass timber and affordable, single-family units. However, we very recently learned about the Hacienda Community Development Corporation in Oregon whose *Mass Casita* housing program seems to check each of these boxes, and we are hopeful that this provides an avenue for data collection and inclusion in our optimization modeling (Hacienda 2023).

CONCLUSION

This work is very much in-progress, with the synthesizing of our studies happening in the third and current project. We aim to test a range of different housing designs and construction/delivery methods, as characterized by the examples presented in this paper. The solutions will be tectonically and operationally different, but will share the objectives of Flexibility, Modularity (at different scales), Reliability and Adaptability/Expansion to address logistical and policy constraints. The research will create novel stochastic optimization models and solution approaches that will help improve disaster housing logistics network design and operations for SCEMD and beyond, and may result in myriad, blended solutions depending on the specifics of a given disaster scenario. We look forward to publishing our full results in the future.

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Designing Water Self-Sustaining International Projects Using Comprehensive Water Auditing

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ABSTRACT: Moyo Community Health Center is a five-acre campus in Moyo, Uganda that currently receives water for its clinics from a neighboring private well and energy from an existing photovoltaic array. With two prominent rainy seasons, Moyo receives over 20 inches of rainfall each year. This paper investigates the potential for rural health centers with limited water supply to become water self-sustaining through rainwater collection, treatment, and use. A group of fifteen architecture; architectural engineering; and water, society, policy students engaged in a semester-long project to complete a water audit for the health center in Moyo from their classroom in Arizona. The audit was comprised of four modules focused on conservation, passive measures, active measures, and process water. Three rounds of community engagement virtual activities with the health center and a supporting non-governmental organization, Pipeline Worldwide, were conducted to obtain building and fixture measurements, occupancy numbers, typical uses, landscape species specifications, and system details from the site. The audit culminated in an integrated net zero water design for the health center. This paper lays out a method for engaging with an international and rural community partner at a distance to offer water auditing services. Overall, Moyo Mission Health Center's baseline water demand was 570,236 gallons each year. Applying conservation and passive measures, the demand dropped to 376,407 gallons each year. Rainwater harvesting systems with appropriately sized cisterns were designed based on the daily rainfall and existing ten buildings' roof areas and runoff coefficients to meet this 376,407 gallon demand. The paper concludes that this work is possible with committed and communicative community partners and a clearly structured auditing process. The results from the water audit are presented to illustrate this process. The paper concludes with a discussion of ethical concerns and mutual benefits from the international engagement. As an outcome to the audit and net zero water design, the health center is receiving funding from Pipeline Worldwide to install large cisterns to achieve the self-sustaining water balance.

KEYWORDS: net zero water, international partnerships, rainwater harvesting, rural, auditing

INTRODUCTION

Rural projects that exist separate from centralized water infrastructure rely on a fine balance between naturally provided sources of water, storage capacities, and annual demands. To ensure a reliable supply of water, accuracy is important when designing such self-sustaining systems to achieve a net zero water balance in the course of a year. University architecture courses that teach students water auditing skills have the resources to provide auditing services in such conditions. This project was a partnership between a University of Arizona course, Moyo Mission Health Centre in rural Uganda, and the non-governmental organization Pipeline Worldwide. Moyo Mission Health Centre currently relies on a neighboring well for water, but would like to be able to operate independent of this neighborly dependence. The students in the course completed a comprehensive water audit to provide the rural health centre with the volume of cistern(s) necessary to reach a self-sustaining water system with rainwater catchment from the ten buildings on campus. The audit consisted of four modules: conservation, passive systems, active systems, and integrated strategy implementation. The audit and resulting design determined that with correctly sized underground storage cistern(s), Moyo Mission Health Centre could realize a self-sustaining or net zero water system.

This paper investigates the ability for water audits to be done virtually to support international partners in rural conditions. It uses the case study of Moyo Mission Health Centre to assess this potential. The paper starts with a literature review and explanation of background of the case study site. Then, the methodology of the four module water auditing process is outlined. Moyo Mission Health Centre is used to illustrate this process and provide results from the audit work. The findings from the auditing process and resulting design of the self-sustaining net zero water system are presented and analyzed. The ethical challenges and larger benefits to both sides of the international service-learning partnership are discussed. The paper concludes that international partnerships between a university building technology course and a real-world client can be powerful opportunities to provide students with tangible applications for their learning and a partner in need with an important service. Virtual technologies can be a cost-effective way to achieve these outcomes without costly and carbon intensive travel. Pipeline Worldwide has pledged to fund the sized cistern to implement the net zero design for Moyo Mission Health Centre.

1. BACHGROUND AND LITERATURE REVIEW

1.1 Water infrastructure in Moyo Uganda

Moyo Mission Health Center is located outside Moyo town in the north of Uganda on the Sudanese border (Figure 1). Given this location, in addition to Ugandan citizens, there is a large population of refugees from Sudan and central African countries that are serviced by the health centre. In the 2020 Ugandan census, the population was about 12,000 residents in Moyo town and 109,500 residents in the wider Moyo District (City Population, 2023). The town of Moyo is serviced by electricity, water and sanitation. However, the Moyo Water Supply and Sanitation System do not extend these water services outside the town. Thus, facilities like the Moyo Mission Health Centre that sit outside servicing areas need to provide their own power, water, and sanitation services. Currently, the centre receives its power from onsite photovoltaic cells. Water is supplied from a borehole from a neighboring parish (Figure 1). An onsite septic system and leech field for flush toilets with a series of independent compost toilets provide sanitation services. The centre’s goal is to no longer depend on the neighboring parish and become water self-sufficient through onsite rainwater catchment from Moyo’s two rainy seasons on the centre’s ten building roofs.

1.2 Existing status of Moyo mission health centre

Uganda’s health facilities are classified into seven levels based on the services they provide. Moyo Mission Health Centre is a level IV center. In order to move to the next level, Moyo Mission Health Centre needs a reliable source of water and power, which they current do not have. A self-sustaining water system would help the centre to service more people with a broader set of abilities – such as surgery that goes beyond child delivery. Pipeline Worldwide reached out to University of Arizona School of Architecture as Pipeline’s main office is in Phoenix, Arizona. Pipeline Worldwide met officials at the health centre during a recent visit to Moyo in 2021 and identified the needs of the center, then connected them with the capabilities of the University of Arizona Water Efficiency course to conduct a water audit and calculate the necessary cistern sizes to reach water self-sufficiency for the campus.



Figure 1: Moyo Mission Health Centre Campus and Existing Water Supply. Source: (Author 2021)

1.3 Passive and active rainwater harvesting and rural applications

This research modeled an integrated system of passive and active rainwater harvesting to meet the calculated demands of Moyo Mission Health Centre. By definition, passive rainwater systems are designed to retain water until it can be naturally absorbed into the land (swales and pervious pavers are common passive strategies) and do not require energy to function. Active systems, by comparison, collect, clean, and store rainwater for use (tanks and cisterns are prevalent elements of active harvesting). Water harvested passively offsets irrigation demands, whereas water harvested through active systems can be stored and employed to meet non-potable and potable demands, depending on the treatment level achieved. The main design parameters of active rainwater harvesting systems are rainfall volume, catchment area, tank volume, and water demand. Passive systems have the same design parameters, excluding tank volume. These parameters all dictate system efficiency, though rainfall and water demand have been shown to have the largest effect (Mun and Han, 2012). Active rainwater harvesting has been increasingly implemented in areas that face growing water constraints under climatic, environmental, and social changes (Amos et al., 2016). Active system implementations have traditionally centered on irrigation demands, especially in the US (Gao et al., 2016). However, recent literature looks at implementations across countries in Asia, Australia, Africa, and Europe for toilet flushing and other domestic uses (Furumai, 2008). By comparison, passive rainwater harvesting has focused on stormwater mitigation. Passive strategies have featured prominently in literature on Low Impact Development or Sustainable Drainage System approaches (Hamel and Fletcher, 2014).

2. METHOD

The water audit methodology was comprised of four modules: (1) conservation, (2) passive systems, (3) active systems, and (4) integrated strategy implementation (TABLE 1). Each of the first three modules were composed of a baseline assessment, a quantitative and qualitative auditing process, and strategy recommendations. In the fourth module, a comprehensive strategy implementation plan was provided to the health centre and Pipeline Worldwide. Students devised comprehensive strategies to reduce indoor and outdoor building water use together to decrease demand such that a self-sufficiency or net zero state could be achieved. Before the water audit began, it was important to solidify expectations between the three partners in a Memorandum of Understanding. The next sections outline these steps and the results in the Moyo Mission Health Centre case study.

Table 1: Four Module Water Auditing Process. Source: (Author 2023)

Module	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

2.1 Community engagement and memorandum of understanding

A Memorandum of Understanding was formed between the Water Efficiency in Buildings course (ARCH 461/561), Pipeline Worldwide, and Moyo Mission Health Centre. Pipeline Worldwide first reached out to the University of Arizona School of Architecture and identified the necessary water auditing work during their most recent trip prior to the MOU. The MOU laid out the basic expectation from all involved parties in supplying data, conducting interviews by students during the semester, and the ultimate deliverable that would be provided by the course in the form of a final recorded presentation accompanied by a printed version. Pipeline Worldwide has partnered with several University of Arizona courses and courses from other universities. Pipeline Worldwide calls themselves “a conduit for facilitating connections between donors and vulnerable communities in East Africa, based on the needs voiced by local leaders. Pipeline Worldwide provides funding, time and resources for projects that deliver access to clean water, sanitation, education, healthcare, and development in the region’s most impoverished communities (Pipeline Worldwide, 2022).” In the case of the water audit and University of Arizona course, Pipeline Worldwide was the conduit for connecting resources and the future funder of the cisterns needed to reach a self-sustaining rainwater harvesting system. The University of Arizona course was comprised of fifteen architecture; architectural engineering; and water, society, policy students engaged in the semester-long project to complete a water audit for the health center in Moyo.

2.2 Auditing module 1: conservation

The first step of the water auditing protocol was to establish a baseline use by which future efficiency gains could be measured. The baseline contained both quantitative numbers and qualitative behaviors. In the first month of the course, information was provided by Moyo Mission Health Centre used to calculate overall water demand from the number and type of fixtures and the number and type of building occupants across the ten buildings (FIGURE 2). Occupancy was specified across the ten buildings, so that each rainwater catchment area had an exact linked water demand calculated, in case a modular design of many cisterns was favored.

Full-time equivalency fractions (FTE) were applied to doctors and staff that worked partial days or additional hours past the assume 1.0 FTE for an eight-hour workday. Assumptions of water use per FTE were based on standards taken from the Leadership in Energy and Environmental Design (LEED) Water Efficiency credits that are linked to data from the most recent version of the Environmental Protection Act. 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.

Results from Moyo Mission Health Centre: Indoor water use was calculated for each of the ten buildings with this occupancy, use behavior, and fixture data. Bathroom sinks, laundry sinks, kitchen sinks, flush toilets, compost toilets, showers, and outdoor water taps for maintenance and laundry were the fixtures specified in these calculations. Students used baseline assumptions of the fixtures currently in place and then suggested more efficient fixtures in their conservation strategy implementation. Total percentage reductions are calculated between baseline and potential reduction. An expansion of compost toilets, lower flow shower heads, aerators for hand washing sinks, and higher efficiency toilets were suggested as conservation implementations. With these conservation strategies, an overall 33.5% water savings was calculated from a current 570,236 gallon annual campus baseline to a 379,263 gallon annual use target (Figure 2).

	Building 1	Building 2	Building 3	Building 4	Building 5	Building 6	Building 7	Building 8	Building 9	Building 10
January	7,815.72	1,473.12	4,352.40	8,583.90	6,172.10	4,956.90	7,130.00	1,432.20	682.00	3,831.60
February	7,059.36	1,330.56	3,931.20	7,753.20	5,574.80	4,477.20	6,440.00	1,293.60	616.00	3,460.80
March	7,815.72	1,473.12	4,352.40	8,583.90	6,172.10	4,956.90	7,130.00	1,432.20	682.00	3,831.60
April	7,563.60	1,425.60	4,212.00	8,307.00	5,973.00	4,797.00	6,900.00	1,386.00	660.00	3,708.00
May	7,815.72	1,473.12	4,352.40	8,583.90	6,172.10	4,956.90	7,130.00	1,432.20	682.00	3,831.60
June	7,563.60	1,425.60	4,212.00	8,307.00	5,973.00	4,797.00	6,900.00	1,386.00	660.00	3,708.00
July	7,815.72	1,473.12	4,352.40	8,583.90	6,172.10	4,956.90	7,130.00	1,432.20	682.00	3,831.60
August	9,247.92	1,677.72	4,956.90	11,001.90	7,365.60	5,561.40	7,905.00	1,466.30	716.10	4,470.20
September	8,949.60	1,623.60	4,797.00	10,647.00	7,128.00	5,382.00	7,650.00	1,419.00	693.00	4,326.00
October	9,247.92	1,677.72	4,956.90	11,001.90	7,365.60	5,561.40	7,905.00	1,466.30	716.10	4,470.20
November	7,563.60	1,425.60	4,212.00	8,307.00	5,973.00	4,797.00	6,900.00	1,386.00	660.00	3,708.00
December	7,815.72	1,473.12	4,352.40	8,583.90	6,172.10	4,956.90	7,130.00	1,432.20	682.00	3,831.60
Annually	96,274.20	17,952.00	53,040.00	108,244.50	76,213.50	60,157.50	86,250.00	16,964.20	8,131.20	47,009.20

	Building 1	Building 2	Building 3	Building 4	Building 5	Building 6	Building 7	Building 8	Building 9	Building 10
January	5328.9	1004.4	3158.28	6228.83	4208.25	3,342.73	3,750.38	976.5	465	2585.4
February	4813.2	907.2	2852.64	5626.04	3801	3,019.24	3,387.44	882	420	2335.2
March	5328.9	1004.4	3158.28	6228.83	4208.25	3,342.73	3,750.38	976.5	465	2585.4
April	5157	972	3056.4	6027.9	4072.5	3,234.90	3,629.40	945	450	2502
May	5328.9	1004.4	3158.28	6228.83	4208.25	3,342.73	3,750.38	976.5	465	2585.4
June	5157	972	3056.4	6027.9	4072.5	3,234.90	3,629.40	945	450	2502
July	5328.9	1004.4	3158.28	6228.83	4208.25	3,342.73	3,750.38	976.5	465	2585.4
August	6305.4	1143.9	3596.93	7487.43	5022	3,443.48	4,158.03	999.75	488.25	3016.3
September	6102	1107	3480.9	7245.9	4860	3,332.40	4,023.90	967.5	472.5	2919
October	6305.4	1143.9	3596.93	7487.43	5022	3,443.48	4,158.03	999.75	488.25	3016.3
November	5157	972	3056.4	6027.9	4072.5	3,234.90	3,629.40	945	450	2502
December	5328.9	1004.4	3158.28	6228.83	4208.25	3,342.73	3,750.38	976.5	465	2585.4
Annually	65,641.50	12,240.00	38,488.00	77,074.65	51,963.75	39,656.95	45,367.50	11,566.50	5,544.00	31,719.80

Current	570,236.30
Ambition	379,262.65
Percentage of Savings	33.49%

Figure 2: All numbers in gallons. Moyo Mission Health Centre Campus Current Water Demand (above) and Projected Water Savings with Implementation of Conservation Strategies (below). Source: (students of ARC 461/561 Spring 2021 with Author 2021)

2.3 Auditing module 2: passive systems

In the second month of the course, students completed a site water audit for outdoor uses and consider passive measures to increase efficiency of outdoor water use. The site also had significant flooding issues in areas. Passive rainwater harvesting strategies were designed to reorient water circulation so that flooding was reduced and water was more efficiently used to meet outdoor demands over time.



Figure 3: Moyo Mission Health Centre Campus with Outdoor Water Needs. Source: (Author 2021)

Results from Moyo Mission Health Centre: For this module, students complete a site plan, locating various vegetation species throughout the site (FIGURE 3). To calculate outdoor water demand, the students then used species factors, microclimate factors, and density factors to project vegetation demand. To calculate potential new sources of water (through passive strategies), students then used the site plan, average monthly precipitation, and various pervious material run-off coefficients to calculate possible water collection volumes. Students consider both passive rainwater harvesting, reduction of turf grass, and native and adaptive species as strategies to passively reduce water use outdoors or more efficiently use natural rainfall. Students completed a water budget for outside supply and demand. The total annual passive rainwater supply on the health centre campus was computed to average 4,535,564 gallons a year. Students treated the garden water use for campus-sustaining food production as separate as the landscape beautification of the campus grounds. Students then designed a passive strategies master plan where swales with strategically placed water absorbing vegetation and raised walkways made better use of the natural rainfall, allowed for water to be slowed and circulated throughout the site, and also decreased chronic areas of campus flooding.

2.4 Auditing module 3: active systems

In the third month of the course, students considered active rainwater harvesting as means to achieve self-sufficiency based on the calculations in Module 1 and 2. Typically, active systems to decrease potable water use include rainwater harvesting, gray water use, and condensate recovery. However, in this healthcare and rural Uganda situation, the only applicable active measure was active rainwater harvesting. Graywater harvesting is deemed impermissible in healthcare settings where there is significant disease, bodily fluids, and public health concerns. There were no air-conditioning units, thus no opportunities for condensate recovery.

An array of modelling tools and methods to design and evaluate RWH systems have been developed over the last several decades. As rainfall and water demand are both temporally and spatially variable, models for active RWH have predominantly focused on calculating the volume of storage required to balance these inflows and outflows for a specific location (Campisano et al., 2017). Tank size design has been computed with various methodologies. Approaches include the use of empirical relationships (Ghisi, 2010; Palla et al., 2011), stochastic analysis (Cowden et al., 2008; Basinger et al., 2010), and continuous mass-balance simulations of the tank inflow and outflow (Fewkes and Butler, 2000; Liaw and Tsai, 2004; Campisano and Modica, 2015). Mass-balance models combine the localized rainfall and water demand at a variety of spatial and temporal scales (Campisano and Modica, 2015; Melville-Shreeve et al., 2016). These models have also been used to simulate systems under uncertain climatic shifts (Mitchell, 2007; Lash et al., 2014). Several studies have found that aligning water demands closely with local rainfall patterns significantly increases system efficiency (Zhang et al., 2009). In the case of this water audit performed by students, a mass-balance method was used over monthly periods. Although this is much less accurate than the preferred daily mass-balance approach, this rougher calculation was adequate for the reasonable tolerance for error in the cistern design and the other auditing calculations.

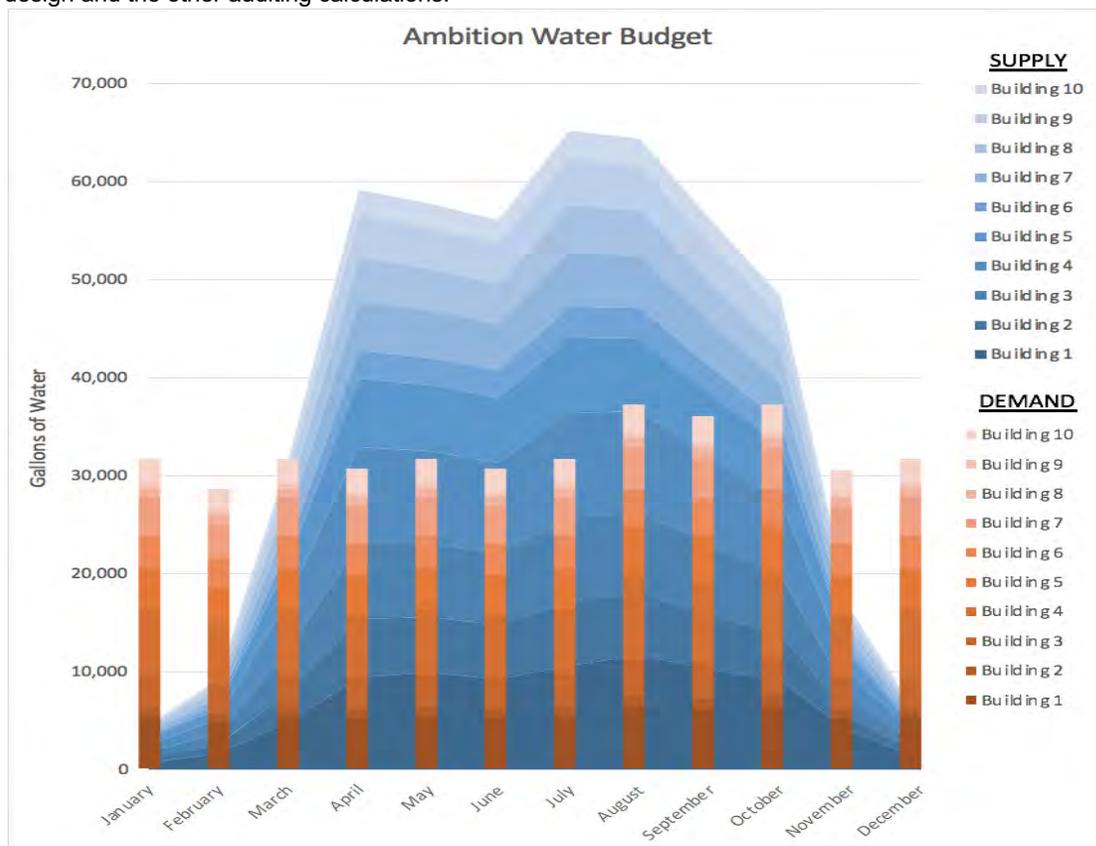


Figure 4: Moyo Mission Health Centre Campus Final Self-Sustaining Water Budget with Outcomes of Four Module Audit and Implementations. Source: (students of ARC 461/561 Spring 2021 with Author 2021)

Results from Moyo Mission Health Centre: Students calculated the total rainwater that could be harvested from each of the roofs from the ten buildings. The students created an overall water budget based on the data from Modules 1, 2, and 3 (Figure 4). Then the water budget is used to size the necessary cistern(s) to lead to a water self-sustaining status. From the calculated indoor demands from this budget, students then ran the monthly mass-balance calculations for active rainwater catchment design for (1) each building having its own cistern and (2) implementing two large underground cisterns that were connected and serviced all buildings as a connected campus water system. From this water budget and the two cistern design proposals, a total potential reduction is calculated. In Figure 4, the blue supply that is exceeded in rainy months is stored in the designed cistern system and used when there is an absence of supply, but still a steady demand (i.e. January, February, November, and December). It was determined for the purposes of overall system resilience and cost; it was better to build the two large underground cisterns and tie buildings together in one water system. A total 29,000 gallon storage capacity for the entire campus was computed to achieve a self-sustaining or net zero water system.

2.5 Auditing module 4: integration of strategies

In the final month of the audit, students looked holistically at data and recommendations from Module 1, 2, and 3. In Module 4, students also added research on new technologies that had also been shown to be successful and could be helpful to further the water goals of the project. In the case of Moyo Mission Health Centre, this included treatment options for the collected rainwater and permeable paving technologies for parking surfaces and erosion control. Students completed a full report for final presentation to Moyo Mission Health Centre and Pipeline Worldwide that was both live and recorded and provided to the international partners.

Results from Moyo Mission Health Centre: Overall, Moyo Mission Health Center's baseline water demand was 570,236 gallons each year. Applying conservation and passive measures, the demand dropped to 376,407 gallons each year. Passive strategies also decreased areas of significant flooding onsite. Active rainwater harvesting systems with appropriately sized cisterns were designed based on the monthly rainfall and existing ten buildings' roof areas and runoff coefficients to meet this 376,407 gallon demand with two cisterns of 29,000 gallons total capacity.

3. DISCUSSION

3.1 International partnerships: a net gain?

International partnerships can be challenging, logistically and ethically. Communication can be difficult due to time zone constraints and cultural differences. Students' ability to fully understand place specific conditions may be limited by never having experienced the location and their own biases from more narrow lived experience. The design of solutions to site specific challenges may be misguided by holes in understanding of local materials, maintenance capacities, and local assumptions about use. Thus, in these partnerships, it is critical to have a strong local partner that can effectively communicate local circumstances and needs and have the buy-in necessary for the long-term maintenance of any design implemented. It is also necessary that students are able to push themselves to stay open, challenge biases and assumptions, listen carefully, and ask good questions when they humbly do not understand. Overall, despite these challenges, international partnerships can be important opportunities to stretch student understanding, student ability to apply concepts and methods to a variety of situations and provide a breadth of perspective. Based on the case study of Moyo Mission Health Centre, the virtual water audit was a net gain both to student learning and application of that learning and the services needed by the international partners that resulted in concrete results.

3.1 Future steps: a self-sustaining net zero water Moyo mission health centre

Moyo Mission Health Centre is expecting the installation of two large underground cisterns as designed by the Water Efficiency in Buildings course (ARCH 461/561) course and sponsored by Pipeline Worldwide. This will support the centre in having its own functioning, self-sustaining water system, potentially leading to its approval as a next level health centre able to conduct surgeries beyond child delivery. Pipeline Worldwide has long standing work and partnerships in Moyo, thus Pipeline Worldwide will aid in the maintenance and long-term success of the new water system. Given the University of Arizona multiyear partnership with Pipeline Worldwide in several courses at the School of Architecture, the author looks forward to staying in touch with the organization and receiving feedback on the functioning of the system.

CONCLUSION

This paper argues that the resources of students in university courses can be connected to international development projects to provide comprehensive water audits using virtual technology. The audit was composed of four modules: (1) conservation, (2) passive design, (3) active design, and (4) holistic strategy implementation to reach a net zero status. In the case of Moyo Mission Health Centre, the audit successfully sized and designed the cisterns necessary to support reaching a self-sustaining status. Students benefited from the direct application of their water auditing knowledge, stretching their understanding of various applications of the water audit to a rural condition in a country with which students were not previously familiar, and the community partners benefited from the service and deliverables.

Architects need to receive training in school to design for a water efficient future. The auditing protocol provides architecture students (and other engaged students such as architectural engineering students) with a systematic tool to apply to each future building they design – whether in urban or rural conditions. The real-world experience of auditing for an actual project with funding for construction developed students' confidence to take on current and future challenges of water with an integrated process of measurement, analysis, and design. Net Zero Water is an important concept for architecture students to learn and have confidence in computing and implementing for the future of our increasingly water stressed built environments (both in scarcity and abundance of water). The author looks forward to future partnerships to achieve similar outcomes both for students and for community partners.

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The author thanks architecture; architectural engineering; and water, society, policy students of the Spring 2021 Water Efficiency in Buildings course (ARCH 461/561), Pipeline Worldwide, and the director and staff of the Moyo Mission Health Centre. Additional gratitude to cross curriculum colleagues in the Critical Practices research concentration at the time of this course: Altaf Engineer, Christopher Trumble, and Aletheia Ida.

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Weaving and Tuning Cast-In-Place Falsework

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ABSTRACT: *This paper examines a novel construction technique the relies on Weaving and Tuning to make the construction of cast-in-place concrete walls assessable to low-skilled labor. In contrast to formwork constructed by highly-skilled craftsmen—by hand or computationally fabricated—the student work product of this semester-long Advanced Architectural Tectonics course demonstrates that a construction system that can be deployed loosely on-site (woven) and later adjusted and fixed into the desired location (tuned), allows for low-skilled labor to execute complex cast-in-place concrete forms. These conclusions are supported by first establishing the experience level of the student participants, documenting their learning process, and work product.*

KEYWORDS: CIP Concrete, Tensile Formwork, Student Construction.

INTRODUCTION

Although tensile systems have proven structural efficient in the construction of complex forms for decades, their use as temporary structural support (falsework) for casting concrete has seen negligible impact on construction practices (Veenendaal 2011). The Fabric-lined tensile formwork system discussed in this paper is an approach to deploying formwork that minimizes the materials consumed and technological equipment required for its deployment (Palagi, 2020). The research presented in this paper focuses on the skill of the labor needed to construct such novel systems.

Current trends in the scholarship of cast-in-place concrete have been dominated by two distinct realms of digital fabrication: novel tectonics and robotic installations. The breadth of research into novel concrete formwork demonstrates multiple paths with which digital fabrication techniques can achieve a high-level of accuracy in complex falsework (Block 2016; Méndez Echenagucia 2019). Various woven or cable-net systems minimize the amount of concrete consumed in the final cast form by maximizing the structural efficiency of the form through computational modeling and the accuracy of digitally fabrication (Popescu 2020; Veenendaal 2012). The falsework required to resist the tensile forces due to the concrete slump (to maintain the tolerances required for structural integrity of these designs) is achieved through robust, novel scaffolding. In contrast, the use of Robotics for the direct placement of concrete slump highlights the potential speed and consistency of future concrete construction when the formwork and the direct contact of a labors' efforts are removed (Buswell 2018). In each of these approaches, the use of bespoke falsework or the requirement of advanced technological equipment on-site, demand highly trained labor to execute their construction (Popescu 2019). In contrast, this paper examines a novel construction technique the relies on hand Weaving and Tuning to facilitate low-skilled labor in the accurate construction of complex concrete walls. This paper presents the findings from 18 novice builders attempting to learn and execute the fabric-lined tensile formwork for small, yet full-scale, structural concrete walls.

This fabric-lined tensile system formwork system does not attempt to minimize the Concrete consumed in the construction of the walls. This formwork system trades an increase of concrete cast in the final form for the minimization of the material consumed by the falsework and the increase of accessibility for low-skilled labor to construction complex cast-in-place structural walls (Palagi 2020). This system relies on the steel reinforcement required for the completed concrete wall as an internal scaffolding during the casting process. Between the vertical reinforcement, a repeated tensegrity system called tensegrity cushions are initially woven into place loosely and later tuned into the orientation desired (Roland 1970). Once in place, a series of external crossing tension members lock the tensegrity cushions together (in effect, created a vertical spaceframe, while, supporting the fabric liner). With the tensions cushions extending roughly equal distances, and internal tension between opposing surfaces, the static pressure of the slump is normalized, balancing the wall.

METHODOLOGY

To document the impact of weave and tuning techniques, four data sets were collected over a semester long elective course with 18 upper-level architecture students:

- A pre-semester survey documented the construction experience of the student participants.
- Lab notes taken while familiarizing themselves with the system, documented the students' time and effort for deploying each phase of the system's sequence of construction.
- Student work product from the Team Research assignment supplies empirical testing of the student's ability to execute the established system through multiple full-scale casts. Each cast approximately 18" wide, 32" tall, and 4-8" thick.

- The final Independent Investigation assignment, demonstrate the student's mastery of the construction system through their attempts to evolve the construction system.

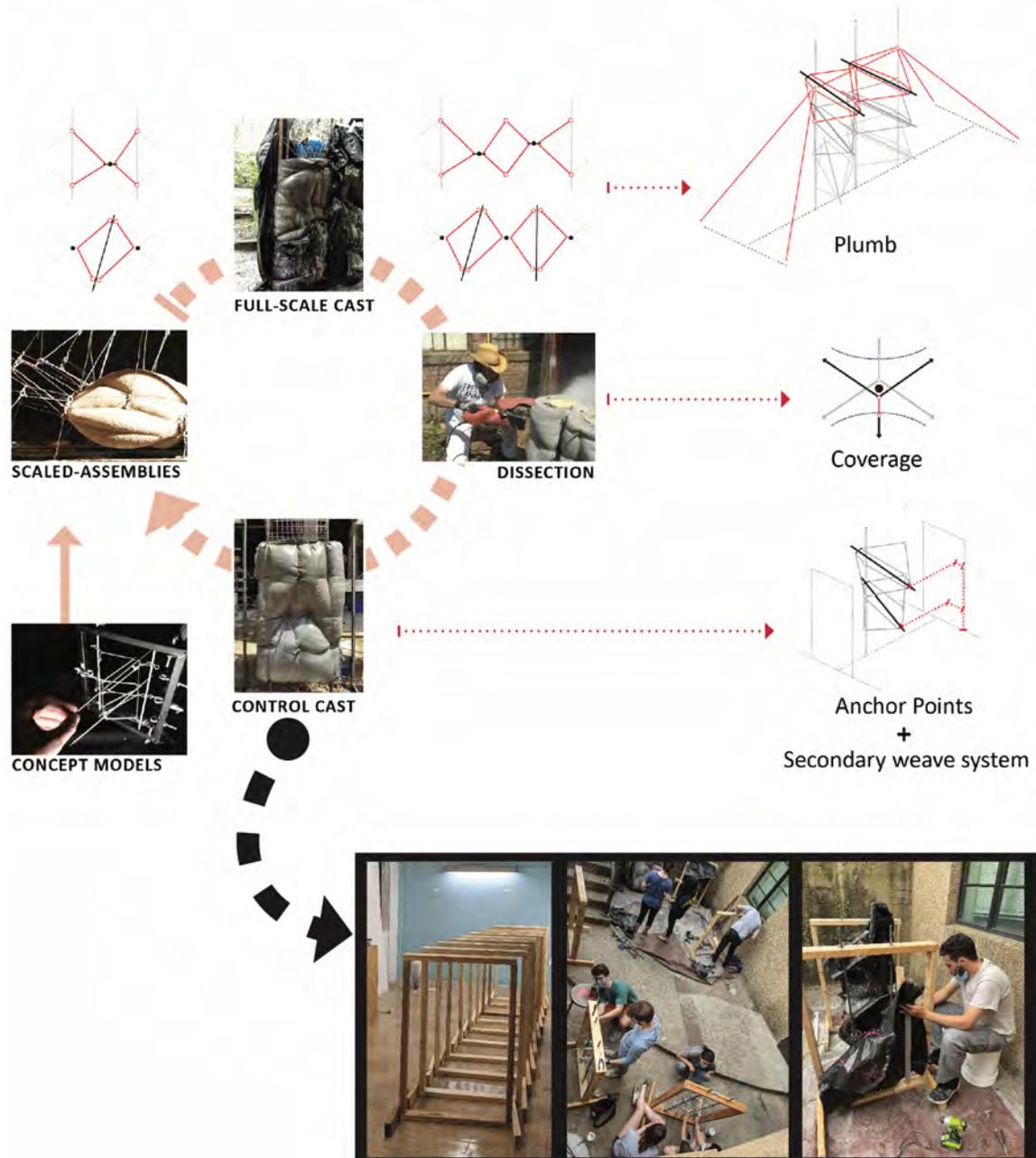


Figure 1: Student investigations furthering initial proof-of-concept (Palagi 2020).

PARSING THE DATA

LABOR_ A clear lack of construction experience was recorded in an 8 question pre-course survey. Of the 18 architecture students enrolled, not one had been employed in any construction field. The class was divided into two cohorts (Blind and Shadow), with a balance of students with equivalent construction experience.

Table 1: Excerpt from Pre-Course Student Survey

Question	-1- Little to None	-2-	-3-	-4- a good deal
Work Experience in any construction field.	14	1	0	3
Personal Experience Casting Concrete.	10	7	1	0

LEARNING CURVE_ The students spent the first two weeks of the semester familiarizing themselves with techniques and sequences of deploying a single structural bay of the construction system, a Tensegrity Cushion. The students identified as the Shadow cohort, watched the instructor deploy a Tensegrity Cushion, while the second cohort, the Blind, were given only written instructions. Through both the verbal and written instructions, five phases were named in the deployment sequence of the system. The students were each tasked with constructing a Tensegrity Cushion a minimum of three times over the two weeks. They document the time each phase of the construction took them, along with recording any specific notes. All data (times and notes) were verified by a witness and compiled in a single, class-wide excel file. Analysis of the data showed the Shadow cohort were initially faster than the Blind along with less struggles noted in their first attempt, but by a third attempt they times and effort balanced. (Approximately 2 weeks or 10 hours)

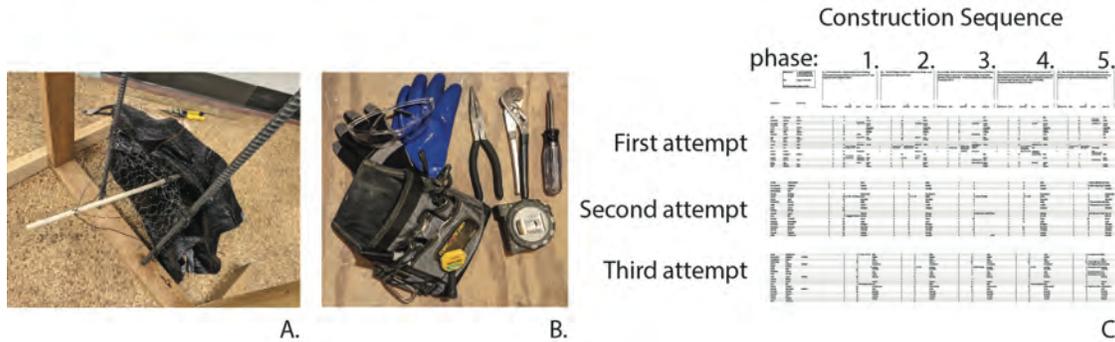


Diagram 2: A. Tensegrity Cushion mock-up. B. tools required for course C. Class-wide collection of Lab notes.

EXPERIENCE_ Following a student-led discussion of possible research agendas, teams of 3 to 5 students formed around personal interests. The agendas each looked at the testing of nuanced variables in the existing system. Each group were required to cast two full-scale tests of their research and completed a research document consisting of the initial proposal, test cast A, findings and proposal, second test cast, and final results. (Approximately 3 weeks 15 hours)

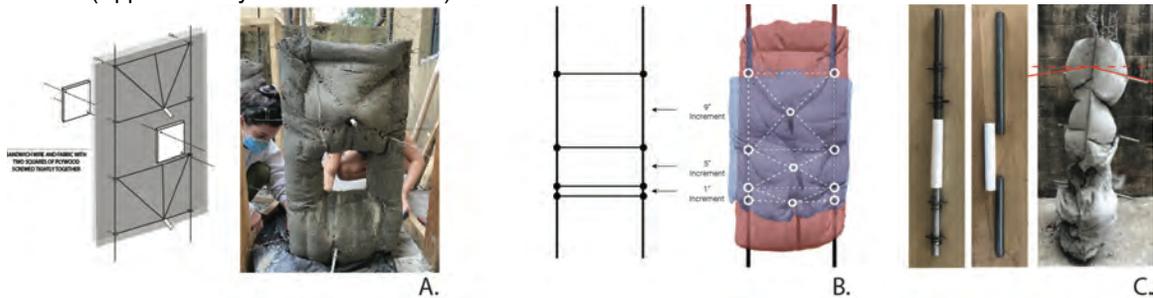


Figure 3: Group: A_ Examining apertures. B_ Challenging novelty of pattern. C_ Incorporating a thermal break.

MASTERY_ Students were then asked to continue independently experimenting with the potential of the system. Unlike in the Team Research assignment, no specific requirements were given to the students for their individual investigations. The final independent student work shows an increase of the students' control when tuning the system, facilitating greater control in the tests. In addition, the independent nature of these investigations demonstrated a cogent understanding by the students of the system at this point in the course. (Approximately 2 weeks or 10 hours)

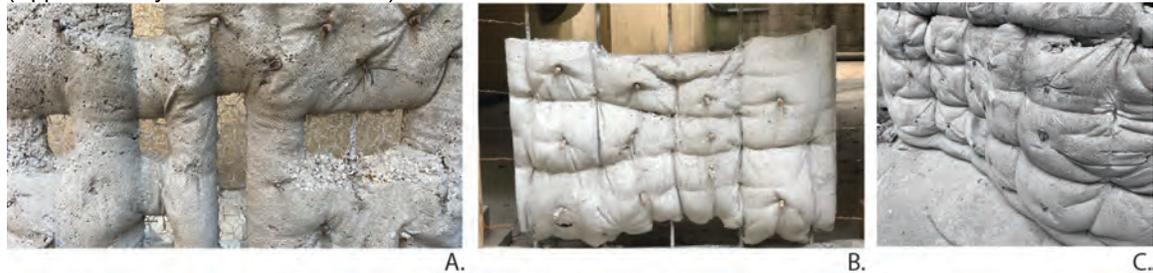


Figure 3: Ind. Research: A_ Examining apertures. B_ Challenging novelty of pattern. C_ Incorporating a thermal break.

CONCLUSION

Prior to this research, the construction of the proposed Fabric-lined tension formwork had been executed solely by the author. This paper documented the ability for 18 students, with little construction experience, to learn and execute this idiosyncratic construction system.

Weaving, unlike the additive construction techniques utilizing wood framing, heavy steel, or masonry, does not require accuracy in the placement of the aggregated elements within an assembly; rather, merely an adherence to spatial relationships between elements. For students with little construction experience, the stress of “measure twice, cut (perfectly) once” did not impact their learning of this system’s construction. The ability for the initial assembly’s weave to remain loose, allowed the novice builders to practice their techniques, reinforcing the conceptualization of the system, without failure due to their low level of craftsmanship. The use of weaving can be attributed to the students’ understanding of the construction sequence, rather than the specific instruction method, as both the apprenticeship (Shadow) and remote (Blind) demonstrated equivalent time and effort after merely three attempts.

In addition, the ability to tune the loose deployed system, circumvented the requirement of a skilled hand in executing a high-level of craftsmanship in the final cast form. The work product from the Team research assignment demonstrates the students’ ability to execute the construction method after merely practicing a single bay three times.

DISCUSSION

The dire need for labor, specifically in the construction of safe, low-cost residential projects, is felt throughout the globe. Yet a curved-concrete wall’s inherent resiliency to severe weather and lateral forces rarely overcomes the high labor costs of its construction (Popescu 2019). The system examined, draws upon the repetitive nature of weaving techniques to facilitate a quick learning curve (broadening the labor pool); while, as the student work exhibits, the ability to tune the exact position of the final falsework, rather than crafting a skilled final cut, opens the door for low-skilled labor to execute a highly accurate level of construction. Moving beyond the mundane act of mimicry, the final independent investigations, in which the students challenged the system with programmatic variations, showed how quickly an unskilled laborer was able to modify the system to their personal goals. Like the act of weaving tapestries, once the logic of the weave was internalized, expressive variations are easily explored. The weaving and tuning of this system extend design authorship to the hands of those on the ground, opening opportunity for cultural, programmatic, and otherwise site-specific intent.

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Negotiating the ground plane: calibrating the geometry of climate-adaptive urban surfaces

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ABSTRACT: *The paper outlines the strategy initiating students to the complex relationships between technology and society in the research studio context. By leveraging accessible open-source databases, digital modeling, and fabrication techniques, the studio systematically addresses the complex, social-cultural, ecological, and economic (infrastructural) relations through the performance of surface geometry of the ground plane with regard to water in three distinct scales.*

KEYWORDS: Water Management, Surface Geometry, Infrastructure, Urban Landscape, Precast Paving Units.

INTRODUCTION

Today, society's reliance on smooth, impermeable street surfaces stifles innovation in the modern transportation infrastructure. At an increasingly accelerated pace, technological innovations have thrust us into the epoch of the Anthropocene¹. Ironically, the "innovative infrastructures" from the past struggle to adapt to the persistent pressure of climate change, creating elevated risks for chronic flooding². The resistance to adaptation and change is referred to as the socio-technical dilemma of urban obduracy³. It suggests why we had overlooked some advantages of the alternative paving systems before they were rapidly phased out in the first quarter of the 20th century (Figure 1).

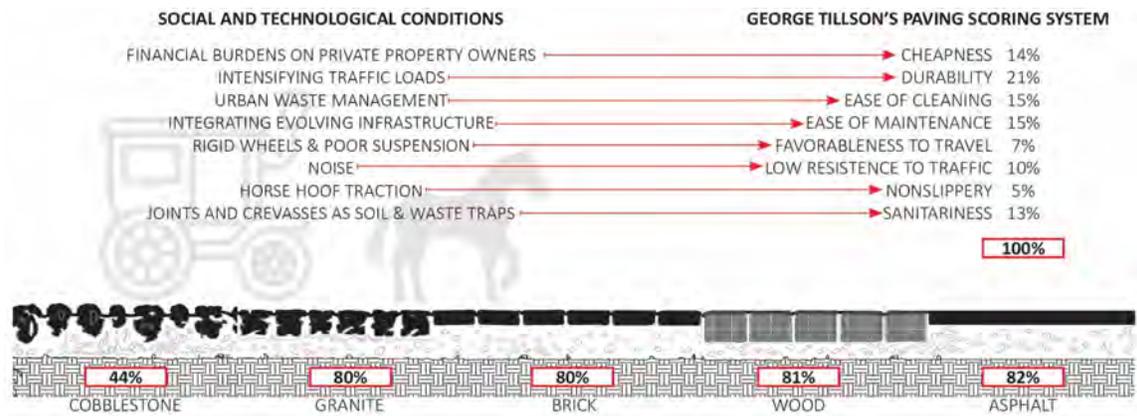


Figure 1: Tillson's Paving Scoring System⁴. Source: (Authors 2021)

New Orleans occupies the Mississippi Delta, the complex ecological system formed by the soil deposits interacting with the river and the gulf. In this soft, fluid ground, finding stability is a constant challenge⁵. With a thoughtful application, modular precast concrete paving systems can reestablish a symbiotic relationship between the built environment and landscape as both infrastructure and public amenity. By leveraging the digital design and fabrication techniques, the ground surface geometry can be reconsidered to be performatively and aesthetically aligned; to detain, retain or permeate water, mitigate flooding, and aesthetically embrace the reflectivity of the water surface. It will contribute to the context's overall spatial quality, encouraging the ground plane's productive occupation.

The paper outlines the strategy initiating students to the complex relationships between technology and society in the research studio context. By leveraging accessible open-source databases, digital modeling, and fabrication techniques, the studio systematically addresses the complex, social-cultural, ecological, and economic (infrastructural) relations through the performance of surface geometry of the ground plane with regard to water in three distinct scales: component, street, and urban scale.

APPROACH

At the component and street scale, we aim to slow down the storm runoff by momentarily storing it where it falls. A discontinuous, textured, permeable surface enhances pedestrian mobility by increasing accessible

surface during and immediately after the rain, channels and detains water to promote plants and tree growth, filter pollutants, and spatially amplify the experience by optically reflecting the surrounding landscape. On an urban scale, we aim to detain overflow from the drainage system during peak storm intensity to maintain the demand at capacity (Figure 2).

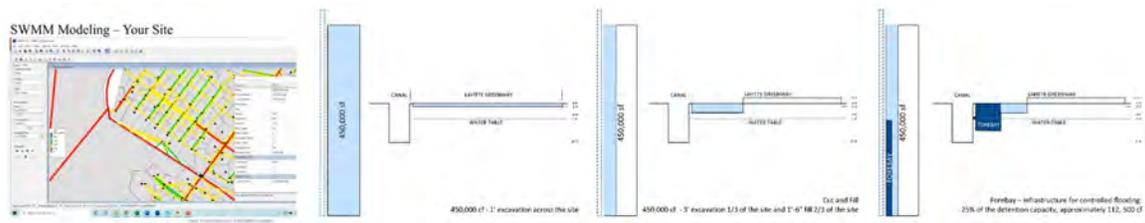


Figure 2: SWMM model analysis⁶ and implications of the storm drainage overflow retention. Source: (Authors 2021)

The studio prioritizes the design process informed by visualized quantifiable parameters through simulations and prototyping to find “the equilibrium” beyond individual beliefs and aesthetic preferences. The design methodology and resulting solutions are internationally relevant, as the water-related issues are no longer unique to our region⁷.

The hypothesis is: Through advanced computational design and fabrication techniques, the surface geometry of the streets and paving units can be performatively and aesthetically aligned; to detain, retain or permeate water, mitigate flooding, and aesthetically embrace the reflective quality of water, contributing to the atmospheric quality of the context and encouraging the productive occupation of the ground plane.

Roads and streets are the earliest, most effective technological utilities related to sustained urban settlements. However, similar to other technological applications developed to overcome the constraints of our physiological adaptation, the benefit is counteracted by adverse impacts on various social-ecological systems.

A good example is smooth, impervious concrete and asphalt surfaces applied to local residential streets. In the era of the Anthropocene, it can be considered a technical overcorrection, accelerating stormwater collection and discharge, overwhelming drainage systems, and causing chronic flooding. The application of smoothness across multiple street typologies is ripe for re-examination. A discontinuous, textured, porous surface can “slow” the water movement by storing it momentarily where it falls. Appropriately channeled and detained water will promote plants and tree growth that provide shade, filter pollutants, and spatially amplify the experience, dynamically capturing the surrounding urban landscape through its reflective surfaces.

To provoke students to reconsider the prevailing smooth, impervious asphalt, and concrete street surfaces, we developed two exercises and a representational technique to engage surface geometry performance at street and component scales.

1. COMPONENT SCALE

1.1 The eccentric tiling units

At the component scale, we’ve explored modular precast systems’ surface geometry and fabrication methods that shape and form the street surface to function as infrastructure and amenity.

eccentric |ikˈsɛntrɪk|
adjective

1. (of a person or their behavior) unconventional and slightly strange: my favorite aunt is very eccentric.
2. technical (of a thing) not placed centrally or not having its axis or other part placed centrally.⁸

Typical masonry units such as bricks, CMUs, and precast paving blocks conform. They are designed to fit in a stable, axial/symmetrical manner, forming predictable, continuous surface planes. The logic of stacking is easily recognizable as repeating patterns. The two-and-a-half-week exercise introduces a biased “eccentric” surface to the default 12” x24” x4” rectangular unit through subtraction. Initial geometric constraints are to alter no more than three sides of the original module. By introducing eccentricity to the geometry of the units, dis/continuous surfaces emerge when tiled on a level horizontal plane. Students systematically investigate the distinct aggregation patterns or absence thereof by paying attention to the dis/continuous extension of surfaces from one unit to another. They speculate the potential function of surface dis/continuity relative to water and sediments, leveraging digital modeling and 3D printing for rapid prototyping and testing (Figure 3).

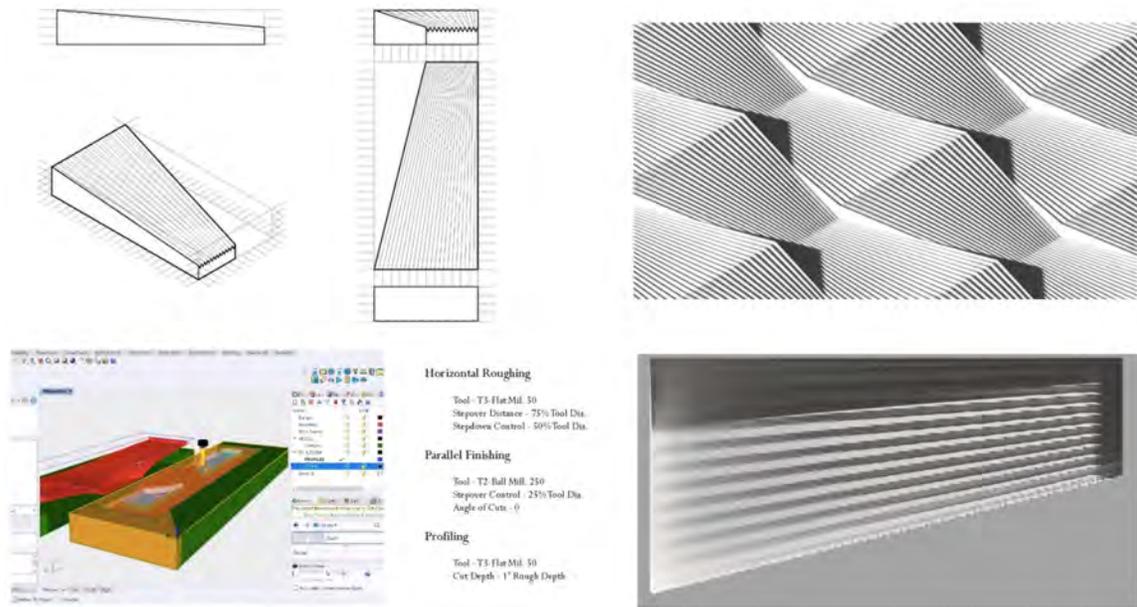


Figure 3: Student work examples of Eccentric Tiling Units exercise. Source: (Authors 2019, 2022)

The two key concepts and skills instilled in students are:

1. The complex surface geometry of the site and the components are abstracted, digitally constructed, and controlled as a series of linear ridges, valleys, and planes, not as contour lines of compound curvilinear surfaces.
2. Slope and water flow analysis tools⁹ are utilized on the abstracted surface geometry to visualize and confirm the performance of the geometry or to identify issues and test improvements.

Students learn how to translate the folded geometry and the constraints of a physical “sheet” material as a guide to rationalize and control the complex surface geometry in Rhino (Figure 3). This simple notion becomes the basis for surface representation and analysis in the street and urban scale exploration (Figure 4).

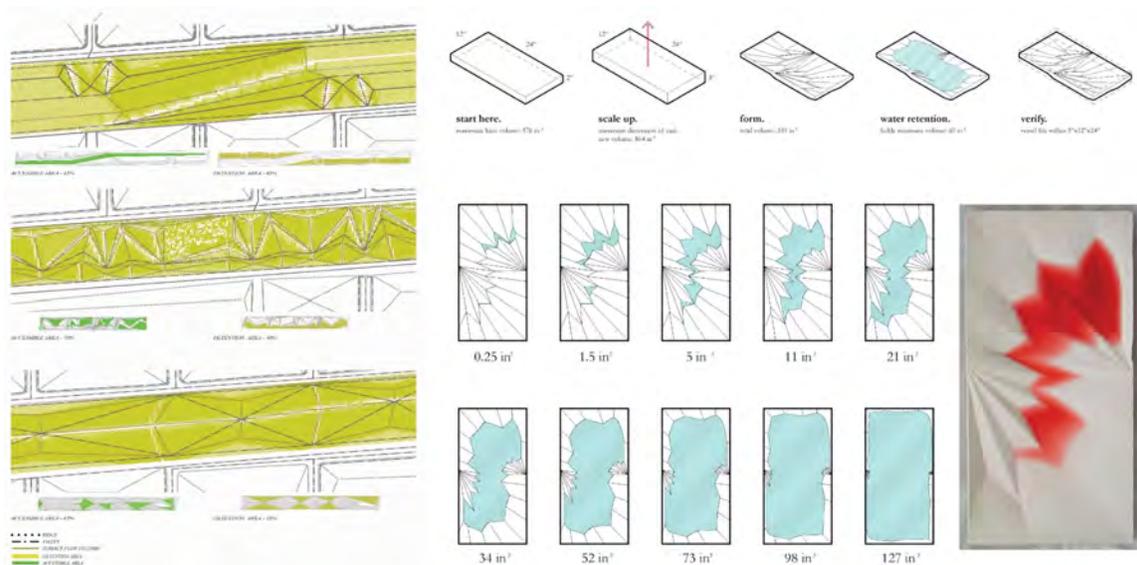


Figure 4: Student work examples of the performance analysis of complex surface geometry at urban and component scales. Source: (Authors 2019, 2021)

Virtual CNC-Milling simulation via Rhino-cam is also introduced to speculate the effect of “tooling” as an additional factor to construct and control surface geometry, jumpstarting the skill development for the

subsequent physical prototyping. The exercises utilize accessible advanced computational design and fabrication techniques to bring attention to the function of complex surface geometry. The potential of dis/continuous aggregated surfaces is investigated through iterative prototyping, testing, and observation while introducing the basic skills necessary for subsequent exploration.

2. STREET SCALE

2.1 The striating the smooth

At the street scale, we've explored the design of street surface geometry in a specific New Orleans location. The Striating the Smooth exercise builds on the Eccentric Tiling Units. The three-week exercise asks students to improve the urban streetscape with enhanced street surfaces by strategically deploying precast paving systems based on eccentric unit prototypes. For developments over 5000 sq. ft., New Orleans mandates owners to detain at least the first 1-1/4" of rainfall on-site. However, public streets are not subject to this code. We leverage the "hypothetical" water detention mandate on public roadways to reconsider the potential of the streetscape.

Using the public database, students identify underprivileged streets in the city to speculate improvements. The topographical surface of New Orleans is composed of three primary characteristics: the backslope, the bowl, and the lowlands. Students select an approximately two-square-mile area in each topographical condition based on their interests. Then, with the i-Tree Landscape web application,¹⁰ the locations are analyzed with a few basic data parameters, starting with an equally weighted scenario of low tree stocking area and high population density. The resulting prioritization maps guide the selection of nine-city blocks with a particular local street within a 1/4 mile of an existing bus stop. Students then examine the surfaces of the selected blocks and their geometry concerning mobility, ecology, and atmosphere mediated by water.

The students are asked to develop two paver variations concerning pedestrian accessibility: accessible and inaccessible. Inaccessible surface type is less suited to be walked on; It is intended to gently delineate pathways (vehicular from pedestrian, for example) or as edge conditions and provide the opportunity to creatively articulate the transition from one type to another. Along with the surface analysis (slope, water flow direction, and retention volume) and reflective surface rendering methods, CNC formwork milling/tooling and Hydrocal casting techniques are all introduced in the workshop format. The intention is to foster iterative physical prototyping and testing of the paving system on a larger scale. The project encourages students to reconsider local residential streets, a fixed, utilitarian infrastructure with high-impact design opportunities, by leveraging the necessary urban water management requirements (Figure 5).

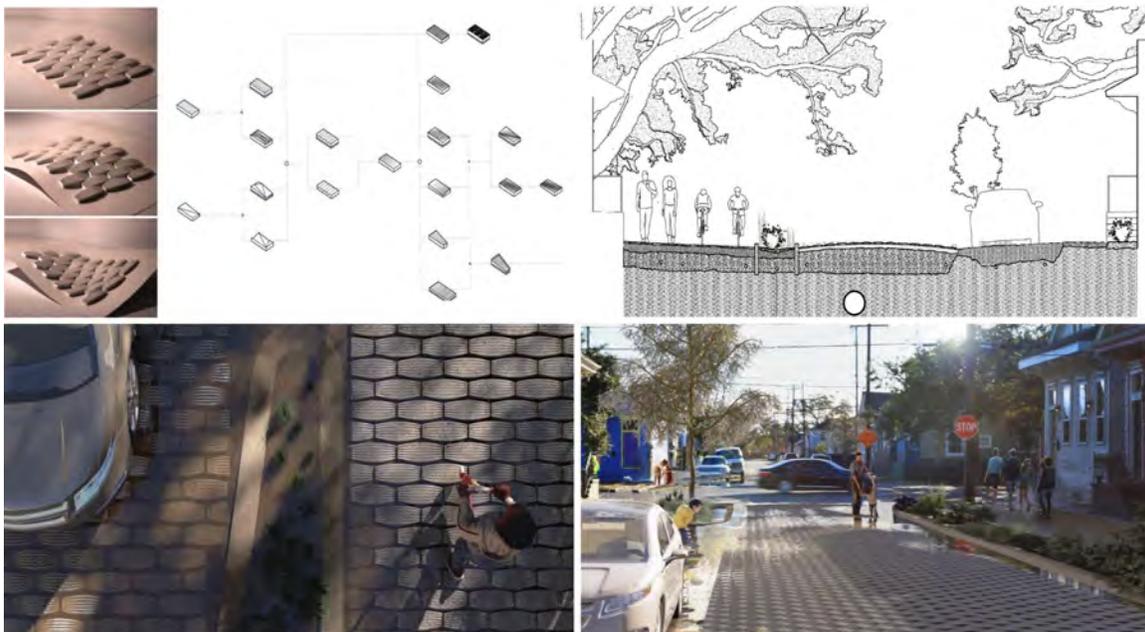


Figure 5: Student work examples of the street scale surface geometry and component application. Source: (Authors 2022)

2.2 The reflective surface representation

The reflective surface representation technique introduces water as a dynamic, reflective surface and a quantifiable interactive substance over the aggregated pavers. Students learn to control the qualitative rubric

of reflective/translucent substances in a digitally simulated environment. Students also learn to quantify how much water the system's surface geometry can detain and speculate the transformation of the amount over time. The change in water level will affect the amount of reflective surface and the perceived quality (Figure 6).

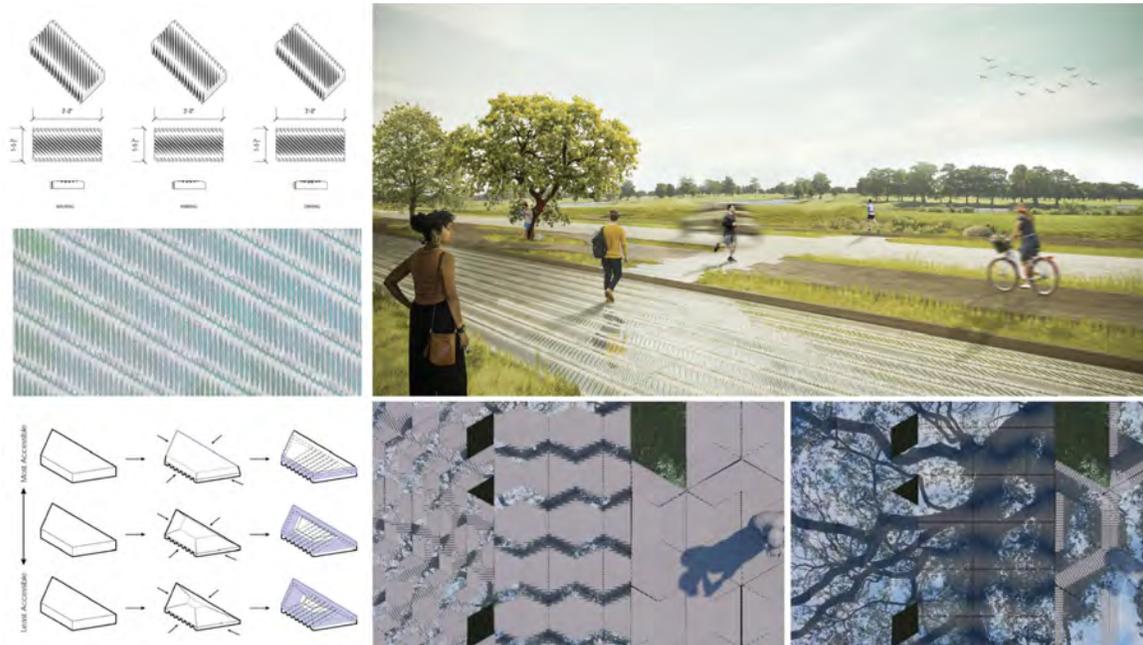


Figure 6: Student work examples of paving unit prototypes and the effect of reflective surfaces. Source: (Authors 2022)

3. URBAN SCALE

3.1 Reimagining the Laffite Greenway

On an urban scale, we explore the surface geometry of the existing urban park on an underutilized post-industrial infrastructure corridor parallel to the city's storm drainage system (Figure 7). Students are prompted to improve the park's function to serve the adjacent communities better while transforming it into a water detention infrastructure. The site context, including the community engagement outcomes from the Laffite Greenway project,¹¹ is thoroughly researched and diagrammed. The performative application of the complex surface geometry is examined at both urban and component scales to guide, detain water and foster productive occupation of the ground plane (Figure 8).



Figure 7: Drone photo of the site. Source: (Authors 2022)

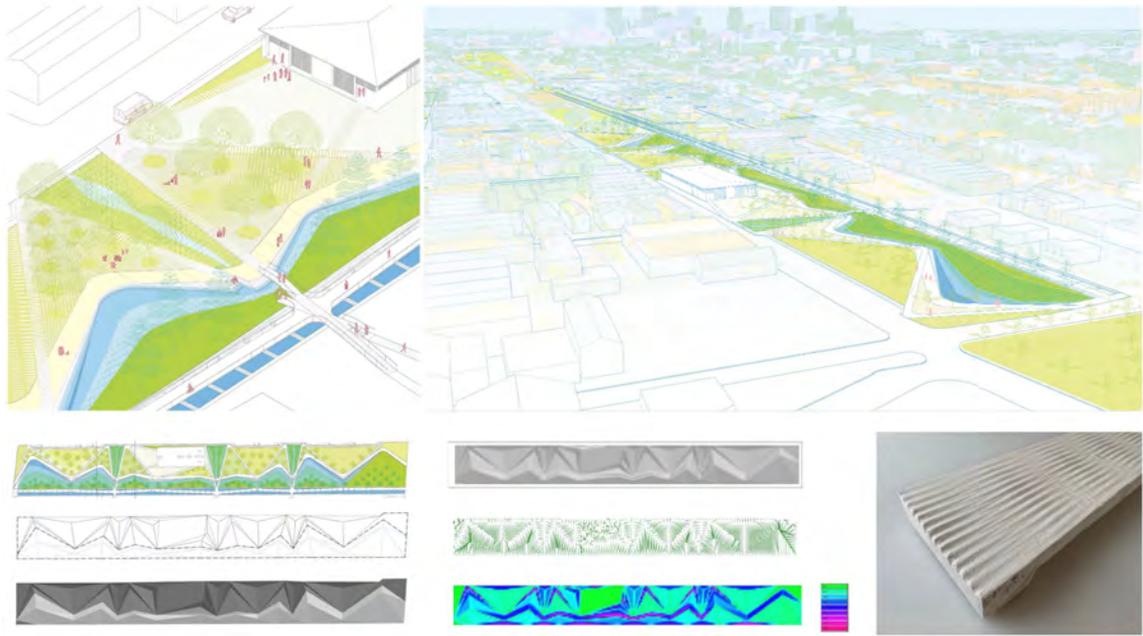


Figure 8: Student examples of the site scale surface geometry (modeling/analysis) and component application. Source: (Authors 2022)

RESULTS

The outcomes elucidate the general design approaches, tactics, and consequences of students' struggles with the complex water management and spatial program distribution challenges at urban scales. It also reveals individual authorship, the aesthetical agenda, fabrication techniques, and component-level invention distinguishing the projects. Representational techniques are explored and developed to consider and communicate the reflective surface quality of water in the urban landscape.

At the urban scale, the surface geometry of the outcomes reveals the following approaches and tactics:

- Carefully orchestrated distribution of floodable and non-floodable surfaces/programs.
- Mound, sloped or stepped landscape with equal cut and fill, leveraging the existing topography and coordinated with estimated groundwater elevation and expected water level of the city's stormwater drainage system.
- System of artificial basins, forebays, weirs, and swales combined with planting materials to slow and momentarily retain stormwater and foster microecology.

At the street scale, the surface geometry of the outcomes reveals the following approaches and tactics:

- Accommodating transverse community pedestrian paths, negotiated with longitudinal bicycle and recreational traffic.
- Purposeful distribution of gradated (blended) surface geometry, textures, and paving patterns.
- Carefully orchestrated edge conditions to delineate program zones.

At the component scale, the surface geometry and fabrication exploration reveal the following potential of the precast paving systems in tandem with the street and urban scale intentions.

- Studied unit and joint profiles to ascertain the surface flexibility as an aggregate to adapt and address the context and function.
- Leveraged unit surfaces to retain/detain or direct water toward the joints and induce vehicular vibrations or graphic illusions for attention.
- The purposeful joint design provides permeability and encourages medium growth.
- Exploration of flexible 3-d printed formwork and surface casting of the photo-luminescent aggregates.
- Consideration for tooling in CNC-milling in rationalizing the complex surface geometry

The authorship and the aesthetic agenda were not the primary concerns of the research studio. Nevertheless, spatial sensibility emerging from the discovery of fractured reflection and interest in illusionary graphics are two potent concepts. Although students became proficient in the representational techniques, further pedagogical consideration is necessary to elicit a more robust response for an aesthetic position (Figure 9).



Figure 9: Student examples of the component application. Source: (Authors 2022)

CONCLUSION

The research addresses the paradigm shift in urban stormwater management concerning climate change. The outdated engineering solution is to increase the drainage system's capacity by enlarging the conduits and pumps to accommodate the increase in peak demand. Instead, we systematically speculate a multi-faceted scenario to delay excess stormwater from entering the drainage system, reducing the peak demand over time. An underutilized post-industrial urban space is revitalized as an amenity for the community and a water management infrastructure for the city. Its ground surface is strategically sculpted to detain water and simultaneously foster accessibility and communal activities. Furthermore, the reintroduction of water as a surface quality strengthens the interlinkages between social and ecological systems by improving our understanding of the natural characteristics of the deltaic landscape.

ACKNOWLEDGEMENTS

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2. <http://www.jstor.org/stable/j.ctvjf9wcc.5>
3. With increasing frequency, we are experiencing rain events equivalent to the peak intensity of the 10-year storm. The recently established city's mandates requires private developers to detain only a fraction (approximately 15%) of the amount necessary on-site for the 10-year storm events. Sewage & Water Board of New Orleans, "Comprehensive S&WB-City of New Orleans Stormwater Management Model (SWMM); July 10, 2019 Rainfall Event Modeling and Mapping," *Ardurra Report*, (September, 2019).
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- ⁷ Richard Campanella. "How Humans Sank New Orleans." *The Atlantic*, February 7, 2018.
- ⁸ <https://www.theatlantic.com/technology/archive/2018/02/how-humans-sank-new-orleans/552323/>.
- ⁹ By diverting the stormwater from the adjacent drainage canal at near-peak capacity and detaining at the site, the overall drainage demand will be kept below the capacity for a period until the storm subsides. The authors collaborated with stormwater management experts to model and test our assumptions on a ten-year storm event via SWMM model, a dynamic rainfall-runoff, subsurface-runoff simulation model developed by EPA.
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- ¹¹ eccentric," *Google Oxford Languages Dictionary*, accessed September 1, 2022,
- ¹² https://www.google.com/search?q=eccentric&rlz=1C1SQJL_enUS830US830&oq=&aqs=chrome.0.35i39i362l2j46i39i175i199i362j35i39i362l2j46i39i175i199i362j46i39i199i362i465j35i39i362.3807027j0j7&sourceid=chrome&ie=UTF-
- ¹³ We used *Bison*, a landscape architecture plugin for Grasshopper and Rhino 6: <https://www.bison.la/> Note that the slope analysis is relevant to identify occupant accessibility and flow speed. The water flow analysis is pertinent to determine the direction and convergence of the flow and the ground surface treatment.
- ¹⁴ i-Tree is a suite of software applications that assists in analyzing urban forestry conditions which help leverage the ecological importance of trees. The platform is managed by the USDA Forestry Service:
- ¹⁵ <https://www.itreetools.org/>
- ¹⁶ David Waggonner and Mac Ball, *Greater New Orleans Urban Water Plan*, (Louisiana State Office of Community Development - Disaster Recovery Unit, 2012).
- ¹⁷ https://livingwithwater.com/blog/urban_water_plan/reports

Proactive Not Reactive: Pandemic-Prepared Commercial Architecture

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ABSTRACT: Throughout the last millennium, humans have experienced four known respiratory pandemics: The Black Death in 1347, Tuberculosis (from the late 1800s, to mid-1900s), the Spanish Flu of 1918, and COVID-19 (current), that have shifted the way people thought about and used space. The Black Death, for example, introduced the concept of quarantining (Huremović, 2019). The Spanish Flu was the first major pandemic to introduce the notion that one could not simply 'escape' the sickness. Tuberculosis took quarantining a step further with revolving quarantine huts in which the patient was exposed to fresh air and would be turned to face the sunlight (Campbell, 2005). Lastly, COVID-19 called for the return to indoor quarantine rooms, with access to the outdoors restricted to limited numbers along with the highly suggested distance of six feet between people.

After the recent Ebola outbreak in 2014, the World Health Organization (WHO) created resources to track the research and development of existing diseases to better inform how to mitigate the next one, or 'Disease X' (WHO, 2022). This term gained traction as a placeholder to describe any pandemic caused by a pathogen (such as bacteria or a virus) currently unknown to cause human disease. Some medical experts believe that COVID-19 may not have been Disease X but instead is a milder version of what Disease X may be (Tahir et al., 2021). As medical professionals have recognized through the development and study of Disease X, it appears another pandemic is inevitable. This paper explores ways to use architecture to help better prepare for it.

This research aims to include architecture within this preparation process for Disease X to reduce the spread and effects of respiratory disease in pandemic conditions. In addition, this research will provoke an architecture that can reduce the spread of Disease X by analyzing existing architectural responses to respiratory outbreaks, interpreting architectural trends from the four major pandemics, developing a taxonomy of strategies, and proposing new ones for future outbreaks.

KEYWORDS: respiratory health, pandemic architecture, ventilation, daylighting, adaptive architecture

1. INTRODUCTION

Architecture and respiratory pandemics in the recent past have had a type of causal relationship in which a shift in public health forces the hand of architecture to change as well. Instead of acting proactively to address public health, architecture reacts in times of crisis which is evident in an examination of select respiratory pandemics' effects on architecture throughout modern history. This may be because after the success of antibiotics by the 1940s, "medicine was emancipated from architecture" (Fezi 2020). Healthcare had changed from preventing disease, to treating disease. Preventative strategies using passive building systems such as thermal massing to mitigate diurnal temperature swings, cross ventilation to provide fresh air, and positioning of building mass and windows to allow for proper daylighting, seemed to matter less and less as mechanical systems gained popularity. As air conditioning became widely used in the mid-1950s, amid a growing technological enthusiasm in the United States, concern for passive design strategies, such as orientation, shading, site planning, and ventilation, rapidly diminished (Böer 2019).

Before the reliance on mechanical systems, and the introduction of antibiotics, architecture was once considered 'part of a health system'. The Spanish Flu of 1918 for each involved hygienics in architecture, helping to pave the way for Modernist Architecture and urbanism (Fezi, 2020). It was also seen as the first truly global pandemic along with the first one occurring alongside the increasingly popular modern medicine (Huremović, 2019). A study on American cities during the Spanish Flu concluded that cities that involved non-pharmaceutical interventions, (NPIs) using methods such as social distancing early on during the Flu, fared better after the pandemic as compared to cities that were not as aggressive or proactive in fighting the disease. In fact, NPIs lowered mortality of pandemics and mitigated economic consequences (Fezi, 2020). But as modern medicine started to gain popularity, hygienics and architecture started to diverge. Architecture can work together with medicine and modern technologies by acting proactively, perhaps by building health-focused infrastructure into everyday lives. There may be no solution to entirely reduce humanity's ability to get sick, but architecture can play a role in mitigating the effects in dense, urban settings before they occur. Architecture can no longer remain a background character when it was "itself one of the technological

alternatives whose role reciprocally destabilizes and shapes the others” (Adams et al. 2008). By examining respiratory pandemics and their impacts on architecture, one can inform how to propose a new pandemic-prepared architecture that balances new building strategies with beneficial modern technologies to be proactive instead of reactive with consideration for respiratory health in addition to energy, comfort, and cost.

Commercial architecture is one of the largest opportunities for these pandemic-prepared strategies as people typically spend up to one third of their lives at work (Pryce-Jones 2010), typically around other people. If proactive strategies are implemented within commercial office buildings to combat the spread of respiratory disease, the health benefits for the general workforce (and potentially the rest of society) could be significantly impactful. This research will look at the four major respiratory pandemics throughout history, analyze the effects these pandemics had on the local population/architecture, and make proposals for a pandemic-prepared architecture. As trends appear in the data, this research will inform possible solutions for Disease X such as adaptive architecture, daylighting strategies, and natural ventilation strategies.

2. BACKGROUND

The term ‘Disease X’ stands as a placeholder for the next pandemic humanity will encounter. It is “not, as of yet, an actual disease caused by a known agent, but a speculated source of the next pandemic that could have devastating effects on humanity” (Huremović, 2019). As mentioned previously, COVID-19 may not be Disease X but may be a milder version of what Disease X could be. In other words, COVID-19 is not the last pandemic. In fact, “virtually every expert on influenza believes another pandemic is nearly inevitable... that it could kill tens of millions... and that it could cause economic and social disruption on a massive scale” (Fezi, 2020). However, architecture can help play a role in preventative measures; to help mitigate the effects of the next pandemic before it occurs. For the purposes of these strategies, the next pandemic is assumed to be respiratory in nature and will follow similar transmission patterns such as the Black Death of 1347, the Tuberculosis outbreak of the late 1800s, to mid-1900s, the Spanish Flu of 1918, and COVID-19. Historical research and case study analysis of successful strategies (and unsuccessful ones) will provide the basis for the theoretical future. Architectural strategies of focus include adaptive architecture such as balcony and outdoor terrace space, daylighting through the inclusion of clerestories and light wells, and ventilation strategies such as double-skins, stack ventilation, and operable windows.

2.1 Quarantine and human density

The word *quarantine* derives from when the period of isolation or waiting away from others so as not to potentially infect people with disease, was later extended to 40 days or (quaranta giorni). During the Black Death in the fourteenth century, medical treatments were limited, so most measures to control the disease were movement-controlled measures such as isolation (see Fig. 1), quarantine, and confinement (Fezi 2020).

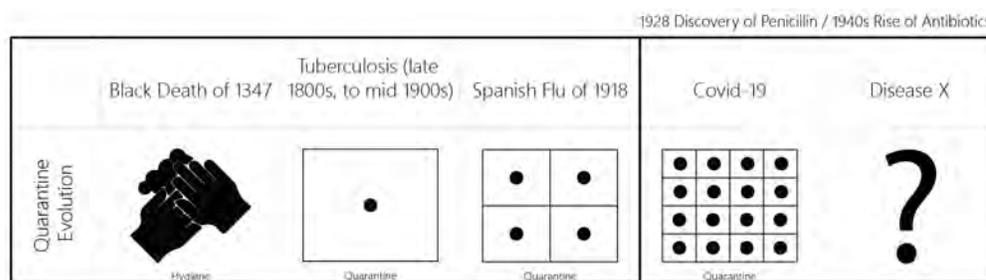


Figure 1: Diagram of the evolution of quarantine. Source: (Garceau, 2022).

During COVID-19, architecture (like in the Black Death with the quick solution of quarantine ships [mobile spaces for visitors to occupy before entering cities]) had to adapt rapidly from the open-concept movement of the 1970s to having to create separate closed-off rooms for people to occupy (Frith 2012, and Fezi 2020). The temporary adaptive architecture solution during COVID-19’s time was utilizing moveable partitions in ‘flex spaces’. These moveable partitions often have structural or acoustical issues that render it ineffective for use. The sterilization, UV lights, or plexiglass dividers also used to tackle COVID-19, became outdated very quickly as our understanding of disease transmission moved from droplets to an airborne disease (Carr et al. 2022). Furthermore, this still involved the concept of isolation, albeit on a much larger scale (see Fig. 1). For now, one can only predict the effects Disease X may have, but architecture’s involvement (beyond the use of quarantined space) may help to mitigate the effects.

In the near year 2100, the world is expected to grow from around 8 billion to 11.2 billion (United Nations, 2019). To reduce the spread of disease indoors, architecture needs to approach design “through a health lens [which] can provide meaningful impacts for individual, population, and global health” (Dannenberg and Burpee, 2018). Architecture can help lessen drastic events from a future pandemic and has existing infrastructure to do so thanks to the previous pandemics. For example, with Tuberculosis, “after 1882, public health concerns that had initially focused on the provision of clean water and efficient sewers shifted to examining the poor physical state of working-class urban housing with a high incidence of Tuberculosis and respiratory diseases” (Campbell 2005). The idea of overcrowding (first brought to attention during Tuberculosis in the late 1800s, to mid-1900s) was revived during COVID-19, with the death rates spiking in the city. The challenge becomes acknowledging density issues and incorporating architectural strategies to help reduce the spread of disease. Regarding office buildings specifically, open spaces seemed to be the main contagious spaces in which COVID-19 spread the most, not because of necessarily the amount of interaction between workers, but the duration or length of contact workers had with each other (Fezi, 2020). This does not account for large social gatherings at the office, but instead concerns the ‘typical’ day of the office worker, as context for the scope of this research.

2.2 Adaptive architecture

Adaptive architecture is an all-encompassing term that groups architecture that can adapt to its environment, and the needs of its inhabitants (Schnädelbach, 2010). In the context of office buildings, this may include an architectural response that puts a focus on purposefully versatility, analyzed within specific case studies to provide a suggested foundation for pandemic-prepared architecture. During Tuberculosis, access to outdoor space became vital as fresh air was believed to be part of the Tuberculosis cure and it gave rise to the use of individual porches, or covered spaces outside so each patient could have personal access to the outdoors (Fig. 2). In this way, architecture “served explicitly as an active physical agent in tuberculosis treatment” (Adams et al. 2008) through outdoor balconies, expansive verandas, sunning galleries, and occupied rooftops (Campbell 2005).



Figure 2: Diagrams of outdoor terrace and outdoor balcony. Source: (Garceau, 2022).

As the introduction to antibiotics came on the rise, the balcony space shrunk (Fig. 3) as it was no longer required for patients to spend a majority of their time outside for the rest cure, showing the influence of disease on architecture during Tuberculosis and the Spanish Flu.

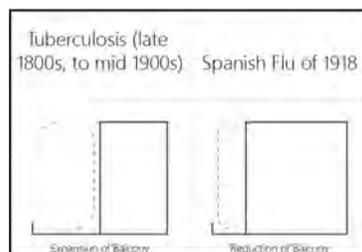


Figure 3: Diagrams of balcony declining. Source: (Garceau, 2022).

Other solutions that came out during Tuberculosis may not be practical due to climate reasons. Flat roofs, outdoor balconies, and roof or garden terraces are not well suited for all climates, particularly during extreme weather (Campbell 2005). However, access to outdoor space throughout the history of pandemics has proved imperative, with COVID-19 also leading to a reactivation of outside space, such as restaurants that used patios more due to limited space inside, the inclusion of more indoor/outdoor classrooms, and more ‘flex spaces’ such as walled off social distancing areas for people to gather. But these actions can be more purposeful within architecture and can relate closer to how one can involve access to the outside within an office setting. For example, CallisonRTKL designed an office building that incorporates access to the outdoors through adaptive architecture in the form of balconies (Fig. 2), terraces (Fig. 2), and rooftop design (Berg 2021). This case study is of 3901 Fairfax Drive, to be built in Arlington, Virginia. At the street level, an outdoor park space is available for corporate or public use, with the rooftop of the building containing a patio space, for informal working areas or open-air presentations. There is also an enclosed central conference room on

the roof as well. Terraces are included on the second floor, connecting the office workers to street activity. In this example, the access to greenspace along with outdoor meeting areas, working terraces, and more are examples of adaptive architecture because these spaces are equipped to mitigate disease spread by providing spaces for humans to occupy under multiple conditions, whether the conditions simply be from the weather, or born out of necessity to prevent disease by spreading out and/or receiving fresh air.

The introduction to outdoor working space helps to transition into the need for proper daylighting and ventilation strategies. Furthering an exploration into what a *flex* or *in-between* space (Fig. 4) might consist of, 125 West End Avenue is a 3.4 acre automotive facility that is to be re-clad and renovated to be a research lab and commercial facility (Young 2022). The project is to be gutted in the interior and changed to have a spiraling ramp in the middle of the facility, with commercial space surrounding the ramp. Glass will clad the outside, allowing for natural light to fill the space, and the project also features a rooftop outdoor terrace. The winding circulation ramp connects the large main floors with smaller, more private areas for collaborative work. To elaborate further, the circulation ramp connects to the main floors, but in between main floors, there are also smaller transition spaces for people to work in.

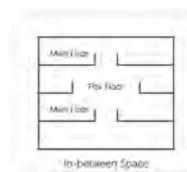


Figure 4: Diagram of in-between Space. Source: (Garceau, 2022).

In this case, the adaptive architecture consists of the transition spaces between floors, along with the outdoor terrace. The inclusion of these smaller spaces of floors in-between floors act as spaces that serve as zones in which people can still collaboratively work together, just more safely, due to the architecture's versatility. Regarding pandemic-prepared architecture, the idea is to purposefully design transition spaces that allow for flexibility in use, while not isolating people from each other. The 'in-between' space is connected to the main atrium and does not act as separate or as an isolated space but acts as a transitional adaptive architecture.

2.3 Daylighting

Sunlight was thought to be a cure for Tuberculosis, as it was good for treating vitamin-deficiency diseases at the time (Campbell 2005, Carr et al. 2022). The requirement for fresh air and exposure to sunlight during the Spanish Flu and Tuberculosis helped to evolve sunning galleries and occupiable rooftop space. During the Tuberculosis era, architects also were able to use new structural steel which was able to remove structural responsibilities from the building envelope and maximize sunlight exposure. The use of structural steel in construction (with the absence of interior structural support) also meant that fresh air had an easier time circulating within the building itself, because the building could be more open (Adams et al. 2008). The term *light and air* became popular in architectural discourse during the Tuberculosis pandemic, with architects creating open, large expansive rooms with extensive glazing "to free the interior space from the dark, claustrophobic, germ harboring" spaces of before (Campbell 2005). These impacts of 'light and air' made their way into the architectural Modernist movement of the early to mid-1900s. This movement is characterized using expansive glass along with steel. The flat roof (Fig. 5) specifically became popular during Tuberculosis as an architectural style for more individual units, such as homes, because a popular cure location of Davos Dorf and Davos Platz in 1865, had an issue with those retreating to this fresh mountain air town getting impaled by icicles from the roofs of the village homes or small shops. Thus, the early flat roof as we know it today was designed so icicles would not form and potentially fall on visitors (Campbell 2005).

One solution these Modernist architects had to allow light and air into dense housing was to implement a stepped-terrace system utilizing the recent popularization of flat roofs. In this way, the flat roof did not necessarily help fight Tuberculosis but instead came because of Tuberculosis. Contrastingly, Tuberculosis sanatoriums (Fig. 5), or large buildings serving as medical facilities specifically for the treatment of Tuberculosis, had steep roofs and high ceilings to allow sunlight to reach most of the space and kill as many germs as possible, becoming a scientific architectural method (Fezi 2020), as the legacy of this daylighting concept lives in the International Building Code (IBC).



Figure 5: Diagram of flat roof with occupiable space and diagram of a typical sanatorium. Source: (Garceau, 2022).

Other less successful alternatives included the use of skylights (Fig. 6) as this disturbed patients' experiencing direct sunlight from skylights as they laid down, as opposed to experiencing side light from clerestory (Fig. 7) windows (Adams and Burke 2006). Fig. 6 shows the evolution of top lighting with pandemics perhaps evolving into a light well strategy, which would maintain the benefits of top lighting while also being adapted to an office typology.

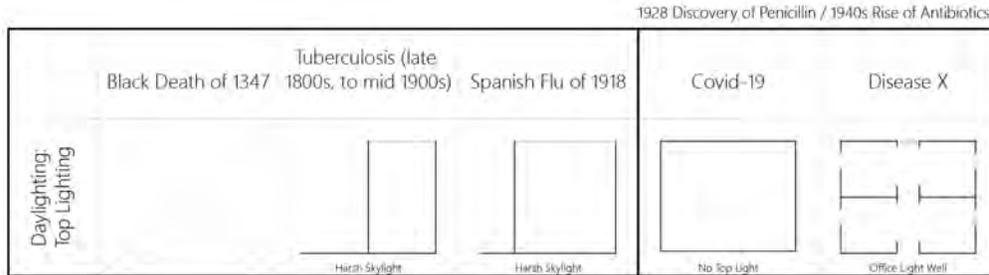


Figure 6: Diagram of steep roofs with popularization of clerestory and high ceilings. Source: (Garceau, 2022).

An example of an expansive light well exists in Bloomberg's London Headquarters which uses a central atrium light well (Fig. 7) alongside a skin framework that uses angled panels to maximize light while reducing direct sunlight glare and heat exposure (Foster + Partners 2017). Due to the building's large size, the addition of the atrium space allows the center of the building to be naturally daylit in addition to the building skin strategy. The orientation of the building is also a key component in daylighting, so the headquarters is oriented with the larger side of the floorplates facing the north and south directions, with the short ends of the building facing the east and west directions. This allows for a reduction of glare from the east and west directions while maximizing controlled exposure from the north and south. The light well utilizes high ceilings and additional windows to allow light to penetrate deep into the building, which was a strategy popularized in Tuberculosis sanatoriums (the idea of large expanses of glazing to allow for a maximum amount of daylighting). These daylighting principles can be applied to larger buildings through innovative methods to allow light to penetrate through the office skyscraper completely. Although this example constitutes a five-story building compared to an office skyscraper, the logic of including daylighting can be applied to this larger scale. One can see in Fig. 7 how the strategy of clerestory windows and side lighting from Tuberculosis and the Spanish Flu may have a modern component in the form of clerestory or atrium glazing.

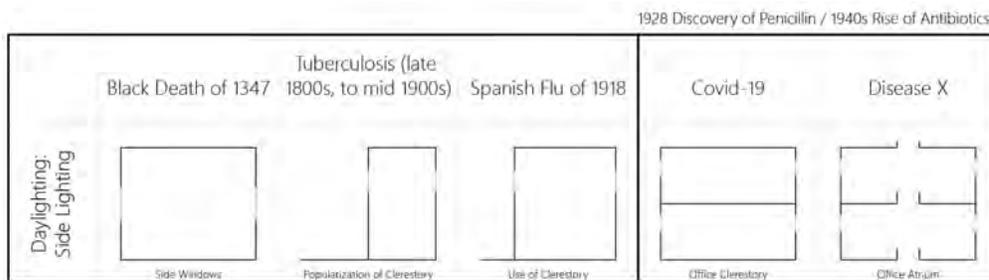


Figure 7: Diagram of an office light well and office atrium. Source: (Garceau, 2022).

2.4 Ventilation

During the Black Death of 1347, the prevailing understanding of how the disease spread was supported by the Miasma theory, which postulated that *bad air* caused disease (Karamanou et al. 2012). As a result, those that could, sought the thought to be purer air of the mountains (Campbell 2005). This same idea came back during Tuberculosis during the late 1800s, to mid-1900s. Before the arrival of antibiotics in 1944, the fight against Tuberculosis mostly involved an architectural response in the form of the rest cure, lasting until the beginning of the 20th century. Even in modern times, the regulation of airflow is important because "at the architectural scale, viruses can transmit in confined spaces not only by transmission but also by aerosol that can remain airborne for hours" (Fezi 2020). Modern ventilation systems can take this idea of fresh air as

important to fighting disease (popularized during Tuberculosis) one step further. The ASHRAE 2014 report on Airborne Infectious Diseases mentions that in studies from 2012, “dilution ventilation can support pandemic management as an essential complement to social distancing” (Schoen et al. 2014). In addition to a medically supported solution of separation, proper ventilation can play an important role in mitigating the transmission of respiratory disease. However, the recirculation component of modern air conditioning systems may increase the transmission of respiratory diseases, such as the virus that causes COVID-19 (Fezi 2020).

A 2007 study measuring air-changes per hour (the amount of times air in a room is completely replenished) in hospitals comparing natural ventilation to mechanical ventilation found that the natural ventilation was more than two times as effective in reducing healthcare-associated infections within the hospital (Escombe et al. 2007). In this case, the natural ventilation involved opening doors and windows to the outside (Fig. 8). Even though this relates to a hospital, this concept can provide insight into the importance of natural ventilation in helping to combat disease in office. Thus, utilizing natural ventilation instead of mechanical systems, or perhaps a hybrid of the two, may help reduce the spread of respiratory viruses more than a mechanical system could alone.



Figure 8: Diagram of modern air conditioning and diagram of Escombe natural ventilation. Source: (Garceau, 2022).

3. RESULTS AND DISCUSSION

Looking at COVID-19 specifically, “the COVID-19 pandemic has revealed the weaknesses of our health systems that were unprepared to cope with a very large number of patients requiring respiratory support therapy in a short time frame” (Ciotti et al, 2020). Perhaps better preventative measures may have been able to lessen these numbers and result in a health system less ill-equipped. Architecture, designed in conjunction with mechanical systems, can provide for a healthier future through preventative means such as the use of adaptive architecture, daylighting strategies, and natural ventilation. One way this may be achieved is through balconies, occupiable roofs / terraces, and in-between transitional spaces. The research findings depict a loss of a balcony from the introduction of antibiotics (Fig. 9). The expansion of the balcony occurred during Tuberculosis so beds could fit outside to help with the ‘rest cure’. As the ‘rest cure’ started to lose popularity, during the Spanish Flu, there became a reduction of this outdoor space through the form of a balcony. During COVID-19, and with the introduction of HVAC systems, access to fresh air through balconies was not a focus.

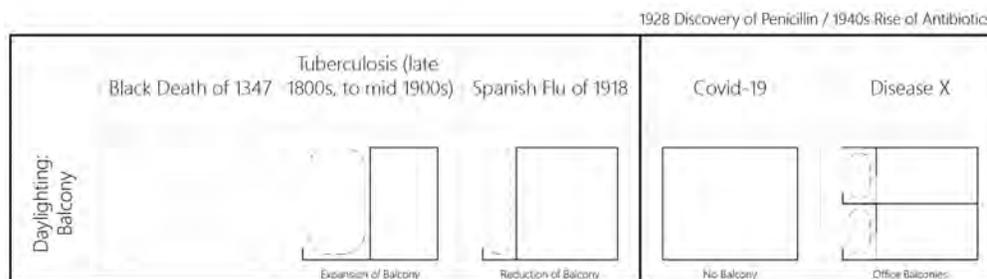


Figure 9: Diagram of balconies over time in relation to pandemics. Source: (Garceau, 2022).

Thus, a solution to architecturally impact Disease X may include a reintroduction of balconies in office space, to garner fresh air, and flexibility through multi-use of the space. Over time, one can examine how the status of roof occupancy has shifted throughout the pandemics (Fig. 10). During the Black Death, the shape of the roof relied mostly on the climate the building occupied. Meaning, the occupancy of the roof varied. However, during Tuberculosis, the popularity of the steep roof with high ceilings and balconies allowed for light to penetrate throughout the entire building and for people to occupy personal balconies to gain fresh air. As time passed, during the end of Tuberculosis and the rise of the Spanish Flu, the flat roof started to become more popular, allowing for people to start to occupy this ‘extra’ space. COVID-19 saw a decrease of the occupiable roof, and fresh air from the outside could be gained through means of HVAC systems alone. A way to pandemic-prepare buildings may include a reintroduction or integration of an occupiable rooftop and terrace, echoing the principles within Tuberculosis with an emphasis on fresh air, the importance of which is highlighted in the 2007 Escombe study.

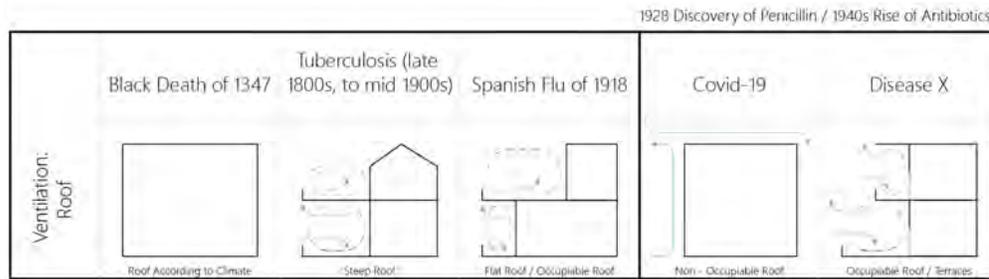


Figure 10: Diagram of roof occupancy over time in relation to pandemics. Source: (Garceau, 2022)

4. CONCLUSION

The four major respiratory pandemics: The Black Death, Tuberculosis, the Spanish Flu, and now COVID-19 have provided historical data as to how solutions such as adaptive architecture, daylighting, and ventilation have changed over time. These time-tested solutions provide a basis as to how to evaluate pandemic-proof commercial buildings of the future that act more proactively. To mitigate against the next respiratory pandemic, otherwise named as 'Disease X', architecture may incorporate these proactive building strategies discussed above and documented in Fig. 11, such as in-between transitional spaces, balconies, and outdoor terraces. Proper daylighting contributes to the overall health level of people in general. Light wells can penetrate light deep into the heart of an office and high ceilings allow for light to seep into a space. Mechanical systems alone may help spread disease, but the combination of mechanical systems with natural ventilation help mitigate the airborne spread. Ventilation may include engineering windows to open and shut based on temperature and/or air quality levels within the building, utilizing balconies and operable windows to the office space. Automated windows open and shut to regulate airflow and temperature within the building instead of the typical reliance on ductwork. In this manner, natural ventilation is engineered intentionally to reduce a spread of airborne disease. These strategies help to equip architecture against respiratory pandemics before they occur and create a more proactive architecture instead of a reactive one.

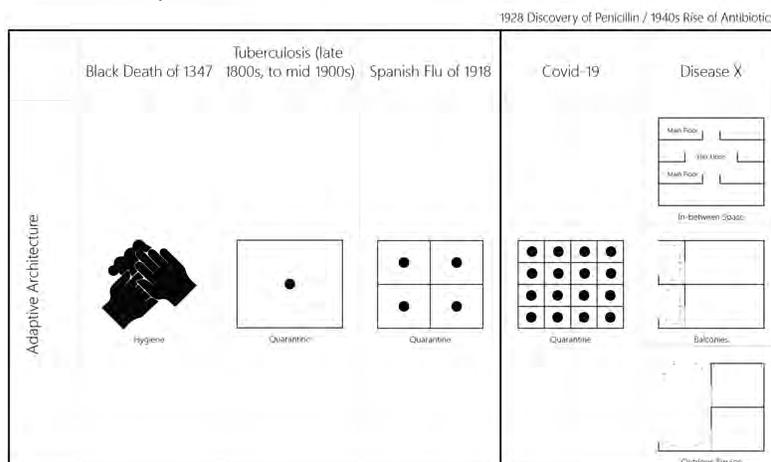


Figure 11: Diagram of research findings of adaptive architecture. Source: (Garceau, 2022).

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(In)Determinacy: Material and Joint Constraints to Unleash Tectonic Thinking

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ABSTRACT: Tectonics has been defined as the art of joinings. The focus on expressive potential of joints differentiates tectonic material systems, those built from multiple visible components, from atectonic material systems, those bonded or made solid by and, in some cases, indistinguishable from the joints. Kenneth Frampton's account of the history of modern architecture through construction reinterpreted Gottfried Semper's Four Elements as two categories of building crafts: the tectonics of the frame, that is the "lightweight linear components...assembled to encompass a spatial matrix" associated with tension; and the stereotomics of the earthwork, produced through "the piling up of the heavyweight elements" and associated with compression. That places wood and some metal assemblies in the first category, and cast-in-place concrete and masonry in the latter. Although joints are central to tectonic thinking, the implication of different structural methods of joining, and their primarily shear and friction forces, are mostly absent in the discourse. This paper argues that structural determinacy is an important differentiator between tectonic and atectonic expression by eliminating rigid joints. To test this idea, the constraint of determinacy was introduced through material choice in a design project for a Structural Systems course. Constraints are essential in any pedagogy to focus learning and avoid cognitive overload. For example, in previous years the course introduced constraints of program and site to focus structural decisions on load path patterns and hierarchy without added complexities of enclosure or type. Students could make material decisions based on conceptual drivers or interests, but the fear of complexity in the assignment resulted in many misguided and self-imposed limits. Students selected certain material and joint types, specifically concrete flat slabs or steel moment frames, believing it would simplify model making and diagramming of lateral systems, i.e. being able to ignore joints and their dynamic movement in detailing and the configuration of systems. The decision was quickly regretted once calculations with indeterminate rigid structures became too complex. This represented a challenge for this one-semester course—the only structures course in the curriculum—which limits content to determinate systems. This necessitated more one-on-one guidance, often with imperfect shortcuts that did not improve learning. To address this issue, a new iteration of the course introduced a new constraint of determinacy, requiring a wood structure where all joints are naturally pinned. The intention was to introduce more complexity in compositional design, physical modeling and details and, in turn, simplify the quantitative analysis. This paper draws on tectonics discourse to explain the pedagogical motivations and methods, analyze student learning outcomes and performance in comparison with previous iterations of the course, and share insights from student reflections. Findings suggest that the physical modeling of joints to simulate pinned behavior increased understanding of the torsional effects of configurations, increased student interest in the pragmatic and aesthetic implications of joint detailing, and in the context of wood, placed new and unprompted attention on the connection to the ground and its expressive potential. Refocusing on pinned joints motivated tectonic thinking, improved learning, and increased the quality of quantitative analysis.

KEYWORDS: determinacy, structural systems, tectonics, joints, timber

INTRODUCTION

Tectonics, understood as the expressive potential of construction, is unquestionably central to architectural discourse and education. In contrast, knowledge of structural systems is often perceived as the domain of engineering. However, there is an implicit relationship between structural systems and tectonics. But unlike to the craft of construction and inherent logics of materials, which are the foundation of tectonics, the concepts of structural analysis are not explicitly theorized in that body of architecture discourse. Structural systems analysis, as referred to here, is the domain of knowledge that applies scientific and quantitative reasoning from physics and mechanics of materials to understand stability, strength, and serviceability. In other words, it represents the problem-solving approach aligned with engineering structures, as opposed to the space- and form-making approach in architectural structures. Ongoing debate in building technology education question the need for this knowledge domain in the education of an architect, with Ed Allen being one of the most convincing proponents that structures should be taught in design, not quantitatively (Allen 2006). Yet, this knowledge is not only still required in professional licensing exams for architects in the United States, but also, as argued in this paper, potentially underutilized as a productive method of modeling, iterating, and evaluating design solutions. Considering the central role of tectonics in architectural education, making the connection between tectonics and structural analysis more explicit may be critical to connect the science of structural systems with the spatial, material aspects of structural design in architecture. The argument made in this paper is that making this connection explicit does not mean to replace but to better integrate quantitative reasoning

of structures with the generative process of design. The challenge is to define conceptual connections at different levels of design education. As this paper shows in an introductory level class, these conceptual connections can create productive constraints that can focus learning and improve outcomes.

This paper specifically explores the idea of (in)determinacy—a characteristic defined by the type and arrangement of joints that determines whether a structure can be analyzed with simple equilibrium equations—as a path to more rigorous and liberating tectonic thinking in architectural education. Studying (in)determinacy as a condition created by critical architectural decisions, specifically the type of lateral resistive system, has the goal of foregrounding tectonics in structural design, to bring structural detailing into the fold of a richer tectonics discourse. Specifically, the paper explains why the constraint of determinacy, a purely quantitative concept, aligns with the fundamental role of joints in tectonic expression. Drawing on seminal discourse on tectonics, this paper explains the pedagogical motivations and methods to introduce determinacy as a constraint, present examples of work, examines quantitative results of student learning outcomes in comparison with previous years and finds meaning in the data from student reflections of the project.

1. REVIEWING THE DISCOURSE

1.1 Tectonics and the art of joints

Kenneth Frampton traced the history of the term tectonics in his seminal 1995 book, ascribing it with a foundational role—the emergence of the master builder or *architekton*, (Frampton 1995, 4). In this account, Frampton quoted Adolf Heinrich Borbein who suggested a sense of correctness found in the application of artisanal rules when defining tectonic as “the art of joinings,”. Marco Frascari also arrived at the joint as a means of constructing and construing architecture, that is, an instrument of production and interpretation. In the chapter *The Tell-the-Tale Detail*, Frascari offers a multi-scalar view of architecture where any element that is called a detail “is always a joint”—a small part “in relation to a whole,” and the “minimal units of signification.” (Frascari 1996, 500–501) Louis Kahn, whose spent his entire career pursuing a new order from the logics of material and construction, made the joint the beginning of aesthetic expression, saying “the joint is the beginning of ornament...” and “ornament is the adoration of the joint.” Of course, tectonics is not exclusively or rarely explicitly about structure, and more about its aesthetic language, such as the reinterpretation of the timber frame in the entablature of stone Greek temples. Similarly joints in the enclosure and other non-load bearing systems are equally in the realm of the tectonic. Ironically, it is the architecture of Mies van der Rohe, who advocated for structural honesty and expression in design, that surfaced in the discourse as an example of erasing structural joints in the interest of abstraction. In Farnsworth House columns and beams are connected with spot welds that are temporarily bolted in place, then welded, cut, ground smooth and painted to disappear, leaving no trace of construction. (Cadwell 2007) The beam disappears into the abstracted plane of the roof, leaving no trace of the type or existence of a column-to-beam connection. The mere possibility afforded by the selection of steel explains this atectonic abstraction, which is a sharp contrast with the contingency and difference that is inherent to the joining of other materials.

1.2 Material taxonomies: tectonic and the atectonic

Karl Otfried Müller’s 1830 handbook, which Frampton claimed to be the first to use the term tectonics in architecture, noted the junctional implication, or the role of dry jointing as unique to certain materials, specifically those used by cabinetmakers (Frampton 1995, 4–5). The implication may be that the mechanical attachment of elements controlled by human hands, even with the aid of sophisticated tools, creates the distinction between tectonic material systems, those built from multiple and distinguishable components, from atectonic material systems, those made solid and either bonded with or indistinguishable from the joints. Gottfried Semper’s attempt at defining the origins of architecture in *The Four Elements* (Semper 1889) was based on a generalization from observing or reconstructing a presumably primitive architecture of a hut, but Frampton’s reinterpretation and validation of the theory provided a contemporary distinction. More specifically, Semper’s taxonomy organized these four elements into different but somewhat universal categories of material crafts found in construction, the mound (earth), hearth (tile), frame (carpentry) and enclosing wall (textiles); whereas Frampton reinterpreted these four elements as two categories of building crafts: the tectonics of the frame, that is the “lightweight linear components...assembled to encompass a spatial matrix” associated with tension; and the stereotomics of the earthwork, produced through “the piling up of the heavyweight elements” and associated with compression. This distinction between tension and compression is the closest connection between tectonics discourse and structural analysis, in that it references magnitude and direction of forces, which can be quantified and analyzed against varying stress capacities of materials. That places wood and some metal assemblies in first category, versus cast-in-place concrete and masonry in the latter. However, the nature of these two fundamental forces of compression and tension mostly refer to the components being joined, but not the nature of joints, or more specifically the connecting elements, which are more likely to involve friction and shear forces. Despite joints being so essential to tectonic thinking and expression, the discourse is less clear about the implication of different structural methods of joining, and thus the resistance forces and movement constraints they introduce remain outside of tectonic discourse. However,

within the tension-resisting components in the tectonic tradition, there are important differences between wood and steel. Only wood involves a different material for joining. Steel is connected with steel, whether through bolting or welding. The directionality of wood grain and the low shear resistance means its connections are most often of a different material, mainly steel, sometimes aluminum. Those connections are visible by visual contrast, and decisions have to be made about exposing that difference or somewhat concealing it in recessed knife plates and wood plugs, whether for fire protection, design for deconstruction, or aesthetic (M. Laboy 2021). Furthermore, steel-to-steel connections can be rigid, providing an inherent lateral stability to the frame only resulting in reduced slenderness of members. That is a much more difficult for wood, which is more likely to require other means of providing lateral stability that will be visible in the architecture. Timber construction, which is emerging as a growing alternative to steel and concrete in taller buildings because of advances in performance-based design and the potential to reduce embodied carbon, could refocus architecture on the nature of structural connections and their spatial and aesthetic effects.

1.3 Determinacy as differentiator

In this realm of the seminal definition of tectonics, thinking primarily of wood and steel, it can be said that determinacy emerges as the structural concept that explains this difference. Determinacy is defined as the condition of being determinate, that is, being unequivocally characterized. In different fields from math and game theory to engineering, that could mean having predictable results, a known and unique answer, a winning strategy, or solution. In structures, this refers to conditions of equilibrium to applied loads that have one solution, and where all reaction forces can be found using the three simple equations of static equilibrium:

$$\begin{aligned}\sum F_x &= 0 \\ \sum F_y &= 0 \\ \sum M_o &= 0\end{aligned}$$

Eq. 1: Sum of forces in the x-axis

Eq. 2: Sum of forces in the y-axis

Eq. 3: Sum of moment

Determinacy is achieved if the structure or its individual components have three or less unknown reactions. Rigid joints introduce three forms of restraint: movement along the two x and y axis and rotation. Pinned joints introduce two forms of restraint, translatory movement along the two axis. Roller joints introduce a restraint in only one direction. Any of these joints, individually, can be analyzed using three equations of equilibrium. However, architecture rarely involves a single joint. Therefore, assemblies and frames can quickly become indeterminate if a rigid connection is introduced with a member that is connected to another joint of any type (four or more unknown variables).

(In)determinacy is a characteristic specifically related to the joints that define the lateral stability of “stick-built” structures or frames, as opposed to massive structures such as load-bearing walls that can integrate laterally resistance either inherently through mass or as composites through reinforcement. The type of connection, or joint types, introduce forms of restraint to either translatory movement or rotation of the structure and/or its components. This is the result of a strictly architectural decision, mostly connected to spatial concepts, transparency, and legibility. More specifically, the use of rigid, pinned or roller connections determines whether a structure is inherently stable to lateral forces or it needs to be layered with diagonal braces or shear walls.

2. METHODS

2.1 Curriculum and pedagogy

To test this conceptual connection, the constraint of determinacy was introduced through material choice in a design project for a Structural Systems course. This is a required course for the accredited Master in Architecture degree at Northeastern University, and serves mostly undergraduates in the pre-professional degree and graduate students in the 3-year program for students with no prior architecture background. It is the third of a 4-course building technology curriculum sequence that involves three introductory systems courses covering principles of materials, comfort, and structures, and an advanced Integrated Systems course. The introductory level Structural Systems course builds on prior knowledge from physics, calculus, and architectonic systems courses (Fig. 1a). It is designed to explore the intersections of science, systems thinking, and design (Fig. 1b). Centered on experiential and project-based learning instead of traditional exams, the course seeks to connect design decisions with the scientific and quantitative principles and processes that inform them. The phases of the project involve diagramming, model making, and calculation. These phases are supported by a *flipped classroom* video demos, diagramming in field trips, hands-on modeling labs to understand system and connection types using sophisticated teaching tools (“Mola Structural Model: A New Way to Learn About Structures” n.d.), and in-class workshops with Excel.

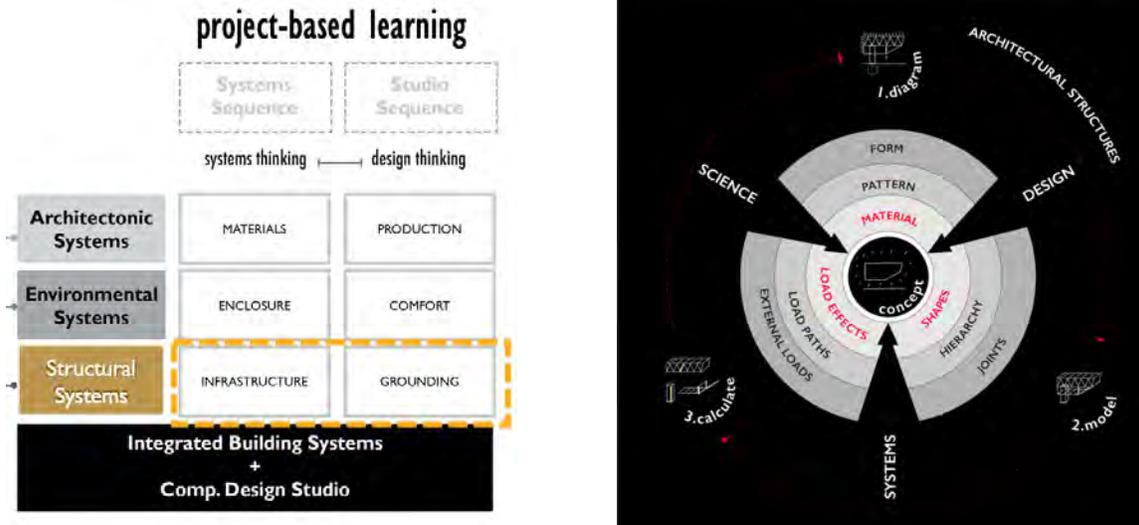


Figure 1: (a) Course in the curriculum sequence (left) and (b) Diagram of course themes organized around three vectors of knowledge (right). Joints are in the outer (first) ring between systems thinking and design, examined through physical modeling that reveals the behaviors of the structural system. This diagram is a revision of an early diagram published after some of the earlier ideas for design-project-based learning were tested (M. M. Laboy 2019). The order and organization of the diagram changed in response to these new constraints, with joints moving to the first ring as an early design decision connected to form and space making.

As a technical course taken alongside different design studios, the design project always had constraints to reduce cognitive load and focus learning. In past years the constraints to program (open market structure or a pavilion with limited use requirements) and site (infill site or with strict dimensional constraints) focused the project on structural decisions without the complexities of enclosure, urbanism or type. Students could make decisions about material based on conceptual drivers or personal interest, but all of them were required to build models that behaved like the structural system based on the construction of joints, and to eventually diagram the load path and calculate the size of one floor and vertical support. Often the students' self-imposed limits were driven by fear of complexity of modeling or diagramming these dynamic lateral systems. Some selected material and joint types, specifically concrete flat slabs or steel moment frames, believing they could ignore the nature of joints in detailing and the compositional resolution of layers of cross-bracing. The decision was quickly regretted in the calculation phase, when indeterminate rigid structures were found to be too complex for their level. This represented a challenge for the faculty in this one-semester course—the only one in the curriculum—because it was not designed to cover indeterminate structures. This necessitated more one-on-one guidance, often with imperfect shortcuts and rules of thumb that did not improve learning. To address this issue, a new iteration of the course in 2022 introduced new and additional constraints. Requiring a wood structure where naturally all joints needed to be pins or rollers (slotted) eliminated rigid connections. This meant that all projects needed to contend with the spatial configuration of lateral systems in diagram and model. This is less about simulating magnitude or testing adequacy, but ensuring students are “looking for geometric stability” (Whitehead 2020, 382). But the result has quantitative implications, as calculations of the gravity system were more likely to be determinate. The intention was to introduce more complexity in compositional design and details and, in turn, simplify the quantitative analysis.

2.2 Project sequence

A 3-phase project sequence moving from diagram to physical model to spreadsheet model had been tried before, and although linear, it was designed for iteration, feedback, and reflection (M. M. Laboy 2022). Students were required to develop a generative cross-section, the architectural drawing with the power to generate both spatial and tectonic ideas. Students deployed this section in a site plan. As shown in one full example on Figure 2, from the section students directly translate into a structural diagram that could be further analyzed as a system of components with individual free body diagrams. In structural analysis the free body diagram reduces a three-dimensional loading condition into a two-dimensional representation of structural elements and forces at the joints, and serves as the foundation for internal moment and shear diagrams. Requiring physical models that were not precious like the lab tools, but true in terms of movement, focused on pattern making, aggregation, behavior and composition. Models are pushed by faculty and students to understand dynamics of deflection, raking, and torsion, and address issues uncovered by the model. In the last phase, spreadsheets allowed students to build their own quantitative models, derived from matching the free body diagram with standard and published shear and moment diagrams that they could use to build an

iterative tool with three parts: (a) inputs, i.e. design decisions such as span, spacing, cross-section, and wood species, (b) cells that read the inputs in formulas students entered for equilibrium and stress, and (c) output cells with conditional-formatting that indicated success or failure of the iteration. This allowed quick comparisons between options (strength of wood species, structural sizes, etc) rather than requiring a demonstration of lengthy and tedious manual calculations for one solution.

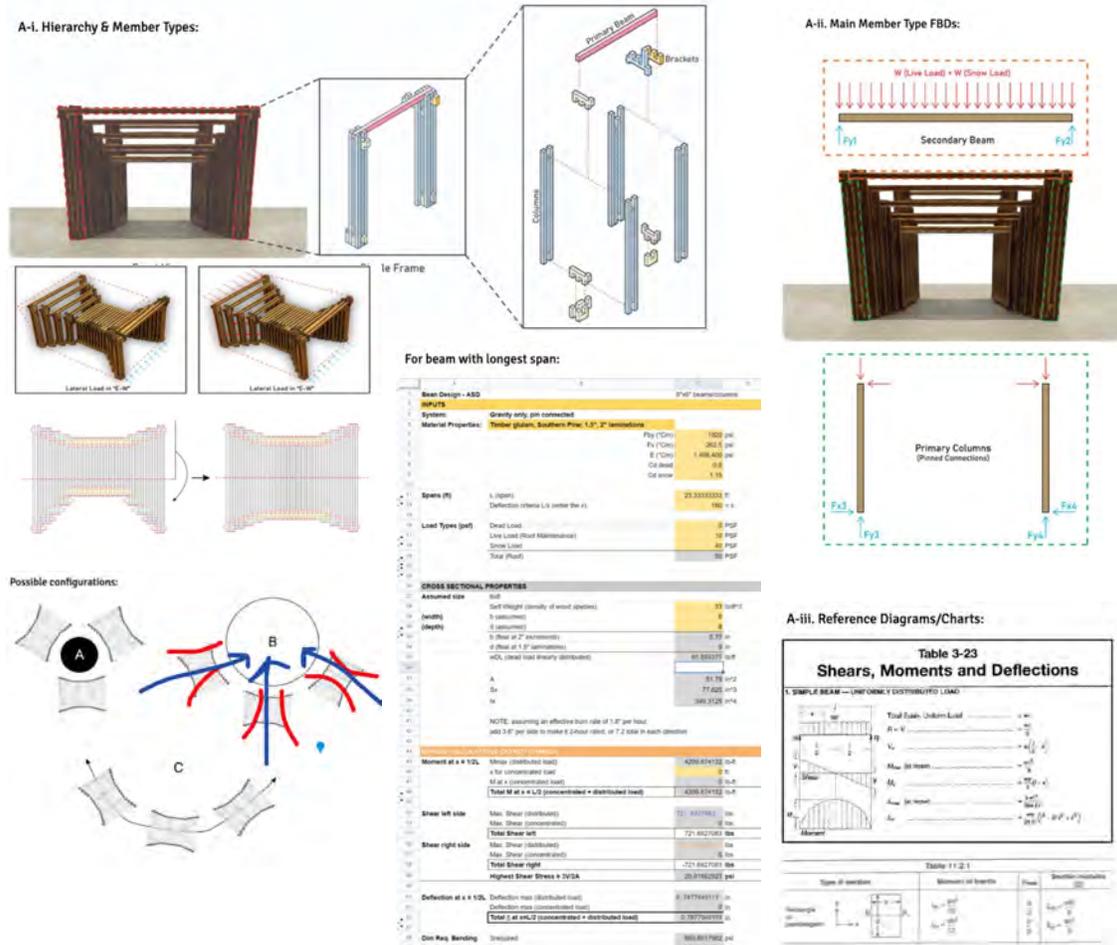


Figure 2: Images of work by students Qiling Cai and Jean Choi, showing a representation of all phases and most steps of the project sequence. Top (left): Sectional concept of bundled columns and brackets to weave beams through. The components were digitally and physically modeled to be dry joined, simulating pinned behavior. The whole building physical model was used to understand lateral resistance, to diagram hierarchy of components and to develop free body diagrams for preliminary sizing using rules-of-thumb (Allen 2011). Students verified and compared preliminary sizes in spreadsheets they built to take dimensional inputs (span, loads) and modeled standard formulas for shear, moment and deflection, to calculate component sizes (bottom center and right).

2.3 Pedagogical evaluation: sources of evidence

To understand the effectiveness of these new constraints, this study analyzes a few sources of evidence:

- **Student performance in the project** (graded by project, not by individual student): the project with determinacy and material constraints was compared with the average of three previous years without such constraints, separating qualitative (diagrams, physical models) and quantitative phases.
- **Student performance in the course** (individual): the distribution of final course grades. The grades are grouped into high pass, average and low pass to show general shifts and trends. This grade includes individual and collaborative work, therefore can better capture individual outcomes.
- **Instructor's observations of process** from one-on-one and class discussions, and work quality.
- **Individual Student Reflections:** at end of the project, which contextualize and explain the findings

3. RESULTS & DISCUSSION

Table 1 shows the quantitative analysis of student performance. Although grades can be imperfect indicators of learning, the comparison is adequate because the grading criteria for the project and learning goals of the course remained consistent throughout the years, with the only change in 2022 being the added constraint of determinacy and material. Overall there was a significant increase in the mean grade of both the qualitative and quantitative phases of the project; and a significant increase in the percentage of high pass grades (almost double). In general the class shifted in performance by about one letter grade across the board.

Table 1: Student Performance Trends. Source: (Author 2022)

INDICATOR	Description	Previous 3 years*	2022	Trend
PROJECT	Qualitative Phase	84%	90%	↑
MEAN GRADE	Quantitative Phase	80%	85%	↑
COURSE GRADE DISTRIBUTION	High Pass Grades	29%	53%	↑
	Average grades	61%	43%	↓
	Below average grades	11%	4%	↓

* Weighted Average considers accounts for class size differences.

3.1 Modeling joints

Similar to previous years, the class included field trips to outdoor pavilions with exposed structural components (M. M. Laboy 2022) but this time these happened much earlier, and students spent more time observing and sketching the different types of connections. In the lab, joints were also foregrounded early in the semester. Using the Mola kit ("Mola Structural Model: A New Way to Learn About Structures" n.d.), multiple lab activity were dedicated solely to modeling and observing the behavior of pins, rollers and rigid connections, diagramming conventional symbol as well as allowed movements and restraints, for different systems.

Observations of the student work suggest that the emphasis on joint behavior and movement, when explored with physical modeling of joints to simulate pinned behavior, resulted in better understanding of lateral resistive systems and movement in structures, more interest in form-based resistance, and integration of bracing into overall geometry. Compared to previous years, students seemed less concerned with oversimplifying the structure to have "easier" calculations, because physical modeling and diagramming was emphasized as an experimental and equally important form of validating the system.

During in-progress discussions with students, faculty could observe an increased interest in the detailed design of joints, more genuine questions about means and methods of construction, and attempts at sketching connection types, which were not required but students saw as essential to their understanding of their system, its expressive potential, and its construction, even at a very small scale of the models. The attention to joints and modeling of more behaviorally-accurate representations of pins resulted in more projects exploring bundling, layering and weaving column and beam members, as well as dry jointing, brackets, and triangulation. (Fig. 2 and 3).

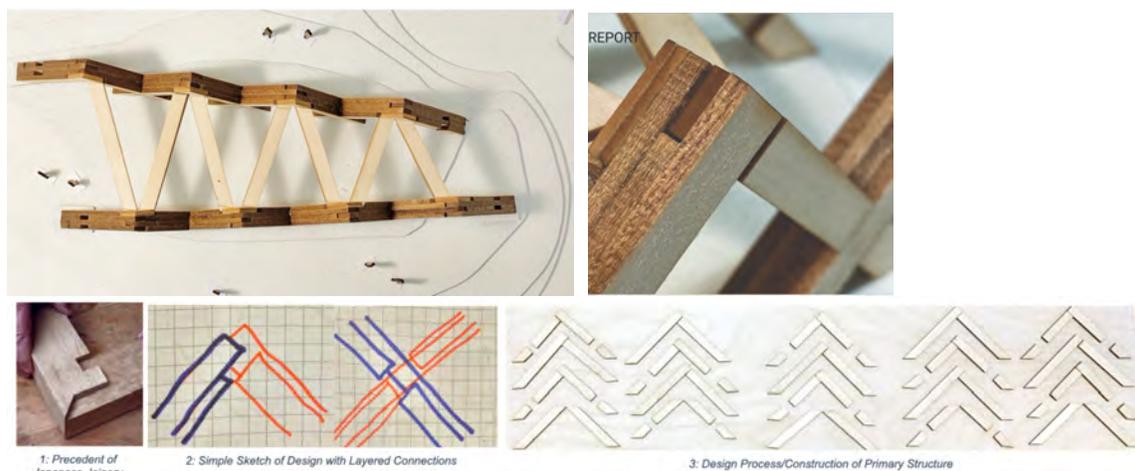


Figure 3: Integrated triangulation of primary systems in plan and elevation achieved with oversize layering for dry jointing and stability through mass and geometry. Contending with the requirement of pinned connections in wood, these students were inspired by Japanese joinery to develop a method of connection. Student work by Remi Messier and Michael Rathz.

The modeling at a small scale required creative approaches to pin jointing (flexible hot glue, threading, laser cutting, and 3d printing). One of the students whose work is shown here (figure 3) reflected on how through

modeling joints “the importance of lateral support definitely became clearer. The concept of joinery in our project also taught me a lot about how structures can work at joints, where notches, slots, and shelves, etc can bring elements together securely.” In contrast to these observed benefits, the scale required and the almost exclusive focus on behavior was a real impediment to representation of the joint, therefore the impact was limited to the relationship between components being joined and spatial / formal configurations. In future iterations it may be helpful to require models at different scales, one of just the joints at a larger size in parallel with the smaller but full building models.

3.2 Assemblies for determinacy

The requirement for determinacy elicited more nuanced understanding of constructability. This was especially true in projects with column lines that contained more than two supports. In past years students would propose and model continuous beams (indeterminate) in longitudinal (usually primary) directions and would model simple spans in secondary spans (determinate), because they only had to diagram and calculate the size of one beam. The new constraint led to discussions about constructability and efficiency. For example, students asked if introducing joints at the top of columns to make simple beams when beams are intended to be continuous would complicate the connection, by requiring the column to interrupt the beam length or adding more connectors. Some of the solutions discussed included compound beams made of double overhangs supporting simple spans result in less connectors. Similarly, when students needed to find the available (published) shear and moment diagrams for their beam type and load condition (e.g. an overhand beam with a distributed load), which were used for building their spreadsheet models, they had to think creatively about construction in order to redesign the system to better match existing diagrams with known solutions. The inability to find continuous beams of any number of spans encouraged discussions about true methods of compound beam assemblies. This process of breaking one indeterminate system into a few more determinate parts had never been part of student project discussions before, even though such examples were shown in the quantitative analysis part of the class. (Fig. 4) This attempt at editing and simplification in analysis led to debates about transportation of members, site access, and unnecessarily complicated construction process, e.g. placing beams over multiple columns that must be kept plumb. When determinacy was not a constraint, students found a way around these by selecting uncomplicated, albeit secondary members of the system.



Figure 4: Class example of a continuous beam (indeterminate, left) transformed into a 3-part compound beam (determinate, right) that became a more common discussion in projects with the introduction of determinacy as a constraint.

3.3 Ground connections

The constraint of material to wood invited questions from students about the support of the column. When students picked concrete in past years the lack of material differentiation between column and foundation left that detail out of the representation and tectonic expression. Similarly, steel structures were often assumed to be embedded in the ground (somehow the concern for oxidation was never in the mind of students). But with wood, there was a significant preoccupation with and interest on the connection to the ground and its expressive potential. Students intuitively knew that there was something wrong with embedding wood into the ground. More students asked about the connection at the ground and tried to model that separation from grade as part of the logic and expression of the column. (Fig. 5). Many involved interesting approaches to physical modeling to create a pin connection at the base of a model.



Figure 5: Column base elevated above grade, modeled to behave like a pin. Student work by Alice Clements and Shannon Rooney.

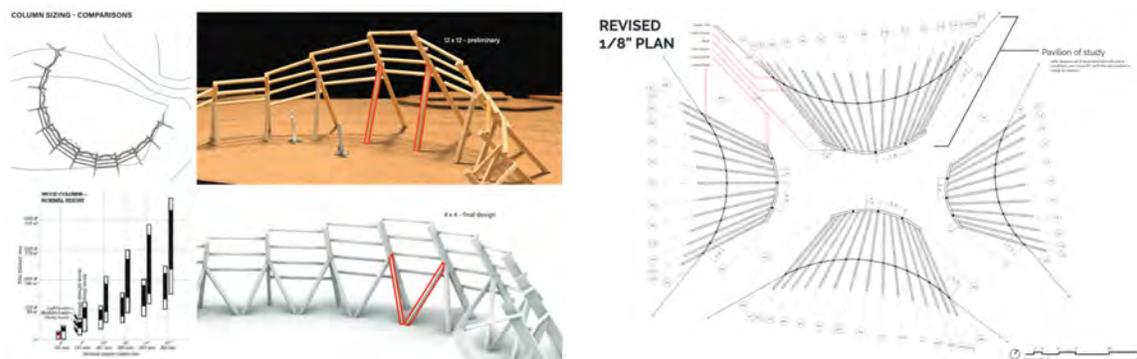


Figure 6: (a) Student work by Katie Dumigan & Ben Harding (left) shows how columns changed from two dimensional to a three-dimensional pattern. (b) Work by Ethan Matthews & Valentina Riera (right) show diagonal braces extending outward from bent girders to lengthen the thresholds from the site into the center of the space in this radial pattern.

3.4 Lateral stability

The new constraint of determinacy and the requirement to more genuinely model pinned connections for wood structures encouraged more students to identify and respond to lateral instabilities. Students could not resort to cantilevered columns (rigid base) that could resist lateral loads in any direction. Now all students had to content with more visible lateral systems that required experimenting with how their spatial configuration cause or prevent torsion. As a result more students integrated these logics into spatial patterns, such as the triangulation of vertical supports to work in three dimensions (Fig. 6a), or leveraging form resistant geometries, e.g. girders curved in plan connected to external braces (Fig. 6b). Even the less ambitious projects that added traditional cross bracing within regular bays without changing geometries revealed their lateral behavior, and had to consider its spatial and aesthetic implications. The contrast is that in previous years the majority of students largely avoided these compositional complexities, and the competency achieved in lateral stability was generally less consistent, especially when calculating the size of columns became more complex by requiring combined axial-bending processes. Although small messy models were less effective at exploring the aesthetic of joints, the modeling of pinned behavior at building scale made torsion very visible, allowing quick experimentation with physical bracing methods, and simplifying the calculations into axial-load only.

3.5 Modeling iterations

The focus on one material and analytical process had a positive impact on learning and increased the students' comfort with and overall quality of quantitative analysis. The constraint of material meant more time to do group activities during class where everyone shared in the general process of building the spreadsheet model and equations, making sense of them collectively, while allowing breaks during class for testing specific aspects of their own design in the model, e.g. selecting a species or changing span length. The slower pace and increased contact time of faculty during the development of the projects, even in the context of a large class (n=68) resulted in much less anecdotal evidence of struggle with calculations, more collaboration between groups, and more creativity in the use of quantitative models to test multiple details of the design. This observation of the faculty was confirmed in the reflections, where most students expressed more confidence in their understanding of the concepts and variables because they could instantly see the impact of manipulating different design inputs with a highly visual and physical tools. The annotations and

diagramming over photos of the physical model and the spreadsheet also indicated much more sophisticated understanding of concepts and numbers. This selection of comments from the reflections are most representative of what was seen across all the projects, students for the first time seeing equal value in physical and numerical modeling because of the way they support productive iterations and understanding:

"By designing and constructing in this way, we were able to physically see where the structure needed extra support...I was more focused on the connections between the members."

"The physical model allowed us to understand the hierarchy of structural members and helped us understand where further lateral reinforcements were required.... With our spreadsheet, we were much more comfortable understanding numbers... This felt eyeballed in our physical model, but the spreadsheet either confirmed or disproved assumptions."

"The most effective tool in learning for this exercise was the tactile element of trial and error, both within the spreadsheet model and the physical model. I found it very helpful to be able to push and pull on the model, substitute supports, enter different dimensions and densities, and compare these changes with my anticipations and prior understanding of the structure."

"The spreadsheets were a really good visual aid... allowed me to instantly see how changing one singular value could change the "ok" or "fail" of any given property that we were checking. It was actually really fascinating and actually fun trying to change the values at certain points... [to] yield 'ok' results."

CONCLUSION

The literature review established that learning about structures is most effective in a project-based pedagogy connected to design. And yet, it is still common to see a disconnect between the structural design projects that involve quantitative analysis for problem solving and those architectural design projects that are more conceptual and qualitative in nature. This paper shows that quantitative analysis can be meaningfully connected to the generative process through constraints that transform quantitative concepts into design opportunities. The study argues for and shows examples of how the constraint of determinacy, that is, structural systems that can be divided into and analyzed using the three equations of equilibrium, can unleash tectonic thinking.

Determinacy can be an important differentiator between tectonic and atectonic expression in architecture, by more intentionally engaging with the both the expressive potential and behavior of joints. This expression potential is of course traditionally associated with the detailing of the individual connections, but it also emerges from geometric configuration of lateral systems into a whole building, especially the placement of and expression of bracing. The use of small-scale physical models that could resemble the behavior of pinned joints (allow rotation but not x- or y- displacement) became a pedagogical and empirical tool to test the stability of configurations of multiple braced frames into whole buildings. One downside of prioritizing geometric stability of the whole building was that the nuanced expression and complexity of the joint does not always scale down to these small models. However, in some cases, as shown in examples, students had the initiative of using the drawing and/or digital model to understand the nature of the joint itself, and to overcome the expressive limitations of the physical model. It is not surprising that architecture students show interest in joinery in a construction class focused on tectonic thinking, but this was completely new for a structures class that still has a significantly more analytical and quantitative approach. Based on these findings, future iterations of the course will further encourage tectonic thinking by including more intentional prompts or requirements for digital and physical modelling of the connections at larger scales, to better connect the tectonic detailing with the tectonic thinking happening at the scale of structural patterns.

The motivation to introduce this conceptual constraint in a pedagogy for structural systems was to make quantitative reasoning a more powerful and generative process, and to anticipate the type of design decisions, such as materials, that could limit tectonic development and thus student learning. The results not only showed a significant improvement in student performance on quantitative reasoning, but just as importantly improved the qualitative performance, i.e. it shows that the intentional use of meaningful constraints imposed in the context of architectural education (less math background, more design) are also opportunities to more intentional connections between building technology and design.

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KSU Mini Pavilion: A Constructed Ecology and A Didactic Tool for Learning

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ABSTRACT: *The KSU Mini Pavilion Project consists of an inter-disciplinary team that includes faculty from computer engineering, construction management and architecture as well as administrators from the county's school system (see acknowledgements) with a focus on STEM and its intersection with elementary school education. The project began in 2019 with a vision to construct an exhibition space that would demonstrate to elementary students the connection between safety and sustainability at the Cobb County Safety Village (CCSV) in Marietta, GA. The CCSV is an eight-acre campus the replicates a reduced size village that teaches students of the county subjects like fire safety and crime prevention. In recent years, local businesses and institutions have constructed mini versions of themselves to represent their contribution to the community. Our mini pavilion will represent Kennesaw State University, the largest university in the county and the third largest post-secondary institution in Georgia.*

The philosophy of the Mini Pavilion project echoes the thoughts of the Tokyo-based architect, Kengo Kuma and his notion that architecture of the 21st century must be less monumental and more environmental. Kuma suggests in his writings and work that buildings echo the local geography and ecologies and merge with the environments, so they become less formalistic, and more performance driven. Performance that is not only technological but also a kind of visual performance that contributes to the cultural identity of a place. It is hope that the project is a built realization of this philosophy and that it engages the imaginations of both young and old for vision of future that is not only safe and sustainable but regenerative in the Age of Man in the Epoch of the Anthropocene.

KEYWORDS: Sustainability, Safety, Community, Constructed Ecologies

THE PROJECT

The KSU Mini Pavilion is a five hundred and seventy-six square foot interactive exhibit space that will demonstrate to elementary students the interconnection between safety and sustainability through both the building's design as well as its interactive VR/AR displays. The pavilion will be constructed at the Cobb County Safety Village (CCSV) in Marietta, GA, an eight-acre interactive safety facility that is a microcosm of a typical American town complete with roads, traffic lights, a civic central square and neighborhoods (Figure 1). The CCSV serves as an educational tool for elementary school students to learn about safety through a variety of experiences offered onsite. The mini-pavilion projects sited at the CCSV are an integral part of the hands-on safety learning experience for target audiences of K-12 students and adult seniors.

The project has a dual nature. Not only is it an interactive classroom, but it will also be an annex building for KSU that both faculty and graduate/undergraduate students can use for their research. One can imagine the pavilion embedded with electronic sensors that measure heat transfer through a wall assembly, the amount of electricity generated by the roof-mounted photovoltaic arrays or the rainfall that percolates through custom designed pervious concrete tiles installed on site. We envision the pavilion as a place that can foster new interdisciplinary capstone design projects for our undergraduate students and be a key resource in the development of new courses developed around cutting-edge technologies installed upon or embedded within the mini-pavilion's walls, roof, floor, or surrounding landscape.

Our project seeks to build a platform that provides KSU and our external partners the ability to connect with our local community. We intend to establish a physical space in the community that can be used as research infrastructure for our faculty, while providing a positive branding image to the public as our testament to progress and innovation in safe and sustainable communities. In the big picture, the pavilion becomes part of a university's research infrastructure that improves the competitiveness of KSU, a Carnegie-designated doctoral research institution (R2), placing it among a group of only 7 percent of U.S. colleges and universities with an R1 or R2 status.¹

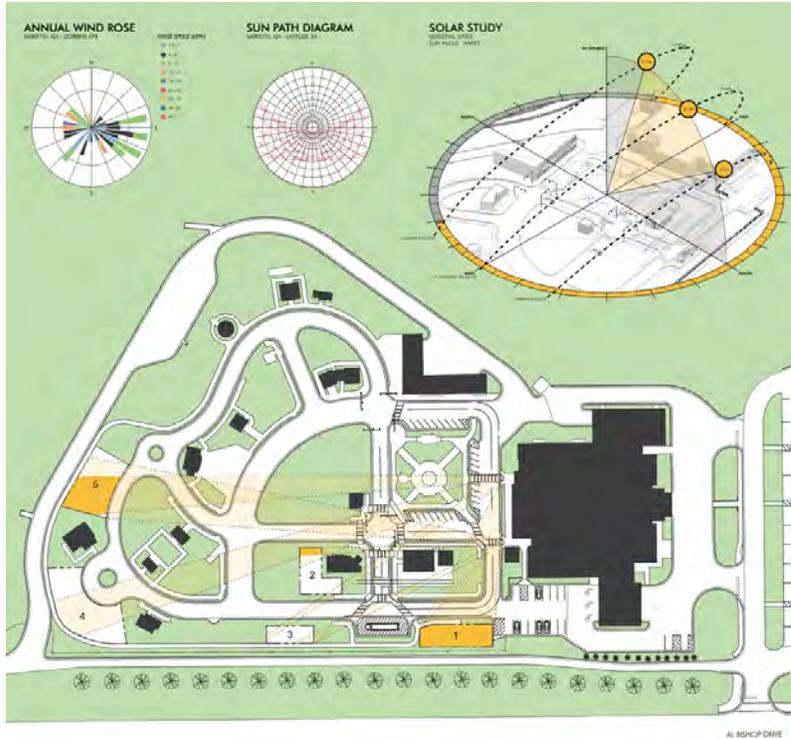


Figure 1: Site Plan of Cobb County Safety Village with Initial Solar/ Isovist and Wind Rose Analysis. The Elongated Yellow Box #1 Indicates the Location of the KSU Mini Pavilion. (Michael Carroll 2021)

PORCHES, DOG TROTS, AND THE SOUTHERN VERNACULAR

Given that the project represents a university with an emphasis on innovation regarding its research and teaching, it was important that the architectural expression of the pavilion was forward thinking and contemporary in its tone and incorporated, where possible, cutting-edge building technologies. Given its objective to be sustainable, it was also paramount that the project addressed the rich architectural vernacular of the region. Given that the vernacular, as a typology and as a way of building is inherently in sync with the climate, the materials, the topography, and culture of a place, it was a key point of departure in the design of the KSU Mini Pavilion. From the project's initial sketches, both the dog-trot plan typology and the porch (Figure 2) were referenced as key ingredients of a southeastern American vernacular and were incorporated in the generation of the pavilion's design. Both the dog-trot's breezeway and the open porch provide buffered semi-enclosed spaces that are conducive to passive ventilation in moderate climates with varying degrees of relative humidity. The dogtrot is referenced in the project's plan with its entry breezeway. It provides a sheltered space where students can gather and queue before entering the exhibit space. The porch along the pavilion's north elevation provides shade, shelter from rain and thermal buffering but most importantly signals social interaction. One can imagine the porch as an ideal location where students and their teacher can gather for a group photo, a memento of their afternoon outing to the CCSV.

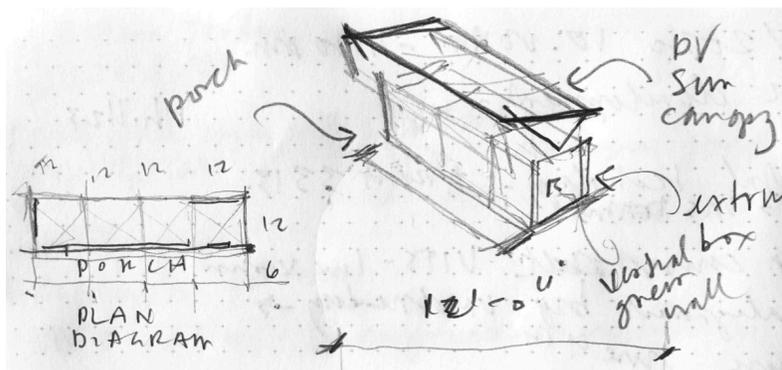


Figure 2: Schematic Design Sketches (Michael Carroll 2021)



Figure 3: Rendered View: KSU Mini Pavilion, Breezeway/Entry Court (Michael Carroll 2022)

ELONGATED FORM AND THE 12'-0" BAY

The 48'-0" x 12'-0" foot elongated form of the pavilion that is oriented directly south, maximizes its solar and wind exposure. The plan of the building is regulated by its four 12'-0" by 12'-0" bays (Figure 4). The 12'-0" bay size minimizes material waste in platform frame construction with wood studs that have an 18" on-center spacing and sheet material that is available in 4'-0" by 8'-0" formats. Three 12'-0" x 12'-0" x 12'-0" cubic bays encompass the pavilion's exhibition space and classroom. The final bay is split in two to create a partially covered entry breezeway and vestibule. The other half is a dedicated electronics' room that can house equipment as well as display monitors that can produce real-time data that can be read by the students as they gather in the pavilion's entry breezeway. A large rolling door ensures the security of the entry area as well as contribute to dynamic and interactive character of the building. One can imagine a motion sensor, with a manual override, that opens and closes the perforated metal sliding door.

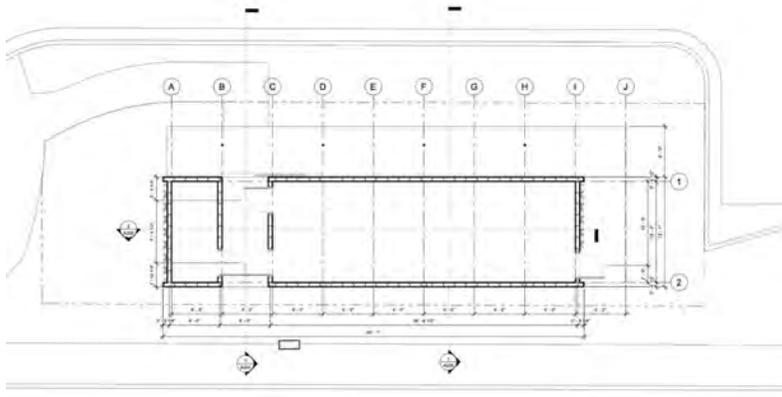


Figure 4: Ground Floor Plan: KSU Mini Pavilion with Dimensioned Structural Grid (Michael Carroll 2022)

CROSS SECTIONS, PV CANOPIES, AND THE SOLAR CHIMNEY

In terms of project's volumetric qualities, the overall dimension of the cross section of the main room is 12'-0" wide and 12'-0" high. The high ceiling ensures that projectors and other equipment for the VR/AR installation can be accommodated. The roof is sloped slightly to drain to a rain gutter installed along the south eave. At the end of each gutter is a laser cut acrylic chain that will direct water to be collected in a sub-terranean water cistern. Water from the cistern will be used to irrigate the two vegetal walls that comprise both the east and west elevations.

To accommodate the photovoltaic arrays, a skeletal metal frame is anchored to the project's nominally flat roof. Once the PVs are mounted on the frame, they will help shade the roof and induce cross ventilation which not only increases the efficiency of the PVs but also helps reduce any heat island effect. Along the northern side of the building, the open skeletal frame extends 6'-0" past the building's enclosure to create a semi-enclosed porch. This design move also increases the project's overall massing along pavilion's north elevation. The linear bulkhead above the porch is an ideal location for the branding and signage as it has a high visual exposure from the CCSVs main building.

To help passively vent the exhibition space, a solar chimney which measures approximately 6'-0" x 6'-0" was incorporated with the pavilion's design and can be seen in the project's longitudinal section (Figure 6). The glass faced Trombe wall that forms the top of the solar chimney is oriented directly south. Using the greenhouse effect, the air between the glass and the dark metal surface is heated. This hot air is exhausted in a vent at the top of the solar chimney and contributes to the overall stack effect that helps vent the warm air the accumulates in the exhibition space. This air from below rises through the linear slot at the base of the solar chimney. Once installed the movement of the air will be monitored and adjustments can be made to the solar chimney to optimize its performance.

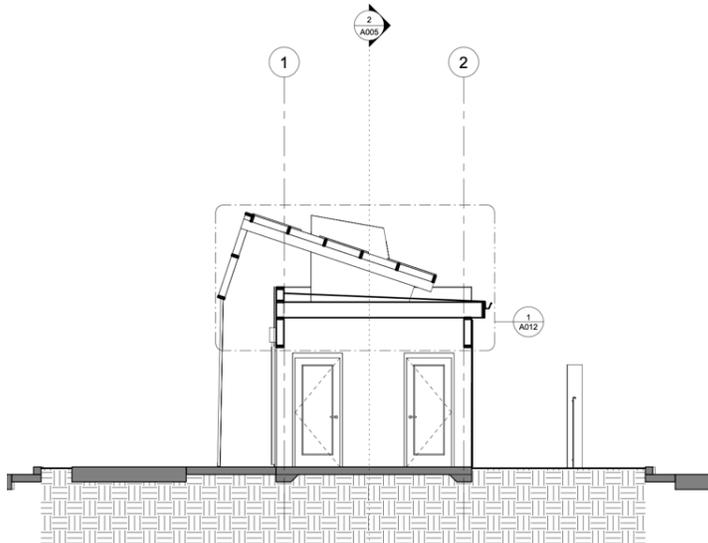


Figure 5: Cross Section: KSU Mini Pavilion with Structural Grid. (Michael Carroll 2022)

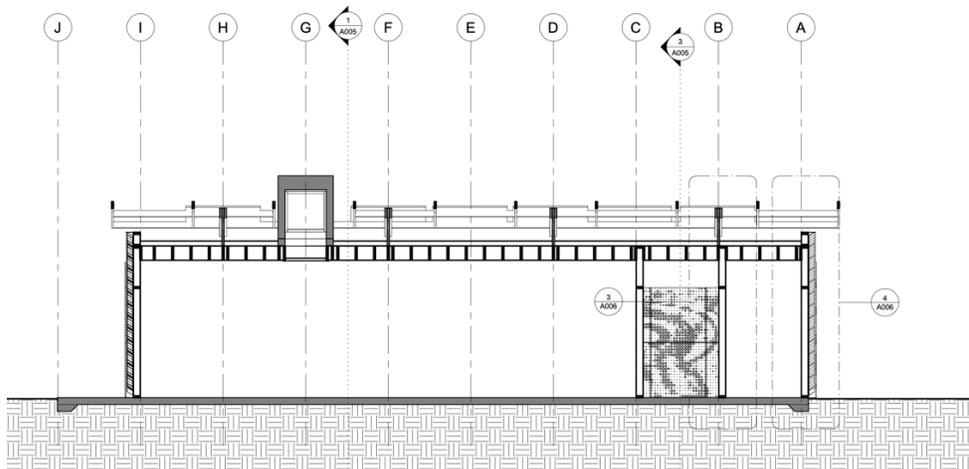


Figure 6: Longitudinal Section: KSU Mini Pavilion with Structural Grid. (Michael Carroll 2022)

SENSORS DEVICES AND EMBEDDED TECHNOLOGIES

As previously mentioned, beyond the basic enclosure of the building, a second phase of the project will entail the implementation of research activities that use the CCSV pavilion site as a testbed to perform experiments related to building-integrated renewable energy generation and energy efficient smart-building technologies. Arrays of novel low-power, multi-sensor devices will be installed at strategic locations inside and outside of the pavilion to monitor ambient, environmental conditions, and human activity for improved energy efficiency and safety of the building. As well, high performance photovoltaic arrays and bladeless wind energy harvesting devices can be installed, and their energy efficiencies can be calculated. The acquired sensor data and energy data will be used to optimize the energy output of the renewable system and energy efficiency of the building through machine-learning and deep-learning algorithms.

In terms of experimentation with sensor device, in the Fall 2021 semester, architecture and computer engineering students from Professor Carroll's and Professor Kihei's² classes collaborated in a fifth-year design

studio project that resulted in a series of interactive architectonic objects that were mounted and displayed on the rooftop gallery of the KSU Arch Gallery in December 2021.

In this process, twenty-two Computer Engineering (CPE) students learning about the Internet-of-Things (IoT) were matched with fourteen architecture (ARCH) students. The multidisciplinary teams proceeded to design a series of installations that were welcoming to children and featured embedded sensors and connectivity. Visitors to the rooftop were able to interact with the projects using a local Wi-Fi network. A QR code provided a link to the exhibit landing page where visitors could select the project of their choice and view the output of the sensors graphed on the webpage. This provided an experimentation environment of how the connected embedded sensors could be used to enhance the performance. Visitors were delighted with the transformation of the projects from daytime to nighttime, enjoyed the playfulness of the interactivity of the projects, and were intrigued with the sensor values streaming in real-time to their mobile devices. Post completion of the performance, the ARCH students were asked to evaluate their consultant teams which directly affected the CPE student grades and provided constructive feedback to them.



Figure 7: Studio X: Engineering and Architecture Students Collaborating on Roof Top Installations (Billy Kihei 2021)

Most of the architectonic objects fabricated used laser-cut edge-lit and mirrored sheet acrylic and were assembled using 3-D printed mounts and fasteners (Figure 7). An inspiration for this project a 1:50 scale model in the NYC MoMA collection of the Hotel Habitat Project sited in the L'Hospitalet de Llobrega area of Barcelona, Spain.³ The hotel project designed by Eric Ruiz-Geli of Cloud 9 (Barcelona) and Acconci Studio (New York) features a cubic like form enveloped in a netting embedded with sensors and lights (Figure 8).



Figure 8: Studio X: Interactive Architectonic Objects: Roof-Top Exhibition (Michael Carroll 2021)

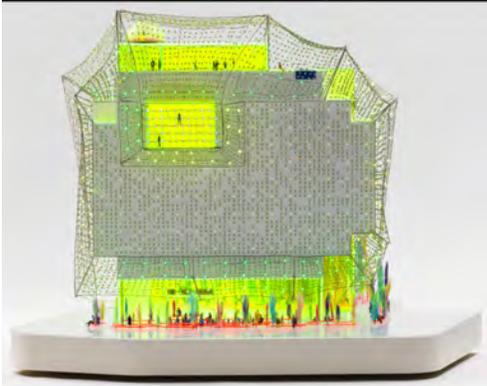


Figure 9: 1:50 Scale Model, Hotel Habitat Project, Cloud 9, and Acconci Studio 2004-08 (NYC MoMA Collection) <https://www.moma.org/collection/works/100415>

WATER, RAIN SCREENS, AND THE BUTTERFLY EFFECT

Water is a central theme of the pavilion project. As previously indicated, rainwater is collected from the roof and directed to water cisterns where it is stored. This water is used to irrigate 12'-0" x 12'-0" vegetal walls that line the east and west elevations of the pavilion. The green wall system specified for the project was designed and fabricated by, GrowUp a company based in Vista, California⁴. As a test run, a 4'-0" x 6'-0" section of the GrowUp wall was installed by fifth-year undergraduate architectural students as a design/build project in the KSU MAT_Lab in September 2021 (Figure 9). It is the intention that the plant specification for Pavilion's vegetal walls include those that attract butterflies, bees, and birds. Therefore, the project's green wall is not seen as a static entity but instead it is a living ecosystem. One can imagine the sensory delight of an array of plants like lavender, salvia and others that are not only attractors but also have a calming effect for humans and contribute to a sense of well-being.

To further reference water, the north and south elevations of the pavilion feature yellow powder-coated metal panels perforated in a dot-matrix pattern derived from a photographic image of water droplets (Figure 10). Performing as a rain screen, the Alucobond panels hover an inch in front of a Blueskin house wrap which forms a vertical drainage plane. Water collected at the base of the rain screen is collected in a channel and directed to the water cisterns used for irrigation.



Figure 10: GrowUp Wall Mock-Up, MAT_Lab, KSU Architecture (Michael Carroll 2021)

PAVILIONS, PATTERNS, AND THE BUTTERFLY EFFECT

The façade's photographic image of droplets of water and the resulting wave interference pattern on the surface of a pond hopefully attracts the eye of CCSV visitors. As butterflies hover on the nearby vegetal wall, maybe imaginations are sparked with visions of the butterfly effect – a concept in which patterns and butterflies collide. The butterfly effect is a reminder that seemingly insignificant changes in initial conditions can have large and unanticipated impacts within larger systems. The micro and the macro systems are inter-related as observed by Edward Lorenz, the mathematician and meteorologist who invented the term. In his observation

the flapping of a butterfly's wings in Brazil could, in theory, set off a chain of events that could ultimately lead to a tornado in Texas. This is an important lesson for the pavilion project in terms of the inter-connection of safety and indeed sustainability. The smallest action here can have bigger unanticipated results elsewhere. Safety requires us to consider how the slightest movements or trivial distractions can have much bigger results – in an instant our fate can change for the better or for the worse.

This may resonate with an elementary student who begins to realize that turning off a water faucet while brushing their teeth or picking up pieces of plastic on a beach may have a real effect in creating communities that are safer and more sustainable globally. Saving water locally may help areas of drought in sub-Saharan Africa or collecting and recycling plastic may improve the overall health of sea life and in turn the planet. The connections between the micro and the macro, the local and global, the individual and the community are key. Maybe butterflies and the butterfly effect and their interconnection with the KSU Mini Pavilion are not so distant. After all the word pavilion, is derived from the word pavilion comes from the Latin *pavilionem* meaning tent or literally butterfly.

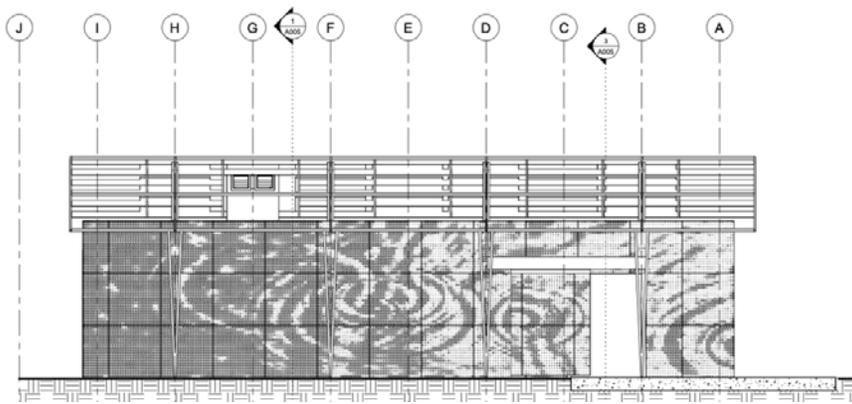


Figure 11 North Elevation: KSU Mini Pavilion (Michael Carroll 2022)



Figure 12 Rendered View: North Elevation with Perforated Rain Screen + Vertical Vegetal Wall (Michael Carroll 2022)

CONCLUSION: FROM OBJECT TO FIELD_ARCHITECTURE AS ENVIRONMENT

The KSU Mini Pavilion is a project that has a philosophical position centered on the idea that the architectural work is not an object per se, but a constructed environment with varying degrees of enclosure that engages both its physical location as well as the minds and imaginations of all who visit it. Although the exhibition room is essentially a black box optimized for its digital displays, the overall tone of the project is open-ended and experimental. The pavilion's perforated façades, mirrored panels, skeletal frames, PV arrays and vegetal walls (Figure 12) are elements that help it merge with its surroundings. As Japanese architect, Kengo Kuma might say, it is more anti-object than object. Inspired by his work and writings, Kuma has emerged as a leading figure in 21 century architecture. Known for his use of traditional Japanese materials and techniques in his designs, and for his commitment to sustainable architecture, his works are also resolutely contemporary as they test the limits of possibility in architecture, certainly in terms of their material and spatial porosity. Kengo Kuma discussed his position of time, space, and existence as they relate to architecture in an interview produced and curated by The European Cultural Centre, in collaboration with global consulting agency

PLANE—SITE. The following is an excerpt of that interview with Kengo Kuma in which he articulates where architecture has been and where it is going. He states:

“Time, Space, and Existence is a definition of three things that are slowly changing, from architecture as monument to architecture as environment; from 20th century to 21st century; from industrialization to post-industrialization. We cannot control time. Time is always flowing. Architecture also should be part of that kind of flow.”⁵

It seems clear that Kengo Kuma suggests that architecture in the 21st century should prioritize environmental sustainability and move away from monumental, large-scale buildings that have a high impact on the environment. This seems especially apt in age of the Anthropocene, the geological epoch that is used to describe the current time, in which human activity is the dominant influence on climate and the environment. As we address the emerging challenges of climate change and the rise of the human population in the coming decades and indeed centuries, it seems apt that we would be more aligned with the goal of designing and creating spaces that are in harmony and attuned to their surroundings using materials that have a lower environmental impact, and prioritizing the comfort and well-being of the people who use them.

Although the KSU Mini Pavilion is indeed small in scale, its objectives are ambitious. To create a place where we impart these lessons of safety, well-being and sustainability to elementary students as well as create a laboratory where environments and materials can be monitored with a variety of sensing devices, so we can create better and more responsive buildings in the future. Although not yet constructed, it is the hope that the KSU Mini Pavilion can be part of a butterfly effect and be part of a larger movement where buildings begin to merge and resonate with their environments and begin to make a difference not only with the well-being of an individual but with the larger society – a movement that is essentially cultural and not merely technical.

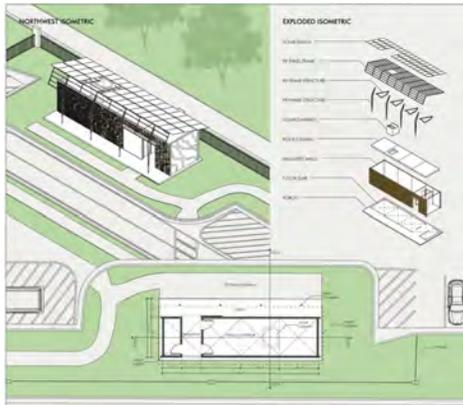


Figure 12 Projection, Ground Floor Plan + Exploded Anoxometric (Michael Carroll 2022)

ACKNOWLEDGEMENTS

In the context of this paper, it is important to acknowledge the KSU Mini Pavilion's interdisciplinary team comprised of Michael J. Carroll (Principal Investigator), an architect, and an Associate Professor at KSU Architecture and Dr. Billy Kihei (Co-Principal Investigator), Assistant Professor in the Department of Electrical and Computer Engineering at Southern Polytechnic College of Engineering and Engineering Technology. The project team also involved undergraduate student-assistant, Daryl Rowe, in the production of the digital and physical model of the pavilion as well as content for the exhibition *KSU_Mini Pavilion: Deploying Research Infrastructure @ Cobb County Safety Village*. Throughout the design process the team met on regular basis with the director of the Cobb County Safety Village, Alison Carter. The KSU Mini Pavilion project was launched by a grant from the Verizon Foundation secured by Dr. Kihei. In Fall 2021, architecture and computer engineering students from Carroll's and Kihei's classes collaborated in a design studio project that resulted in a series of interactive architectonic objects that were displayed on the rooftop gallery of the KSU Arch Gallery. This was an experiment to explore a range of electronic sensors that can be incorporated in architectural design project, a key goal in the research agenda of the KSU Mini Pavilion project.

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END NOTE

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Professor Kihei is Co-PI of the project. Please see acknowledgements.

<https://www.moma.org/collection/works/100415>

Cloud 9, Barcelona, Acconci Studio, New York, Ruy Ohtake, Enric Ruiz-GeliHotel Habitat, L'Hospitalet de Llobregat, Barcelona, Spain, Scale model 1:502004-08

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https://www.youtube.com/watch?v=ttTh29iq_gE

The European Cultural Centre, in collaboration with global consulting agency PLANE—SITE, has produced and curated an interview series presenting the ideas and practices of the internationally renowned architects selected for the 2016 TIME SPACE EXISTENCE exhibition at Palazzo Bembo and Palazzo Mora. Touching on theoretical and philosophical concerns, as well as personal trajectories, each interview presents a candid discussion of where architecture has been and where it is going.

Tectonics & Stereotomy

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ABSTRACT: *In the last decade architectural education has embraced the exploration of tectonics without investigating stereotomy. Educators might have created a semantic pitfall regarding how to define tectonics in architecture. Perhaps tectonics is today perceived to be a technique, but the terminology is architecturally immersed, entangled, and complementary to stereotomy. Tectonics should be taught in relation to stereotomy as they both are fundamental to spatial thinking. Why is tectonics not discussed in relation to stereotomy? Is it because of modernism, factories and production lines, or the path that architects followed during and after the industrial revolution? Is spatial thinking in terms of stereotomy in decline? Has the relation of tectonics and stereotomy, first used by the German architect, art critic, and professor of architecture Gottfried Semper disappeared from architectural teaching, and in such case why has nobody noticed?*

In this paper the author argues that tectonics and stereotomy should be taught in conjunction and that emerging architects should be given the opportunity to elaborate on the differences of the two classifications. Tectonics and stereotomy can be explored building artifacts. The pedagogical question is 'How can tectonics and stereotomy be taught in architectural education' and the outcome is 'A tower made of hundreds of sticks that balance and extrude from a plinth'. The architectural models presented in this paper are the results of a student exercise designed to develop an understanding of the concepts of tectonics and stereotomy in the creation of structures and the intersection of architectural spaces. This paper evaluates the outcome of this challenge given to second year architecture students. They were required to build towers using popsicle sticks, without using glue. The construction of a tower and plinth necessitated the examination of the relationship between tectonics, connections, stereotomy, carving and cavity, to form integral structural architecture.

KEYWORDS: Tectonics, stereotomy, education, architecture, structure.

INTRODUCTION – TOWERS VERSUS BRIDGES

When students in engineering or building and construction are introduced to their first assignment, they are often asked to execute a physical model of a bridge to span between two concrete blocks or similar support. This kind of assignment is often executed with small wooden sticks or similar materials. By placing weights on the structure, load is made tangible for the emerging engineer, and it is often done as a competition among students to see which structure is the strongest. It is an assignment done at many schools all over the world in the first years of study. Architects on the other hand, when finding themselves in a structure class, are often not presented hands-on or design-making objectives when investigating structures in the first or second year, although some instructors might ask students to design bridges and test them in a similar fashion as engineers. If this is done via tangible physical means, it gives the emerging architect a tactile and experiential understanding of structures and load, and it provides a great insight into engineering. However, a bridge is not an objective that architects would often design when working in the field, as it is a structural entity with limited architectural spatial range. When teaching an architectural structures seminar, I struggled to find an assignment that would allow the students to explore structure in an architectural sense. I eventually created the popsicle stick tower assignment. I found that it explores both structure and architectural spaces that would not only involve stereotomy and tectonics, but also the transition between the two classifications. This paper describes a challenge given to second year architecture students that require them to build a tower out of popsicle sticks without using glue. This exercise is suitable for emerging architects that desire to explore space, load, and balance, as well as instructors that are interested in the stimulation of a hands-on-assignment providing significant experiences of integrated principles in the field of architecture and structure.

1. WHAT IS TECTONICS? WHAT IS STEREOTOMY? WHY ARE THEY LINKED?

Perhaps the teaching of architecture would have been more diverse today if Gottfried Semper and his writings had been translated from German to English before modernism. Unfortunately, the monumental study *Style in the Technical and Tectonic Arts; or, Practical Aesthetics: A handbook for Technicians, Artists, and Friends of the Arts* was not translated and published in English until 2004. Architects and instructors will enjoy the following statement on the first page of chapter two: *Classification of the Technical Arts*. Here one can find a description of four categories of raw materials. Based on those raw materials, Gottfried Semper defines artistic activities to be explored and studied such as:

[There] are four main artistic activities... [that] ...require greater of lesser effort and technical procedures to make the raw material serve a definite purpose suited to its qualification... [each] ...divided into the following classes: 1) textiles, 2) ceramics, 3) tectonics (carpentry), and 4) stereotomy (masonry etc.) (p. 109).

This was written in 1860, in an utterly transformative industrializing time when Semper extracted 1) *textiles*, 2) *ceramics*, 3) *tectonics (carpentry)*, and 4) *stereotomy (masonry etc.)*. Notice that tectonics is immediately

followed by stereotomy in the four classes. My interpretation of this concept is that tectonics and stereotomy are in opposition to each other just like textiles are in opposition to ceramics. To understand the relationship of tectonics and stereotomy one could look at the first two classes: Textiles are made of strings that become surfaces when woven together that then drape or envelope or embrace something. Ceramics is made using clay that by nature is mass that embodies something. Polarization is helpful when thinking about classification: Textiles versus ceramics followed by tectonics versus stereotomy. To further elaborate on artistic activities and classification, I recommend looking at physical embedded properties and then align those with a concept. Textiles align with tectonics, or 1) + 3), as they are woven surfaces that in architecture often will be dependent on a structure or substructure. Ceramics align with stereotomy, or 2) + 4), as ceramics is a solid, mass, something that often stand alone, and is an excellent material that can be carved.

In Fallacara and Barberio's *An Unfinished Manifesto for Stereotomy 2.0* (2018), the reader not only finds physical digital installations of research in stereotomy, but also a statement of the origin of stereotomy:

Since ancient times, men have looked at the sky and wondered about its origin, its ending, and the space–time–dimension... The term "stereotomy" in architectural literature was used for the first time in 1644, in the *Examen des oeuvres de Sr. Desargues* by Curabelle. It is useful to note that the term stereotomy appeared here without the support of a specific terminological or a comprehensive graphic description for the first time. It was solely used to refer to the sections of solids, probably deriving from the union of two Greek words: Στερεός, "solid", and Τομή, "cut" (p. 251).

About 200 years later it appears to be the classical scholar Karl Ottfried Müller who first mentioned tectonics (p. 34), followed by tectonics and stereotomy linked/defined as complementary, in 1860 by Gottfried Semper's categorizations: 1) textiles, 2) ceramics, 3) tectonics (carpentry), and 4) stereotomy (masonry etc.) (p. 109).

1.1 Tectonics is not a technique

I wonder if there is a misunderstanding among architects and instructors that is etymological, i.e., — that tectonics is perceived as a technique. Or could it be that Gottfried Semper is not that well known, which is understandable because the translation into English of his most significant book emerged late? In his book *Studies in Tectonic Culture* (1995) Kenneth Frampton writes about the etymology of the class or term tectonic and presents how the word has been used in the past: ...*Greek in origin, the term tectonic derives from the word tekton, signifying carpenter or builder...* (p. 3). He continues: ...*The first architectural use of the term in German dates from its appearance in Karl Ottfried Müller's Handbuch der Archäologie der Kunst (Handbook of the Archeology of Art), published in 1830...* (p. 4). Kenneth Frampton briefly mentions Gottfried Semper and his tectonic/stereotomy distinction to set the premise of the book, *Studies in Tectonic Culture* on the concept of tectonics only. He does not discuss stereotomy any further nor the categorizations proposed by Gottfried Semper elsewhere in the book. This limited view may lead the reader to misinterpretations, such as in the chapter *Jørn Utzon: Transcultural Form and the Tectonic Metaphor* (p. 246) where Frampton would have served the reader better by not using the category tectonic; instead, he should have presented an examination of the projects within the category stereotomy. I wonder if there is such a thing as a *tectonic metaphor*, because most of the architectural portfolio by Jørn Utzon can be seen as spatial explorations of form, mass, solids, and light, which are findings executed almost entirely in the stereotomy classification. We can observe from Semper and Utzon that tectonics and stereotomy emerge from embedded properties.

2. HOW CAN TECTONICS AND STEREOTOMY BE TAUGHT IN ARCHITECTURAL EDUCATION?

Tectonics and stereotomy are artistic activities. Both are significant operations in spatial exploration that, fundamentally, and in their nature, point in opposite directions. When architects design, they will either come up with ideas that are based on points, strings, edges, surfaces or similar, then act and execute them by riveting, stitching, gluing, and maybe folding something. These are all tectonic activities. When architects work with stereotomy they will be extracting mass in particular areas. The activity is to remove mass to create void or a progression of void. Stereotomy can efficiently be explored in 3D printing. The use of 3D printing is rarely a tectonic activity, as most 3D printers would apply string material that immediately merges into a single mass or a clump. Recently a 3D printing technology has also become available that prints within a soluble material, creating objects that emerge from within! Surrounding soluble material is removed after the print is complete, and this approach can produce highly complex spatial geometries. When 3D printing, the mass unfolds by leaving voids behind where space is needed for functions or to embrace light and air, thus creating a 3D printed spatial investigation in stereotomy that probably would have excited Gottfried Semper. The CNC router or cutter can also be used in spatial exploration, another interesting technology for explorative activity in stereotomy when modifying solids to form space.

2.1 Exploring relations between tectonics and stereotomy in a popsicle tower assignment

Tectonics and stereotomy can be studied with computer, but the haptic experiences are absent. Touch is eliminated as the hand has been reduced to connecting vector point to vector point. This is a pedagogical problem when educating architects. When teaching architectural structures for the undergraduate architecture students, I created a popsicle tower assignment because the tower is a fundamental typology in the field of architecture. The physical stick becomes a thing to think with as they must be interlinked or attached to something as the tower is constructed, however, each student must not only create the tower itself but must also design a plinth to be able to begin a construction. During the assignment, I observed that most of the students began the tectonic activity of tower construction through simple geometry. Also, most students approached the assignment through the application of tectonic activities for tower construction and would single out stereotomy in the development of the plinth. Some did combine the two classifications, and only a few students produced a tower such that the entire structure could be placed in the stereotomy classification.

2.2 Teaching tectonics and stereotomy using sticks and plinth

If one considers a skyscraper, it is made of curtain walls, columns, folded surfaces, individual elements, and something enclosing a steel frame; this describes tectonics. But a skyscraper cannot be placed entirely in the tectonic classification. It cannot be ignored how a skyscraper is fixed to the ground. First there is excavation. To carve is an act that is executed in the classification of stereotomy. Perhaps it is possible to argue that piles driven into the ground is extending tectonic explorations from various structures above ground, but even if rammed piles or pile-driven-profiles are used as the only means, they are all set within the carving of the ground that has been done before anything could be assembled using piles or sticks. In this light, the education of an architect is twofold: Design an assignment that first embraces stereotomy and then tectonic and explore the transition between both. The construction of the popsicle towers was accomplished by asking students to first design a plinth, in solid wood, that along the edges or in the top part required implementing voids or details that would help the transition from something solid to something made as a structure. Figures 1 and 2 show the transformation between tectonics (top/structure) and stereotomy (base/plinth) as popsicle sticks are *pulled* or *extracted* from the plinth or *embedded* or *inserted* into the mass at the same time. Notice the diversity within each individual plinth as seen in figure 2. Some proposals are mass that has been hollowed out, other proposals have surfaces put together rather quickly, creating a wide range of different outcomes and spatial exploration of each plinth.

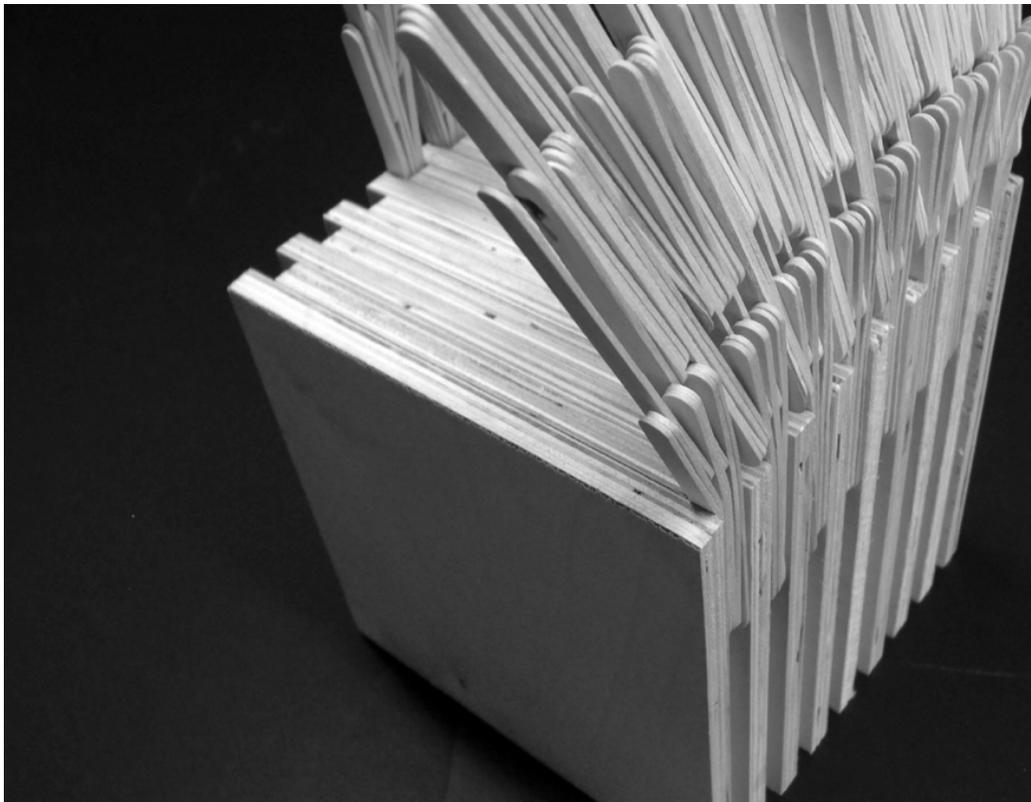


Figure 1 – transition between tectonic (top/structure) and stereotomy (base/plinth)



Figure 2 – various structures executed by different students in an architectural structures class

3. METHOD – OBJECTIVE – OUTCOME

In this exercise the students were required to build a tower rising from a plinth. Conceptually there are five basic requirements for this project: 1) make a plinth using wood or popsicle sticks, 1 x 1 x 1 foot in dimension, that is solid, heavy, and dense, 2) the tower placed on or emerging from the plinth must be a spatial tectonic construct, involving hundreds of connection points using popsicle sticks, 3) develop any method of connecting the sticks, without the use of glue, 4) the tower, including plinth, is to be as tall as the student who is creating the proposal, 5) a photographic record over the course of the construction must be made and the finished tower must be successfully transported to an exhibition area.

Any kind of wood could be used for the plinth, but the tower had to be made of popsicle sticks. The challenge was that none of the popsicle sticks could be glued, but any means of otherwise holding the tower together was permitted, from strings to clips to interlocking systems, or 3D printed connectors of the student's own design. It was important to let the students know that failure, such as a collapsed tower, could be evaluated to be good or even excellent, so recording the efforts while building the tower was as important as the outcome. Photographic evidence of the making of the tower was, therefore, strongly encouraged. Each architecture student had to transport the tower from the architecture school to an exhibition hall, and in doing so the day of stress-testing-while-transporting the physical structures faced a somewhat ultimate test. The restrictions were demanding from a technological aspect, however, when evaluating the design aspects, the outcomes were exceptionally diverse, as seen in figure 3.



Figure 3 – The task was to design and construct a structure made of popsicle sticks that raised from a plinth

3.1 Constraints and possibilities in the teaching of architectural structures

Most of the popsicle structures were static in their design, fixed in space with rigid connections. Some architecture students opted for variable geometry, such as creating a compressed structure for the design proposal, and then simply unfolding the tower on the day the structure had to be transported and presented in the exhibition hall. Figure 4 shows a student who created a balancing act attached to a plinth, and from this position the tower could unfold and be stabilized with static friction within an integrated locking system.



Figure 4 – a tower made of popsicle sticks that was unfolded from the plinth on presentation day

Investigating tectonics is different from stereotomy when making decisions regarding details and connections. To establish a system, a student must select a point in space where elements meet and define a way to connect one popsicle stick to the next and do so efficiently. The students soon found that this act is analogous to weaving, an artistic approach that belongs in the tectonic classification. It was important not to instruct how the students should execute the connection points. Teaching architectural structures should be a place for trial-and-error creativity, letting mistakes happen, and create time and space for students to reflect on those, finding successful ideas by making, thus fostering imagination.

When teaching architectural structure, I was interested in invigorating the environment of the typical lecture hall and creating a formula for learning that would merge the lecture hall and studio environment. I enjoy seeing design proposals and discoveries that students find on their own terms. This hands-on assignment in a structure class would let students work with gravity. By constructing a tower students can *feel* how a structure responds and behaves. The idea was to embrace as many as possible and a range of possibilities, including towers that might be failures. Any intervention of the instructor might limit potential outcomes or path of construction, reducing the number of ideas to which the students are exposed.

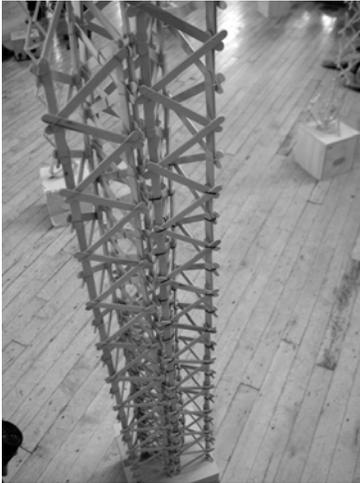


Figure 5 – the triangle is the strongest shape

The approach was to surround the popsicle assignment with lectures and then convert the lecture hall briefly to a studio environment for a display of structures in the making and discussion. Geometry was studied before constructing the popsicle towers. I would ask the students why the triangle is the strongest shape and have them compare triangles and squares using popsicle sticks that were put together not using glue. The students also discussed how it can be that there are not many towers that have a triangle footprint, or, in most cases, no visible triangles in their sections. Students selecting a triangle for their tower design proposal, would create and shape an intriguing spatial and structural exploration, as seen in figure V, but the outcome was sometimes not successful for a few students as seen in figure 6.

In my findings I discovered that tectonics are never flat. Every connection point must be imagined in three dimensions and all students demonstrated to do so in this assignment. Exploring stereotomy was difficult for many students as the plinth often was left as a mass without spatial consideration for a transition or developed implanted anchor point such as carving or similar for the tower.



Figure 6 – a design proposal with no transition between plinth/structure and a somewhat elegant failure in section

CONCLUSION – A SENSE OF GRAVITY

Mathematical principles by Isaac Newton and the theory of general relativity by Albert Einstein brings us an understanding of gravity, matter, and the fabric of spacetime. However, this question is still open in physics:

Where is gravity? Why is matter attracted to other matter? So far, a *gravity-quark* or similar has not been found by scientists. Gravity is not necessarily an equation for architects but is it spatial? In the last decade scientists provided exceptional visual evidence that all material in a galaxy is a balancing act responding to the imploded singularity of a black hole. In *The Eyes of the Skin. Architecture and the Senses* (1996), architect and architectural theoretician Juhani Pallasmaa reflects upon gravity:

The sense of gravity is the essence of all architectonic structures and great architecture makes us aware of gravity and earth. Architecture strengthens the experience of the vertical dimension of the world. At the same time as making us aware of the depth of the earth, it makes us dream of levitation and flight. (p. 57)

From a pedagogical point of view, it is beneficial for students to engage sense of touch, to feel how gravity operates within design solutions, and to get a sense of load in architectural models. Creating a physical hands-on assignment in an architectural structure class that asks students to establish a moment of balance with sticks and connection points will make evident the positive and negative interaction of their strategies with gravity, the primary physical constant affecting all building. Simulated virtual realities are driven by algorithms that first are available at the end of the design process and is not a haptic spatial investigation. This is in stark contrast to immediate learning that students enjoy when creating a physical architectural structure. The popsicle towers instantly respond to gravity while being constructed. Problems emerge during construction, such as an unintended slightly sagging “S-shape” (see figure 7), causing the student to adjust his or her approach, finding a new path, and learning unscripted lessons while going forward.

After teaching the popsicle stick assignment a few times, the benefits became evident. By including theory (tectonics and stereotomy) and studio culture (one or two assignments would interrupt the traditional lecture hall curriculum) to an undergraduate structure class I found students not to be passive listeners but to be engaged with the task at hand. When physically and mentally engaged in hands-on assignments the students were excited to explore concepts such as tectonics and stereotomy while building a tower and a plinth.



Figure 7 – detail of a popsicle structure that would sway and behave differently from the original intention

In my findings students would have no problems exploring geometric principals when thinking and building with sticks and connection points and investigating tectonics. It was the artistic approach in the design of a plinth and being able to engage and study stereotomy that often was challenging. That to carve, to hollow, to extract, to expand, and so on (see figure 8), was often overlooked as most students would define the base as a simple plinth with no transition to the tower. It is perhaps in the nature of human beings that when we first engage in something it is difficult to change. I found that stereotomy was dependent on geometry and tectonics in the upper part of the popsicle tower, and that students used feedback from the construction of the tower when developing the shape of the base. The exploration of the plinth (see figure 1 – first page of this paper) is interesting when a student would develop a transition zone between tower and plinth, but a majority of students would make tectonics primary to stereotomy as seen in most executed proposals. Being the instructor of this assignment, I could not help to think of tectonics and stereotomy to be equal by definition, however, I learned that stereotomy must have additional promotion today. If included in an architectural structure assignment at the same time, tectonics and stereotomy can both be invigorating teaching tools and a

fundamental dimension in the exploration of spatial thinking in architecture and architectural structures for emerging architects.

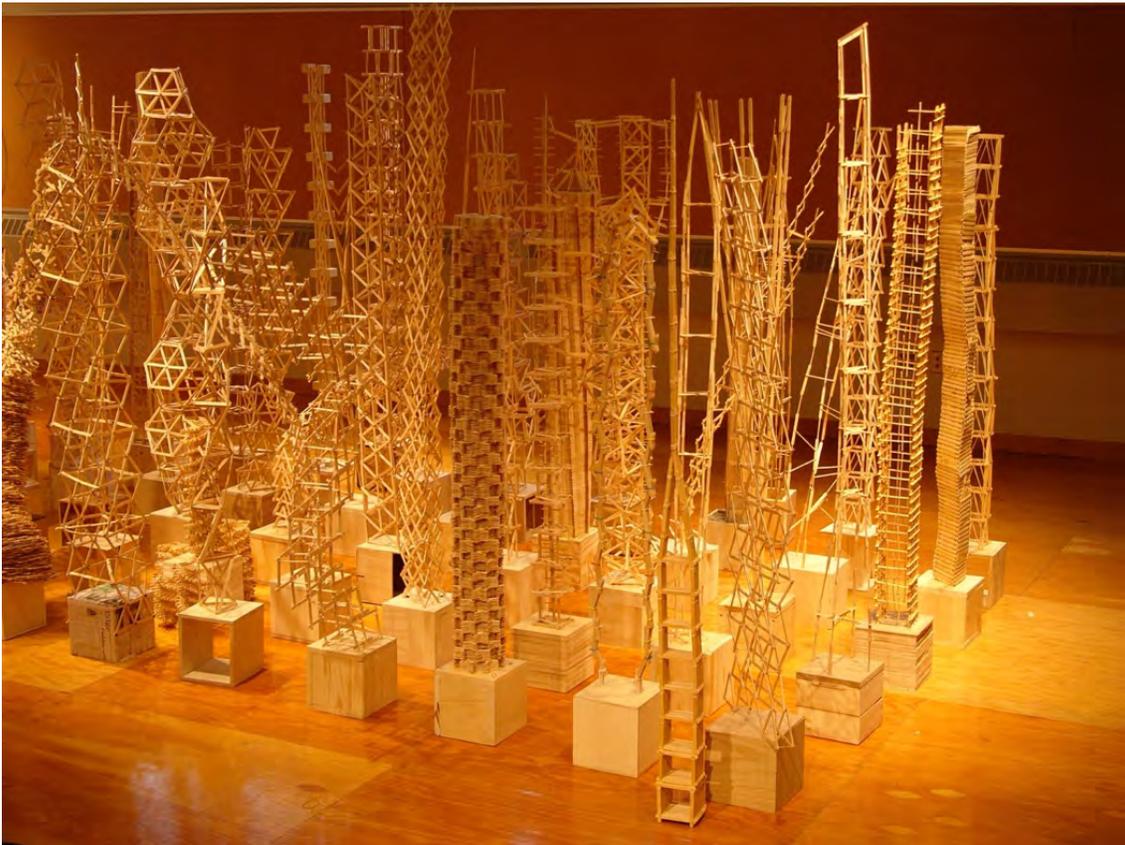


Figure 8 – notice that most plinths are simple cubes with few examples in how to investigate stereotomy

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CREDITS AND PHOTOS

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OPEN ARTIFACT

The process of 'making' through abstraction and autonomy as a speculative mode of architectural production.

The Site of Ornament

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ABSTRACT: *Historically, ornament has provided a tether to cultural meaning in the built world. Ornament is tied to specific cultural attributes. As an integral part of the construction, ornament negotiates with the culture from which it emerges. It is a built grammar, but it is also expressive of its own making as well as the society that shaped it. Modernity has largely reversed this connection with some important exceptions. There is a strong history of architects developing space through the design of the construction that provides what Louis Sullivan would call an “organic” link to the ornament that emerges, and this nexus of structure and form becomes the “site” of the ornament. Luigi Nervi’s ferro-cement shells and Frank Lloyd Wright’s textile blocks are two salient examples that have, through necessity or interest, developed details that generate entire projects, which then generate new projects as that construction/detail is refined and builds on the culture that inspired it. Ornament is thus a negotiation between the built artifact and the meaning of its “ornamented” expression.*

As architects, we now operate in a world of off-the-shelf selected components. This attitude, combined with the integration of building components into BIM programs, has made the architect a selector/consumer rather than a designer of the construction, making ornament a part of this selection process – i.e., decoration. The research project Woven Blocks is an attempt to reexamine the way in which architects can shape space through the design of the construction itself. Pulling from Frank Lloyd Wright’s textile block system, Woven Blocks imagines a 3D-printed block capable of taking advantage of a self-supporting system of enclosure that can be “programmed” with function, take on aspects of the context it resides in, and reflect the nature of its making. The project is the design of the manufacturing process as well as its end-product. This enables the building material to respond directly to its program, shaping space/meaning in potentially a more “plastic” way. This paper is first a consideration of architects thinking through construction, then a reflection on the cultural implication of their production. The site of ornament also implies a shift in perception from the textile patterns of specific cultures found in ceramics, clothing, wall mats, or flooring onto the building surface and into its lashing to the frame and the integration of its various services/systems. This lens will serve to frame the research around the project Woven Blocks, examining the efforts of the authors to shape the process of construction as a place from which ornament can emerge and meaning can be rediscovered.

KEYWORDS: 3D Printing, Additive Manufacturing, Frank Lloyd Wright, Ornament, Construction

INTRODUCTION

[Frank Lloyd] Wright attempted to derive an authentic ornament from the process of fabrication, irrespective of whether this entailed the mechanized manufacture of basic building blocks or the systematic assembly of prefabricated modular timber elements... - Kenneth Frampton (Frampton 1995, 101)

Historically, ornament has provided a tether to cultural meaning in the built world. We can see this in ancient Greek, Mayan, and Egyptian temples – the ornament on the walls and integrated sculptures like caryatids quite literally or abstractly tell stories and convey meaning. Ornament is tied to specific cultural attributes – as an integral part of the construction, ornament negotiates with the culture from which it emerges. As Michael Hann describes in his book, *Symbol, Pattern, and Symmetry*, ornamentation is also a system of abstract communication, “...when visual forms resonate with such strength that they are retained again and again.” (Hann 2013, 301) It is a built grammar, but it is also expressive – expressive of its own making as well as the society that shaped it. This is echoed in the study Wright and Sullivan made of Owen Jones’ *The Grammar of Ornament*, which laid the foundation for their own “...geometric design methods.” (McCarter 1997, 15) Additionally, and as Farshid Moussavi elaborates on Louis Sullivan’s *The Function of Ornament*, Sullivan posited that ornament, “...emerges from the material substrate, the expression of the embedded forces through processes of construction...” (Moussavi 2006, 8) Ornament, for Sullivan, was an organic, or natural, outgrowth of the building construction that becomes the “site” of ornament, where culture and building systems meet. Frank Lloyd Wright, building on Sullivan’s approach to ornament, saw ornament and form as fundamentally tied to the environment through the construction, where “form and function are one.” (Wright 1949, 298)

Modernity espoused building as a universal technological endeavor, rather than as a craft tied to a specific cultural base.¹ This has led to a disassociation between technology and tectonic, where the expression of the

building's construction is no longer tied to the technological means of its production. As Kenneth Frampton argues:

The maximization of comfort, verging on gratuitous consumption leads... to a phenomenological and cultural devaluation of the tectonic and a state of affairs in which *simulation* rather than *presentation* and *representation* becomes the main expressive mode. (Frampton 1995, 381)

The expression of a building becomes something that is no longer part of its making, converting the building into a vessel (or shed) on which meaning can only be added/applied (decoration). Many inhabitants of modern architecture, whether of its best examples or of its more average derivations, out of a necessity for meaning that the abstraction of Modern space didn't fill, bring vestiges of their personal cultural past (i.e. immigrants, refugees, etc.) to these unadorned buildings in the form of specific decoration that is then hung on its largely unarticulated walls. This unintentional cross-fertilization between the modern, universal, technological and the traditional, cultural, persistent/specific provides a strong impulse to be intentional with ornament, finding a way to integrate these dialectical ideologies more literally into a kind of built tension that can acknowledge the past and present, universal and cultural.

Where do we find ornament both in the past and today? Textile (rugs, clothing, fabric) and tile (terracotta, ceramics, mosaics) ornament elaborates something or enhances something that has utility. You can't add it on, or it becomes merely decorative. Architects like Sullivan and Wright, and later Nervi with his ferro-cement shells, all used material, structure and pattern as a means of creating space that required no decoration for the conveyance of meaning. Their ornament was timeless, in the same sense as Hann introduces in Symbol, Pattern, and Symmetry, and crossed multiple cultural lines as abstraction. These architects through necessity or interest, developed details derived from textile production and then used that analogy for their principles of construction. These details generated entire projects and were often reexamined in a later project(s) as the construction (and meaning) was refined. Ornament is thus a negotiation between the built artifact and the meaning of its "ornamented" expression.

1. ORNAMENT THROUGH PROCESS

For Tadao Ando, the wall is the site from which architecture emerges. Ando typically uses the traditional scale of the woven tatami mat (Curtis 2001, 16) which historically served as a means of modulation for traditional Japanese floors and which is a textile) to create the formwork. The lines of the formwork left on the concrete then create an intentional pattern that echoes Japanese scale and culture throughout his architecture. This is reinforced through his detail drawings where lines (formwork boards) and circles (form tie holes) are deliberately drawn in elevation and carefully arrayed on the facade, acknowledging both the construction and the ornamentation that is left by the formwork. This expression of site cast concrete as a building system, like that of Louis Kahn, presents the wall as the premier location through which cultural meaning is presented. For both Kahn and Ando, the modulation of the wall is important. Both are interested in the development of space animated by light on and from the surface of the wall.

...the surface of the walls is not created by the concrete but by the regular rectangular design of the small circular holes made by the concrete, and that inside this surface... unfolds a landscape, or rather a wash drawing, the image of a landscape. (Andreu 1991, 97)

His work then uses the wall to negotiate between outside (universal/heavy) and inside as a reflection (cultural/light). In their adherence to the Modernist notion of building with industrial technology, both Ando and Kahn put faith in the idea that the wall should express both heaviness and lightness at the same time by way of the material (fabricated stone) and by way of light revealing lines of modulation and the scars of its making (form ties as evidence of the walls once erected to form the final concrete wall).

Reading Sullivan's idea of "organic" ornament onto Ando and Kahn, it could be said that the traces of the production (the material substrate) of the site cast concrete wall exhibit a desire for the ornamentation of the blank Modernist surface and thus a belief in the need for architecture to be less a universalist proposition and that there is something lacking in the Modernist agenda for the specific cultures it has come to serve. This is also a larger (not Ando-specific) way to open history to reinterpretation through architectural expression without it becoming pastiche. As Antoine Picon frames it:

...history reveals itself more productive when the present does not appear as a mere extension of the past but seems, rather, to stem from a complex reinterpretation of some of its elements, a reinterpretation in which continuities and discontinuities need to be carefully sorted and weighted. (Picon 2013, 14)

The opportunity is not in regurgitating historical forms, but in their reinterpretation and re-grounding through the method of construction. This is reflected in Sullivan's work, and by extension in the work of Frank Lloyd Wright, and it comes out of a Semperian foundation where the wall acts as textile and also the locale for ornament. This is also the lineage from which Woven Blocks emerges. (Fig. 1)

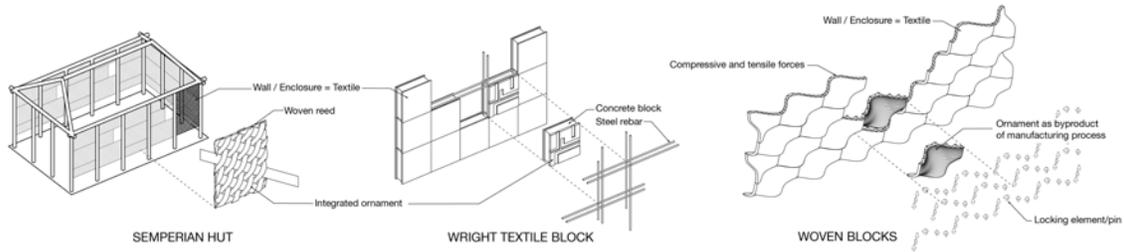


Figure 1: Lineage from Semper's primitive hut through Wright's Textile Blocks to Woven Blocks. Source: (Authors 2022)

Another approach to this kind of thinking emerges from Luigi Nervi. Thomas Leslie, writing on Nervi, states that:

Nervi insisted that his forms arose not from sculptural ideals or historical precedent but rather from ironclad economic and static logic. (Leslie 2017, xiii)

While even Nervi was one to admire the forms generated through structural optimization, (Nervi 1955, 526) the cathedral-like qualities that he could lend to the humble airplane hangar and sports stadium were produced through the geometric means and structural understanding that built the cathedrals themselves. Nervi's knowledge of construction emerges from the same knowledge that gave flight to the most impressive domes in architecture. The resultant systematic forms often bridge abstractly (in terms of their geometry) to the culture of Islam, Japan, and more. The work is ornamented, but that ornamentation is embedded in the construction process and the assembly design of the prefabricated precast module that pervades Nervi's work.

Architectural history is a history of construction and materials, and within this history, there is an arc that spans critical moments where assembly and material exploration combine and provide a point of departure for the invention of novel construction systems and their resultant spatial orders. Often this is immediate, as in the case of Le Corbusier's Maison Domino system of concrete columns and floors, which is a system still in use today. Alternatively, this moment lies dormant, in advance of its time, as in the case of Frank Lloyd Wright's concrete textile block system. Wright was interested in a construction system that was of its time and that could integrate more fully the ornament with the building:

For a true integration of ornament and building...he had to invent an entirely new architectural language that was based on forms that the machine could make and based on the true nature of materials. (Hanks 1979, 7)

His block's system of ornament and wall spanned from the ancient Egyptians and Greeks to the Celts and even the Aztecs and Mayans, with a material as a generalized construction system of pattern and woven concrete block. It incorporated glass as punctuation within the block itself and was tied/woven together with metal threads (rods) to complete the structural action of the system. (Authors 2021, 2-4)

2. WOVEN BLOCKS

The project Woven Blocks takes inspiration from Frank Lloyd Wright's textile block system as well as the manufacturing processes and integrated ornament found in Islamic tile pattern, Salish Coast imbricated coiled baskets, Congoese Kuba cut pile cloth, Japanese Sashiko stitching, and Quipu Incan Knotting. These systems of ornament literally weave strands that become spatial, whether as calligraphy intertwined with lines, circles and polygons as in the case of the Islamic system, as unique woven motifs as illustrated by the Salish Tribes of the Pacific Northwest who produced baskets that could weave ornamentation into highly functional yet minimal objects, Japanese Sashiko, where reinforcing threads could make a fabric last longer and introduce elaborate patterns, or by the Inca who used a system of knotting for accounting purposes that acted as a kind of wearable ledger that still holds visual intrigue. What unites these disparate systems of ornamentation is the way functional items are elaborated through their method of manufacture to produce a culturally significant "reading" to that object. The ornamentation is intentionally abstract and systematic (Fig. 2).

To return to Sullivan, "...he believed that ornament must be 'of the surface and substance, rather than on it.'" (McCarter 1997, 15) The ornamentation shown in Fig. 2 is derived through the construction of the functional item. Woven Blocks is an evolving hypothetical design that utilizes additive manufacturing to create a block that can integrate modern/universal technology while pulling cultural meaning out of the block through its suggested ornamentation. The design of Woven Blocks began as two offset sinusoidal surfaces, then evolved into a flat surface offset from the more undulating surface. Both surfaces are "woven" together by an infill that both separates and stitches these surfaces together (in structural action similar to cardboard). (Fig. 3) This allows the overall system to be quite thin, operating more like a stressed skin system, while still being self-supporting in its structure.

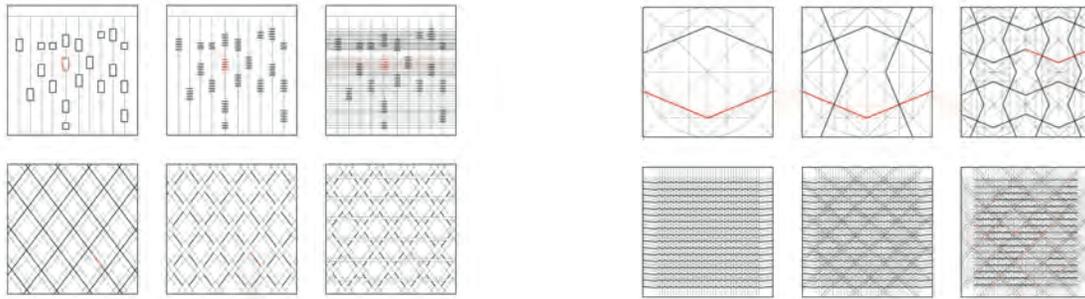


Figure 2: Diagrams illustrating woven ornament generated through process of construction. Top left: Incan Quipu knotting; bottom left: Japanese Sashiko stitching; top right: Islamic tile; bottom right: Congoese Kuba cloth. Source: (Authors 2023)

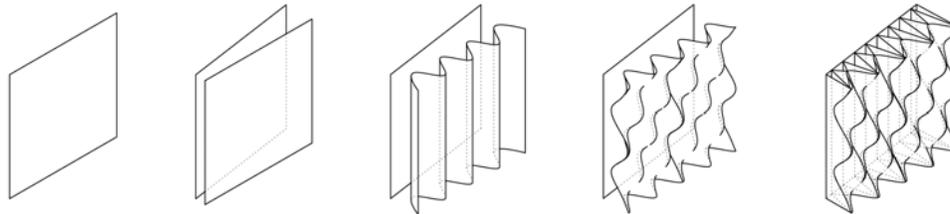


Figure 3: Diagrams illustrating evolution of Woven Block design from single surface to a woven structural patterned hollow block. Source: (Authors 2023)

Laid in sequence, the blocks undulate to provide lateral stability. The voids in the block naturally create space for services. As Kahn states it:

In Gothic times, architects built in solid stones. Now we build with hollow stones. The spaces defined by the members of a structure are as important as the members. (Kahn 1953, 23)

Because of the undulation in the block the more resistantly vertical services puncture the block and, like the sashiko stitch or Kuba cut-pile ornamentation, the services become visible through the surface of the block. Electrical conduit, interrupted by outlets that operate like the quipu knotting, push through this system to create a kind of third order to the façade. When a service is oversized to the block, the block can distort to accommodate that service, enveloping it and marking its presence on the façade and taking advantage of the opportunities that the digital fabrication process provides. Horizontal services also offer another layer of disruption/ornamentation to the block. The resultant figure/ornament celebrates a thesis of function and form (Fig. 4). Cultural meaning emerges from the prototypical weave, which can then absorb more specific patterns from both the building program and its attendant systems, drawn from the historical or current patterns of a particular culture or society, by which the block prototypes varies and thus becomes site specific.

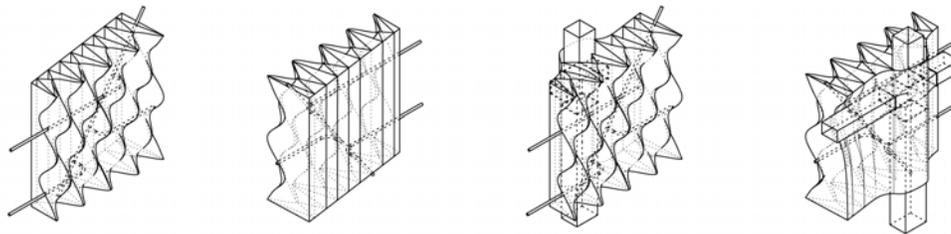


Figure 4: Diagrams illustrating the potential to use services (plumbing, electrical, HVAC) as integrated ornament with structure. Source: (Authors 2023)

2.1 Construction process

Woven Blocks began by considering FDM (fused deposition modeling) printing's potential as a manufacturing process for construction. This process essentially lays down a line of material much like you might imagine drawing with a tube of toothpaste. The hand squeezing the toothpaste is "extruding" the material. This material

is either heated or allowed to dry to “cure” and fuse the layers together. The printing process simply tells the extruder where to lay down material and how quickly (“drawing” in the toothpaste analogy). The challenge with this manufacturing process is in the limitation of available materials – primarily concrete, plastic, and clay. 3D printed concrete is where many architects collaborating with manufacturers see potential,² but the timing of the curing process and the viscosity of the concrete are very tricky to perfect and when there are failures (like air bubbles in the tube of toothpaste to extend the analogy), there is also a large amount of waste because you can’t repair or reuse the material. While a material like clay can be reworked and reused, concrete and plastic take much more effort to re-process. The design for this project always considered a block form because of the manufacturing process’s inability to recover from failure. A block not only restores the scale of the human being to the construction process, it acknowledges the necessity to reduce the scale to prevent monolithic failure. This does introduce another complexity to the system: how the blocks can join together. With the FDM printing process, this became a separate linking pin that could allow these blocks to lock together, not unlike a LEGO. This created a potential structural weakness in the system as the point of load transfer was enabled through a separate locking pin. This necessity was created by another disadvantage to FDM as a manufacturing method. It is best utilized as a kind of continuous line of printing, without what’s called “retraction” where the material (“toothpaste”) is essentially sucked back into the extruder to then allow it to travel to another printing point. Retraction enables a tremendous amount of variation in the form of the thing being printed, however it can also exponentially increase the potential for failure as it is picking up and moving to a new location. Continuous line printing does not use retraction, but the limitation in the process is then how one can accommodate interruptions to a surface (such as a hole) and support for overhanging surfaces (anything that tilts more than 45 degrees from vertical), which is why a separate pin to interlock the blocks was introduced (Fig. 5).

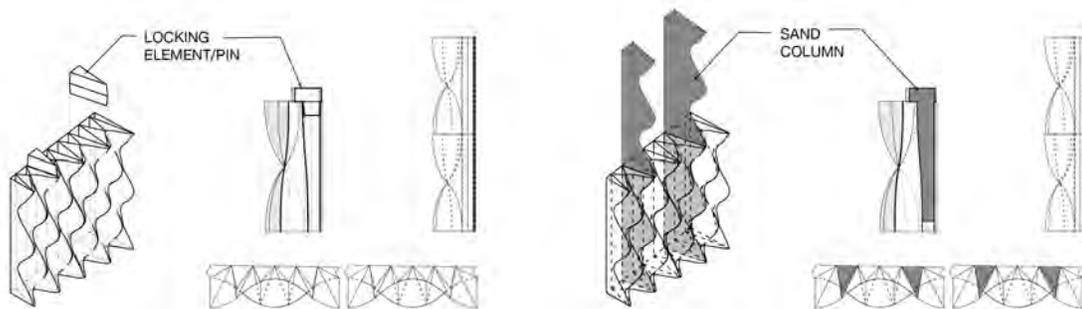


Figure 5: Diagrams illustrating the tiling, the initial FDM locking pin and the binder jet “sand column” encased in a shell of bindered sand. Source: (Authors 2023)

The design of Woven Blocks has evolved to consider an alternative method of construction more akin to what’s called BJP (binder jet printing). The Diné (Navajo) painted with sand – now we can print with sand. The structure of Woven Blocks is a weave of printed sand, a line/thread, where the thin is made thicker in order to bring more lateral resistance to the block. Within the block there are several scales of weaving that occur simultaneously or in layers. A primary stitch is the truss-like infill that operates to lace the outer shells together to stiffen the basic block. The design imagines a hypothetical system of production where a layer of dry, coarsely sorted sand is rolled out and a layer of binder is then “printed” on the layer of sand, similar to a basic inkjet printer. This research is a part of a larger collaborative effort where the material and manufacturing process are being developed simultaneously through a National Science Foundation Grant.³ The formal potential of both iterations of the block is the same. They utilize a kind of stressed skin outer shell with an infill that weaves the opposing sides of the outer shell together to create a stiff, thin block. A key structural difference with binder jet technology is the potential to “encase” the sand within a print, creating an additional embedded structural frame that can stiffen the overall wall. Because the sand is also the support structure for the print, this method of manufacturing can much more easily accommodate disruptions in a surface. This also enabled the design of an integrated pin within the block (making it even more like a LEGO than its FDM iteration) that could essentially stack columns of encased sand within the block to create the basic load-bearing frame.

The Woven Block begins thin and is distorted by the routing of systems within and through it. This produces visible variation and advances a point of departure. Where Wright or Sullivan might begin the process of ornamentation through the methodical examination or analysis of nature or a natural element, Woven Blocks begins with structural and programmatic/Semperian elements (structure, wall, void) to shape the larger formal ordering system that can adapt to particular functional/programmatic needs (Fig. 6). The systems – electrical, plumbing, air – are then fed through that formal order to create a densely interwoven wall where the structure and services push and pull to create ornamentation that can pay homage to the culture from which it springs. A key introduction to the evolution of this design is the possibility for on-site manufacturing. This provides

advantages for reducing transportation costs and the labor to move the blocks to site. Phenomenologically, it also allows the block to be literally built from the site, tying the ephemeral, tectonic wall/screen to the heavy, stereotomic ground. Returning to the larger formal ordering system, currently the Woven Blocks system has been designed from a kind of middle typical condition. It is the intention of the project to move from the wall to a more solid foundation block and a transitional roof block configuration, looking at how the block can be printed out of the land, shaping the transition from stereotomic base to screen/wall.

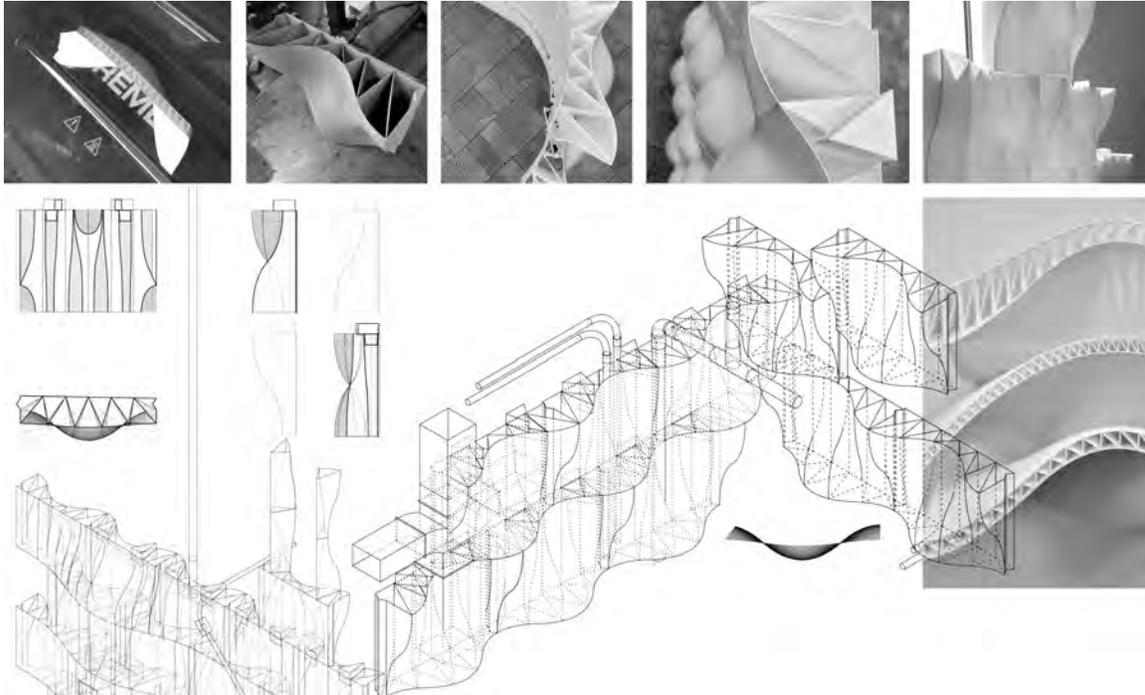


Figure 6: Composite Drawing showing the evolution of Woven Blocks from initial FDM-printed structural prototypes to hypothetical iterations utilizing binder jet processes and integrating services to create ornament. Source: (Authors 2023)

CONCLUSION

Woven Blocks attempts to reconcile industrial convenience and precision with the human need for variation and intricacy as provided by cultural ornament. Woven Blocks weaves pattern (cultural expression) and space while integrating structure, skin and services/systems in a unique on-site printed design for a specific context. Woven Blocks operates from the perspective that contemporary buildings, whether residential, commercial or public, are already woven constructs, and that this weaving is deliberately not expressed. Rather, the interwoven nature of services/systems with structure is intentionally repressed. Consider the consumer/client's desire to hide or obscure electrical, mechanical, plumbing and other systems that run in strands or threads throughout the building that follow and necessarily diverge from the main structure to adequately serve the building. This project questions both the necessity and the cultural loss of this repression.

In a dawning age of environmental concern, perhaps an expression of these essential services/systems would continue and enhance the prospect of energy stewardship. An obvious way to achieve this is simply to expose these systems as they weave to their destinations. This exposure is made far more complex because as architects, we now operate in a world of off-the-shelf selected components. We assume that the services can only arrive in certain configurations and assemblies, and the work of their integration is in the hands of the mechanical engineer. There are architects, like Richard Rogers and Renzo Piano, who have charted a path towards exposing services as an integral part of the architecture, but they are the exception, not the norm. And the more normative "off-the-shelf" attitude, combined with the integration of building components into BIM programs has made the architect a selector/consumer rather than a designer of the construction. This in turn, has also made ornament a part of this selection process – i.e., decoration. The research project *Woven Blocks* is an attempt to reexamine the way in which architects can shape space through the design of the construction itself. It is also a provocation - can a printed building system develop spatially and morph to convey a residue of the services/systems and then offer this intersection as a site of ornament, forming unique functional patterns which are then modified towards local custom?

Architecture has long grappled with the advent of new technologies and building materials, and what may be clear to those developing cutting edge high technologies in places like Silicon Valley is that what is typical practice today will not be typical practice in a decade, whether we are talking about architecture, telecommunications, or pharmacology. Woven Blocks attempts to explore and test the latest technological advances in building construction systems in a manner that can continue the relevance of human expression and the long trajectory of meaning tied to both ornament as derived from its history as a culture-based textile, and from modular unit construction. The potential of this convergence could create a site-fabricated building system that can interlace wall, space, and cultural identity with mechanical, plumbing, electrical, and future systems as yet defined. There are many precedents from the arts and architecture to draw from in this search. The notion of systems integration, as inherited from Rome's infamous concealed hypocaust floor heating system, was refined by Wright in the ventilation system of the Larkin Building and then reclaimed by Kahn in the Richards and Salk Laboratories. In reality, Kahn may not have fully integrated the systems, as he hid them in giant structural tubes in order to save the expense of shaping these oversized chases to the step downs and transitions of the services themselves. But rather than focus on the compromises that were made, the trajectory of the design intent is significant. Wright's interest in integrating systems was not without failures (such as the radiant heating in many of the concrete slab constructed homes he designed), but it is not a reason to negate the design intent nor to shy away from the larger idea of making the technology a part of the design.

Today's technology can allow architects to immediately integrate the services/systems and facilitate an appropriate expression tied to site and culture, where site is both the architecture's locale and the location where cultural meaning intersects with physical building that becomes spatial practice. This expression can aid in the stewardship necessary for our planet in the near future. We have returned to a moment of possibility that Wright saw in the Textile Block. Former President Obama has stated that 3D printing "...has the potential to revolutionize the way we make almost everything..." (Obama 2013) This "revolution" is the potential democratization of the design and the construction process. 3D printing in the construction industry is still nascent, but as it is refined and perfected, the ability for anyone and everyone to one day design and print their own buildings (or even their home) and integrate their personal/cultural history by way of the surface/structure/system is there. This may ultimately put the architect side by side with the owner, but it also has the potential to restore cultural expression to the making of the architecture through the nature of its materials.

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ENDNOTES

¹This is elaborated on in Kenneth Frampton's "Towards a Critical Regionalism: Six Points of Architectural Resistance" as well as the epilogue in *Studies in Tectonic Culture*.

²There are many examples published on collaborative partnerships between 3D printed concrete manufacturers and architectural firms, such as ICON / Lake Flato or ICON / Bjarke Ingels Group. This article elaborates on the ICON / Lake Flato relationship: Symone Strong, "House Zero," in *Builder*, 2022, Vol.45 (6), 28.

³Please refer to the Acknowledgments regarding the details of this grant.

Introducing Robotics to Students Through Novel Architectural Fabrication

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ABSTRACT: In spring 2021, a research-based graduate robotics studio was developed. The question posed to the students was: how robotic construction can facilitate new and innovative architectural construction methods? Each student was tasked with developing a new construction workflow using a custom-designed tool or end-effector attached to the end of a robotic arm. Robotic arms enable and encourage the use and creation of custom end-effectors or tools to create new manufacturing methods. The development of new end-effectors and construction workflows allows for greater customization and variability of the fabricated outputs. The studio began with an examination of the field of architectural robotics. This was facilitated through a preliminary precedent study where the students were asked to document ten conference papers through a brief description of their relevance, how the investigation could be expanded, as well as their associated images and diagrams. This study aided in the student's understanding of what is possible in addition to the common materials and end-effectors used in robotic fabrication. The goal was to narrow their focus and cultivate a novel research question. In conjunction with this study, the students were tasked with small robotic fabrication projects to understand how to develop a toolpath for the robotic arm to follow using McNeel's Grasshopper and the plugin KUKA|prc. The students spent four weeks of the semester working on their custom tool and fabrication process. These tests were documented with videos, photographs, and written observations. This allowed each student to create small mock-ups of their projects before refining and creating the final full-scale projects. These new construction workflows looked for ways to limit waste, expedite fabrication processes, and generate customization with purpose. The students' work investigated robotic clay 3D printing, aluminum embossing, and sewn fabric as means for concrete formwork and thermoforming informed by computational fluid dynamics (CFD) to generate optimized acrylic panels that control airflow. Each student was asked to document their projects with a 600-word academic research paper with a minimum of five figures explaining a novel process. When the semester began, the students had no experience with fabrication or robotics. When the studio concluded, all felt comfortable using the machinery independently. This paper will provide an overview of the course, and its assignments, discuss the students' resulting work, and reflect on the course and what was learned.

KEYWORDS: Robotics, Digital Fabrication, Formwork, Additive Manufacturing, Design-Build

INTRODUCTION

Computational design and digital fabrication technologies have become a distinct force within contemporary architecture. The translation from digital to fabricated objects is enabled by a wide range of tools and processes, such as computer numerically controlled (CNC) milling and 3D printing. The tools have been further democratized concerning accessibility and affordability within the last 15 years. These processes have altered how buildings are envisioned and constructed. It has allowed designers to engage with manufacturing and materials in new ways, allowing new opportunities and challenges in realizing architectural elements (Dunn, 2012).

Robotic fabrication permits greater flexibility with double the axes provided by a standard cartesian CNC machine. Robots enable and encourage the use and creation of custom tools or end-effectors to create new manufacturing methods. The development of new end-effectors and fabrication workflows allows for greater customization and variability of the fabricated outputs. Robotic fabrication courses tend to be cloistered within specific programs with an emphasis on this niche and at highly funded institutions. The outcomes of these student projects are the focus of their publication rather than their pedagogy. Therefore, documentation of proposed teaching methods for the integration of these tools into the architectural curriculum is needed.

Large firms such as Perkins and Will, Kieran Timberlake, Corgan, and SOM have integrated design research into their practices (Davis, 2015). When Huckabee College of Architecture (HCoA) alums are asked how faculty can best prepare students to join their firms, most ask that the students are able to conduct research. The National Architectural Accrediting Board, Inc. (NAAB) has emphasized research and innovation in its 2020 Conditions and Procedures for Accreditation. Placing significance on how the curriculum prepares students to innovate through engagement and participation in architectural research.

This paper will discuss a second-year graduate research-based option studio that introduced architectural robotic fabrication to the students. Before this studio, the students had little knowledge of computational design

and digital fabrication. None of the students had ever used a robotic arm. This was the first-time robotic arms were integrated into a course at the HCoA. Therefore, the final project brief was open-ended to allow the outcomes to be altered, if necessary, during the semester. This paper will discuss the organization of the course, review student work, reflect on the course, and how it might inform future teaching.

1. METHODS

1.1 Course overview

This studio was offered as part of the design, computation, and fabrication (DCF) certificate at the HCoA. This certificate program allows Master of Architecture (MArch) students to have a specific focus. The DCF students are required to take a research-based studio in their final year of the two-year program that emphasizes their certificate niche. The studio discussed in this paper filled that criterion. In addition to this studio, the students must take additional courses within this specialty to fulfill the certificate. It met three days per week for four hours in the college's robotics lab. The faculty's research funding covered almost all the fabrication costs.

1.3 Studio assignments

This was the first course in which the students engaged with robotic arms. Therefore, the class began by introducing the equipment and this architecture area to the students. As knowledge and confidence were gained, the assigned tasks increased in complexity. The overarching project for the semester was the development of a novel fabrication workflow using a custom-designed end-effector or tool that could attach to a KUKA KR10 sixx or a KUKA KR120 QUANTEC. The end-effector could be created using 3D printing, CNC routing, laser cutting, or other fabrication methods. It might also utilize off-the-shelf hardware or electronic components. The robotic arm with this custom end-effector could perform fabrication tasks such as embossing, carving, marking, etc. The fabrication investigations were iterative, meaning the students produced multiple versions of their end-effectors to refine the design and fabrication workflow. The iterations were documented with videos, photographs, and written observations. The students were encouraged to consider workflows with limited waste, expedited fabrication processes, and create purposeful customization. The students were required to develop a research paper to document the final project.

Review of Literature

The studio began with a three-week examination into the field of architectural robotics. This was facilitated through a preliminary study where the students were introduced to CumInCAD, a website housing a cumulative index for the many computational design and digital fabrication in architecture publications. First, each student was asked to document ten conference papers by briefly describing their relevance, how the investigation could be expanded, and their associated images and diagrams. This study aided in the student's understanding of what was possible in addition to the common materials and tools used in robotic fabrication. In the second round of the review, the students were encouraged to narrow their focus to a specific material or workflow they would be interested in pursuing in their final project. The goal was for the student to understand the work being done and ask how it could be expanded in their project so they could start developing their research questions. The students presented each literature review to their peers during class, which allowed the students to see a higher quantity of research projects collectively. It also allowed the students to see what other students were interested in and provoked conversation.

Robotic Workouts

On the first day of class, the students were given a robotics tutorial. First, a presentation was shown that discussed the various axes, and the digital workflow, and showed some precedents. The students were taught how to operate the robotic arms by jogging each of the six-axis and also how to jog the arm in cartesian mode. A 3D-printed tool was placed on the end of the robotic arm, that's shape was a cylinder with a cone at the end. This same tool was placed in various locations in the robotic arms workspace. The goal was that the students move the arm so that the tool on the end of the arm and the tool within the workspace was touching. This allowed the students to get familiar with changing the speed, the various movement types, and the pendant (the tablet used to control the robotic arm). Since there were only two robotic arms, this provided the students with an icebreaker and a fun way to learn how to use the equipment. An additional two short robotic fabrication workouts were assigned over the first three weeks of the studio. These short workouts allowed them to understand how to operate the robotic arm to perform a specific task. The first workout was milling foam with an integrated spindle. The second was wire cutting a piece of foam. This aided in the students' understanding of the digital workflow, assisting them in learning how to create toolpath files for the robotic arms using McNeel's Grasshopper with the plugin KUKA|prc. These fabrication workouts were archived through the creation of a portfolio documenting the fabrication process, the result, and a short summary of what they learned.

Electronics Assignments

The students were introduced to electronics during the first four weeks using the Arduino Project Book (Fitzgerald, 2012). Each student was provided with a small starter kit and worked through each chapter. The goal of this assignment was for the students to engage with electronics in their robotic end-effector designs. These assignments were completed outside of studio time and were documented through a portfolio submission where the students took photos of the created circuits and wrote a brief summary of what was learned.

Preliminary Material and Fabrication Testing

During the third and fourth weeks of the studio, using the inspiration from their literature review, students started selecting materials and fabrication methods. These materials were explored through small mockups. The tests were rudimentary and quick studies focusing on understanding what might be possible and the potential limitations of the selected material. Many students tried to recreate work that had been investigated within their literature review. One tested the ability of various 3D-printed plastics to withstand heat and act as an impression device for heated acrylic. Another tested various fabric formwork techniques. During this period, they were encouraged to start considering how they could build off the precedent research projects and add a new, innovative contribution. Additionally, they were asked to consider how the small mockups could be translated into robotic fabrication processes.

End-Effector Design and Fabrication Development

The students spent around eight weeks developing their custom end effectors. No student had a fully functional end-effector on their first attempt. Each created at least two more iterations resolving design flaws. Depending on the task they were asking the robotic arm to perform, some end effectors would break under pressure or prove unsuitable for the desired objective. This refinement allowed the students to test a variety of materials and methods of fabrication.

The students were asked to physically act out the tasks they were requesting the robotic arms to perform and then write each step chronologically. This process would help the students to understand better how they might develop a toolpath for the robotic arm. Since the students were new to robotics, Grasshopper, and the plugin KUKA|prc, the instructor and the student would develop these initial toolpath files together. As confidence and knowledge grew, the students started to be able to modify the definitions alone. Additionally, when students ran new toolpaths on the robotic arm, the instructor was present to monitor and assist if modifications to the robotic program were needed.

The development of the end-effector and the small fabrication tests started to provoke ideas for their final full-scale fabrication projects. The viability of the final end-effectors and the fabrication methods were tested through the development of a final fabricated output during the last 3-4 weeks of the semester. These ranged from a 3 ft wide vault to a 10ft x 4.5 ft wall. The student work will be further discussed in the Results.

Research Papers

The students developed 600-word academic research papers. Through lectures, the students were introduced to writing an academic research paper. The initial review of the literature helped the students in the development of their introduction, allowing them to specify how their research project and fabrication workflow was new, innovative research building on prior work with similar materials and methods. The archiving of their design iterations allowed the methods section of their papers to be well documented. The written reflections that the students kept while working through their end-effector designs and the fabrication of their final projects allowed them to recall specific issues they had along the way so they could better articulate the struggles in the discussion and results section of their paper. The students also received a final review prior to their paper's due date, which allowed them to start considering how the work could be expanded or further resolved to aid in the creation of their conclusion.

2. RESULTS

Four examples of student projects completed in this studio will be discussed in this section of the paper. These new construction workflows looked for ways to limit waste, expedite fabrication processes, and generate customization with purpose. The students' work investigated thermoforming informed by computational fluid dynamics (CFD) to generate optimized acrylic panels that control airflow, sewn fabric as means for concrete formwork, aluminum embossing, and clay extrusion.

2.1 AirForms

Robotic thermoforming has been utilized in multiple published works. It often relied on the robot holding and pushing a tool into a heated polymer held at its edges by a rigid frame (Tian, et al., 2017; Zhu, et al., 2021). This student's research focused on manipulating two edge conditions, not solely the center of the polymer.

Instead of pushing the entire tool into the material, this student leveraged the curvature of a 3D-printed ellipsoidal design to create varied edge conditions on each panel.

This fabrication began by hovering an acrylic panel over a heat gun until it was malleable. This was completed by developing a rectangular frame as the robotic end-effector that held a single 6-inch square of 1/8-inch acrylic. Depending on the panel design, the time and distance over the heat varied to allow differing levels of plasticity. These parameters and limitations were documented throughout the development of the fabrication process. After the heat was applied, the acrylic was moved to the proper position and pressed at a specific depth into a 3D-printed impression device allowing for the manipulation of the edge profile of the panel (Fig. 1). Thirty panels were created to test the system's feasibility as a façade. Each row was given a specific wind direction and speed, which informed the panel designs (Fig. 2). Autodesk CFD simulated wind movement and informed each panel's designs. This allowed the digital designs to be tested. The wind is controlled and directed in specific ways based on the panel's curvature, which could allow for prevalent local winds to be considered and inform panel designs. Considering the proposed fabrication method's flexibility, this could allow for custom façade designs to be informed by specific site requirements and climates.

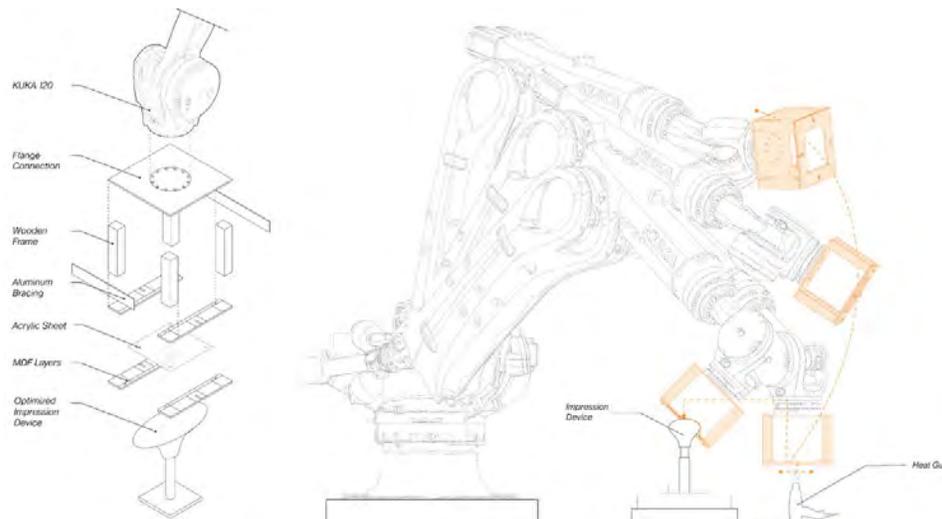


Figure 1: The drawing on the left shows the student's end-effector design and the 3D-printed impression device. The diagram at the right denotes the robotic workflow—work by Mark Eisenmann. Source: (Mark Eisenmann 2022)

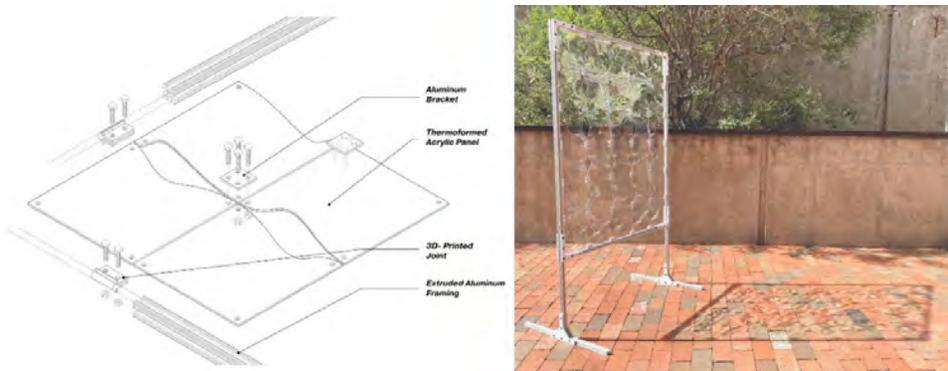


Figure 2: The drawing on the left shows the custom components designed to hold the panels. The image at right shows the completed 30 panels housed in a custom frame. Work by Mark Eisenmann. Source: (Work by Mark Eisenmann 2022)

2.1 Formwork waste

A reoccurring theme in the student projects was concrete formwork which is the instructor's area of research focus. Each project considered formwork waste differently but attempted to limit it as much as possible. The construction industry contributes around 35% of solid waste produced globally and annually (Llatas, 2011). The creation of concrete structures has contributed significantly to this problem since single-use formworks are often needed to cast concrete. Globally, the number of concrete construction projects continues to increase (Leder, 2020).

2.2 Robotically assisted reconfigurable fabric formwork

Fabric formwork has been investigated in architectural fabrication due to its low material use and versatility. Previous fabric formwork investigations have utilized rigid structures with reconfigurable components and single-use formwork (West, 2016; Kudless, 2011). The MARS pavilion combined the precision of robotic movement to orient fabric formwork to create seventy unique casts to construct a pavilion (Sarafin, et al., 2017).

This research project investigated the creation of an efficient, reconfigurable, and reusable robotically assisted fabric formwork system for casting. This proposed system utilized a single reusable fabric hexagonal unit 6 in long and 2 in wide, tapering at the center. The tapering was to prevent the bulging of the cast material at the center. A custom robotic end-effector was designed to hold the formwork for casting. Through the precise placement of the robotic arm, unique designs can be obtained. The same fabric formwork can be repeated and reused throughout the project as it increases in scale and complexity (Fig. 3).

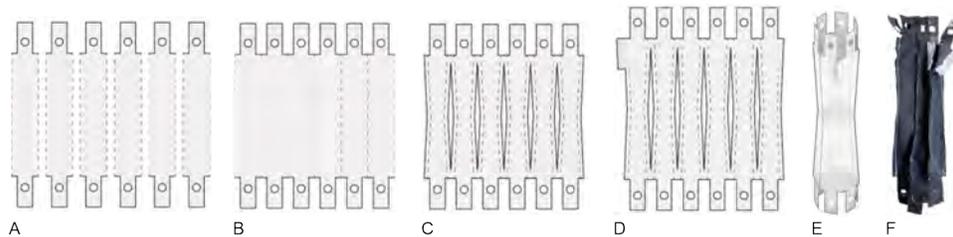


Figure 3: A- D are the fabric formwork designs that were explored. Design D, the final design, is denoted in an isometric drawing (E) and an image of the formwork (F). This formwork was used six times and showed minor wear. Work by Mohammad Karkoutly. Source: (Mohammad Karkoutly 2022)

A variety of fabrics were investigated. Aggregation of a single formwork unit was developed. Bipod and tripod iterations were achieved by adding VELCRO® strips that allowed the formworks to be combined by providing a sufficient material connection. A column was created over two days to test this fabrication system's viability (Fig. 4). It was chosen to highlight the versatility of the formwork system. This system allows for infinite design variations.



Figure 4: This image shows the process of pouring Rockite (A), placing all thread reinforcement immediately after casting (B), and leaving the material to cure (C). The bottom images represent the casting of the layers using the robotic arm (D and E) and the final column design without the base and the bottom formwork removed (F). Work by Mohammad Karkoutly. Source: (Mohammad Karkoutly 2022)

2.3 Reconfigurable embossed aluminum formwork

This work builds on robotic incremental metal forming explored extensively in the last decade (Hong-Fen, et al., 2019; Qiang, et al., 2022) in conjunction with concrete casting to produce prefabricated concrete panels. It embraces the qualities of thin (0.0019 in) aluminum sheets through their ability to retain patterns, be contorted into doubly curved forms, and their durability. This panel fabrication method allows for various novel designs and utilizes limited, reusable formwork through a constrained kit of parts.

This student project investigated a method to reuse highly customizable formwork. The proposed formwork system uses robotically embossed aluminum sheets with custom-milled formwork assembled with off-the-shelf hardware. A wall of eighteen bespoke panels was created to test the viability of the fabrication method. It was designed as a sinusoidal wall, each row tapering in thickness, to allow greater structural integrity. A seamless pattern was chosen to allow for greater versatility and reconfigurability. Eight aluminum panels were created with four pattern designs and their mirrored versions. Two of the eight metal sheets would be used for each cast, one on either side of the routed components to create the formwork (Fig. 5). The panels connect with welded joints to create a structure without additional support (Fig. 6). The use of metal sheets allows for infinite patterns to be embossed. The ability to reuse the metal sheets for multiple casts was key since their reconfigurability allowed the patterns to be used in various ways regardless of orientation.

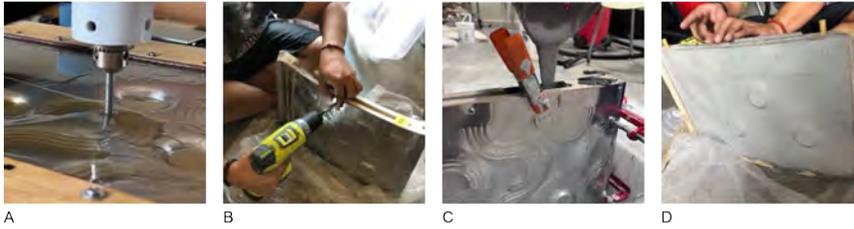


Figure 5: The robot embossing the aluminum sheet using a 3D-printed end-effector holding a drill press chuck with a rounded metal rod (A), Assembling the formwork (B), casting (C), and formwork removal (D). Work by Adrian Reyna. Source: (Adrian Reyna 2022)



Figure 6: Image A shows the hole left within the cast for the welded connection (B). This welded component holds the tiles together. Photo C shows the final wall—work by Adrian Reyna. Source: (Adrian Reyna 2022)

2.4 Modular and reconfigurable paper clay formwork

This project deviated from the brief. While it was computationally derived and digitally fabricated, the student strongly desired to 3D print in clay. Instead of re-creating an end-effector, the student used an existing clay 3D printer. The work focused on combining 3D printing and conventional hand-building of unfired clay to leverage each strength in creating custom, zero-waste, reusable formwork.

The fabrication method relied on the plasticity and water-solubility of clay in an unfired state to permit the production of larger, more complex clay formwork. This is achieved by aggregating 3D-printed units with hand joinery (Fig. 7). Since unfired clay possesses limited strength and struggles to hold its weight, shredded paper was introduced. After casting, the paper clay can be removed, rehydrated, and recycled to create additional 3D-printed formwork.

The same design was printed to test the compressive strength of 15%, 25%, and 35% paper-to-clay ratios. The test concluded that these additions successfully reduced the clay's weight while increasing its load capacity. The first two fabrication tests used small units (1 in x 1 in x 2 in). The first was tessellated into an arch using hexagonal prisms. This tested the feasibility of the unit bottom used for joinery and the top holding the casting material. The second iteration assessed the possibilities of custom patterning through toolpath manipulation. The final test increased the scale of the units (6.45 in x 5.75 in x 5 in), resulting in a three-foot-wide dome (Fig. 8). Fifty-four units were printed, then stored in a container to avoid significant drying. The cast was successful without formwork failure. The clay was removed and reused.



Figure 7: This series of images shows the joinery process of the 3D-printed units. Scoring the clay (A), applying slip (B), connecting to other units (C), applying pressure (D) The tessellated units resting on a bag of paper for support (E)—work by Haley Arthur Eisenmann. (Haley Arthur Eisenmann 2022)



Figure 8: Image A shows the 52 units. The plastic keeps them from drying further as they are assembled. A diagram denoting the assembly logic can be seen in Image A. Image B shows the students constructing the formwork, and Image C shows the additional clay added to prevent leaking. Image D shows students removing the clay formwork. The clay is beginning to dry and fall off in image E. The final cast is displayed in image F. Work by Haley Arthur Eisenmann. (Haley Arthur Eisenmann 2022)

3. DISCUSSION

Now that the studio has completed its first iteration, there are a number of things that could be refined and further developed if it were to be taught again. This section will reflect on the course.

It was noted that too much time was spent on the initial robotic assignments. Dropping one of the first introductory robotic assignments, which took place over the first month of the semester, could increase the final project fabrication time, which was too short. It was noted that students who engaged with the robotic arms learned substantially more about its operation through the design of their novel processes. When the semester began, they could not create a tool path for or operate the arm on their own. After a couple of weeks of working on their projects, they gained confidence and an understanding of its workflow. The only criticism within the student evaluations was the studio's pacing. This was a direct result of the majority of the final project fabrication taking place in the last two weeks of the course. The students felt it required additional time. It might be best in future iterations of the course to have the students work in pairs rather than individually. The workload proved to be too extensive for a single student. While some students were excited to spend a lot of time refining and redeveloping their projects, other students found it frustrating and too time-consuming as a result, the final projects varied in quality. The four discussed in the paper were the most successful of the seven proposals. The other three needed additional iterations and more time to be developed further. Additionally, it would be easier to mentor and technically assist with half the number of projects.

The assignments throughout the semester could be refined and provide more guidance to the students. It would be helpful to have an outline instructing the students on how to compose a research paper. Contemplating the studio's structure, it could be possible to break the paper into manageable parts, executing various sections chronologically in conjunction with the assignment briefs. This would assist in student reflection throughout the course of the semester. Most students were able to use the research projects referenced within their preliminary literature review to help in the writing of their papers. Although, many had found additional references that they added to their review throughout the semester. No student elected to use electronics in the creation of their end-effector or to augment their final project. This has resulted in the questioning of the inclusion of the Arduino Projects Book assignment. The use of electronics could be integrated without such an assignment based on the need of each student project.

One of the great successes of the studio was the bond between the entire cohort. The students were always talking to each other and trying to help others develop their projects. The students would offer advice and share what they had learned with others. This was very evident at the end of the semester when the students were fabricating their final models. There was much collaboration and support between the students. They helped each other cast and construct their final models. This created pride in not only their own work but that of their classmates. This can be seen in Figure 8, where all students are assisting in the assembly of the clay final clay formwork. Since the students picked such varied approaches and materials, it was sometimes difficult for students to learn from one another. The one throughline throughout nearly all the projects was the integration of casting. This allowed the students to learn from the other formwork systems. In future iterations

of the course, it might be beneficial to limit the material or fabrication task to casting or something that allows the student projects to be more connected so that there could be more shared learning from project to project. Overall, the studio was a success and was reviewed highly by the students who participated.

CONCLUSION

This studio was developed to allow the students an opportunity to investigate how robots can be integrated into construction practices and aid in the development of new fabrication workflows. Each student developed a project, and all but one utilized robotic fabrication. The students ended the course with an understanding of the field of architectural robotics. By the conclusion of the studio, all students felt comfortable operating the robotic arms and creating their toolpaths with the Grasshopper plugin KUKA|prc. The students further engaged with fabrication through the creation of their custom end-effectors using 3D printing, laser cutting, and off-the-shelf hardware. They created iterative variations of their projects, starting at a small scale and then moving to full-scale fabrication. The projects focused on limiting waste and expediting fabrication processes. Each student generated a project that used purposeful customization. This studio provided the students with a greater understanding of digital fabrication methods and the future possibilities of these tools.

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Pneumatic Reality: An Exploration of Inflatables as a Pedagogical Design Tool

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ABSTRACT: *Since the 1960s, inflatable structures have captivated generations of architects and designers. This method of construction has fostered a diversity of responses in fields from architecture and visual arts to fashion and play.*

Pneumatic Reality was a course that explored inflatables as a rapid "design-build" tool in which students translated digital sketches into building-scale, spatial experiences. Through this approach, students explored a range of architectural topics including ephemerality, the mediation of environment, the notion of boundary and amorphous form. The inflatable became the conduit through which students engaged in discourse at the intervals of permanence and temporality, old and new, natural and synthetic. Moreover, this process invited students to discuss the idea of air systems and the medium of air itself in architecture and culture at large.

The Pneumatic Reality design pipeline started in the digital realm inviting students to hypothesize through modeling potential inflatable forms. The process then progressed to a study in translation via unrolled surfaces or tessellations, and finally, manifested in material through full-scale pattern making. In a matter of hours, with minimal, low-cost or even recycled materials, students were able to produce the first iteration of their design. Due to the simplicity of the fabrication method, what followed was a process of rapid iteration at an architectural scale, a form of spatial sketching.

Students tested and responded to materials while confronting questions of form and scale. The Pneumatic Reality project took on additional significance in relationship to the legacy of Frank Lloyd Wright. In a lesser-known project, Wright explored inflatable designs by envisioning a method to construct low-cost shelters. Students at The School of Architecture (at Taliesin) revived this experimentation by building their own inflatables and then inserting them into the historic architecture and surrounding landscape thereby engaging in a direct dialogue with their environment. Due to the inherent temporality of these design inventions, this project offered up inflatables as a means through which students could temporarily disrupt spaces they already inhabited.

An inflatable structure transforms the moment people begin to interact with it. This interaction is a critical component to understanding the power of the inflatable as a teaching device in terms of its relationship to the human body and permutable program. Designs are at once an object in space and an experience to inhabit. For students at Taliesin Spring Green, their inflatables became sites for community engagement. Students' projects morphed from gathering areas to placemaking markers to an interactive gallery exhibition. Therefore, the inflatables became a means through which students reimaged program. Overall, this project provided an opportunity for students to think critically about Wright and his work, and posited architecture as an ecologically based, collaborative, open-source flow of ideas and things.

KEYWORDS: inflatable, fabrication, design-build, pedagogy, ecology

1. INTRODUCTION

Let walls, ceilings, floors now become not only party to each other but *part of each other*, reacting upon and within one another; continuity in all, eliminating any merely constructed features as such, or any fixture or appliance whatsoever as such. (Frank Lloyd Wright 1954, 20-21)

To unfold, inflate and see each other in a black white red purple cloudballoon can (conditions right) help to break down people's category walls about each other and their own abilities and can be a hint at the idea that maybe maybe anybody can should must take space-making beautifying into her, his own hands. (Ant Farm)

*Pneumatic Reality*¹ was a course that explored inflatables as a rapid "design-build" tool during the summers of 2018 and 2019 at The School of Architecture² on Frank Lloyd Wright's Taliesin estate in Spring Green, Wisconsin. Graduate students gathered for group charrette sessions and then translated digital sketches into building-scale spatial experiences. Through these exercises and intensive study of texts, the inflatable became a conduit for students to engage a range of architectural topics including ephemerality, the mediation of environment, notion of boundary, and embodiment. Moreover, this process invited students to discuss the idea of air systems and the medium of air itself in architecture and culture, spanning a range of sources including Gaston Bachelard, Luce Irigaray, Reyner Banham, Peter Sloterdijk and his characterization of the 20th century as a period concerned with *making things explicit* (2016), Graham Stevens' and his *Atmosfields*, the countercultural practice Ant Farm, sci-fi novels and films, and contemporary inflatable art and fashion.

Among these conversations and within the inflatable “happenings” they created, students were able to reflect on Frank Lloyd Wright’s passive energy strategies and concept of “integral architecture”³ that merges inside and outside – prescient frameworks to challenge the sealed architecture of today’s Comfortocene⁴ (Fig. 1). With the cohort of students and instructor working as a team, the course embraced The School of Architecture’s ethos of “live architecture” promoting a model of architectural practice based in community. The following is a reflection on the process.



Figure 1: Inflatable wedged under the north porch and encompassing the hearth of the Hillside Home School (II) designed by Frank Lloyd Wright at the Taliesin estate in Spring Green, Wisconsin. Source: (Author 2018)

2. THE PROJECT

In parallel with assigned texts and course themes, the project brief challenged students to create a sequence of three inhabitable inflatables in response to the Taliesin estate, and then a stage final comprehensive installation in downtown Spring Green. Students made design choices in attempting to negotiate the constraints of site and material with an intended experience.

2.1 Designing the medium of air

Following guidance from Ant Farm’s *Inflatocookbook*, students first set out to make an inhabitable inflatable around the Hillside Home School (II) studio with only materials at hand. Taking cues from the surrounding landscape and architecture, and using only a box fan, packaging tape, and a roll of polyethylene – each borrowed from the Taliesin Preservation’s maintenance team – the group could quickly design and build a structure at full scale (Fig. 2).



Figure 2: Students inside inflatable positioned in Taliesin estate landscape. Source: (Author, 2018).

The design pipeline continued with sketches and flowed to the digital realm, inviting students to hypothesize potential inflatable forms through 3D modeling. Significantly, Ant Farm's (and later, Wright's) exploration of inflatables preceded software. Digitally modeling the proposed form was a new step in an inflatables workflow that allowed students to explore the relationship and often disconnection between digital model and physical material.

The process entailed a study in translation, i.e., how to discretize or tessellate the volumes and create developable surfaces that could be unrolled with the intention of taking the three-dimensional form and, like a tailor, constructing a series of flat, full-scale patterns. After testing a number of workflows, students ultimately used Rhino/Grasshopper and a papercraft software called Pepakura. They were able to approximate a range of forms including a spherical shape via a truncated icosahedron that was unrolled into a template with two repeatable shapes (Figs. 3 and 4).



Figures 3 & 4: Translating digital forms into discretized surfaces – testing with paper models and full-scale prototypes, Hillside Home School (II) drafting studio. Source: (Author 2019).

Because of the simplicity of fabricating inflatables, students were able to produce a first iteration of their design in a matter of hours. What followed was a process of development at an architectural scale as students confronted questions of form, threshold, and atmospheric effects. With inflatables, air becomes a key material and structural component integral to the function and aesthetic of the design.

Through this process of translation, students investigated the benefits and limitations of creating a computer-generated design sans forces such as air pressure and gravity. When those forces were introduced, they discovered their designs behaved in ways they didn't expect as areas sagged and needed reinforcement, and facets that looked orthogonal in Rhino were rounded under air pressure.

The system of pumping air into inflatables was also made manifest, and this aspect was used to spark conversation about the role of mechanical systems in architecture at large. Never was the impact of infiltration or air leakage more apparent than via an unintentional opening, or in pondering the necessary porosity of an inflatable membrane to allow for air exchange.

Following these physical experiments, the result was a move to more discretized/rationalized forms/surfaces for reasons of constructability (modularity/repeatability vs. custom individuated pieces) and more balance in overall air resistance. The students became less interested in form-making than the material effects, and the collective act of making and occupying a space.

2.2 The inflated object

Inflatables require only two key components: a lightweight membrane and an air flow source. Therefore, material workability is critical. Throughout the course, students tested sheet plastic, mylar, and fabric, joining them with tape, heat fusing, and sewing methods respectively.

As previously introduced, the first material students explored was polyethylene sheet plastic. This humble material was readily available and proved unmatched in its ease of manipulation and constructability. Students had to develop a methodology for construction via patterning and labeling the plastic sheets prior to carefully seaming the edges with heat and/or tape. An emphasis was placed on the level of craft and care in each seam as students found ways to avoid puckering or folding so as to create an airtight seal.

Upon inflation, it became immediately apparent where the structural stress points were located and students needed to address these intersections. They deflated the structure, reconfigured their design and then reinflated. By operating at full scale, students physically experienced the resultant consequences of their design choices such as the manner of entrance/exit, durability of materials, or the ability to transfer conditioned air. In addition, designs were informed by a sense of scale in relationship to the human body and explored a range from an individual pod to a space for group gatherings.

The second material, mylar donated from a Wisconsin company that manufactures party balloons, proved to be more delicate than the robust sheet plastic and also invited a new form of seaming. Mylar, as a material, is utilized by a variety of industries as a hygienic, sealable method for packaging items ranging from vitamins to candy, in essence, creating miniature airtight bags. Through their research, students recognized an opportunity to employ this system of sealing at an architecture scale. They discovered, prototyped, and developed a way to heat-seal the edges, resulting in a resilient seam that removed, as in the previous studies, the need for an additional adhesive component. This process proved more time intensive and less forgiving, and by extension, necessitated a more resolved design prior to the start of fabrication in addition to requiring a standing heat sealing machine. Yet, the color and translucent properties of the mylar added a sense of playfulness and celebration to the spaces encompassed by the material. In one instance, students chose to evoke Andy Warhol's Silver Clouds.

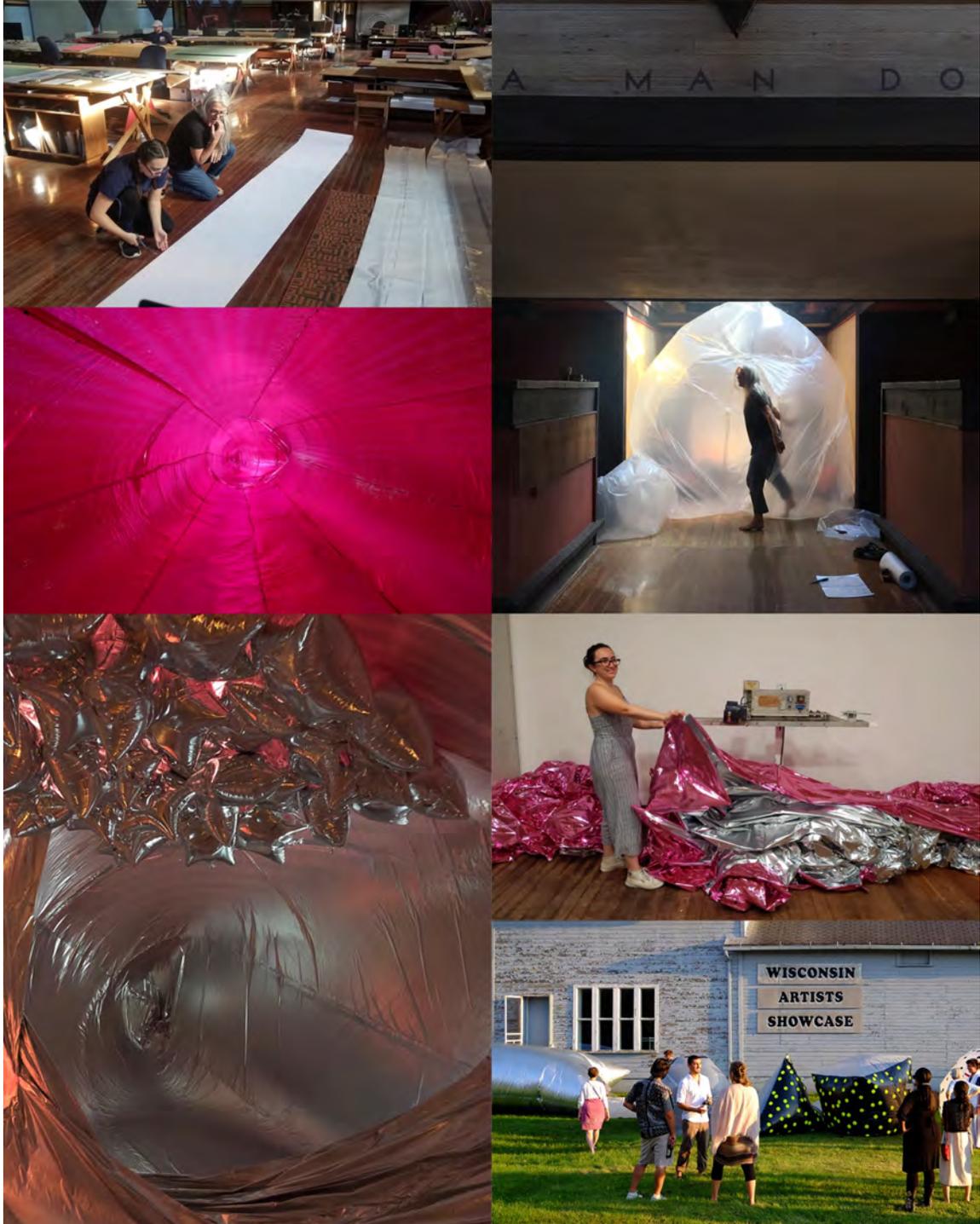


Figure 5: Installations at the Hillside Home School (II) & Wisconsin Artists Showcase gallery in Spring Green. Source: (Author 2019)

By exploring the same construction approach through multiple materials, students discovered the intricacies and nuances of how each material fundamentally impacted the experience of the structure whether tactilely, audibly, or simply visually. Differences such as the ability to illuminate the translucent plastic vs. achieving a “fun house mirror” distortion of images through the reflective mylar highlighted the significance of their material choice (Figs. 6 & 7).



Figure 6: Reflective mylar meditation pod. Source: (Author, 2019).



Figure 7: Mylar inflatable interior inflected by the wind. Source: (Author, 2019).

2.3 Boundary, form & Wright

The *Pneumatic Reality* project was initially conceived as a deliberate juxtaposition to Frank Lloyd Wright's earthbound work generally (think, especially, of the hearth) and particularly to the Taliesin estate. The conceit took on additional significance upon discovering an obscure project by Wright envisioning a method to construct low-cost shelters in partnership with the US Rubber Company. The November 11, 1957 issue of *Life* magazine featured the Fiberthin Airhouse, a pneumatic dome fabricated from a "durable vinyl-covered nylon material called fiber thin." (Frank Lloyd Wright Foundation 2019) Programs were compartmentalized into living, sleeping, and work inflatables. Wright then expanded this vision of a single house to a community called the Rubber Village. A group of prototypes were produced for the New York International Home Building Exhibition in May 1957 and later exhibited and photographed at a Kentucky university (Fig. 8).

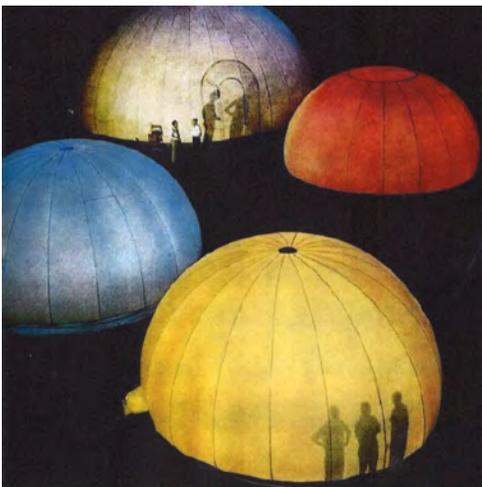


Figure 8: Wright's Fiberthin Airhouses. Source: (Frank Lloyd Wright Foundation/Life 2019/1957).

The *Pneumatic Reality* project was rooted in both Wright's own interest in technology and material experimentation, his pedagogical motto of learning by doing embraced by The School of Architecture and

perhaps best represented by the student self-build shelter tradition. In this project students were challenged to push back by inserting inflatables into the landscape of Taliesin and against/within the historic architecture of Wright, thereby creating a dialogue with their environment and raising the idea of architecture as a form of spatial intervention and climate mitigation. Students eventually weighed the inflatable against Wright's own terms: organic architecture, continuity, integral architecture, essential architecture, structure-pattern made visibly articulate, etc. (Wright 1954)

Students would be drawn to attend the Taliesin program out of a reverence for Wright's work, and would approach living and working in these historic buildings with tentativeness. The inflatables allowed them to begin to engage with the architecture more directly by inserting their design into and occupying the "empty space." They began to see the space between ceiling and floor and walls an integral to the architectural design and something they can explore through their work by creating different responses through form. The inflatable could operate more like a standalone object or if built at a larger scale be "squeezed" into the void, using the surrounding structure to distort the inflatable and draw attention to the low ceiling or angled walls. Students began to experiment with how inflatables changed their experience and perception of landscape elements by placing them under trees, over leaves and grass and even cantilevered into water (Fig. 9).



Figure 9: Inflatable over the Taliesin pond bridge across from the main house's cantilevered Bird Walk. Source: (Author, 2018).

After disassembling a prototype that was blown up for a few days on the lawn near the Hillside Home School (II), students were particularly struck by how thoroughly and quickly the inflatable membrane's coverage killed the grass below. Later, students observed inflatables responding to wind, causing them to come alive, rippling and breathing almost like a bodily organ. The disruptions and transformations brought by these interventions gifted students a new means to understand spaces they already were inhabiting.

3. CONCLUSION

Finally, as the *Inflatocookbook* describes, an inflatable structure transforms the moment people begin to act upon and within it. Interaction is a critical component to understanding the power of the inflatable as a teaching device in terms of its relationship to the human body and permutable program. Designs are at once an object in space but more importantly an experience to inhabit, a catalyst for communal engagement. Students' projects morphed from gathering areas to singular meditative spaces to place markers to an interactive exhibition adapted to the Wisconsin Artists Showcase art gallery in downtown Spring Green. Students even created an inflatable gathering space for the annual Taliesin summer formal held at the main house by hijacking the air supply from an upstairs air conditioning vent, thus literally utilizing another structure's air system (Fig. 10). The inflatable became a group agent for exploring, testing, and rethinking program. Overall, this project provided an opportunity for students to think critically about Wright and his work, and posited architecture as an ecologically minded, collaborative, open-source flow of ideas and things.

The project of *Pneumatic Reality* challenged students to notice and critically reflect upon their environment, and to work opportunistically with site and material constraints. Bridging the gap from representations of space

to full-scale interior experiences, realizing inflatable installations made manifest the limitations of digital and physical design models. Speculating on a new mode of architectural production, *Pneumatic Reality* centered community, temporality, and resourcefulness.



Figure 10: Room for the annual Taliesin summer formal leeching from the air conditioning supply from the main house. Source: (Author, 2019).

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ENDNOTE

1. Title derived from the quote: "A line of poetry is a pneumatic reality." In Gaston Bachelard, *Air and Dreams*, trans. Edith R. Farrell & C. Frederick Farrell (Dallas: The Dallas Institute Publications, 1988), 242.
2. Now called "The School of Architecture" and based at Arcosanti and Cosanti.
3. For example: "Architecture now becomes integral, the expression of a new-old reality: the livable interior space of the room itself. In integral architecture the *room-space itself must come through*. The *room* must be seen as architecture, or we have no architecture. We have no longer an outside as outside. We have no longer an outside and an inside as two separate things. Now the outside may come inside, and the inside may and does go outside. They are *of each other*." In Frank Lloyd Wright, *The Natural House*. (New York: Horizon Press, 1954), 50.
4. "...an era defined by a global order predicated on manufactured interior consistency." In Daniel Barber, "After Comfort," *Log 47: Overcoming Carbon Form* (Fall 2019): 47.

A Tectonics of Ontogenetic Materialism: Three Projects

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ABSTRACT: *The effects of human activity at global scale are largely absent from tectonic discourse. This paper presents preliminary concepts and examples toward an expanded conception of what might constitute an architectural tectonics in the Anthropocene. Our habit of evaluating buildings as artifacts – as singular, autonomous objects, as ‘articulations’ of assembly, ‘expressive details,’ or ‘transparencies’ of program or assembly – too often limits building to representation, to mere significations of ecological, cultural, and political realities. Our recent collective focus on building systems ‘performance’ can also limit our understanding and responsibilities relative to larger systems: the assumed fuel of said systems, of material extraction, production, distribution, assembly, and disassembly. Further, our collective entanglement with dynamic, complex planetary systems is at odds with a dominate hylomorphic model of thinking, an ontology of separation: between human and non-human, organic and inorganic, matter and form, thing and idea.*

Using three recent student architectural thesis projects alongside concepts from recent ‘materialist’ scholars, the author argues that reframing of our epochal perspective from the Holocene to the Anthropocene productively alters our ontological biases. Repositioning our understanding to the human impact on terrestrial systems is crucial to an engaged practice of architecture. The paper addresses design strategies and materialist concepts within the presented works that can potentially shift our tectonic conceptions.

KEYWORDS: Tectonics, Anthropocene, Materialism

INTRODUCTION

The realization that we affect the earth on a geologic scale has transformed our planetary understanding from an epoch of the Holocene to that of the Anthropocene; this perspectival shift challenges our assumed human privilege. As Nigel Clark and Bronislaw Szerszynski write, “the Anthropocene offers incitements for thinking about our planet across a range of timescales, fields of vision and trajectories,” (Clark 2021, 3). An architectural tectonic discourse that attempts to grasp the scale of the Anthropocene is imperative, one that provides new design strategies and conceptual frameworks for revised and expanded practices.

The dominant discourse of architectural tectonics has tended to relegate social, political, and material imports of construction to signification and representation. ‘Articulation,’ ‘transparency,’ and ‘expressive detail’ are generally deployed as cultural, political, ontological, and cosmological stand-ins. An influential example is Kenneth Frampton’s *Studies in Tectonic Culture*; here, it is ultimately the structural frame and the climatic envelope that constitutes “poetic construction.” Frampton states that tectonics is not “the mere revelation of constructional technique but rather its expressive potential,” (Frampton 1995, 2). We are suggesting that Frampton’s distinction between the representational and ontological aspects of tectonic form, “between the skin that re-presents the composite character of the construction and the core of the building that is simultaneously both its fundamental structure and its substance,” does not go far enough, that such a conception of tectonic potential limits architecture’s agency to representation and thus, to a solely human-centered ontology (Frampton 1995, 16).

Ecological dynamics also elude the discourse of tectonics. ‘Site specificity’ rarely extends to material networks and is seemingly limited to the singular artifact of building form. For example, even the Semperian category of mound, “earthwork” in Frampton’s terms, is too often merely an inert foil to the ‘framework’ tectonic. The ‘universal’ categories of “framework” and “cladding” are also routinely decontextualized from their material realities in order to emphasize their formal and representational attributes.

Our tectonic thinking has also restricted its grasp of energy, eliding material processes and transformations. A materialist reframing of energy, such as Kiel Moe’s use of H. T. Odum’s ecosystem science method, “emergy analyses,” would begin to account for the numerous interactions between energy and form beyond the symbolic. Moe states: “The emergy method forces consideration of myriad factors and dynamics otherwise externalized to the discipline of architecture” (Moe, 2020, p 106).

The problem is manifold, the absence, or marginalization at best, of Earth from the discourse of tectonics, systems of extraction, production and distribution as well as consideration of planetary processes. These absences obscure our ability to perceive the possibilities of a material, ecological tectonics at scale.

“For materiality is always something more than ‘mere’ matter: an excess, force, vitality, relationality, or difference that renders matter active, self-creative, productive, unpredictable. In sum, new materialists are

rediscovering a materiality that materializes, evincing immanent modes of self-transformation that compel us to think of causation in far more complex terms; to recognize that phenomena are caught in a multitude of interlocking systems and forces and to consider anew the location and nature of capacities for agency” (Coole and Frost, 9).

What might be a tectonics of ontogenetic materialism? Barry Bergdoll traces a shift away from the stylistic and anthropological debates of architectural form in the 19th century; in his essay, “Of Crystals, Cells, and Strata,” he outlines investigations into the ‘underlying structures and phenomena’ of both geology and biology as they relate to architectural form (Bergdoll, 2007). Highlighting the works of René Binet, Violet-le-Duc and others, Bergdoll points to a nascent, vital materialism in architectural discourse, a search for an architecture “in resonance with the building blocks of the universe” (Ibid, p 26).

As Elizabeth Grosz writes in *The Incorporeal: Ontology, Ethics, and the Limits of Materialism*, the Stoic’s (3rd century BCE) ontology includes not only all objects, forces and qualities, but also “the nonthings that frame things, put them in the same field and create a plane or context for their actions and being acted upon” (Grosz, p 28). Here, Grosz emphasizes the necessity of an incorporeal framework for the Stoics; it is the inclusion of the immaterial, the form or idea, as the condition and substance of the material itself and as the ontological and ethical basis of living consistently with nature. This monistic model of thinking stands in contrast to our deeply embedded hylomorphic disposition, where ‘nature’ is a reserve from which to draw and form and idea are imposed upon malleable matter. Tim Ingold summarizes the hylomorphic disposition succinctly: “Form came to be seen as imposed by an agent with a particular design in mind, while matter, thus rendered passive and inert, became that which was imposed upon” (Ingold, 2010, p 92).

Recent theories of materialism contribute to an adequate framing of problems that architecture might address. Overcoming the hylomorphic disposition is key to this reframing. Etienne Turpin, in *Architecture in the Anthropocene*, addresses the necessity of a shift in our thinking if we are to provide sufficient formations of the existential problems we face. He writes that it is “the act of *de-ontologizing* the separation between humans and nature [that] allows contemporary theorists, activists and designers to develop problem-formations adequate to the politics of hypercomplexity that accompany our postnatural inhabitations of the earth (Turpin, 2013, P 10).

An expanded accounting of material, energy, and time can enable a more meaningful and agentic architecture. Providing conceptual frameworks that capture the ecological, social and political within the discourse of tectonics is also critical to that endeavor. Kiel Moe borrows the conceptual term, “terrestrial,” from Bruno Latour stating, “‘terrestrial’ describes all the human and nonhuman, organic and inorganic, ‘natural’ and ‘unnatural’ dynamics of entities on the surface of the planet” (Moe, 2020, p 30).

A tectonics of ontogenetic materialism is an attempt to rethink the hierarchy of idea and form over matter, to include and account for the agency and dynamics of material, of energy, of terrestrial systems; it is an effort to provide possible strategies and conceptual frameworks for an architectonics in the Anthropocene. Below are three recent student works, architecture thesis projects that attempt illustrate possible approaches. The first project proposes a tectonics of ameliorative infrastructure, of agentic, dynamic cores; it seeks ‘emergent forms’ of reciprocity between human, animal, plant, and material systems projected across an expanded timeline. The second looks for the ‘edges and cracks’ within a consumerist spatial order, proposing a folding of interstitial spaces into ‘found’ and constructed systems to explore an ecological tectonics at multiple scales. The third project speculates a tectonics of ‘immanent materiality.’ Rescaling away from representations of a resolved object, the project proposes a tectonics of material intensities and entropic dilations. The author, the thesis advisor for each of the three projects, provides a brief analysis of each and an overview of opportunities for expanding tectonic discourse and practice toward a tectonics of ontogenetic materialism

PROJECT 1: TRANSECT THROUGH TIME

The project site is a brownfield contaminated by the decades-long occupation of a fuel storage and transport business. Adjacent to a channelized river and at the edge of an urban core for a city of 250,000, the site is also bounded by Interstate ‘connectors’ to the north and south. The student sought ‘emergent forms’ of reciprocity between human, animal, plant, and material systems projected across an expanded timeline, ultimately resulting in a proposal for an ameliorative infrastructure that functions as the principal armature for future growth or decay.

The critical developments of this project are threefold: the understanding the site as a metabolic assemblage in distress, the programming of the site and architectural interventions as adaptive infrastructure, both remedial and productive, and a proposal of development and transformation over an expanded period of time. Ultimately, the project proposes a tectonics of dynamic core.

Understanding the site as a polyvalent organism, a hybrid of constructed and organic systems, enables the project to immediately formulate a problem outside of the constraints of a hylomorphic model. The initial analysis revealed that the site was formerly a wetland made buildable by channelizing the river. Modifying the riverbank and reintroducing seasonal flooding to the site is key to its amelioration.

Numerous site tactics follow. The reintroduction of a gradient of plant species, native aquatic - to wetland - to upland, stabilize the site, phytoremediative plantings, mechanical biosparging and bioventing remove toxins from the soil, and strategic intake of urban storm water at the top edge of the site all contribute to the formation of site and its conception of infrastructure (see Figures 1 and 2).

The project conceives infrastructure as a living, ecological commons. The biosparge machines function as the seven 'cores' of the project, the founding elements for building and site infrastructure. Over time, one of the cores transitions to drinking water infrastructure, another to water treatment, and the remaining five, to public/mechanical cores for mixed use buildings. Each core, then, becomes both mechanical and social infrastructure for future building formations as well as continuing ecological performers within the site.

The expanded timeline of the project, a 20-year buildout before all elements are even in place, allows for expanded considerations of design. In addition to the infrastructure discussed above, building façade elements are understood as modular and energy producing, disassembled, and reconfigured as necessary in response to future change of program, or need altogether. As Cristina Parreño Alonso points out, "architects must develop deep-time literacy to become true planetary stewards" (Alonso, p 3). The extended timeline of the project helps make clear the possibilities of fusing infrastructural site systems with larger, terrestrial systems, as well as building-scale systems toward the development of a complex building-site hybrid of dynamic cores. (see Figure 3).



Figure 1: Transect through Time: Site systems diagram. Source: (Kayla Duclos, University of Idaho, 2021)

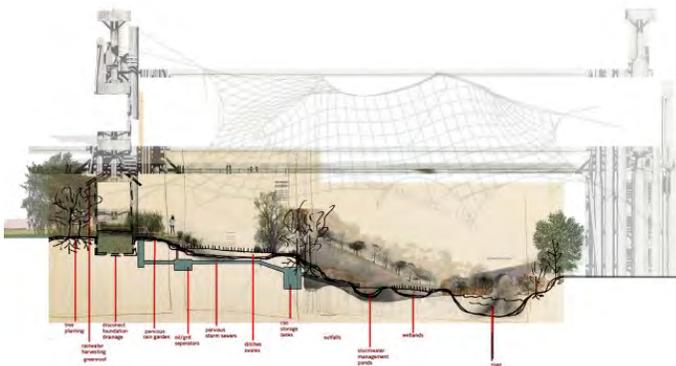


Figure 2: Transect through Time: Site section. Source: (Kayla Duclos, University of Idaho, 2021)

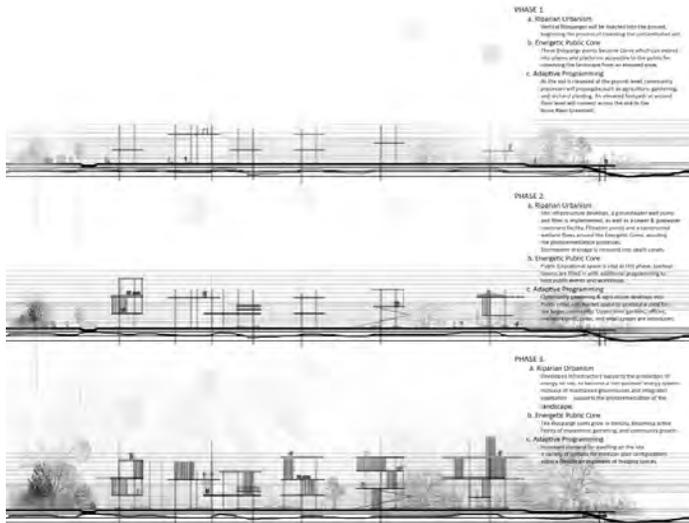


Figure 3: Transect through Time: Timeline of 'cores'. Source: (Kayla Duclos, University of Idaho, 2021)

PROJECT 2: ECOLOGICAL TECTONICS

The second project looks for the 'edges and cracks' within a consumerist spatial order, proposing a folding of interstitial spaces into 'found' and constructed systems to explore an ecological tectonics at building, urban, and territory scales. The project site is in a small city of 50,000 people. Agricultural and livestock ranching have been the principal activities since white settlement in the 1860s, accomplished by the irrigation of a sagebrush steppe. The city is bounded by two rivers, one at surface, where the city center resides, and the other at the base of a 500-foot-deep canyon that cuts through the geological plain running 400 miles east to west.

Strip development characterizes the more recent growth pattern of the city. Over the last 60 years, the city has spread north from the city center to the canyon edge. Here, one finds typical arterial strip development, 20,000-foot 'big box' stores surrounded by vast swaths of surface parking. Low-density, single-family residential neighborhoods surround the commercial zone. The project site is a portion of this commercial district, a principal vehicular intersection and its surrounds of approximately 100 acres.

From the point of view of our materialist discussion, the key attributes of this project are its attempt at an 'ecological tectonics' and what that might mean in the context of suburban development patterns; its proposed building figurations of thermal performance; its urban design elements as ecological performatives; and its resistance' or critical stance toward consumer culture via the development of new spatial and programmatic types toward an 'ecological commons.'

The project develops its urban-scale pattern and building form by way of mapping multiple natural and constructed systems: watershed, animal migrations, agricultural irrigation, land division, commodity networks, vehicular and rail. Daylighting a series of underground canals, the project reroutes contaminated agricultural run-off waters into an integrated network of public landscapes designed for surface water treatment. The reconfigured canal system functions as an open space network, in concert with a wetland park, organizing the new zone.

The canal network also organizes the building forms and programs. Indoor public spaces are created as interstitials, between layers of parking, shopping, and dwelling. These interstitials are proposed as continuous public flows that develop and nurture cultural space, potentially resistant to commodification. As Coole and Frost point out, political and economic materialists are attentive to the "production and consumption of goods, to the uneven effects of globalization on differently located citizens, to the management, distribution, and legitimization of unequal life chances" (Coole, p 28). The project conceives a revitalized public space adjacent to, beneath, and above, private capital (see Figures 4, 5 and 6).

Building forms, in addition to their development as part of the multiple systems listed above, are organized around atria. Formulated as vertical extensions of the continuous horizontal public network below, the atria enable cultural and ecological commons at multiple levels within and atop the structures. Additionally, each

atrium is designed as a public core and “thermal figure,” that is, a thermodynamic building form in the service of climatic performance (Moe, 2008).



Figure 4: Ecological Tectonics: Site systems and morphologies. Source: (Samantha Jesser, University of Idaho, 2021)

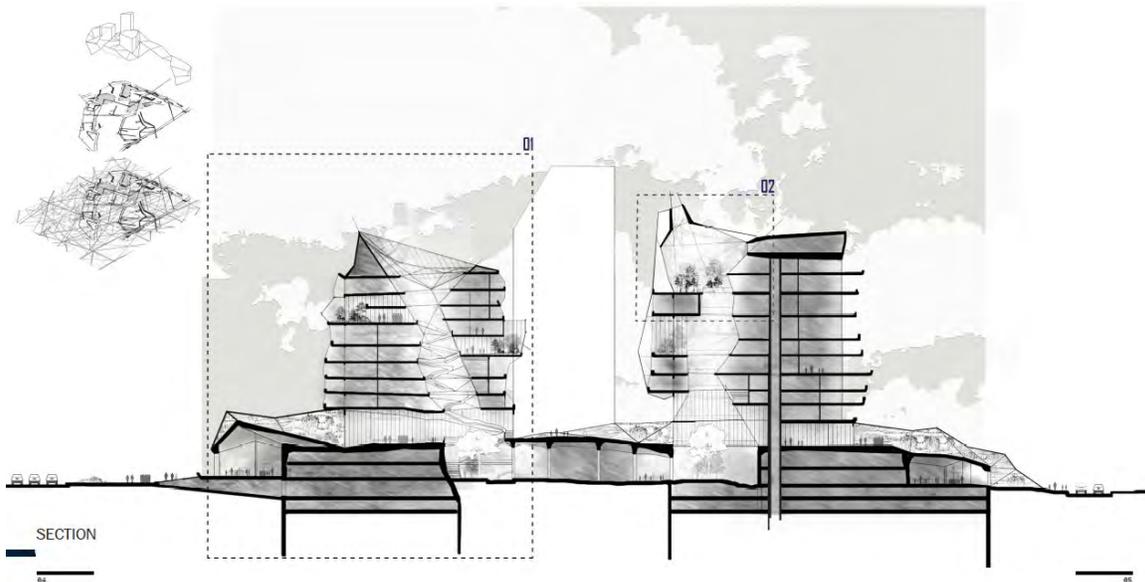


Figure 5: Ecological Tectonics: Site/Building Section. Source: (Samantha Jesser, University of Idaho, 2021)

PROJECT 3: ABSOLUTE UNCERTAINTY: AN INDUCTIVE APPROACH TO MATERIAL TECTONICS

The third project speculates a tectonics of ‘immanent materiality.’ Rescaling away from representation and the resolved object, the project proposes a tectonics of material intensities and entropic dilations. The project is in Butte, Montana engaging three sites: the Berkeley Pit, a former open pit copper mine operational from 1955 to 1982; the Montana Technical University campus; and a district of Butte, now mostly vanished into the southwestern edge of the mining pit, formerly known as Finn Town. The pit and its surrounds constitute one of the largest Superfund sites in the U.S.

The elements of the project pertinent to this discussion are the exploration of a tectonic based on immanent materiality and its possible relation to an emergent form; the proposal for an architecture situated within a geologic horizon; and, again, an infrastructure conceived as a commons, in this case, one of knowledge.

The project proceeds via a series of material studies seeking architectural form. Proposing that material potentials, their latent or immanent order and possible transformations, ought to reside at the root of an architectonic language, the student initiated a series of speculative experiments toward the discovery of a Simondonian architectural ‘individuation.’ Gilbert Simondon theorizes that the development of any individual entity is part of a metastable process of individuation in which formation is continuous. Tim Ingold summarizes, “Simondon’s central postulate of individuation holds that the generation of things should be understood as a process of ontogenesis in which form is ever emergent rather than given in advance” (Ingold, 2012, p 433).

One of the material experiments revolved around the different states of the elemental metal, gallium. A trace element in the earth’s crust, gallium is produced as a by-product of mining operations. Because of its low melting point, 85F, the material’s process of crystallization around a foreign element can easily be observed. For the student, this site-specific element provides a demonstration of Simondon’s individuation process,

characterized by “self-organizing forces of the preindividual and the intrusion of a foreign ‘germ,’ an element that is introduced from outside to a metastable system” (Grosz, 174). The element also directly participates in the history of the site; it is entangled within the processes of mining, processing and global distributions; it is understood as a participant in its own ‘history’ of continuous, emergent qualities (Ingold, 434). The observed processes of gallium crystallization thus led to the exploration of an anisotropic tectonic, an assemblage of heterogeneous qualities seemingly at odds with one another (see Figure 6).

The geologic horizon of the project is literal and direct. The Berkeley Pit is 1800 feet-deep and a mile wide. The project, shifting away from quantitative measure and material ‘properties’ and, instead, toward the qualitative ‘life’ of materials and sites, attempts to reimagine what might constitute a geological architecture in the Anthropocene. In her “Notes on Architecture’s Lapidarium,” Amy Kulper cites Gottfried Semper’s characterization of stone as “lifeless” and “without external existence;” she states he “articulates a moment in which technique eclipses material possibility” (Kulper 95). It is this eclipse of material immanence, its geologic life, that the project seeks to regain.

The project maps and repurposes several of the hundreds of shafts, drifts, and stopes that characterize the site. Extensive mechanical water treatment, extraction of heavy metals, and a network of public programming, displays, overlooks, museums are proposed, a technological individuation of the site’s infrastructure. A university material science laboratory and new steam baths at the former location of ‘Finn Town,’ begin to establish an infrastructure of active knowledge, a loose physical network that might be, nonetheless, understood as a reclaimed commons (see Figure 7).



Figure 6: Absolute Uncertainty: Gallium study. Source: (Kelsey Ramsey, University of Idaho, 2022)

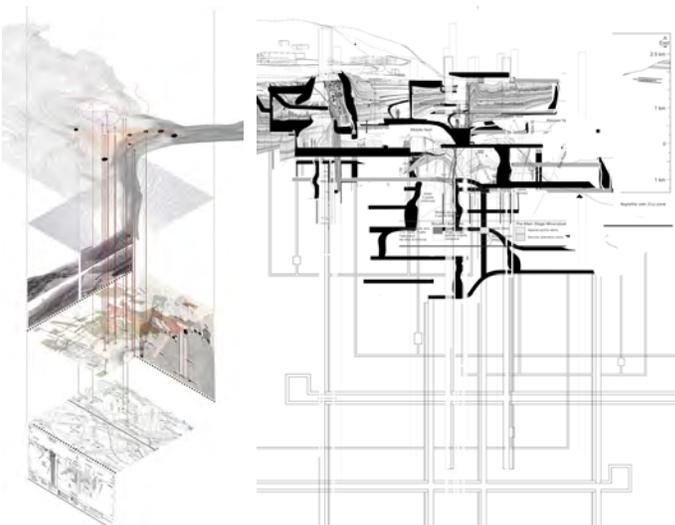


Figure 7: Absolute Uncertainty: Composite image, pit and intervention. Source: (Kelsey Ramsey, University of Idaho, 2022)

CONCLUSION

The above concepts and student design examples are an attempt to expand the conception of architectural tectonics toward material concerns. The projects are the result of a 3-credit course of preparation and research and a subsequent 6-credit course of individual design research work executed in a collective studio setting. The initial course challenges students to develop individual architectural research programs of study. To that end, students are introduced to critical readings in broad categories, material and tectonics among them. The three projects represented here are student works that engaged these particular topics for their individual design research endeavors. Taken together, the three projects seem to reveal an overlap of tectonic concepts and strategies that can be summarized as follows:

'Site' is an organism, a terrestrial system of 'natural' and 'unnatural' elements, continuous and without boundary. In all cases, the understanding of site as an animated complex of multiple systems, both 'living' and 'dead,' 'organic' and 'inorganic,' was crucial to the projects' development. Further, in each case, the strategy was to understand the site's effects beyond its boundaries, the systems and elements prior to their arrival on site, any outputs or effects after or exiting the site, and the transformation of elements or systems on site. All three projects develop an ecology of site that is, or substantially participates in, the development of the tectonic language of the project.

Infrastructure is a dynamic commons; social, ecological, adaptive, it is a shared network by which site, building and territory are fused. Each of the projects develops a shared network, a principal infrastructure, operating somewhere between public and private, whether a building core that provides water and energy for the inhabitants, a linear water treatment canal that navigates multiple zones, or an appropriation of an existing private work now made public.

Site and building are hybridized; a strategy of dismantling building as autonomous artifact is the integration of site systems into building systems and vice versa. Each of the projects blur distinctions between site and building. Site and infrastructure run through and organize building; buildings expand or dissolve into site.

Material and form are neither separate nor static; form is neither privileged nor a priori; material substance is the thing that connects all things. The three projects all seek tectonic form via an engagement of material and natural systems, whether those of site, watershed, or elemental material. Each of the projects rejects, if only implicitly, the hylomorphic model of thought.

Time is expanded. Each of the projects expands the timeframe and perspective of their proposal. This, too, potentially undermines the building as artifact, demanding a larger, ecological accounting of architecture in the epoch of the Anthropocene.

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Having It Both Ways: Building as Object, Building as Artifact

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ABSTRACT: Increasingly (and understandably!) the act of building, along with the buildings we design and build, gain validation through the recognition of the complex systems in which they are conceived, designed, and built. Today, the success of contemporary buildings is determined primarily through their performance, durability, utility, responsiveness to site, context, social responsibility, and interconnectedness to larger, more complex networked ecologies. But these are not the only metrics of a successful project. In the case study design-build program discussed in this paper, it is especially critical that projects also address the learning objectives of the course, contribute to advancing the research agenda of the faculty and program, and of course positively contribute to the needs of the community in which the work is situated.

The perceived utility of a built project is contingent on its purpose. Multiple utilities are possible; the constraints of one purpose sometimes provides a platform for an alternative understanding. The research generated on-the-ground at the design-build program is applicable to multiple contexts and provides diverse responses that reveal solutions not conceptualized in the original application. The specific informs the universal and, in turn, the universal provides new understanding of the specific. This feedback loop provides a new measure through which to evaluate the utility of the work: if the project provides multiple solution sets, then it demonstrates the strength of the design response.

The authors – who are students, teachers, and critics of the design-build program – examine ways in which prompts enter and exit the studio. Some begin with teaching objectives in mind: the design is an outcome of its teaching process. Others come from a wider field, where a practical need is found to be transferrable into an educational process. This multi-lensed approach allows us to extend the utility of the product beyond the architecture studio and into a broader context. In many ways, designing and building these projects provides a means of illustrating unseen linkages, patterns, and systems.

As Heidegger first described in “Being and Time,” it is through utility that a tool, or in this case, a building, disappears as an object, and becomes just a useful bit of equipment, or simply an artifact of production and performance. But often the best, most beautiful buildings are also simultaneously objects that resist utility, and the authors of this paper will attempt to articulate this necessary friction that exists between Building-as-Object and Building-as-Artifact.

KEYWORDS: Architectural Education, Design-Build, Building Performance, Housing

1. INTRODUCTION

Rural Studio is a design-build program in which architecture students spend anywhere from one semester to as many as two years of their undergraduate education. While at Rural Studio, students work in partnership with their neighbors in the local community to purposefully seek out problems, define solutions, fundraise, design, and ultimately build projects. In its initial years, the Studio first became known for establishing an ethos of recycling, reusing, and remaking. Over the past decade, Rural Studio has expanded the scope and complexity of its projects to include the design and construction of community-oriented infrastructure, the development of more broadly attainable small, high-performance home affordability solutions, and a comprehensive approach to addressing insecurity issues relative to income, energy, food, health, and education resources. Altogether, the Studio continually questions what should be built, rather than simply what can be built.

As a hands-on program, Rural Studio was founded around a handful of simple premises. First, we embrace the idea that the best way to learn how to do something is by actually doing it. Rural Studio is action-oriented, and we get things done. Second, we have found that when faced with difficult problems, it is always best to tackle them together; therefore, Rural Studio is extraordinarily team oriented. Combining this belief in the importance of action with our penchant for teamwork, Rural Studio acts not just as a research “think tank,” but also as a sort of “do tank.” Finally, and perhaps most importantly, we believe that everyone, no matter their circumstance, deserves a safe, durable, healthy, and dignified place to call home.

Our students work directly with real clients, on real projects, with real sites, with real schedules and real budgets, and—hopefully—with real, long-term positive impacts on the lives of our neighbors. In addition to

local clients, the students also work with all sorts of other folks, including community stakeholders and professional consultants such as structural and environmental engineers, healthcare professionals, economists, and social scientists. Through this practice-based process, the students learn everything they need to know about how to both design and build their proposed project, and then of course, they build the project themselves as well.

1.1 SYSTEMIC CHALLENGES DEMAND A SYSTEMS-BASED APPROACH

Rural Studio has always been a “Housing First” organization, which means that before we can begin to address the broader issues faced in our low-wealth communities, we must first make sure everyone is decently housed. That said, over the past three decades, Rural Studio students have designed and built well over 200 projects for our community, including more than just houses. So why do we put so much time and energy into these types of community projects, if we truly believe in the “Housing first” approach?

While working on designing homes, the students came to realize that one of the significant barriers to affordable homeownership in our community was the lack of adequate fire protection. This was a barrier because houses in the community were burning down at an inordinate rate, which made it difficult—if not impossible—for local residents to get homeowner’s insurance. And this was a barrier because if you can’t get homeowner’s insurance, you can’t secure a mortgage. And of course, that becomes a barrier to affordable homeownership, because if you can’t secure a mortgage, no amount of work that we might do as architects by “designing the house this way” or “building it that way” would ever begin to address this systems-based problem through brick-and-mortar design and construction solutions alone. It is in this way that Rural Studio works across the whole system of housing access, first by revealing and understanding the deeply systemic issues faced in our rural communities, and then by bringing together our stakeholder partners across all areas of influence who, through close collaboration, can begin to address these complex challenges.

The nature of Rural Studio’s housing work has evolved since its inception nearly 30 years ago. The designs of early client homes were specific to the families for which they were built and were often—out of budgetary necessity—composed of found, reused, or repurposed materials. Less focused on replicability or affordability, the homes were a recognition that good housing is not always affordable, but that people deserve it anyway. After years of designing these “custom” homes, the Studio began to question if the resources put into the projects could be utilized to effect greater change. Therefore, the Studio began a program of developing home prototypes, designed and constructed with replicability in mind. These prototypes serve as a growing library of spatial arrangements, assemblies and construction methods, and material palettes and details. Furthermore, the prototype development program introduced an iterative nature to the work. Home designs are built multiple times, to both refine the designs as well as introduce variations that allow greater flexibility (Fig. 1).



Figure 1: Example of a prototype home; this design—Joanne’s House—has been built over 5 times in multiple locations. Source: Auburn University Rural Studio

2. EXPANDING THE FEEDBACK LOOP

As an academic institution, the method and mission of Rural Studio involves the activities of teaching, research, and outreach. This provides us with a unique opportunity to engage with partners across local, regional, and national scales. The relationship between Rural Studio and our partners is one of reciprocal knowledge-building and information sharing.

The design-build nature of the work at Rural Studio creates a natural feedback loop; decisions are analyzed through the act of *building* those decisions. Inputs to the projects include design briefs based on observation of need, aggregated data, and experience gained from preceding student work. Inputs also come from community partner clients, for whom the homes are built. Prompts are both intrinsic and extrinsic. Intrinsically, Rural Studio needs a client with whom to work; this is crucial to fulfilling student learning outcomes. Extrinsically, many community members need access to better housing. Combining these needs, Rural Studio works in a “mutual aid” model; where students design, build, and ultimately provide houses to homeowners that under no circumstance could provide a home for themselves via more traditional means. In return, acting as real-life clients, the homeowners play an invaluable role in the students’ architectural education.

With the aim of extending the impact of the housing design and research produced by our students, through the Front Porch Initiative, Rural Studio offers housing products and technical assistance to external housing providers working to deliver homes in their own often under-resourced communities. The Front Porch Initiative takes the knowledge and products developed on the ground in West Alabama and shares them with housing providers so that they in turn can provide the same energy efficient, resilient, and healthy homes in their communities. This process further expands the feedback loop. The object of the house becomes a vessel, or a type of artifact, not only to understand how the design of the home can affect its performance, but also to explore how the procurement of that home affects land tenure and use, zoning, lending, insurance, and more. As Rural Studio’s academic program provides outreach to the local community, the Front Porch Initiative expands the field, developing alliances with regional housing providers and organizations in a wider national housing network (Fig. 2). These relationships are based on both application and implementation. And through this variety of partnerships, we examine the universal and the particular: which opportunities and challenges are relatable across varying geographies, and which elements are specific per location, community, client, and context.

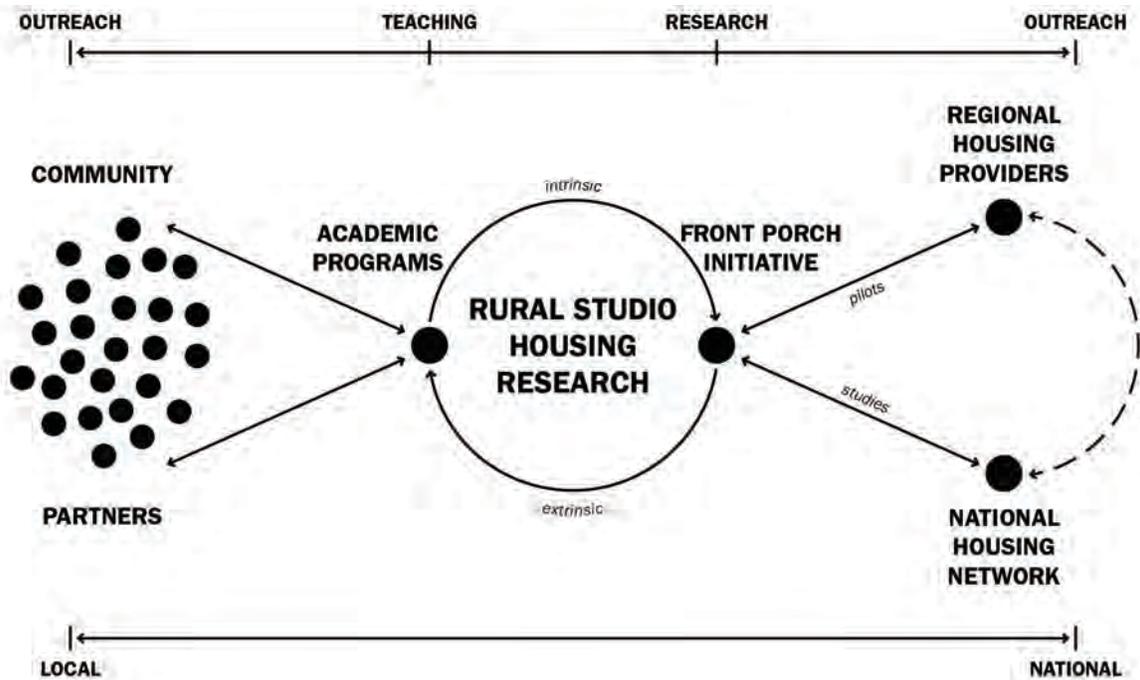


Figure 2: Diagram of housing research at Rural Studio. Source: Auburn University Rural Studio

This expanded field provides both frictions and opportunities. Prior to Front Porch Initiative, prompts for the academic program were localized – coming from within Rural Studio itself (intrinsic) or from the local community (extrinsic). When Front Porch Initiative first began, generally products were pushed from the academic side toward the broader field. However, as the work of the Initiative has grown, inputs and outputs have become increasingly bi-directional. Through Front Porch Initiative, extrinsic prompts can originate regionally, and sometimes even nationally. However, if undertaken by Rural Studio’s academic programs, those prompts must be deemed to both a) offer suitable learning objectives for the students and b) serve the needs of the local community.

2.1 Building as artifact

Today, the success of a contemporary building is most often determined primarily through its performance, durability, utility, responsiveness to site, context, social responsibility, and interconnectedness to larger, more complex networked ecologies, and in relationship to the process through which these issues are addressed. In other words, buildings gain validation through the recognition of the complex systems in which they are conceived, designed, and built. To qualify a building as “sustainable,” or “LEED Certified,” or “beyond code” is to express something about the “goodness” of the resultant artifact of the building, with little consideration of the resultant constructed object. In the work of Rural Studio this is equally true: it is essential that all projects be designed to be efficient, durable, weatherproof, secure, and buildable. But these are just the minimum of performance requirements. We also believe that successful proposals must perform as a system of aspirations as well. Buildings should directly express a sense of presence and dignity for the occupant, and they should intentionally foster a sense of community and engagement in their design. Buildings should also actively contribute to the health and well-being of those that build them, as well as those that inhabit them. Buildings should be accommodating to all, and no matter the circumstances in which they exist, they must be well crafted. Necessary to overcome the systemic inequities found in the communities we serve; it is perhaps these aspirational performance requirements that begin to blur the boundaries and distinctions between the artifact and object of a building.

2.2 Building as object

But because buildings ultimately exist in the world, they cannot help but be perceived as objects. As architects we have developed a formalized object-oriented language to describe buildings; we speak of elements that create form, form that defines space, and spaces that are ordered by principles, proportion, circulation, and scale. Because these descriptive ordering principles are so highly visual, they can easily subsume even the most basic performance considerations of efficiency, resilience, and constructability. However, we believe that buildings should look like what they do. And if they do that thing well, and that thing they do is good, then the building will be beautiful. In this way, aesthetics as a pursuit is a form of building performance in its own right. With this in mind, we are no longer faced with the false “Artifact/Object” binary and are instead armed with an architectural language by which we might analyze the form of the building through a more formal description of its utility.

3. PROJECT DESIGN

It should now be clear that the responsibilities of projects taken on by Rural Studio are exceedingly complex. In addition to negotiating the multivariate challenges found in systemically disinvested communities, the design of the project must simultaneously address the learning objectives of an accredited program of architecture, contribute to advancing the research agenda of the faculty and program, and must positively contribute to the needs of the community in which the work is situated. None of these concerns can take precedent over the other, but neither can any be left as simply a collateral outcome. Following are two case studies of projects that work to address all of these agendas.

3.1 Intrinsic prompt case study: Rosie’s home

Intrinsic design prompts are developed through local observations of need, demographic data, and research inquiries focused on materials, systems, or typologies. Finding a community client with needs that match a project’s design criteria is simple, as prompts are designed to address common issues. One example of a project prompted by an intrinsic inquiry is Rosie’s Home, which explores a new house typology—the Pole Barn House—to provide room to grow under one roof for families and changing needs and a way to rapidly build a sheltered work site.

Rural Studio projects are named for who they serve and what they are. We name the houses we build after their owner. Rosie’s Home is a phased project spanning four semesters. Each semester, a new group of students joins Rural Studio and inherits the last group’s work. The students are given a group design prompt for the portion of the project they are responsible for, and must respond to work that is already complete. Houses are designed collaboratively through many iterations of sharing, review, and consensus building, and it is the faculty’s responsibility to make sure the project is cohesive from one semester to the next. The nature of building a Pole Barn House is phased, so its delivery method matches with the academic calendar and the exploration of expansion through time.

Our clients are friends and neighbors, and their input is critical for project development. The multiple needs of a client hold our students accountable for their decisions and provide motivation to do the work. Serving clients provides a two-fold benefit: first, there is a shortage of affordable and decent housing in our community and few opportunities to build new or repair existing homes; second, our students need a project. The requirements are simple to qualify for a house: clients must need a house (their current house is bad repair or outlived its useful life), their property (or their family’s property) must be in close proximity to our campus, and their space

requirements must meet our abilities (one- and two-bedrooms are most common due to time constraints and skill level). There is no credit check to get started and no mortgage or lien after completion – houses are paid for through donations to the Studio. In return, clients agree to work with our students and faculty throughout the process of design and construction. They allow us into their homes, accommodate questions and interviews, and respond to design proposals; their patience is extraordinary. Most often our clients live on the same property as the house being built, so we see them every day and they become an endeared member of the team. As personal as the process is, the houses are prototypes not custom homes. This means the client's particular needs must match with intrinsic design prompt set forth.

Predictive expansion is an intrinsic prompt conceptualized to help us explore how houses may better respond to the needs of a changing family. Through years of working with community members, we learned that many of our client's original homes started small and were added onto as their families grew and needs changed. Where the additions were attached, shifting soils and inadequate foundations caused connections to fail, water leaked in and damaged the home. A big roof – like a pole barn – provides space as new rooms are added without having to worry about roof connections.

Pole barns are typically agricultural buildings used for storage and covered workspace. They are built from a kit or by a local contractor, often in a couple days. They have width requirements because of the span limitations of a truss but the length is endless, another bay can simply be added. The nature of their construction makes them research-worthy for several reasons: a) they can be built in a couple days giving quick cover for what follows (rapidly built), b) as more is built underneath the roof provides protection from weather (time-saving), and c) a large, inexpensive roof leaves extra space for rooms we cannot predict the homeowners will need in the future (it allows for expansion as it is necessary).

Rosie's Home is simple in plan—a 16'x48' rectangle under a 26'x48' pole barn roof—but lofty in section (Fig. 3). The pole barn roof sparked an exploration of the ceiling form that raised questions about the healthfulness of indoor environments. The overhead space is used for a variety of purposes: in the living and bedroom vaulted ceilings provide high ventilation and daylight and over the bathroom core additional conditioned storage is created. Along the front of the house two front doors lead to two different conditions, the living room and the utility room. Although they are only 12' apart, they give two options for future additions to be added under the 10' porch provided by the pole barn roof while leaving one front door.

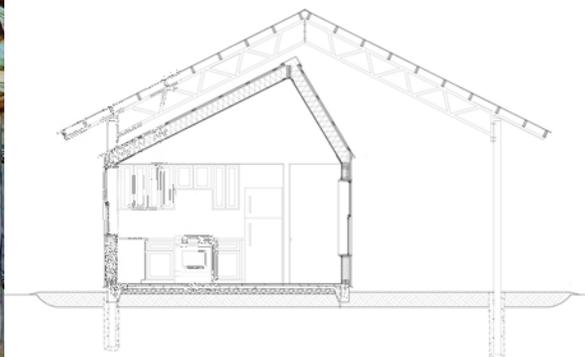


Figure 3. Room to grow is provided under the pole barn roof. Performance of the house is improved with the additional overhead space. Source: Auburn University Rural Studio

Responding to concerns found on the ground in Hale County, the Pole Barn House was initially conceived to have a rapidly constructed roof (to provide a more controlled environment in which to build) and a modular series of core enclosures that could be expanded and modified as a rural family grew into the home over time. But considering the object of the Pole Barn House, several of the Front Porch Initiative partners who are working to provide more affordable, high-performance housing alternatives in “high-hazard” areas quickly recognized a different use: that of disaster recovery replacement housing. While the overall form and delivery process of the Pole Barn House was an artifact defined by the particular needs of rural families living in intergenerational kinship networks, these partners quickly came to realize that the rapid construction of a roof coupled with prefabricated, thermally secure modules that were then expandable could meet the needs of rapid-recovery housing in disaster areas. In this scenario, the displacement of a family from their property (the single largest financial impact when disaster strikes) could be significantly decreased, federal recovery resources could be leveraged to fund the temporary stabilization provided by the installation of the primary core elements, and conventional funding could be utilized to expand the home into a more permanent, long-

term configuration. While the initial resultant form of the Pole Barn House was simply an artifact of the need for more adaptive, long-term, rural housing options, the resultant object lent itself to an unpredicted function as much-needed rapid recovery housing in a disaster scenario. We find the ability for the Pole Barn House prototype to transcend the intrinsic and extrinsic prompts, as well as to act as both artifact and object simultaneously, to be a fundamental measure of the “goodness” of the proposal.

3.2 Extrinsic Prompt Case Study: 18x18 House

The feedback loop offers the applied research and learning generated by student teams out to external partners in the form of housing products and technical assistance, yielding an influx of feedback from external partners in response to their implementation of that technical assistance. In some instances, partners respond back with acute needs identified in their communities.

One extrinsic prompt for a Rural Studio project originated with a Front Porch Initiative partner sharing such a need; this partner was eager to increase housing inventory but stymied by lack of available land. Offered a small parcel of buildable property, the affordable housing developer approached Rural Studio to ask whether housing units could be designed for an 18' x 18' footprint. This dimensional constraint comes from the size of two parking spaces, as some cities are negotiating with developers to reduce parking requirements in exchange for housing units that are affordable.

The partner's request prompted Rural Studio to consider the utility of a small-footprint house in rural areas that might better address limited buildable space. While land may be abundant in some rural areas, many rural properties often have obstacles such as standing ground water, septic fields, power lines, or abandoned structures that can drastically reduce the buildable footprint. A small-footprint house can be built on family properties that may not have usable space for a larger home. The 18x18 House might provide extra space for a growing family or can maintain the kinship network in situations where space may not exist for additions or new construction.

This extrinsic prompt enabled Rural Studio to respond to both urban and rural needs while offering the students challenging learning objectives. Moreover, the constraint of a maximum footprint proved stimulating for the student team; faced with this constraint, their investigations quickly sharpened around the possibilities inherent within this spatial constraint. While the first iteration will be built for a local client on rural family land, students remain aware of the additional urban context for which the project is intended and consider both settings when making decisions (Fig. 4).

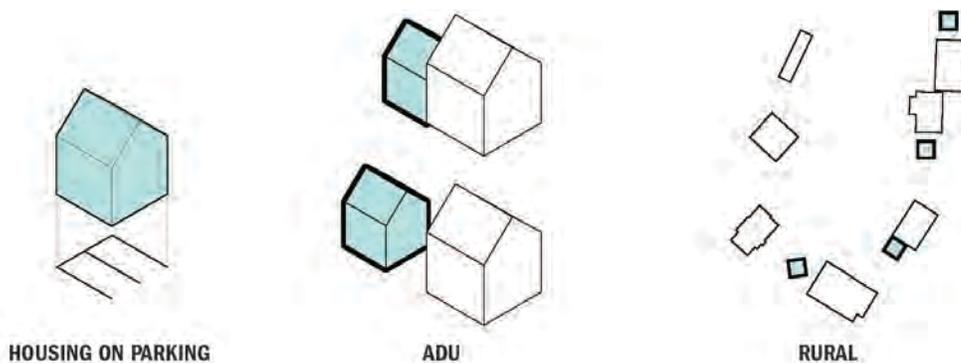


Figure 4. Multiple contexts for 18x18 House prototype include housing in lieu of parking, detached or attached dwelling units (ADU) common in urban areas or scattered detached housing typical of rural areas. Source: Auburn University Rural Studio

The goal of maximizing interior living space led to a multi-story prototype, with a stair as a design opportunity bridging living and sleeping areas. Consideration of a potential need for accessibility prompted study of sleeping and toilet facilities on the ground floor, with living spaces able to capitalize on higher ceilings of the upper floor; this exercise led to consideration of the quality of each space when inverted. Mindful of both rural and urban site settings, the students ultimately evaluated schematic proposals on dignity of space, efficiency, adaptability, and ability to aggregate (Fig. 5).

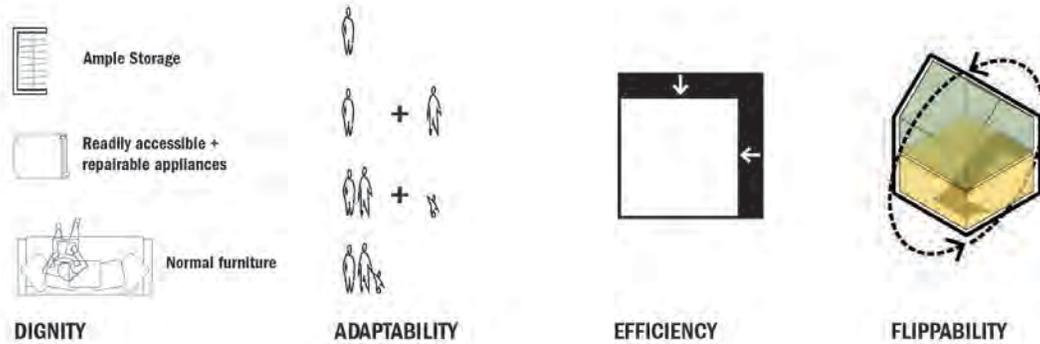


Figure 5. Four criteria developed by student team for evaluating design proposals. Source: Auburn University Rural Studio.

The 18x18 House aims to fulfill the need for a small, adaptable, multistory house in both urban and rural settings. For rural sites with limited buildable area, the small-footprint prototype offers an alternative to manufactured housing. In the case of rural family-owned land, it allows flexibility for housing multiple households on the same parcel. In an urban context, the ability to create housing either as an ADU (accessory dwelling unit) or housing units in place of parking spaces adds housing inventory by increasing density. In the case of the 18x18 House, the initial form (object) of the house was simply the artifact of an urban condition. But when considered in a rural context, the urban object quickly revealed a rural need that was invisible even to us, leading us to better understand the need for a new rural prototype house that could be more responsive to small-parcel land holdings. It is in this way that the feedback loop becomes particularly adroit at negotiating the building as object, building as artifact dichotomy.

4. CONCLUSIONS

The authors of this paper do not pretend that the observations made in this paper are particularly novel, or even new. Over time we have simply come to better articulate the primary attributes of Architecture that make a building “good.” Of course, these attributes were first recognized by Vitruvius over two millennia ago as *Firmitas*, *Utilitas*, and *Venustas*, (strength, usefulness, and beauty). In the 17th century, architect and philosopher Sir Henry Wotton recognized that the forms of architecture in Vitruvius’ time were rather limited materials and construction methods, and therefore the notion of architectural principles of “Beauty” were bound by formal aesthetic constraints. In “The Elements of Architecture” (and amplified in the 20th century by Robert Venturi and Denise Scott Brown in “Learning from Las Vegas”) Wotton expands our understanding of *Venustas* by reframing it as “Delight,” which refers to the cognitive associations a “good” building must intentionally provide, or more simply, its “meaning.” This reframing is important, as it allows us to move beyond formal, object-oriented aesthetics, and to consider these cognitive associations more broadly through the same pragmatic, scientific lens as we do the evaluative criteria of strength and usefulness when determining whether a building is “good” or not. While today we seldom think of the primary attributes of Architecture through this tripartite framework, we do consider that buildings have the responsibility to be efficient and to perform well (*Firmitas*), to steward the environment (*Utilitas*), and to be socially impactful and relevant (*Venustas*). Considered in this way, we find that Vitruvius’ notion that “...Architecture is composed of two things: the manual work and the reasoning behind it,” resonates perhaps more today than ever before. Just as in Vitruvius’ day, the three responsibilities of a) building performance, b) environmental stewardship, and c) social relevance act in synthesis with one another and cannot be taken to pieces. Moreover, in the introduction to *The Architecture of Humanism*, author Geoffrey Scott argues that these three “purposes” are separate and distinct, but converge—or are synthesized—through the act of making Architecture. He states, “They are blended in a single method; they are fulfilled in a single result; yet in their own nature, they are distinguished from each other by a deep and permanent disparity.” In this way, architecture is in a way simply the side effect (artifact) of the act of reconciling the seemingly disparate responsibilities of performance, stewardship, and meaning in built form (object).

So, clearly the design of a “good” building is a complex challenge. But as educators, we have learned that the *design of the design* of a good building is perhaps even more so. We clearly understand that the purpose of utilizing the design-build method in architectural education is a way to leverage the knowledge gained in the classroom and, through direct experience, transfer that knowledge to know-how. But what is sometimes less clear is the knowledge concerning what, and the know-how to do what, and why, and for whom? It is only through the live experience of designing-to-build that this friction generated by the contingent and often conflicting purposes of building performance, environmental stewardship, and social relevance ultimately become visible, and must be synthetically resolved as both an artifact of this struggle as well as an object to be built in its own right. By coupling project prompts around both the intrinsic requirements of educating

knowledgeable, well-prepared architects with the extrinsic needs of our clients and communities, students must grapple with the pragmatic concerns of thermodynamics, building control layers, and constructability, while simultaneously considering the impact of housing programs and policies, and their aspirations for long-term positive impact in the communities we serve. Through this reconciliation, our buildings do look like what they do; form does indeed follow, or become an artifact, of function. But when coupled with the feedback loop provided by working with housing partners well beyond the service area of Rural Studio, and in radically different contexts from what we find on the ground in Hale County, do the linkages between these three disparate purposes truly become clear. For when we apply new intrinsic and extrinsic prompts to the object of our buildings, we often find that even more useful functions might follow form.

ACKNOWLEDGEMENTS

The authors would like to acknowledge all current and former Rural Studio students for their contributions to Rural Studio's portfolio of work, on which this paper is built. We would also like to thank our colleagues: Andrew Freear, Steve Long, John Marusich, Judith Seaman, Christian Ayala, Dick Hudgens, Natalie Butts-Ball, Brenda Wilkerson, Dudley Long, Mason Hinton, Eric Ball, Catherine Tabb, Doris Ward, and Melissa Foster Denney, as well as former Rural Studio faculty and staff. We would like to thank Rural Studio's supporters and research partners. Most importantly, we would like to thank our clients and field test partners without whose patience and willingness, this work would not be possible.

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Living Surfaces: Defying Walls

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ABSTRACT: *The potential to program the Wall as a Living Surface, addressing the needs and demands of its users to respond to the current context for a better quality of life, can provide benefits in many aspects. By reinterpreting the questions using three critical frameworks: social, cultural, and physical, one can deconstruct the Wall as a provocation: Can a wall act as a building element and an element of play: interactive social exchange? Can new tools and technology provide alternate tactics? How can we encapsulate resilience using low-cost modular approaches incorporating human-centered design strategies?*

Many small-scale creative efforts to foster tangible urban change, inspired by the Tactical Urbanism¹ movement, have succeeded. Cities today have become experimental grounds to test ideas using inexpensive short-term tactics as playful provocations that generate social interactions and promote critical discourse. Within this realm, design-build pedagogy in the classroom is an opportunity for students for meaningful social engagement and community building, thus expanding the role of education as a participatory practice-based design research and fabrication lab.

This paper offers evidence-based outcomes as students in Tactical Urbanism class at Kennesaw State University explored ways to redefine and reconstitute the typology of Walls as a Living Surface with new programmatic opportunities defying the traditional notion of Walls separating public and private realms. Responding to the needs of Math Club's desire for a Book Nook that also creates a boundary of sorts in the outdoor greens, students explored how a Wall can act as a Living Surface, an assemblage for various functions: seating, pop-up library, and collaborative spaces.

*The course follows a rigorous process to achieve outcomes that can stand up to public scrutiny for a product ready for on-site installation and real-time testing by citizen-users in a public space as a testament to the project's efficacy. Teachings that engage real-life matters of grave importance allow upper-level students to practice design and making skills in the service of citizen-users within the urban realm. Pedagogically, design-build is an excellent alternative method to give students real-life experience of project scope from conception to designing to prototyping: testing scalar mock-ups to actual fabrication and deployment, whereby the students' engagement with materials, tectonics, and tools and techniques gives them design feedback that is critical to the creative process as attested by Richard Sennett in the book *The Craftsman*.*

KEYWORDS: Walls, Living Surfaces, Tactical Urbanism, Architectural Installation, Design-Build

INTRODUCTION

Architecture is the physical form which envelops people's lives in all the complexity of their relations with their environment.²

Inspired by the work of Rem Koolhaas in *Elements of Architecture*³, this proposal aims to reconstitute the typology of *Walls as a Living Surface* addressing the needs and demands of its users by reinterpreting the questions to respond to the current context for a better quality of life using three critical frameworks: social, cultural, and economic platforms. Can a wall act as a building element and an element of play: interactive social exchange and a surface to grow food? Can new tools and technology provide alternate tactics? How can we encapsulate resilience using low-cost modular approaches incorporating human-centered design strategies?

Building upon recent research explorations, the Tactical Urbanism class⁴ explored various ways to program the 'Wall as a Living Surface' that can provide benefits in different aspects. It can be a system of a series of rotating panels as an assemblage that provides many interactions, such as a screen to bring in light, as a threshold to open/close a living room, or as an interactive device for social exchange: library or book nook for cooperative interactions. It can be suitable for vertical gardens offering the user group opportunity to generate income, which is essential for economic independence. It can also function as a space filled with light, color, and sound where all senses are invigorated, providing hope, resilience, rejuvenation, and a safe zone for its users.



Figure 1: Wall as Vertical Garden | Tactical Urbanism 2019

1. DESIGN PROCESS

The Tactical Urbanism 20225 project scope is in response to KSU Math Club's desire for a pop-up library to showcase math books - to allure students to interact with the subject without being intimidated or overwhelmed. To begin the process: students were challenged to think beyond the traditional notion of the Wall - to redefine its construct as a multi-faceted assemblage to respond to user needs. Traditionally, Walls act as boundaries/dividers/thresholds – physically separating public and private realms. Within this most simplistic definition of a wall, how do we, as architects and design students, begin to explore and challenge the Wall to hold an array of experiences through diverse functions?

1.1 Exploring vertical surface

The leap from theoretical drawings and models to represent architecture within a design process leads to a disconnect between the notion of constructability in making things. The nature of the class translating conceptual ideas to real-life assemblage necessitated students to work in teams to develop initial ideas. The class prompt for the first exercise was to interrogate the 'Walls as Vertical Surfaces' that can hold functions while creating a boundary of sorts.

Precedent Study | Each team had to find three innovative precedents of Walls similar in scale and program to learn how their form, materiality, and construction work as a temporary structure within the public space. For the exercise, selected precedents were: Serpentine Wall⁶, Serpentine Summer House⁷, BookWorm Pavilion⁸, and Story Pod⁹.



Serpentine Wall Serpentine Summer House Bookworm Pavilion Story Pod
Figure 2: Precedent Study

1.2 Design exploration | artifact

The design brief called for a temporary modular wall to be deployable with programmatic outcomes: i) a climate-controlled bookshelf to hold 20-25 books, ii) seating, and iii) interactive study areas. Drawing inspiration from the precedents listed above, they were then to represent their findings using creative representational tactics to start the conversation - as an 8" x 8" wall sectional artifact that illustrated their definition of the Wall as a component-based kinetic modular system that adapts and functions on multiple levels. The exercise of scaled physical model-making challenges students to develop conceptual ideas to develop scalar models as testing several different design iterations. The following narrative outlines the process and highlights how the project moves beyond representational artifacts to constructability, engaging form, and materiality as an iterative tool to make critical decisions as assemblies, details, and systems are formalized in the act of making a feedback loop.

The class was divided into two groups to begin the process, where each group communicated their initial design concepts by creating 1'=1/16" or 1'=1/8" models. As the design developed, the feasibility of the proposals was tested through a change in scale. The next step was to produce 1"=1'-0" models to test modularity, assemblage, ergonomics, and ease of construction. The first team proposed 'The Summit,' a design that used a waffle structure strategy for the building. The ribs run in horizontal and vertical directions for the design's structural integrity. The intent was to use the space between the ribs to filter light through the structure and storage for the books. Through this tectonic strategy, the team created an organic shape that responded to the site by weaving the form through the foliage. The initial 1/16" inch models were used to test the waffle strategy and design its massing. This model failed to answer the dimensions of the horizontal and vertical layers to place books and comfortable seating. It also questioned the constructability; in the following iterations, it was tested through modularity and scale of the design in terms of fabrication materials/equipment

constraints. The change in scale 1'=1"-0" in the following study models allowed a closer observation of fabrication tactics and material takeoffs. The design was more intentional regarding dimensions and how it would respond to the human body.



Figure 3: Group 2 | Waffle Nook

Another team, using the Fibonacci spiral as a formal language, discovers through experimentation of scale that this particular design iteration, expressing verticality through its material makeup, needs to be revised for constructability. By fabricating a segment of the overall design in a scaled manner, several questions arise about joinery, material selection, ergonomics, and budget. Gathering the feedback from the results, each team refines its designs at a larger scale. The group using the Fibonacci spiral as a concept shifts the verticality-based design language to a horizontal arrangement through the representation of stacking. This configuration is analyzed by extending the scale upward and expanding the model's focus to experiment with connections and form. By scaling the physical models' representational focus, solutions to the questions at hand begin to arise in an apparent resolution that aligns with the program requirements. The students found that the proportions of the storage units for the math books were successful ergonomically for a broad range of users. Another successful takeaway is that the horizontal configuration was found to be more aesthetically pleasing to the eye for the occupants as a play in the scalar distribution of the material in the z-axis affects the overall appearance of the structure. Other takeaways in the feedback loop hinted towards the need for another series of scalar testing's, such as construction practicality and segmentations through modularity, which ties back to the program requirement of transportability.

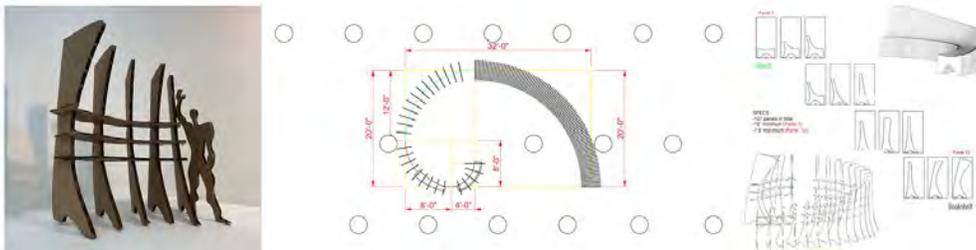


Figure 4: Group 1 | Fibonacci Nook

The jury consisted of an experienced design-build professor¹⁰, a structural engineer¹¹, and a community engagement manager¹² engaged in public space activation projects. Having her as part of the jury gave students a real-life perspective on how temporary and modular small-scale projects have excellent prospects for activating public space. After much deliberation, the jury selected the Fibonacci Book Nook to move forward based on its conceptual integrity and design-build strategy, i.e., construction, deployment, transport logistics and budget.

1.3 Final design development

After selecting the Fibonacci Nook design, the class came together to undergo another iteration in which they combined the strengths of both proposals to move forward. The Fibonacci Nook had a more robust concept and ease of assembly than The Summit project. The Fibonacci Nooks modular system can be broken down into segments for custom arrangement and offer a simple construction and transportation process. The ergonomic components used on The Summit Project were incorporated into the Fibonacci Nook. The idea was to integrate seating and storage as components of a wall system at varying heights to generate a form that fulfills functional requirements as desired. The design concept is a mathematical sequence derived from the proportions of the Summation Sequence, better known as the Fibonacci sequence, connecting it to the mathematics building. Its growth ratios can be found in nature, especially on the site. The pine trees on the site express this sequence of growth directly.

The conceptual design was reinforced using a stacking strategy as horizontal profiles of wood with spacers accommodated structural and programmatic requirements: seating, interactive spaces, and books. The grasshopper script derived the final form as a topographical gesture slowly rising from the landscape into a wall with rectangular openings to create a sense of porosity and functionally hold books. These openings are

lined with acrylic panels to protect books from elements and security. Material, transportation, joinery, human comfort, and more decisions occurred during workshops. The class regrouped into three teams to refine the final design into a feasible design-build project. After the groups teamed up to answer the programmatic requirements and fabrication, they created a 1'=1' scale model to refine testing and finalize the design.

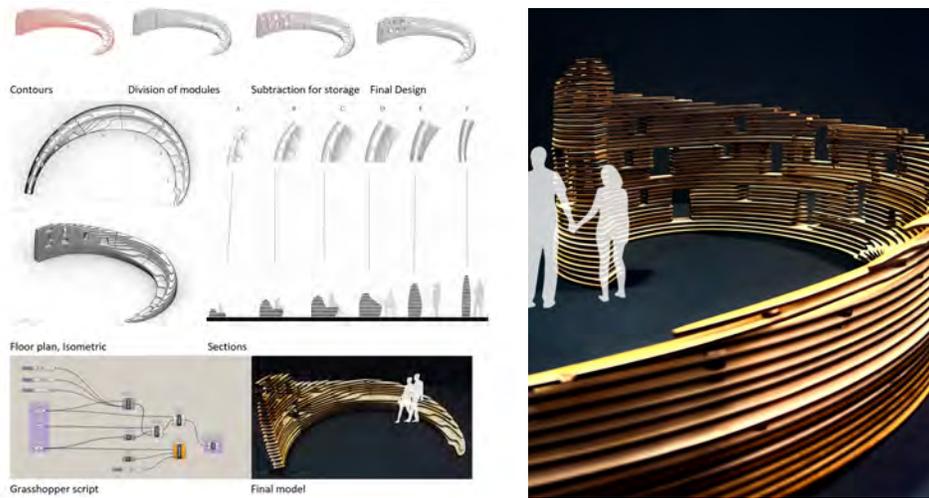


Figure 5: Final Design Development | Fibonacci Nook

1.4 Mockup and testing

Strategically the Fibonacci curve was divided into five modules, with a specific number of wood profiles stacked. This approach aided in transportation and the constraints of the lab equipment. Students collaborated for the remainder of the semester, working out design details such as tectonics, material selection, ergonomics, fabrication schedule, and budget limits. Volunteers were recruited from NOMAS and KSU Math Club.

A full-scale mockup tested the design's efficacy: joinery, structural integrity, ergonomics, assembly, finishes, and transportation logistics. Students used the mockup to test the strength of the structure from shearing or breaking. For the mockup, students employed square spacers for stacking the wood profiles as a system with 1/4" rods to align the shapes precisely to each other. From the initial test; they discovered that the 1/4" rods were too thin during assembly and decided to use 3/4" rods for the final installation. During this process, the class switched from square to round spacers. Friction would move the square spacers, and they would lose their alignment. The feedback loop proved fine-tuned fabrication details, as attested by Sennet. Another lesson from this scaled mock-up was the transportation of the modules. Each layer consists of 3/4" inch-thick plywood sheets; the weight made transporting them difficult after stacking them. Therefore, the shop drawings for the bottom sheets had square cutouts that would lighten the sheet's load without compromising the module's structural integrity. Now the project was ready to move into its final phase.



Figure 6: Mock-up and Testing | Fibonacci Nook

1.5 Fabrication and assembly

Project management and schedule creation became the top priority as students organized themselves as an atelier, each playing a pivotal role. Each student was given a specific task based on their interest, from purchasing materials to coordinating with the woodshop for the fabrication schedule, preparing shop drawings, CNC loading-unloading, cutting tabs and spacers, route edges, sanding, drilling, prepping, painting, and

assembling. Students performed multiple tasks to keep to the timeline; each work stream was recorded on the lean board so that each member could independently pick up jobs left off by others – thus giving autonomy to the process for efficiency.

The organization was the key to the design-build aspect of such a project. Meticulously, all profiles were numbered during CNC fabrication and organized as woodshop modules. Once the module was cut and sanded, it went to the paint station and was finally stained and waterproofed before it was ready for assembly.



Figure 7: Process | Fibonacci Nook

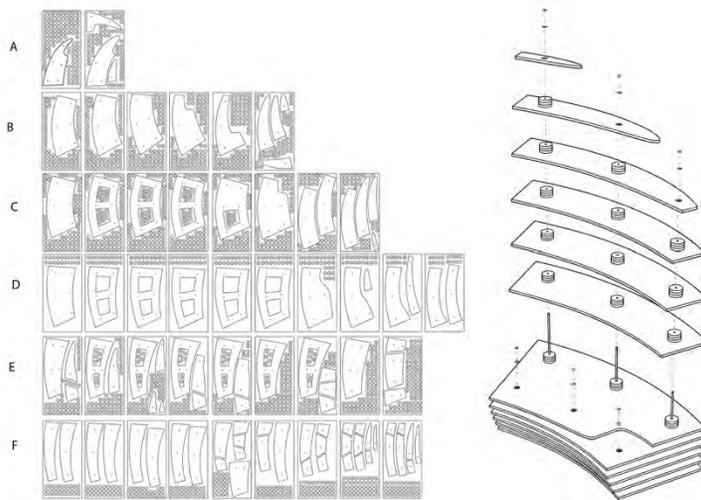


Figure 8: Shop and Assembly drawings

A design-build class of this nature expects commitment from students, and this was achieved through teamwork with upper-level thesis students leading the efforts. A test installation was deployed inside the architecture building due to weather constraints. It was a soft opening with the Math club, architecture students, faculty, and other guests enjoying the installation over good food, great conversations, and social exchange. In the final analysis, the Wall did prove the thesis it set out to prove: the Wall as a multi-faceted construct: a boundary, seating, library, conversational areas, and more.

CONCLUSION

Design can improve the quality of life of their users' needs and demands by reinterpreting the questions to respond to the current context. Challenging the basic assumption of in-town shelter as an alternative housing option for young adults and baby boomers - students in this course interrogate the basic assumption of housing typology by dissecting its elements as individual fragments: walls, floors, ceilings, and roofs through multiple filters. Through case studies and analysis, they strive to offer new meaning to age-old issues of building design, construction, and materiality by exploring innovative directions for an architectural outcome rooted in history and theory but employing contemporary strategies related to the modular design, materiality, construction

tools and techniques, programming, accessibility, smart technology, and sustainable practices that have a direct impact on users.

Evidence-based research of design ideas and strategies, when tested on a small-scale as tactical urbanism projects, have the power to be scaled up for various applications, including shelter, engaging social, cultural, and physical needs of its users for equity and resilience. Pedagogically, the design-build is an opportunity to prototype real-life projects engaging tools and techniques by looking at materiality and fabrication processes through environmental and sustainable metrics. In the words of Richard Sennett, "Making is thinking ... an enduring, basic human impulse, the desire to do a job well for its own sake." The final construct of the Walls as Living Surfaces as a design-build installation is a testimony to the design process as digital and analog methods work in tandem to move the project forward beyond representational artifacts – as a full-scale installation ready for deployment in the public space. These design-build projects catapult students' interest as independent research projects beyond the scope of the class that generates a life of their own beyond the classroom. These projects allow students to develop research as competitions and conference papers as they leap into the profession or pursue graduate work.



Figure 9: Opening Night Installation (Soft Opening)



Walls | Boundary

Walls | Programmatic Elements

Figure 10: Evidence Based Research - Walls as Living Surfaces | Defying Walls

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END NOTES

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2. Jean Renaudie
3. Koolhaas, R. 2018, *Elements of Architecture*. Taschen
4. Tactical Urbanism Class | 2019
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6. BIG – Bjarke Ingels Group; *Serpentine Wall*; 2009
7. Khan, Asif; *Serpentine Summer House*, 2016
8. Nudes, *BookWorm Pavilion*, 2019
9. Atelier Kastelic Buffey, *Story Pod*, 2015
10. Welty, C. Architect –Professor.
11. Loreto, G. Structural Engineer. Associate Professor
12. Sharp, A. Community Engagement Manager. Liveable Buckhead Inc.



POSTERS

The Unknowing of the Outcome

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The unknowing of the outcome

Exploration of components and structural form in architecture foundations studios

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ABSTRACT

The design studio - where ideas are formed and tested through making - is at the core of architectural education. The design process is an iterative process where ideas are constantly growing in complexity and refinement. Existing literature emphasizes the importance of hands-on full-scale fabrication projects in early architecture education. This paper explores studio pedagogy through a team-based temporary design-build project which introduces material reuse and the exploration of components and material assemblies in the foundation architecture studios. In this project, students were introduced to concepts of 3D structural components / units and surface assembly at the "Component" Scale. They then aggregated these to generate architectural forms / space at the "Spatial" Scale. The goals were to develop a "pop-up" pavilion which: 1. Explores structural forms by addressing gravity and lateral loads, and 2. Provides for human interaction and experience. After gathering salvaged cardboard to use as their primary construction material, student teams designed and built their pavilions to explore three-dimensional geometries and transitions. The goals were to: 1. Generate surface assembly and treatment at the Component level to understand how this influenced human scale, and 2. Create different atmospheric conditions of light and movement at the Spatial level.

Students started the design process by individually developing MANY 3D components / units. As a team they then engaged in an iterative process of elimination and refinement by discovering assembly methods via investigations of the material and iterations of possible aggregations, and eventually settling on one component / unit system. Student teams designed the assembly / disassembly of Components to address constraints of the materials and joinery. 1. No glue was allowed, only friction-fit joints and mechanical fasteners. 2. The teams were required to design their assemblies so the Pavilions could be set up within 15 minutes. At the Spatial level, the teams explored ideas of human interaction and movement through and around the space. Two tensions were important sources of learning in this project. First, the tension between the "bottom-up" and "top-down" design strategies was an important source of design ideation. Second, this was the students' first team project. Skillful navigation of team goals and methods were necessary to achieve design consensus, which provided an important lesson for not just their future education, but for their careers in the inherently team-based practice of architecture. This presentation discusses how this studio pedagogy embraced transformative ideas and critical reflection to formulate design proposals incorporating the 'unknowing' of the outcome - starting the design process from the Component level and generating an architectural form and Spatial conditions through the aggregation of components / units. Finally, this paper aims to inform future teaching research and pedagogy in architecture studios at the foundation level by providing a record of a successful process.



Fig. 1. Work on component unit prior to assembly. Design by S. Lopez Barrera, D. McLemore, and J. Ross.



Fig. 2. Aggregated component unit generating a surface. Design by A. Ghosh, J. Aronson, A. Thompson, and K. Saito.



Fig. 3. Aggregated component unit generating a surface. Design by S. Lopez Barrera, D. McLemore, C. Roberts, and B. Sauer.



Fig. 4. Transportation of pop-up pavilion. Design by S. Lopez Barrera, D. McLemore, C. Roberts, and A. Ghosh.

DESIGN PROCESS: CONSTRAINTS, MATERIALS, AND ASSEMBLY

At the beginning of this project students gathered salvaged cardboard to use as their primary construction material and started their design process by identifying architectural geometric patterns and structures from different buildings around campus. Once they selected a space with a geometric pattern and structure, they found compelling, students were asked to describe its materials, spatial conditions, the visual experience it generated. Based on this study of architectural geometric patterns, students created a series of small three-dimensional physical mock-up models and explored a series of different types of joints using cardboard. An important constraint for the joinery was that no glue was allowed. Students focused their joinery investigations on friction-fit joints and the use of mechanical fasteners. Materials allowed for mechanical fasteners included zip ties, natural jute, cotton, and sisal twine; tape is only allowed for early "research" versions but not in the final version.

After the initial explorations of architectural geometric patterns and joinery, students were grouped in teams of four or five students to design and fabricate their pavilions exploring three-dimensional geometries and transitions. As the teams developed their designs, they considered the following questions:

- 1. Micro/Component Level: architectural patterns and 3D geometries**
 What geometrical potential do you see from your study of patterns? Does it include geometrical transitions, structure vs. surface assembly, folding joints, voids vs. surface treatment, or volumetric elements? How do you extend/transform/imagine these patterns for your architectural purpose or goals?
- 2. More to Macro Transition: from 3D geometries to Surface and Structure**
 How do you aggregate or combine components? What forms/spaces does it generate when combined? Are there multiple ways of combining components? How do the aggregated structural forms address gravity and lateral loads?
- 3. Macro/Spatial Level: Architectural Purpose and Experience**
 What does your architecture respond to?
 Human Occupation - how does it deal with human scale, movement, human limb extensions, and the overall perspective from different sides as you move through and around the space?
 Atmospherics (Ex. Light or Air) - with what force are you dealing with? How do you harness or channel that force and for what purpose? At what scale are you dealing with this force - texture, micro (component), or macro (spatial or pavilion) scale?
 Others (Ex. Human Force or interaction) - what force are you dealing with? How is it transferred to your structure through vectors? What effects does this force have on your pavilion - what is it changing from, or changing to?

A key aspect of this project is the development of a consistent assembly system that is portable and could be set up within 15 minutes. During the design process students considered the how they would transport their pavilion components and assembly process within the timeframe, they considered the human labor involved (combining, attaching, or other), and geometrical mechanisms or actions (folding, telescoping, or other) that could facilitate the assembly process.



Fig. 5. Aggregated component unit generating a surface. Photo by Wayne Dean. Design by S. Lopez Barrera, D. McLemore, C. Roberts, and J. Ross.



Fig. 6. Work on component unit prior to assembly. Photo by Wayne Dean. Design by S. Lopez Barrera, D. McLemore, C. Roberts, and J. Ross.



Fig. 7. Work on component unit prior to assembly. Photo by Wayne Dean. Design by S. Lopez Barrera, D. McLemore, C. Roberts, and J. Ross.



Fig. 8. Work on component unit prior to assembly. Photo by Wayne Dean. Design by S. Lopez Barrera, D. McLemore, C. Roberts, and J. Ross.

COLLABORATION: TEAM-BASED LEARNING

This studio project used team-based learning (TBL) methodology. As a first-year studio project, this offered the unique opportunity to introduce the idea of collaboration in architecture and design, working with others to conceive, develop, produce design artifacts, and design-build structures. Throughout this project, students were accountable for their own work, as well as their work as part of a team. Evaluations were based on both individual and teamwork. Team-based learning cultivated an environment of mutual respect and collaboration among team members and classmates. Peer assessment is an integral component of team-based learning methodology. At the end of the project, each student in the class was asked to assess the performance of their team members. This assessment was figured into individual final grades.

CONCLUSION

Students "pop-up" pavilions were implemented successfully and were able to withstand for an extended period without exhibiting any major structural failures. At the Spatial level, all the pavilions exhibited complex applications of three-dimensional geometries to achieve self-standing structures and at the same time they enhanced human interaction and movement through and around the space. As the first collaborative project in their architectural education, throughout this project, students learn to navigate the tensions between "bottom-up" and "top-down" design strategies and to collaborate with others to design, fabricate, and implement their pavilion ideas. This team-based project offered the opportunity to create an awareness about the importance of collaboration in architecture and design professions where students learn about conception and consensus building in the design process decision-making. This project challenged students' design ideas and encouraged them to critically reflect and evaluate their design proposals embracing the 'unknowing' of the outcome, where the final pavilion form is the result of the aggregation of three-dimensional components at the micro level. The pedagogy implemented in this project provides a record of a successful learning process that can inform future teaching research and pedagogy in architecture studios at the foundation level.

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Integrating Performance Thinking and Sustainability Knowledge in Architecture Pedagogy

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Integrating Performance Thinking and Sustainability Knowledge in Architecture Pedagogy

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BACKGROUND

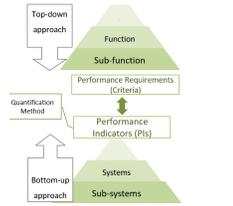
Integrating sustainability knowledge and performance-based thinking into architecture education is a challenging task and studies have suggested a lack of practical framework how sustainability knowledge should be taught theoretically and practically to design and deliver sustainable, resource-efficient buildings. Integrated performance-based design education involves several modules. Students should learn: 1) sustainable design methods and get familiar with implementation of these methods into design, 2) modelling building with different passive and low-energy design strategies to be able to quantify their performance, and 3) performance-based design theory, including how to define performance objectives and measures.

This poster gives an account of three graduate courses related to sustainable high-performance building design and modeling. These courses include Performance-based Design, Building Information Modelling using Autodesk Revit, and Sustainable Design Methods. It discusses course objectives, contents taught, teaching methods, assessment strategies, learning outcomes, and lessons learned.

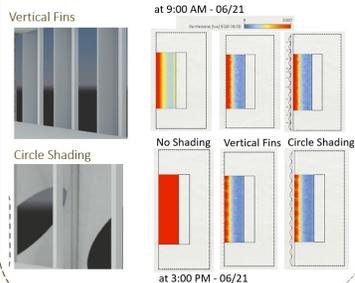
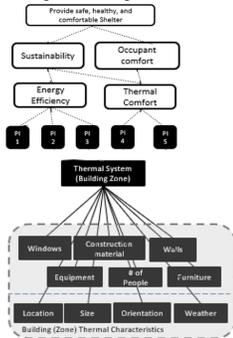
Performance-based Design

Upon completion of the course, students have:

- an understanding performance-based design and an ability to assess building performance in terms of energy consumption, occupant comfort, and environmental factors.
- an understanding of different design methods, such as proper treatment of different building orientations, selection of window-to-wall ratio, shading elements, and daylighting.
- capability to use computer modeling and simulation tools for comparative analysis of different design alternatives.



Students designed and compared performance of two types of shading devices using the framework above.



Building Information Modeling

Topics	
Revit Interface	Visualization and Rendering
Walls, Curtain Walls, and Windows	Details and Annotations Workflow
Floors, Roofs, and Ceilings	Schedules Cons Documentation
Stairs, Ramps, and Railings	Drawing Sets Site Modeling
Adding Families - Modifying Families	Mechanical System
Massing Model In-Place	Structural System
Schematic Design and Rooms	Energy Analysis, Shading Study, Daylight Analysis
& Color Fill Plans	

In this course, I experimented with **innovative teaching strategies** (e.g., open educational resource and gamified flipped classroom) and assessed impact on students learning and performance.

CONTENT DEVELOPMENT	DATA COLLECTION	STATISTICAL ANALYSIS
Prepare BIM Lessons and Instructions	Experiment Design	Hypothesis Testing (t-test)
Prepare Educational Videos with Subtitles and Closed Captioning	Course without intervention	Analysis of Variance (ANOVA)
Develop Games and Integrate them with flipped classrooms	Course with innovative teaching	
Create a Web-based Educational Platform	Variables	Analysis of Covariance (ANCOVA)
	Independent Variables: GPA, Major, Family background	
	Dependent Variables: Overall Grade, Project Grade	
	Field Experience (OER) background, Effort level	

The ANOVAs help determine whether the availability of the open educational resource is the primary reason behind the improvements.

ANCOVA was used to examine the main and interaction effects of the open educational resource and the independent variables (e.g., GPA). The ANCOVAs help determine whether the availability of the OER is the primary reason behind the improvements.

Results

T-test results for the project and overall grades

	Project Grade	Overall Grade
OER	83.9	92.4
Without OER	79.6	92.0
Difference	4.3	2.4
p-value (one-tailed)	0.032	0.028

Note: level of significance (α) = 0.05; OER = Open Education Resources

The t-test results show that the average grades of students who had access to the open educational resource were higher than those students who did not.

Conclusion of innovative teaching impact

The average overall and project grades of students were improved by offering the open educational resource. These improvements were statistically significant. The results of ANOVA and ANCOVA tests show that the open educational resource was a significant factor in improving average overall and project grades even after considering the effects of the control variables (i.e., GPA, major, employment status, family background, field experience, effort level, and past BIM experience).

Sustainable Design Methods

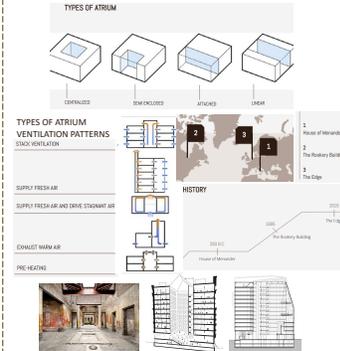
Topics	
Energy Sources	Shading Design
Thermal Energy Basics	Passive Cooling
Thermal Envelope	Lighting, Basics of Light
Thermal Comfort	Daylighting
Climate	Electric Lighting
Solar Geometry	Mechanical System
Passive Solar	Climate-based Design (Case Studies)



Upon completion of the course, students have:

- an understanding of energy consumption in buildings and the importance of considering energy issues in architectural design,
- an understanding of building sustainability and sustainable design methods,
- an ability to use architectural approaches and methods to design sustainable buildings,
- an understanding of climate and capability to use climate-based design methods,
- an understanding of the impact of recent energy code legislation on building design.

Atriums through time (student project)



Students select two to three buildings with a sustainable design strategy (e.g., atrium) or integrative climate-based design approaches over time and across climate zones and compare their design and performance. They are not expected to model these buildings but they should do a literature review and draw conclusions based on results found in existing body of knowledge.

LESSONS LEARNED

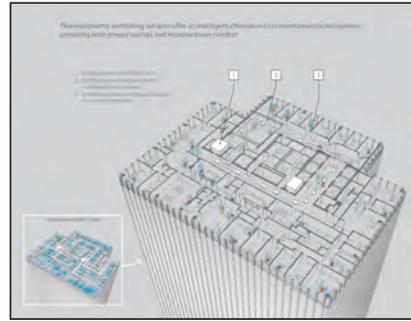
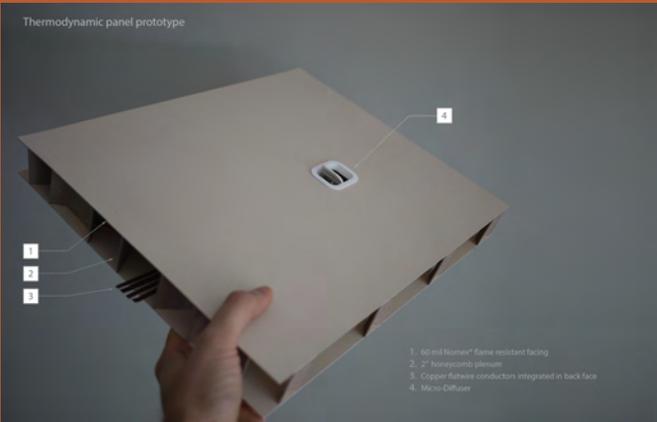
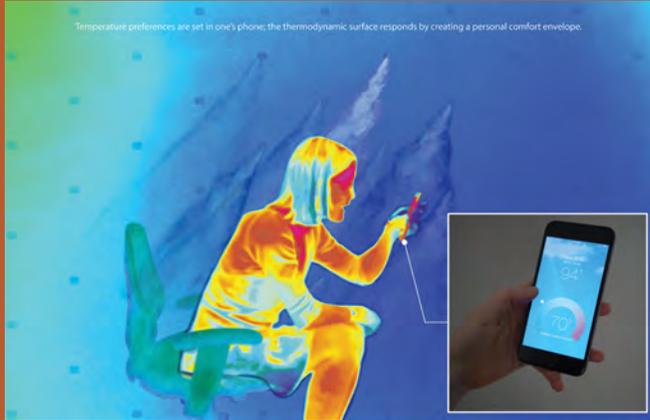
Courses that cover sustainable design methods such as passive heating and cooling strategies are critical and should be taken prior to learning the process of performance-based design. Students need this preliminary knowledge to be able to think of performance objectives and select the right performance criteria. On the other hand, modelling skills enable performance quantification. Hence, gaining sustainable building design knowledge, understanding theory of performance-driven design, and using software judiciously are essential for students to become capable of designing sustainable, resource-efficient high-performance buildings. Results of students' satisfaction survey show students have found these courses useful and try to incorporate this knowledge into their design studio projects. Students also mentioned that the use of simplified real-life applications was helpful to grasp the concept of complex methods and systems. It is expected that the adoption of the open education resource platform and gamified flipped classroom to have a positive impact on the academic success of students learning software such as Revit.

Sensor-Based Intelligent HVAC Distribution System for Buildings

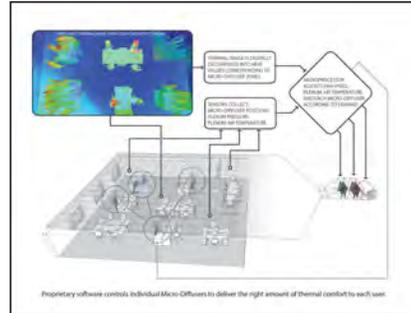
Eric Olsen

Woodbury University, Burbank, California

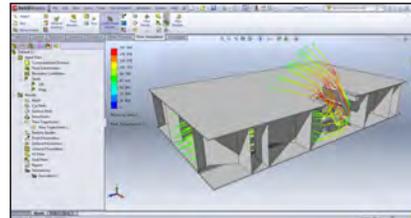
SENSOR-BASED INTELLIGENT HVAC DISTRIBUTION SYSTEM FOR BUILDINGS
ERIC OLSEN, WOODBURY UNIVERSITY



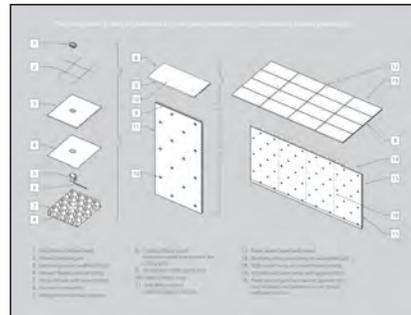
Within many cities, there is a legacy of older office buildings with obsolete and inefficient HVAC systems (such as the Seagram Building in New York which earned an Energy Star rating of 3, compared to a median rating of 58 for similar buildings). In addition to their inherent inefficiencies, these legacy environmental systems tend to have little capacity to respond or adapt to user needs, resulting in imbalanced environments and the familiar fight for control of the thermostat. By contrast, Thermal Ventilating Tiles actively create a microclimate of conditioned air around the user that accompanies them as they move from space to space within a building based on their specific temperature preference, allowing for increased individual thermal comfort and resulting in increased productivity.



Is it possible to imagine a more intelligent way of providing thermal comfort to workspace users while simultaneously conserving energy? With the shift toward solid-state lighting and low demand appliances and equipment, workspaces have become more energy efficient, yet HVAC, heating, ventilation and air conditioning systems continue to operate according to principles developed during the Industrial Revolution. In order to realize the potential of adaptive and intelligent materials in in workplace environments, we have developed a software/hardware system - Thermodynamic Ventilating Tiles - to reimagine the way we evaluate and temper the environments of our buildings. The Thermodynamic Ventilating Tile Project seeks to replace the conventional air distribution system of ductwork and registers with an intelligent sensing surface of Micro-Diffusers that provide variable amounts of conditioned air in response to localized user demands.



Emerging material systems must engage and transform the buildings we've inherited from Modernism and examine opportunities for strategic adaptation within their established material orders. The Thermodynamic Ventilating Tiles are designed to seamlessly integrate into existing office building material systems and can be configured to replace the acoustic tile ceiling grids or gypsum wallboard surfaces of a room without compromising sound transmission or fire resistance requirements. The Thermodynamic Ventilating Tile system is engineered to interface with existing ductwork and requires minor upgrades - such as the installation of variable fan speed technology - to plug into an existing heating and cooling plant. Because of this compatibility with existing material and mechanical systems, along with the inherent energy efficiency and enhanced environmental comfort for users.



The Thermodynamic Ventilating Tiles combine an architectural product - the panelized system - with computational intelligence - the sensors, controls, and software - to holistically provide comfortable interior environments. Depending on the size and configuration of the Thermodynamic Ventilating Surface, one or more thermal imaging cameras are integrated into the surface to record the presence of any thermal bodies (such as a person). Data collected from the sensors and thermal cameras is processed by proprietary software which analyzes thermal bodies and other inputs, selectively activating Micro-Diffusers based on demand. Through real-time locating system technology, users are able to set temperature preferences in their smart phone and the proprietary software recognizes their position within the thermal image data, adjusting the Thermodynamic Ventilating Surface's response according to their preferences.

Ambient Intelligence in Built Environment for Enhancing Students' Cognitive Performance

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Ambient Intelligence in Built Environment for Enhancing Students' Cognitive Performance

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1. Ambient Intelligence for Human-centered Built Environment

Students spend more than 90% of their time in the built environment, which makes human-environment interactions essential for their long term cognitive performance and well-being. Human cognitive performance refers to the ability of the brain to process, store, and retrieve information. It encompasses a wide range of cognitive abilities, such as attention, memory, reasoning, problem-solving, and decision-making. These abilities are essential for daily living, academic and professional success, and overall well-being. The built environment plays a crucial role in shaping human cognitive performance. Research has shown that environmental factors can significantly impact cognitive abilities, including light, air quality, and sound. Ambient intelligence (Aml) is a concept where the environment is equipped with smart sensors and devices that can observe, learn, and respond to the users' behaviour and needs. It aims to create an intelligent environment that can enhance the user's experience, comfort, and performance. In this study, we aim to explore the multi-faceted impact of ambient intelligence in the built environment on students' cognitive performance.

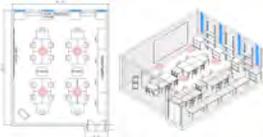


Figure 1: Smart Classroom Supported by Ambient Intelligence

2. Ambient Intelligence for Built Environment: A Multi-channel Model

Environmental condition data will be collected through a variety of sensors, including indoor illumination, temperature, humidity, CO₂ and VOC concentrations [7]. Ambient radio frequency measurements and instrumental cognitive tests will be used to characterize the participants' activity levels and performance. Experiments will be conducted in 16 tempo-

ral and spatial segments of different building environmental conditions. The experiment setup allows for the comparison between the AI-supported dynamic conditions and constant conditions. Several machine learning models are used to derive ambient intelligence from environmental sensory data for supporting targeted activities at specific times under certain built environmental conditions. The data was split into training and test sets. The machine learning models will be evaluated and the best model will be identified. In subsequent experiments, the model will be used to assist occupants' activities. Recommendations will be generated to inform occupants for better interactions with the built environment.

3. Pilot Study & Forthcoming Research

The study will be conducted over a period of four weeks, during which the classroom will be equipped with a range of environmental sensors, cyber-physical systems. The radio frequency detection systems allow us to characterize the occupants' activities while filtering out vital privacy information about the user and the environment around him/her. The data collected will be used to analyze the effects of the Aml-supported environmental adjustments on the students cognitive performance.

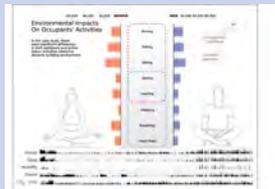


Figure 2: Impacts of Ambient Intelligence in Built Environment on Students' Cognitive Performance

The results of the study will allow the researchers to better understand how the ambient intelligence in built environment influence students cognitive performance based on analysis of specific active or stationary activities.

4. Discussion

Ambient intelligence in smart building environment has been explored as a promising solution to improve occupants' experience, productivity, comfort levels and cognitive performance. However, there are still many challenges that need to be addressed before we can rely on AI for coordinating our dynamic temporal and spatial human-building interactions. Firstly, currently there is the limited experimental data for theoretical development and interpretation of machine-learning-based AI models for understanding diverse and ever-changing individual cognitive performance. Secondly, there is a major limitation in terms of unified platforms for the integration of the various ambient intelligence technologies in the smart building environment. Furthermore, the monitoring, storage and analysis of the data collected from the building environment may increase risks related to security and privacy. In order to address these challenges, future research should focus on the development of effective ambient intelligence technologies that can be integrated into a unified platform. Moreover, the development of effective data collection, storage and analysis techniques should be explored to serve more diverse populations. These techniques should be able to enhance cognitive performance and provide better user experience. Additionally, the privacy and security of occupants in AI-supported building environment should be properly protected.

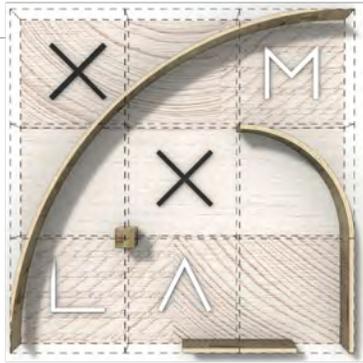
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XX-LAM: An Exploration of Curved-CTL within a Midwestern Context

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Caroline Goertz
Pegah Rahmani
Jacob Urban
Jason Griffiths**

University of Nebraska–Lincoln, Nebraska



XX-LAM

an exploration of curved-CLT within a midwestern context

in association with

PLAIN D+B

march students

Chris Bean, Cotton, Corrin,
 Caroline Goertz, Pegah
 Bahmani, & Jacob Urban

advisor

Jason Griffiths
 associate professor of
 architecture, UNL



INTRODUCTION

XX-Lam explores the spatial and structural possibilities of curved, cross-laminated timber construction. It adopts the "cross lamination" bonding pattern of CLT as a conceptual strategy for exploring the language of mass-timber architecture. XX-Lam applies (crosses) the technical capabilities of CLT with the architectural principles of John Hejduk's Nine Square Grid exercise in an installation of curved and linear components set within a 3X3 architectural grid.

RESEARCH PROCESS

This research examines the use of cross laminated timber (CLT) in a curvilinear form for interior applications. It questions every step of the manufacturing process of CLT including timber sourcing, milling, layup, gluing, bending, and cutting. Additionally, it evaluates the feasibility of CLT construction supported by the Nebraska forestry industry. Different wood species with varying stiffness were examined, including Eastern Red Cedar, Douglas Fir/Pine, Elm, and Basswood. Other experiments included layup conditions, ranging from 3 to 7 layers, and varied thickness of individual plies between tests. Steam bending, clamp molds, and ratchet molds were all explored as bending methods; however, a vacuum former was ascertained to be the most effective strategy for maintaining consistent pressure on the larger panels. Polyurethane glue was used for preliminary testing, but for our final production we relied on Titebond 2 to prolong the life of the vacuum bag.



CONSTRUCTION/ ASSEMBLY PROCESS

Each panel takes thirty hours from material prep to glue-up, cure time, and finally panel sanding and finishing. The panel and board dimensions we have chosen make it possible to streamline production and make it as efficient as possible without industrial-scale machinery. All 45 boards in each panel are milled to 3/8" thick by 5.5" wide by 4' long. Each "sheet" is made of 9 of these boards. After they have been curved, the panels are all cut down to 3'-6" x 3'-10" and drilled with four connection holes and affixed with self-leveling feet. In this way, we have been able to produce a kit-of-parts including 20 panels that are interchangeable and could be arranged out in millions of orientations. While no panel is perfect, we improved in quality and consistency with each repetition to produce industrial-scale panels from a typical woodshop and 4'x4' vac-bed.



MOVING FORWARD

Ultimately, we conceptualized our design from the perspective of a local sawmill capable of producing curved CLT after installing a vacuum former. We propose that it is feasible for local sawmills to produce structural, curved CLT, however, there is currently a scarcity of appropriately dimensioned lumber. The Nebraska forestry industry should explore standardization for CLT board and panel sizes. Many examples of Pine CLT exist, but this research proved Eastern Red Cedar, a local invasive species, performs well in curved CLT applications. This research anticipates a time when invasive species are harvested throughout Nebraska as the component to a sustainable building technology.



PLAIN D+B WEBSITE



XX-LAM INSTAGRAM

Deep Learning for Estimating Energy Savings of Early-Stage Facade Design Decisions

Mohsen Shahandashti

Santosh Acharya

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The University of Texas at Arlington, Arlington, Texas



Deep Learning for Estimating Energy Savings of Early-Stage Facade Design Decisions

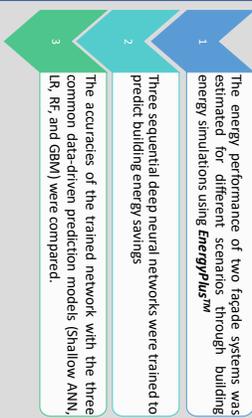
Mohsen Shahandashti, Ph.D., P.E., Associate Professor, Santosh Acharya, Bahram Abedinjangerabi
Department of Civil Engineering, College of Engineering, The University of Texas at Arlington

Background

- Buildings contribute significantly (about 20 percent) to worldwide energy use.
- Energy efficiency improvement in the building construction industry prompts decrease in building's energy use, operating costs, and life cycle cost which is more pressing than ever.
- The selection of high-performance building facade systems is essential to promote building energy efficiency.
- However, this selection is highly dependent on early-stage design decisions, which are extremely challenging considering numerous design parameters with early-stage uncertainties.

Objectives

- To evaluate the applicability of deep learning networks in estimating the energy savings of different facade alternatives in the early-stage design of buildings.
- Two competing facade systems:
 - Ultra-high-performance Fiber-Reinforced-Concrete
 - Conventional Panels



Significance of Study

- The early stage of a building design is critical for implementing energy-efficiency strategies.
- The selection of an energy-efficient building facade system at the early stage of building design can aid to improve the buildings' energy performance but are difficult to select due to numerous design parameters with early-stage uncertainties.
- Even though Building Performance Simulations provide accurate results, they require detailed building models, which are only accessible at the later stages of building design limiting their use.
- Despite numerous attempts to quantify building energy efficiency through the use of artificial neural networks, no attempts have been made to justify the use of deep learning alternatives in the early stage design of buildings.

Methodology

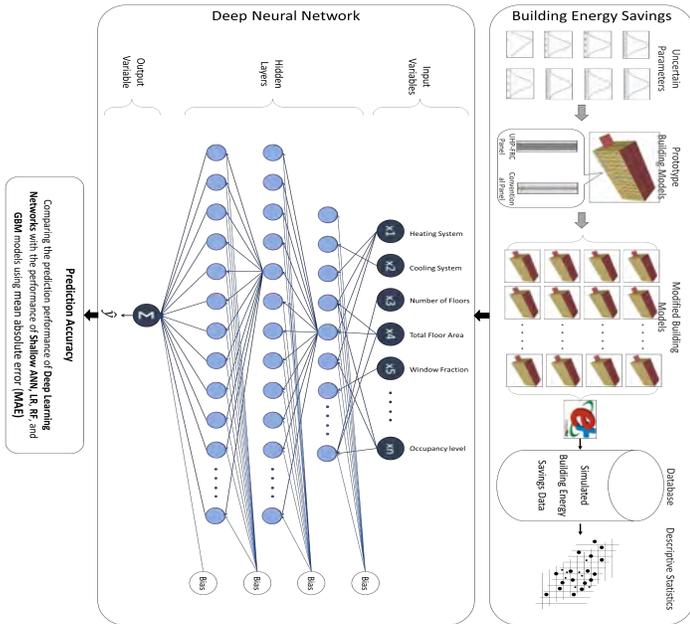


Figure 2: Modeling Approach

Results

1. Descriptive Statistics

Heating Energy Savings	Cooling Energy Savings	Total Site Energy Savings
Minimum: -5.74E+11	Minimum: 5.54E+10	Minimum: -5.69E+11
Maximum: 1.12E+12	Maximum: 7.70E+10	Maximum: 1.20E+12
Mean: 0.127	Mean: 0.143	Mean: 0.173
Standard Deviation: 0.127	Standard Deviation: 0.173	Standard Deviation: 0.173

Table 1: Spearman correlation between categorical features and building energy savings

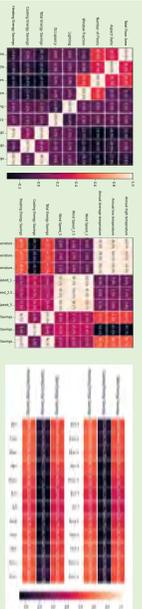


Figure 3: Pearson correlation between building physical, weather-related features characteristics, and building energy savings

2. Prediction Results

- High accuracies in the prediction of buildings cooling energy savings on both training and testing datasets compared to other methods
- Narrow margin between the training and testing accuracies
- Relative importance of predictive features for deep networks
- The deep neural networks, shallow neural networks including GBM models, random forest models, and three generalized regression models were trained for predicting total site, cooling, and heating energy savings of buildings.

Models	Training		Testing	
	MAE	RMSE	MAE	RMSE
Shallow ANN	162	158	158	148
LR	101	101	101	117
RF	101	101	101	117
GBM	101	101	101	117

Table 2: Accuracy matrix of DNN



Figure 4: The relative importance of predictive feature of DNN

Table 3 : Testing accuracy matrix of DNN, SVM, GBM, Random Forest, and GAN Models

Models	Training		Testing	
	MAE	RMSE	MAE	RMSE
Deep Neural Network	0.20	0.39	0.20	0.39
Support Vector Machine	1.17	2.72	1.17	2.72
Gradient Boosting Machine	6.80	10.79	6.80	10.79
Random Forest	0.51	0.86	0.51	0.86
Generalized Linear Model	5.70	10.16	5.70	10.16
Gradient Boosting Machine	1.85	3.57	1.85	3.57
Support Vector Machine	0.21	0.59	0.21	0.59
Random Forest	1.44	3.08	1.44	3.08
Generalized Linear Model	3.85	7.74	3.85	7.74
Deep Neural Network	0.40	0.95	0.40	0.95
Support Vector Machine	3.09	6.99	3.09	6.99
Gradient Boosting Machine	9.20	14.47	9.20	14.47
Random Forest	0.88	1.58	0.88	1.58
Generalized Linear Model	8.69	15.08	8.69	15.08

Conclusions

- Deep neural networks outperformed the other common prediction models (i.e., Gradient Boosting Machine, Random Forest, and Generalized Linear Regression) as well as shallow neural networks.
- The importance of the explanatory features, derived from the trained deep neural network showed six features had a higher contribution to the prediction over others.
- The advantages of deep learning in the evaluation of energy saving of early-stage facade decisions can be used by designers in the early stage to make well-informed decisions.

