Building with Air: The Internet of Things (IoT) as a Pedagogical Tool for Design-Build Education

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Opening Figure: In this investigation the Internet of Things (IoT) serves as a pedagogical tool for allowing students to experience changes in temperature, wind speed, and humidity through shifts in hue, saturation, and brightness. Source: (Author 2019).

ABSTRACT: How can we teach design and building performance as an integrated process to instill principles of resilience in our next generation of architectural designers? Through the analysis of a project that integrates temperature, wind speed, and humidity data in the design of a passively heated and cooled interactive installation, this paper proposes methods for leveraging the Internet of Things (IoT) to make tangible the relationship between buildings and their environments. By combining sensor data with the experience of building, the paper examines how IoT can serve as a pedagogical tool for students to learn, understand, and apply building performance concepts in their architectural designs.

This paper investigates the growing field of IoT, detailing its current applications and future opportunities for impacting architectural research and practice. It next covers the methods and results of a one-semester design-build project that incorporates IoT technology in the construction of a digitally fabricated tea house to create a feedback loop for students to understand the performance of their built structure.

The research outcomes of this investigation are two-fold: 1) the development of a method for translating real time sensor and web data into microcontroller outputs for creating an interactive interface, and 2) a pedagogical model for teaching design and building performance as an integrated process by combining IoT technology with design-build projects. By teaching design and building performance as an integrated process through an experience-centered approach, this paper argues students can better understand and apply performance concepts in their architectural designs to help achieve our goals for urban resilience.

KEYWORDS: Digital Design and Practices, Design-Build, Interactive Architecture, Computational Design, Internet of Things

PAPER SESSION TRACK: Digital Design and Practices

INTRODUCTION

The growing complexity of architectural practice asks us to reevaluate our approaches to educating students in preparation for an evolving discipline. The increasing demand for building performance; the large role building systems and technologies play in the design, development, and construction process; the growing number of consultants and contractors needed to collaborate with; and the expanding suite of software and digital design tools makes the task of educating contemporary architecture students a challenging endeavor. By teaching design and building technology in isolation from one another, content is abstracted and students' opportunities to understand "why" certain technologies and methods are implemented in practice are curtailed.

To bridge the existing divide between design and evaluation, this paper advocates for an experiential approach to learning to address the diverse and growing responsibilities of practitioners in the discipline today. This sentiment is reflected by contemporary educators such a Kiel Moe's call for "integrated design" (Moe 2008) and Tricia Stuth's "designbuild-and-evaluate" (Stuth 2017) approach that frame the act of design and assessment as an interrelated process. Through a project that teaches students fundamentals on building performance, this investigation leverages the Internet of Things (IoT) as a pedagogical tool for deepening students' cognitive understanding of the structures they design and build through the framework of experience.

1.0 CONTEXT

This investigation asks the question: "how can IoT technologies be leveraged as a pedagogical tool for students to learn, understand, and apply concepts related to building performance in their architectural designs?" While IoT is advancing at a rapid rate and becoming increasingly present in our built environment, its application in design education remains untested and limited. This paper envisions IoT, with its capacity to interface with buildings and their environments, as an asset for helping students learn, understand, and apply building performance concepts in their architectural designs. By integrating IoT with design-build projects, students can understand building performance concepts through the process of making and building.

Defined as "'things' or 'objects' that connect to the internet" by Samuel Greengard in his book, *The Internet of Things*, IoT's value lies in connecting "physical-first products and items to each other as well as connecting them to digital-first devices" (Greengard 2015). Beginning in 2007 with Apple's introduction of the iPhone and its sale of approximately 37 million units in 2008, IoT is poised for an era of rapid expansion and application within our built environment (Greengard 2015). IoT machine to machine communication (M2M) devices are expected to grow from 6.1 billion in 2018 to 14.7 billion by 2023, with home applications predicted to represent 48 percent of all connections by 2023 and connected cities applications slated to have the second-fastest growth (26 CAGR) over the six-year period (Cisco 2020).

The proliferation of IoT smart devices in the built environment has provided new opportunities for understanding how our cities perform through the large-scale collection of data. The term "smart cities" provides a framework for addressing issues related to resilience at an urban level, as reflected by architectural historian Antoine Picon (2015) who identifies "sustainable development" as a central point of focus and poses the question "is it possible to speak of smart cities if urban zones continue…to contribute to environmental degradation?" If smart cities represent an optimistic vision on the role technology may play in outlining strategies for resilience, recent discourse amongst architects and urbanists provides more critical and rigorous methods for realizing these cities' potential. Allen Sayegh and Harvard's Responsive Environments and Artifacts Lab's (REAL) (2021) concept of "responsive environments" serves as a counterpoint to smart cities' top-down and optimized approach and focuses on the intersection of architecture and urbanism to develop ways for integrating emerging technologies such as IoT into cities and exploring the dynamic relationship between physical and digital spaces. Through responsive environments, resilience can be framed as being achieved through bottom-up processes, especially those that involve designing the ways in which smart technologies are integrated into the built environment. Such moments of integration not only provide a higher resolution picture of how our cities perform, but also the potential to reveal new architectural meaning latent within our buildings and environments.

Taken within the context of architecture schools, this paper frames IoT as a pedagogical opportunity frame the processes of design and performance evaluation as an interrelated process through the creation of real-time feedback loops that, when applied at scale, have the potential to enhance resilience at architectural and urban scales. As a means for integrating IoT in the design-build process, this investigation identifies microcontrollers as a suitable platform for learning and understanding how buildings perform. Microcontrollers are a familiar technology in architecture schools with a robust community of users to draw upon and learn from. They provide an ideal tool for experimenting and prototyping IoT setups and are customizable to address the specific demands of design-build projects. The arrival of Wi-Fi-enabled microcontrollers in recent years has provided designers a gateway to engage in the world of IoT. No longer inhibited by a need for a computer connection, this generation of microcontrollers allow users to monitor and relay environmental conditions across distributed networks and at a variety of scales.

In focusing on the emerging potential of IoT, the intention of this paper is not to advocate for a shift towards a utilitarian application of technology or vocational attitude in design education, but rather identifying a currently underutilized tool to enhance student cognition through the framework of experience. By leveraging IoT as a pedagogical opportunity for learning, understanding, and applying disciplinary concepts through the act of making and building, this investigation promotes a student-centered model for engaging the growing complexity of architectural practice.

2.0 METHODOLOGY

[Project Name Redacted] is an installation that explores the pedagogical potential of IoT to allow students to study thermodynamic principles through their architectural designs. This project was designed, fabricated, and constructed with undergraduate and graduate students at [Institution Name Redacted]. The installation integrates computer coding, Wi-Fi enabled microcontrollers, and sensor data with digital fabrication techniques and construction methods to produce a space that allows visitors to understand thermodynamic principles through their interactions with the structure. The methods used to create this installation serve to teach students thermal concepts, digital fabrication techniques, and construction logics through the process of making and building.

The project is designed as a feedback loop for understanding thermodynamic principles through an interactive space that makes tangible for visitors the temperature, wind speed, and humidity of the air around them. The installation's feedback system combines sensors, weather data, and addressable LED lights to communicate thermal conditions by comparing and contrasting building interiors with their exterior environment. In a three-step process, sensor data collected at the ventilation openings is measured in relation to local weather data and translated in the form of light. Using hue, saturation, and brightness to communicate differences in temperature, wind speed, and humidity respectively, the system creates a qualitative interface for understanding quantitative differences within the space.

[Project Name Redacted] is an 84 square-foot tea house that leverages intelligence gained through the integration of IoT to reduce material excess and eliminate the use of active building systems. (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 (Figure 1). Movable furniture and the doorway located at the corners create a system for modulating airflow through the interior. By understanding and applying thermal principles through reading the lights and arranging the furniture, occupants can regulate their thermal comfort through their interactions with the structure (Figure 2).

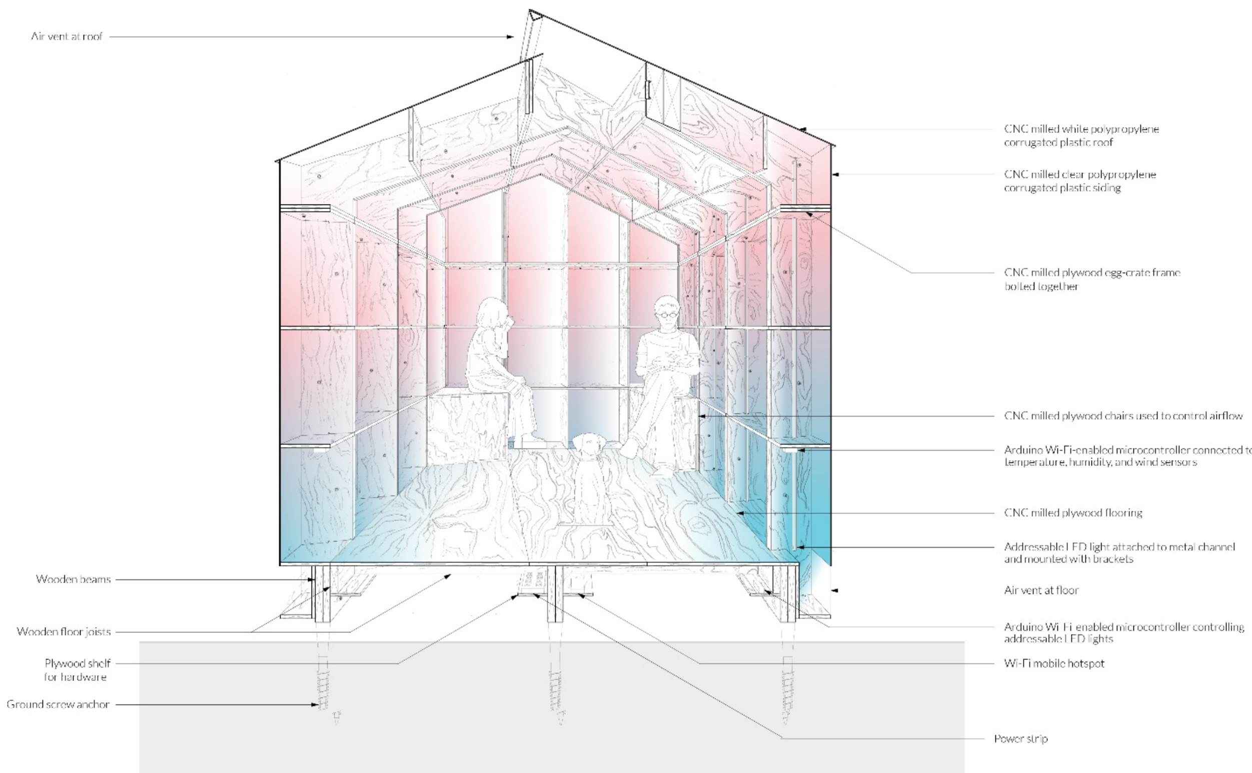


Figure 1: Openings at the floor and along the roof ridge induce natural ventilation through the space. Source: (Matthew Conway + Author 2019)

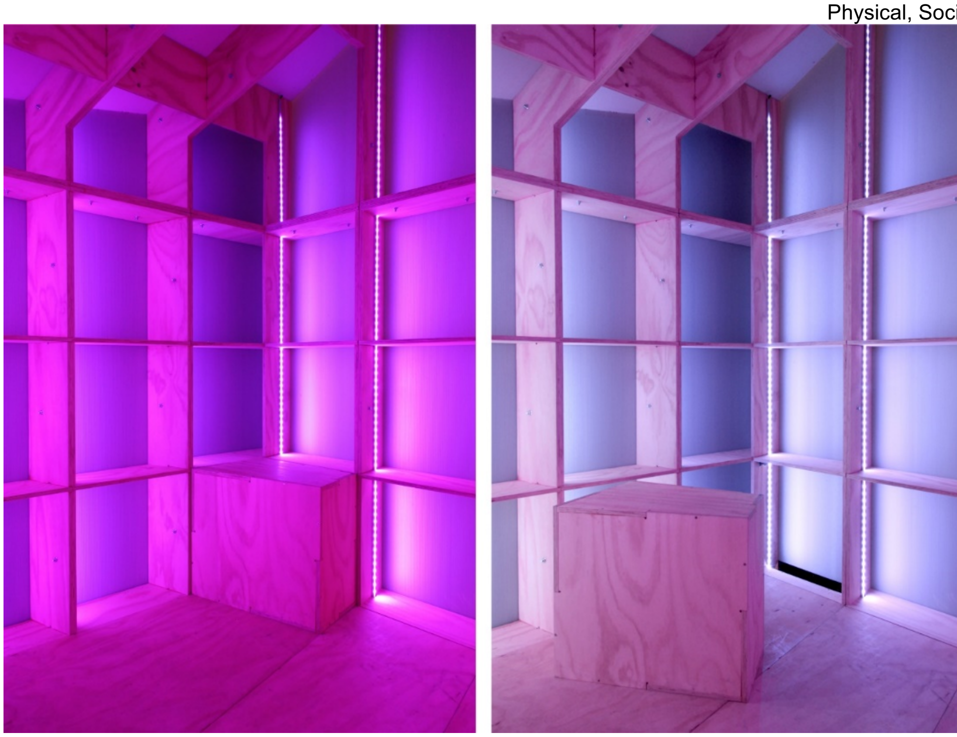


Figure 2: Movable furniture can restrict airflow by being positioned at the corners (left) or induce it by being positioned further away (right). Source: (Author 2019)

2.1. Translating Weather and Sensor Data to LED Lights

To represent the thermal conditions within the installation in real-time, addressable LED lights are used to communicate the temperature, wind speed, and humidity of the air within the space. The process of translating thermal sensor data is a three-part process: 1) Wi-Fi-enabled microcontrollers connected to sensors monitor temperature, wind speed, and humidity conditions while a JavaScript code parses local weather information from the publicly accessible website OpenWeatherMap, 2) an MQ Telemetry Transport (MQTT) platform shares the parsed data with Wi-Fi enabled Arduinos connected to addressable LED lights, and 3) the Arduino microcontrollers operate the LED lights to communicate the data through changes in hue, saturation, and brightness (Figure 3).

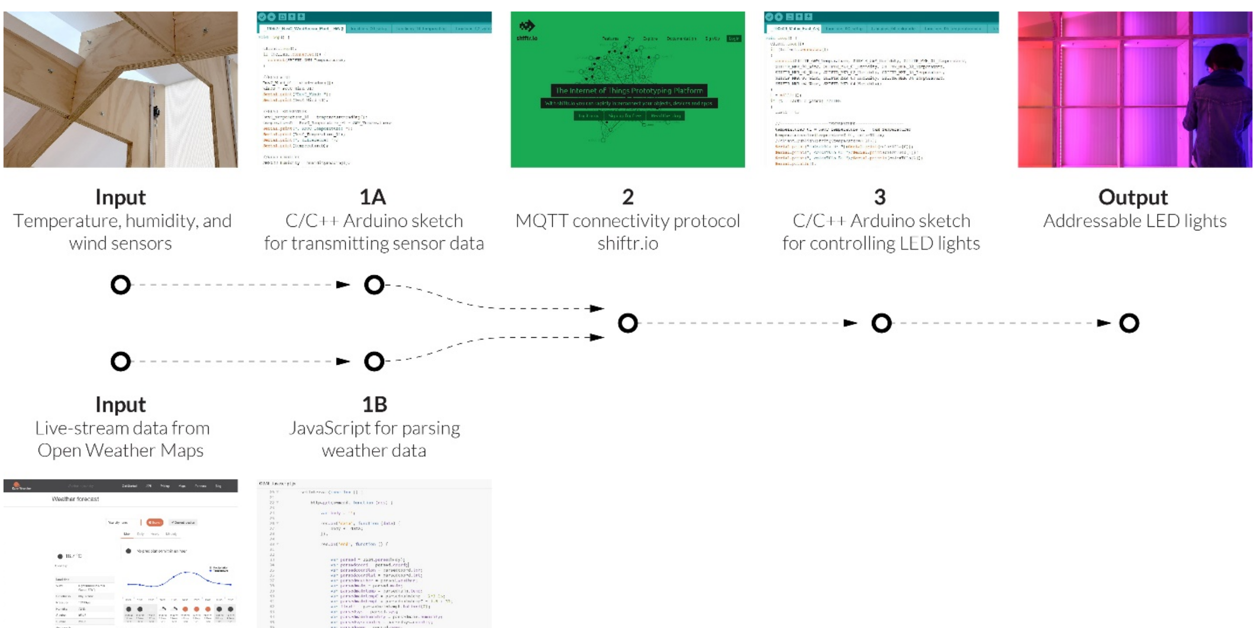


Figure 3: Sensor data collected at the ventilation openings is measured in relation to local weather data and translated into lights through a three-step process. Source: (Author 2019)

2.2. Collecting Temperature, Wind Speed, and Humidity Data

Arduino MKR1000 microcontrollers are used for their Wi-Fi capacity and compact size. (6) MKR1000s are each connected to an AM 2320 digital temperature and humidity sensor and a Modern Device Rev C. wind sensor. C/C++ sketches written using Arduino's Integrated Development Environment (IDE) gather data generated by the sensors.

Simultaneously, local weather data is collected from OpenWeatherMap to calculate the temperature difference between the installation's interior and the exterior environment. OpenWeatherMap allows local temperature data to be publicly accessible through their Application Programming Interface (API) in the form of a JavaScript Object Notification (JSON). A JavaScript code parses the JSON and returns the local temperature in Fahrenheit degrees. The JavaScript code is executed on a Wi-Fi-enabled Raspberry Pi Zero using the JavaScript runtime environment Node.js (Node.js n.d.).

2.3. Using MQTT to Connect JavaScript and C/C++Arduino Devices

An MQTT machine to machine (M2M) IoT connectivity protocol is used to network Arduino devices running C/C++ and the Raspberry Pi Zero running JavaScript (MQTT n.d.). The IoT prototyping platform shiftr.io was selected for its capacity to connect JavaScript and Arduino devices and its visual interface that shows these connections in real-time (Shiftr.io n.d.). This platform permits (15) devices to be connected simultaneously: (6) Wi-Fi-enabled MKR1000s connected to AM 2320 digital temperature and humidity sensors and Rev C. wind sensors, (1) Wi-Fi-enabled Raspberry Pi Zero running the JavaScript code, and (8) Wi-Fi-enabled MKR1000s operating addressable LED lights.

2.4. Controlling Addressable LED Lights

(8) MKR1000s each control (2) strips of WS2812B "NeoPixel" addressable LED lights with strips running between 11 to 87 pixels in length depending upon the height of the facade. Each facade contains (4) strips of LED lights operated by (2) MKR1000s. C/C++ sketches written using Arduino's IDE translate temperature, wind speed, and humidity data as changes in hue, saturation, and brightness respectively. For changes in temperature, the sketch calculates the difference between sensor data and the local weather temperature to communicate the relationship between interior and exterior conditions. A warmer interior temperature results in a red hue, whereas a cooler interior temperature results in a blue hue. For changes in wind speed, no airflow results in no change to the lights' color, whereas increased airflow results in a desaturated white color. For changes in humidity, low humidity results in decreased brightness, whereas high humidity results in increased brightness.

The sketch calculates the data gathered from each sensor location and translates the quantitative values into a qualitative gradient of lights (Figure 4). East and west facades create a gradient from (4) sensor locations: (2) along the roof ridge and (2) at the floor corners and door. North and south facades create a gradient from (3) sensor locations: (1) along the roof ridge and (2) at the floor corners and door. The result is an interface that provides continuous feedback on the installation's thermodynamics through constantly updating lights. By studying the lighting patterns and arranging the movable furniture and door, occupants can understand and apply stack-effect principles through their interactions and experience within the space.

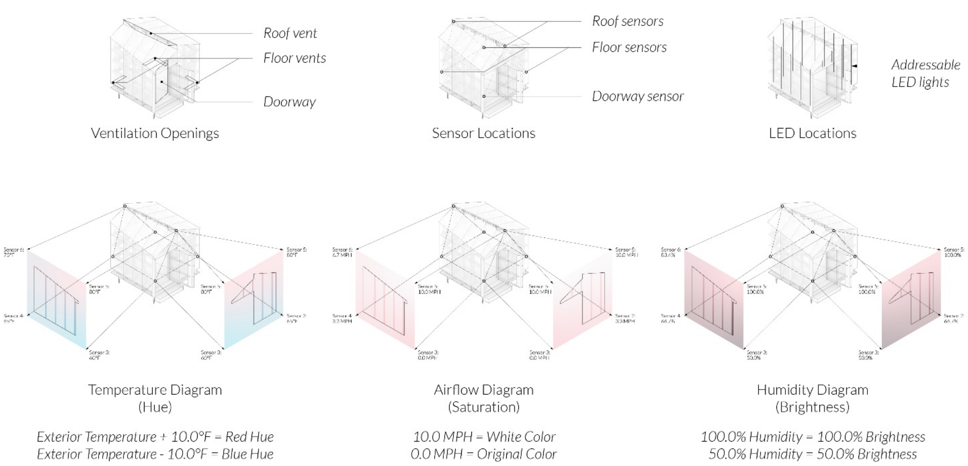


Figure 4: Differences in temperature, wind speed, and humidity are registered as shifts in the lights' hue, saturation, and brightness, respectively. Source: (Author 2019)

3.0 DESIGN PEDAGOGY

The installation was realized through a one-semester seminar course that sought to leverage IoT technology as a pedagogical tool to teach thermodynamic concepts through the process of making and building. The class was composed of eleven students—six undergraduate and five graduate students from [Institution Name Redacted]. Students worked on the design development, fabrication, and construction of the 1:1 scale tea house to be installed on campus and at the local botanical garden and arboretum. Students at the outset of the semester were subdivided into four teams—material research, digital fabrication, lighting design, and computer coding—that worked collaboratively to develop the project as synthetic whole. The teamwork was split into three parts over the course of the semester:

research, design, and fabrication and construction. Students worked on specific aspects of the project in depth within their specific teams and coordinated with other teams in the design, development, and construction of the installation.

The structure's modular design allows for it to be constructed in a single day (Figure 5). The process of assembling and disassembling the structure for installation at [Institution Name Redacted] and the local botanical garden and arboretum not only reinforced students' conceptual understanding of the project's fabrication and construction logics, but also allowed them to evaluate its performance in two distinct environmental conditions (Figure 6).

By seeing the project through from beginning to end, students were able to fully comprehend the installation's conceptual and design intent. Each student was introduced to the project's code on the first day of class, and their familiarity with the IoT technology behind the installation not only allowed them to understand the inner workings of the tea house, but also develop an experiential understanding of the thermal principles that inform design decisions in practice.

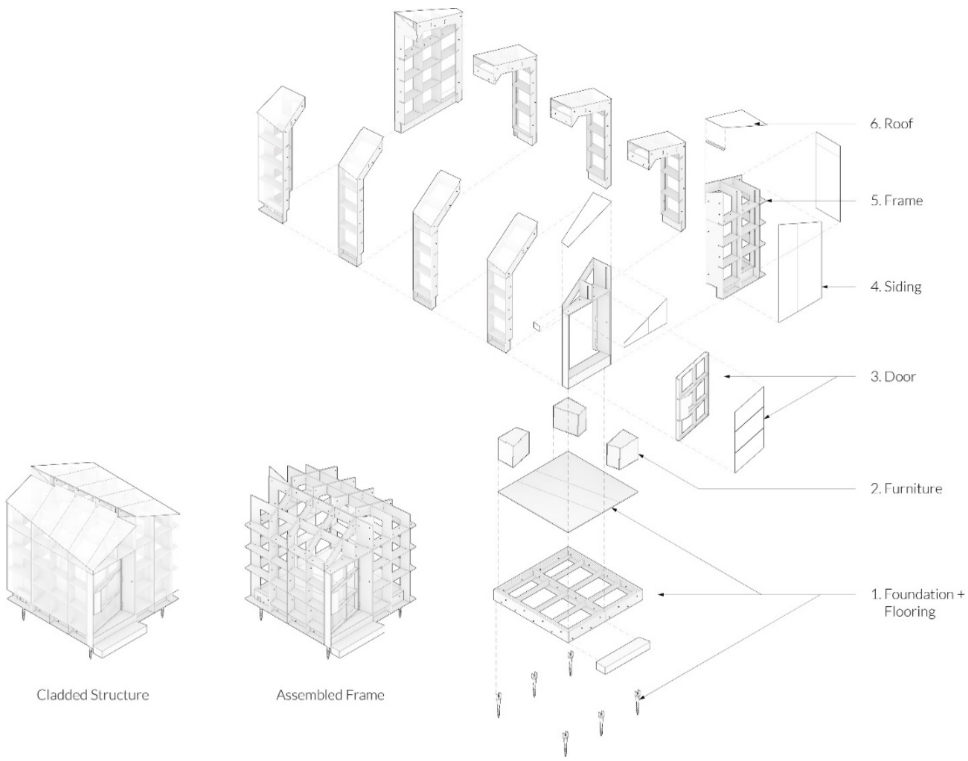


Figure 5: The project combines traditional wood framing and digital fabrication methods to develop a construction system that is modular and designed for disassembly. Source: (Author 2019)

Figure 6: The process of disassembling and reassembling the structure for installation reinforced students' conceptual understanding of the project's fabrication and construction logics. Source: (Author 2019)

4.0 DISCUSSION

Incorporating IoT in the design-build process provides students a pedagogical scaffold for not only understanding how buildings are designed and constructed but also how they perform. Through a pedagogy that emphasizes an experiential approach to learning, this course provides a model for engaging with the growing complexity of the architectural profession today. By integrating topics such as IoT, thermodynamics, fabrication techniques, and construction methods, students are able to draw connections in their education and apply learned concepts through the process of making and building. The integration of IoT into the design process has three observed outcomes: 1) it allows students to understand their environments in quantitative and qualitative terms, 2) the continuous feedback provided by IoT allows students to constantly test hypotheses, evaluate results, and apply learned concepts in their designs, and 3) it provides a framework for students to evaluate and apply their designs at multiple scales.

This investigation sees opportunities to expand upon the project in two ways. The first proposed application is the integration of the project's sensor data with a digital model to produce a "digital twin." Defined as "a dynamic virtual representation of a physical object or system" (Stanford-Clark et al. 2019), digital twins can provide students a real-time digital representation of their built structures that can be used for further analysis. By using data communication plugins such as gHowl for Grasshopper to integrate sensor data, students can engage with digital modeling software not only as a tool for design but also performance evaluation (Grasshopper n.d.). The second proposed application is the further development of the light-weight construction methods utilized in this design-build installation for application in small-scale domestic projects. Referencing UCLA cityLAB's research on Backyard Homes (2010), this investigation sees potential in integrating IoT in the design of lightweight Additional Dwelling Units (ADUs) to address cities housing issues while minimizing the environmental impact of construction. As a housing solution that can add density to a variety of urban conditions and across multiple cities, intelligently designed ADUs that leverage IoT to eliminate material excess can have a profound impact on achieving urban resilience moving forward.

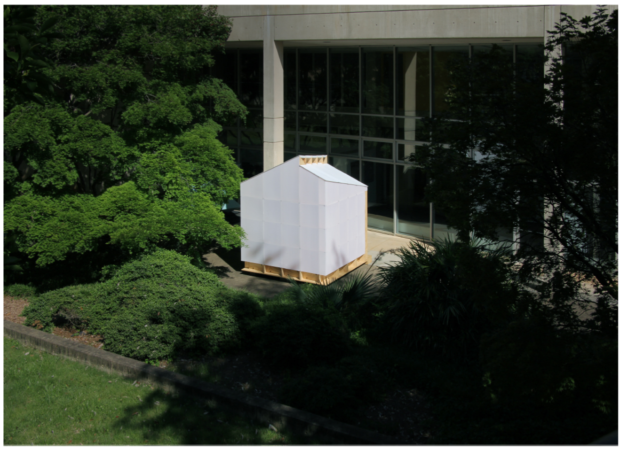
In addition to these future applications, an additional observed pedagogical outcome from this course structure was the active role students took in their design education. For many of the participating students this course served as an introduction to working with microcontrollers, sensors, coding, laser cutting, CNC milling, and vacuum forming. The experiential and project-based approach of the class provided a framework for students to learn, understand, and apply these technologies to their designs. Furthermore, the need to collaborate with each other and coordinate with outside vendors, consultants, and clients gave students experience and confidence to engage the numerous collaborators necessary to practice in today's professional environment.

5.0 CONCLUSION

This investigation proposes a methodology for leveraging IoT as a pedagogical tool for students to learn, understand, and apply concepts related to building performance in their architectural designs. By leveraging IoT to create informative feedback loops between design and performance, architecture schools can provide students a pedagogical scaffold to understand and apply lessons from their education through a teaching approach centered on personal experience.

IoT technology allows students the opportunity to test hypotheses, evaluate results, and apply learned concepts in their designs through scalable networks that provide constant qualitative and quantitative feedback. Combined with the design-build model, IoT is a potent tool for teaching students abstract technical concepts typically isolated from the design process in architecture education. By leveraging IoT to create interactive and tangible interfaces, students can engage their environments to learn, understand, and apply building performance concepts such as thermodynamics through the framework of experience.

Beyond its utilitarian application, the Internet of Things is an impactful pedagogical tool for building intelligence within our students of architecture. By increasing students' cognitive ability through a framework that allows students to learn, understand, and apply building performance concepts in their architectural designs, we can better prepare the next generation of practitioners to engage issues of resilience that impact our cities now and in the future.




Closing Figure: By engaging local contexts and conditions, IoT provides architecture educators a pedagogical tool for teaching building performance principles through the framework of experience. Source: (Author 2019)

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