Developing a Prototyping Model for the Built Environment: Lessons from an Evaporative Cooling Unit Case Study

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Abstract

This paper describes the development of a modular timber evaporative cooling unit (ECU) possessing a complex dendritic formal quality, presented as a case study, and uses the findings to propose a conceptual prototyping model for the built environment. The case study project leverages computational design methods for design detailing and material optimisation, and digital fabrication for part production. The resultant structure was successfully constructed, however challenges relating to material properties were required to be overcome, these challenges could have been mitigated through a structured approach to prototyping. Reflecting on this project, the paper proposes a conceptual model for built environment prototyping, that combines the insights from established theories to enhance project outcomes.

Keywords: Computational Design, Digital Fabrication, Prototyping, Timber Structures

1 Introduction

Stojanovic et al. (2023) present the conceptual design for an evaporative cooling system, comprising multiple ECUs, that utilizes a predictive algorithm to customize the cooling effect according to local weather conditions, and tailored to the number of current occupants. A dendritic form was chosen for the ECU structure designed by the researchers due to its ability to satisfy the performance requirements of an outdoor evaporative cooling system in the Australian context. Design guidelines on evaporative cooling recommend each source be installed at a height of 3 meters, effectively covering an area up to 5 meters in diameter, with a maximum dispersal angle of 70° (Osmond & Sharifi, 2017). The use of a dendritic form enables these guidelines to be achieved, as it helps to disperse water vapor from a single input point across a wide area. Accompanying the work of Stojanovic et al. is the schematic design for an ECU that the researchers prototyped at 1:2 scale using 3D printing. The next step is to translate the design to a full-scale working prototype. Having one (or more) completed prototypes allows subsequent investigation about how multiple units perform, and explore potential inclusion with a digital twin for performance prediction purposes.

This paper investigates the development and testing of a timber dendriform evaporative cooling unit (ECU) prototype (Figure 1), produced as a result of a research-led teaching initiative in 2022 at the Melbourne School of Design through the unit; DF_Lab: Designing Making (DF_Lab). The paper reviews evaporative cooling and dendetric structures in architetcure, to examine significant prototyping theories and their application to the ECU case study. The methodology section outlines the approacch to research that is based on design science and case study. A case study provides practical context, documenting the design, development, and evaluation of a full-scale ECU prototype. By reflecting on this project through the lens of prototyping theory, the study proposes a novel framework for built environment prototyping, emphasizing the integration of digital and physical mediums, and the importance of systematic validation at each stage. The discussion evaluates the project's achievements and limitations, compares it to existing work, and concludes with recommendations for future research, including the refinement of the model and optimization of ECU performance.

Figure 1 - Full-scale prototype ECU in operation

2 Literature Review

2.1 Evaporative Cooling

The Urban Heat Island (UHI) Effect is the term that is used to describe the accumulation of heat in urban settings that is generated by the built infrastructure and has been shown to dissuade people from using outdoor spaces that can in turn negatively affect the health of a population (Shahmohamadi et al. 2011). Evaporative cooling through the use of misting systems has been demonstrated to be a desirable solution to combat the UHI due to its effectiveness, and efficiency (Ulpiani et al. 2019). ECUs can be used to remove heat from the atmosphere and have been shown to be more effective than refrigerative air conditioners in dry climates of many Australian cities. Ford et al. (2012) showed that evaporative cooling systems can be used to achieve comfortable thermal conditions while delivering significant energy savings. Kim and Jong (2013) demonstrated that evaporative cooling systems can save 51% more energy conventional variable air volume cooling systems in particular climates at different times of year. The effectiveness of ECUs has been demonstrated to increase through the augmentation with physical computing systems or artificial intelligence (Asfahan et al.,2021). When incorporated into a digital twin that predicts system performance, evaporative cooling systems have been shown to contribute to the delivery of notable power savings of between 44 % and 47% (Golizadeh Akhlaghi et al., 2020). Such systems have also shown potential to be paired with Computer Aided Facility Management

(CAFM) tools, to present real time information abut energy and cooling, and to inform cost-benefit of temperature adjustments (Zhen et al., 2015).

2.2 Dendritic Structures in Architecture

Dendritic structures can be considered a form of biomimicry due to their close resemblance to trees (Sreelakshmi, 2023). Possessing a unique aesthetic, dendritic structures have been utilized in architecture in various forms across history, particularly in public architecture such as the unfinished Sagrada Familia by Antonio Gaudi, or the Qatar National Convention Centre by Arata Isozaki in 2011 (MD Rian and Sassone, 2014). They are usually favored due to their ability to efficiently transfer surface load to a single point on the ground (Zhao et al., 2018). The current state-of-the-art of dendritic structures in architecture concentrates on innovative fabrication and algorithmic design methods, and less on utilizing their innate qualities for sustainable design outcomes (Bao et al., 2022; Freitas and Leitao, 2019).

2.3 Prototyping

A prototype is essentially the first full-scale version of a new design, equipped with some functional capabilities (Zelenko and Maxwell 2023). Prototyping is a common practice in product development across various fields, each with its own unique methods. Prototyping theory helps contextualize the complexity of projects by providing frameworks to discuss critical aspects of different prototype types. Camburn et al. (2017) outlines four objectives of prototyping as refinement, learning, communication, and exploration. Houde and Hill (1997) introduce an influential model of prototyping in software development, comprising three types: Look and Feel, Implementation, and Role, which can collectively form a fourth type: Integration. In this model, "Role" refers to the functional aspects of a product and its impact on the user's life. "Look and Feel" focuses on the tactile and visual sensory experiences a user has while interacting with the product. "Implementation" deals with the technologies or programming methods used to achieve the product's intended Role. "Integration" prototypes combine these three aspects, providing a preliminary version of the final product to gain a comprehensive understanding of the overall design.

Ullman’s (2010) prototyping classes link prototype production to design process stages: Concept, Product, Process, and Production. Each prototype created serves as a representation of information that characterizes a specific product or design. Ullman’s model is useful because prototypes are used as confirmation devices to indicate successful completion of project milestones. This staged approach helps in systematically validating design choices at each phase, ensuring that critical requirements are met before progressing to the next stage. By doing so, it reduces risks and uncertainties, facilitating a smoother transition from conceptual ideas to fully functional products.

Comparatively analysing these methods, Houde and Hill's model provides a detailed framework for understanding different aspects of a prototype, making it particularly valuable for iterative development where feedback on various dimensions (look and feel, role, implementation, integration) is essential. Ullman’s approach emphasizes the alignment of prototypes with distinct stages of the design process, serving as checkpoints that ensure progress and goal alignment. While Houde and Hill’s model offers a holistic view of a prototype’s functionality and user interaction, Ullman’s method provides a structured roadmap for tracking design maturity and completion, highlighting the use of prototypes as important validation tools throughout the development lifecycle. The case study project implicitly adhered to Ullman’s model. This was due to its structured approach, which aligns prototypes with distinct design process stages. This method facilitated systematic validation of design choices and reduced risks, ensuring a smoother transition from conceptual ideas to a fully functional ECU prototype.

3 Methodology

This study employs a Design Science Research (DSR) methodology, which is well-suited for projects involving the creation and evaluation of artifacts. DSR focuses on building and assessing prototypes to generate both practical and theoretical knowledge, as described by Hevner et al.

(2004) and Vaishnavi and Kuechler (2015). The evaluation of the ECU prototype aimed to confirm the feasibility of constructing such a complex structure from timber at full scale and to assess its functionality as an evaporative cooling unit. Following the evaluation criteria recommended by Peffers et al. (2012), the feasibility assessment focused on the structural integrity and precision of the CNC machined components, ensuring the timber material could sustain the complex dendriform structure. Performance testing primarily involved qualitative measures, such as visual inspections and user feedback, to assess the ECU's cooling effectiveness in an outdoor environment. Although specific quantitative data on temperature reduction and energy efficiency were not collected during this phase, the prototype's performance was qualitatively compared with standard evaporative cooling systems to verify its efficiency and effectiveness.

Additionally, this research is presented as a case study, emphasizing the real-world application and contextual relevance of the ECU prototype. Case study research, as highlighted by Yin (2018), is particularly valuable for providing in-depth insights into complex phenomena within their real-life contexts. By documenting the design, development, and evaluation processes of the ECU prototype, this case study contributes to the understanding of prototyping in the built environment. It offers practical implications for future research and development in architectural and engineering projects, demonstrating how computational design, digital fabrication, and rigorous testing can be integrated into effective prototyping frameworks.

4 Case Study Project Description

4.1 Design Process

Implementing a dendritic formal quality of the proposed ECUs created a novel aesthetic, not usually found in urban evaporative cooling systems, in addition to facilitating an even coverage of water mist. The initial proof-of-concept prototype was 3D-printed in nylon on a HP Multi-Jet Fusion machine, using proprietary printing technology that possesses a fast print time, and high strength of printed parts. It was not feasible to use this method to create the components for a full scale prototype due to cost (estimated at $23,000 AUD), and the need for water resistance, which led to the selection of CNC-machined timber as an alternative fabrication strategy. This choice required the construction details utilized on the project to be updated. The initial prototype consisted of 56 parts that were connected using a rectangular extrusion mortice and tenon detail, concealed with a zig-zag collar to increase the surface areas of mating surfaces. These geometries possessed complex areas that featured; right, and acute angles, between adjacent faces, and would require extensive post-processing if milled using a 3-axis CNC machine. As the number of elements possessing these conditions was high, a re-design was required to create a detail that could fabricated is a simpler way. In addition to complexity issues, all parts required internal ductwork for water piping to be located, that a 3-axis CNC can't produce, and warranted the halving of parts for milling, ahead of subsequent adherence. While this produced extra process steps for the project, it also aided the material, and fabrication strategies as it allowed thinner, cheaper timber to be utilized, minimizing the need for lamination. Having two halves that were joined together through a middle mating surface also meant that this surface could be utilized for work-holding. To respond to these new design constraints, a revised connection detail needed to be designed to reflect the chosen fabrication strategy, but also maintain the existing design intent where possible. As the configuration of these details needed to change according to prototyping and material feedback, and be amended to 56 parts of the design, parametric modelling was utilized to; manage and automate this process.

Timber is an anisotropic material and its properties vary across three perpendicular planes (Martínez-Sala et al. 2013). This factor had to be accounted for in the detailing of the node pieces. Similarly-designed timber parts are often produced from over-sized blocks of stock material. This strategy is simple, but produces an excess waste, and can also lead to weaker parts due to the anisotropy of timber. To minimize material usage on the project, nodes were designed to be produced from stock that followed the direction of a node's branches. All nodes in the design consisted of 3 branches that were optimized to be located on the same plane and enabled each to be split in half evenly for production. Halves were then split into 3 parts, bisecting the angle of each branch curve, to create 2 groups of 3 pieces. A three-way irregular tongue-and-groove joint was created to join the pieces of each group together (Figure 2). The joint was designed to; be proportional to each node, maximize the area of mating surfaces for gluing, and minimize any grain interruption to prevent instances of splitting failure.

4.2 Parametric Modelling Of The ECU

Caetano et al., (2020) refer to parametric design as a subset of computational design, as a design approach that utilizes parameters to define and manipulate sets of designs. As a form of computational design, parametric modelling allows the inclusion of material information into the design process and can be used to drive sustainable architectural outcomes (Yazici and Tanacan, 2020). Janssen and Stouffs (2015) define a parametric model as consisting of a collection of different modelling operations, that are linked to form a network, and has a defined order of execution.

Parametric modelling was chosen to manage the refining of construction detail on the project, as it facilitates the management of various modelling operations and design parameters. Grasshopper for Rhino was the environment that was utilized for this purpose, as it provides a strong, and flexible parametric modelling environment, that can be augmented by additional plugin extensions, and custom-programmed operations where required (Figure 2). In relation to the context of the proof-of-product prototype, Grasshopper was used to manage; the initial transfer of project design data, the restructuring of design data, all revised modelling operations, material estimation and optioneering, and fabrication data generation and layouting. Python scripts were used to efficiently nest all parts within the required laminations of readily available thicknesses, and widths of spotted gum (25mm, and 50mm, and 75mm). Another script used a bin packing algorithm to optimize and nest all parts into increments of a predetermined timber board length, to output material and costing information, along with creating shop drawings to assist with timber machining.

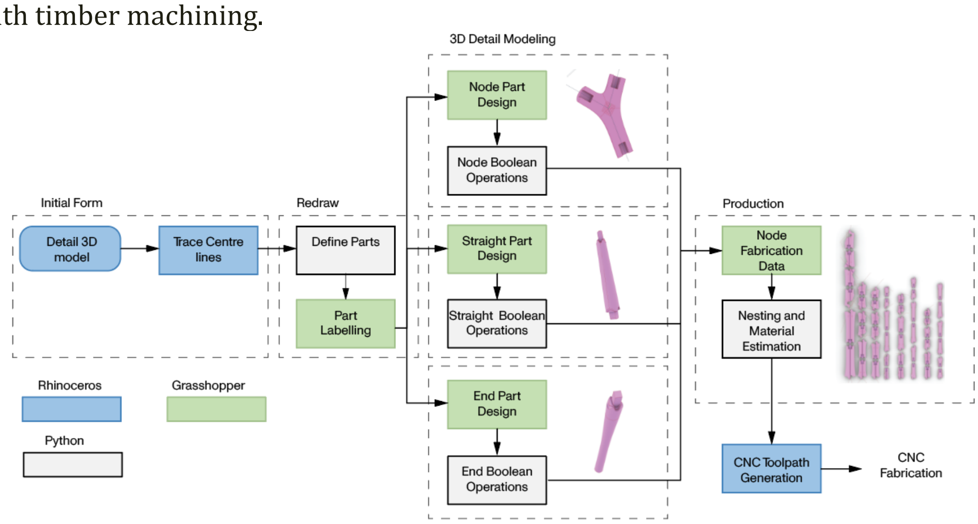


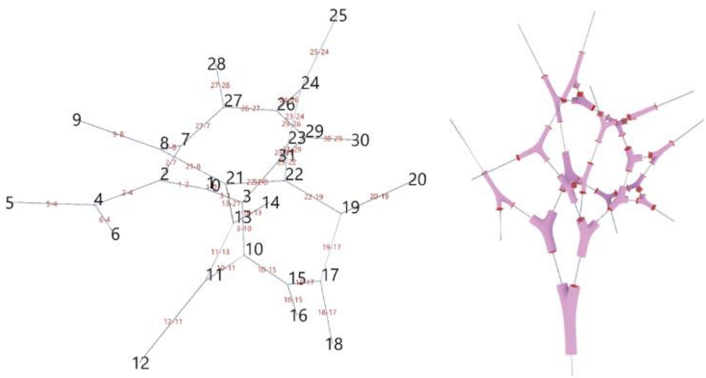
Figure 2 – Computational workflow of Project

The dendritic form of the ECU can be described as a series of interconnected branches and was broken down into three kinds of common parts to aid production; nodes, edges that connect two nodes, and edges that are only connected to one node. Various modelling operations required geometry from different combinations of nodes and edges, in an irregular manner determined by the overall form. Relying on brute force-based approaches was computationally-taxing, and filtering based on distance provided inconsistent results. An approach to restructure this design data was inspired from an abstraction of its form.

4.3 Utilizing Graph Theory

Graphs are basic geometrical representations that consist of nodes, that can be connected by edges that can be used to represent any system based upon binary relation (Chen 2012). At its most basic, this is interpreted as "*an ordered pair of disjoint sets (V, E) such that E is a subset of the* *set V(2) of unordered pairs of V*" (Bollobás 1998). For graph G, the node set of G is V = V(G), and the edge set of G is E = E(G). Vertices {x,y} can be connected by an edge {(x,y)}. Vertices are seen to be adjacent if they are connected through an edge. Graph theory was used to structure the design process. Heteroptera is a plug-in for grasshopper that was used to facilitate the application of graph theory to the project. Centrelines were traced along the extents of the original 3D model to create a network of interconnected lines (Figure 3) that could be input to the Incestuous curve Network component to compute a graph.

The output sets (V and E) were used to isolate node and edge geometries using Python (Figure 4). The previous workflow was also used to in subsequent solid modelling operations to select particular geometries for Boolean operations to re-detail the project to minimize computation time. The use of the graph as a data structuring method proved useful to filter the geometry into relevant streams for appropriate modelling, in a computationally-efficient manner.



Figures 3 and 4 – Graph Diagram of Project, and Isolated Nodes Implemented in Python

5 Results

5.1 Production Strategy

The ECU comprised; 20 nodal pieces, 25 straight section pieces and 11 end pieces, all unique in their size and shape ranging from 960mm to 300 mm long. This informed the manufacturing logic of the structure, and the following criteria was considered: ability to nest within standardized pieces of spotted gum; ability to be milled on both sides of the material with ease; ability to locate the flipped material easily for repeatability; fast machining with standard tool sizes; and, for the toolpath programming to be easy and fast. To house the tree structure's internal misting piping, each part needed through-boring. To achieve this on a 3-axis CNC machine, flip-milling was utilized where the stock material is manually flipped and located on the bed to enable the toolhead to mill the required geometries. This process pushes the limits of the machine used and can potentially introduce tolerance discrepancies and defects due to misalignment. To avoid this, it a jig system and flipping process was used was designed incorporating locating pins to ensure accurate results (Figure 5). Due to the amount of parts, and limited time for fabrication, it was imperative the timber work-holding and part manufacturing was fast, reliable and repeatable.

Utilizing the above approach to fabrication minimized the amount of production time needed to complete the project as CNC milling could be completed efficiently, and production was able to be streamlined that saw multiple parts completed in a single cycle. This helped keep production time down, where milling time for the entire project was between 200-250 hours, and cost between $12,000 -$15,000.

5.2 Outcome, Testing, and Performance

Some challenges had to be overcome to enable the successful assembly of the parts of the ECU prototype, that are unpacked as lessons learnt in the discussion. Parts were joined together with construction adhesive to form four large modules that could be clamped and allowed to dry on the ground. This helped to minimize the amount of work that had to be carried out high off the ground. It also facilitated the installation of the piping that carried the water for the misting system. Piping was first threaded through the base 'trunk' module that was fixed to a fabricated metal housing (Figure 7). Next, subsequent modules were installed and adhered, and each allowed to dry ahead of installing the next module. This process was laborious, but necessary to ensure enough time for the adhesive to dry. Finally, nozzles were installed onto the pipes at the location of six end pieces for testing purposes.

The testing of the misting system of the ECU prototype involved collaborating with an external partner, OZmist, who managed the commissioning of water misting system. OZmist installed a proprietary pump module that pressurized water from an onsite outlet to around 1000psi. The pressurized water is then run through the piping inside the structure, and when forced through the installed nozzles, a fine mist is created. When first turned on, there were small issues arising from the fitment of the nozzles requiring slight rectification. This subsequently led to the successful operation of the prototype ECU that was indicated by the successful operation of the system for multiple periods of twenty minutes. As this iteration of the ECU was a proof-of-concept prototype, success on the project was to be determined by the complete fabrication and assembly of the timber ECU, combined with successful operation of the misting system. As both criteria for the project was met, the prototype ECU was deemed to be successful.

Figures 5,6, and 7 – Jig system on CNC bed, Nodal Connection Detail, Assembly Process of ECU

6 Discussion

6.1 Lessons Learnt - Post-Processing Challenges

In the execution of this project, a few manufacturing discrepancies were encountered, requiring corrective measures prior to the gluing and assembly phase. Some of these problems stemmed from human error, or timber 'blow-out' in relation to the tool pathing process, and could be rectified easily. Others were more systemic, and required considerable rectification. The milled pieces from several nodes didn't align correctly, with their mating surfaces possessing a slight taper. This compounded the difficulty in trying to achieve end grain to end grain adhesion of node pieces. The application of epoxy resin as filler served as solution, but the problem persisted across multiple parts (Figure 6). An upwards curving of parts towards the surface milled by the CNC machine was also observed, that pointed to timber bowing due to uneven material removal. This material deformation due to the machining process is a phenomenon that partially explains the mating surface deformation outlined previously. This discussion illuminates the various challenges encountered in the production process, particularly emphasizing the occurrence of unexpected challenges, and the need for a prototyping strategy to mitigate such issues on future projects.

6.2 Proposed Conceptual Model for Built Environment Prototyping

To address the unique needs of prototyping in the built environment, a model for built environment prototyping is proposed that combines the aspects of Camburn et al, Ullman's and Houde and Hill's frameworks, with the innate nature of production in the built environment — construction (Figure 8). This nature of production is commonly referred to as construction 'peculiarities' and consists of; site production, temporary organizations, and one-of-a-kind production (Vrijhoef and Koskela, 2005).

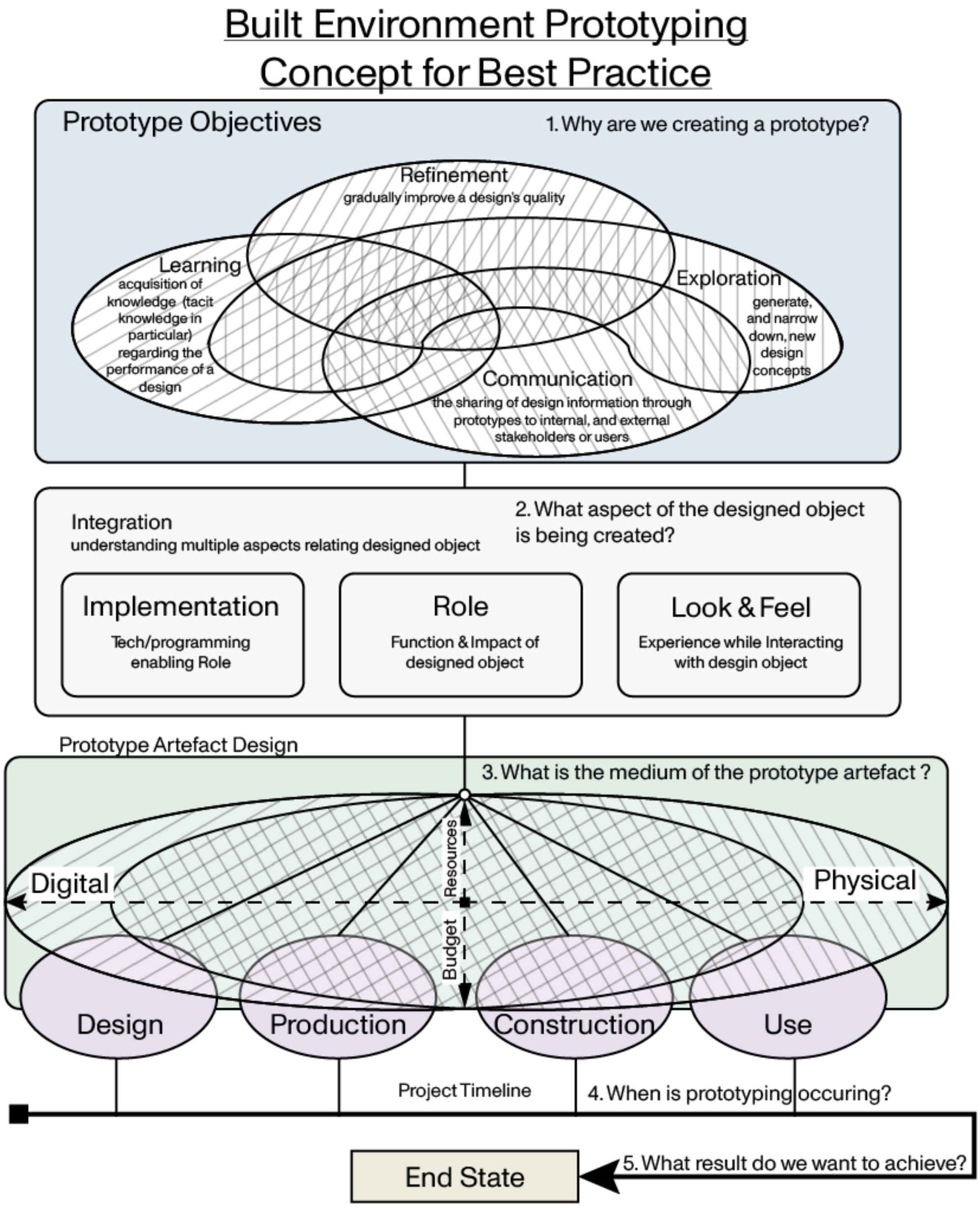


Figure 8 – Built Environment Prototyping – Conceptual Model

This conceptual model is structured to prioritize prototype conceptualization, through directing users to first define an end state, and outline reasons for why the process is needed. Additional questions are asked about what is being tested that are derived from Houde and Hill, the nature of the prototyping medium (physical, digital, or a combination), and what phase of the project delivery process is prototyping taking place (inspired by Ullman). The model acknowledges that outcomes in the built environment often require the creation of combinations of digital and physical artifacts, like digital twins. It also emphasizes the necessity to meet project deadlines, a critical aspect of Ullman's model, while considering the significant time, money, and resources involved in large-scale projects, aligning with Houde and Hill's focus on prototype categorization. By integrating these approaches and transplanting them to the built environment context, the proposed model provides a structured and flexible framework that accommodates the complexity and scale of built environment projects. This hybrid model aims to streamline the prototyping process, reduce risks, and enhance the overall quality and performance of architectural and engineering projects.

7 Conclusion

ECUs have the potential to significantly mitigate the UHI Effect in an energy-efficient manner . This project demonstrated that computational design and digital fabrication can be leveraged to produce an ECU of novel design, but also illustrates that complex design and production methods aren't a simple file-to-factory paradigm. These kinds of production methods need to be augmented by real-world material knowledge, gleaned from subject-matter experts, or generated through a rigorous prototyping process. As evidenced by the case study project, this helps to iron out bugs that can reduce the amount of rework required in the future. The case study project could have been completed in less time, and with less challenges, had the design process been helped by a structured approach to prototyping activities.

There exists a gap in knowledge about an appropriate framework for built environment prototyping. This paper has used a reflective case study project to propose a conceptual model aimed at helping practitioners in the built environment have a greater understanding of the prototyping process. The proposed conceptual model for built environment prototyping offers a hybrid framework that combines the strengths of existing prototyping theories with the unique nature of construction. This model emphasizes the importance of defining clear end goals, understanding the specific aspects being tested, and balancing digital and physical prototyping mediums. By addressing the peculiarities of construction, such as site production and one-of-a-kind production processes, this model aims to streamline the prototyping process, reduce risks, and enhance overall quality and performance in the built environment. Future research should refine and validate the conceptual model across with input from industry experts and further studies. Future research work can further develop the ECU design for broader application. This would involve collecting quantitative data on performance metrics, such as temperature reduction and energy efficiency, and implementing a digital twin for system optimization. These efforts will enhance the prototyping framework and offer valuable insights for similar projects in the built environment.

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