Merging Tradition and Technology: A Zero-Waste Approach to Customizable Clay Facade Systems with Integrated Vegetation

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Abstract

This research explores a novel method for creating customizable clay façade tiles with integrated planters using robotic milling and 3D printing, positioned within the context of sustainable architecture and building performance. Addressing the theme of the BTES 2025 Conference, which emphasizes the integration of architecture and technology, this study investigates how advanced fabrication techniques can enhance water management and potentially increase biodiversity in urban environments. The methodology involves robotic milling of clay formwork, 3D printing of cross-laminated clay slabs optimized for water flow and slumping these slabs over the milled molds to create functional and customizable tiles. Preliminary testing of a half-scale mockup indicated promising water channeling capabilities to integrated planters. This study contributes to the ongoing exploration of how technology can inform sustainable architectural practices.

Introduction

This research aligns with the theme of the BTES Conference 2025, "Historically, shifts in building technology and methodologies have generated changes in the expression and form of architecture"[1]. This conference theme draws inspiration from Eugène-Emmanuel Viollet-le-Duc, who stated that the integration of architecture and technology is necessary to create an honest reflection of societal values, environment, and culture[1]. Advancements in building technology continuously shape architectural expression and functionality, driving innovative design solutions to address contemporary challenges. Integrating traditional materials with modern fabrication aligns with Eugène-Emmanuel Viollet-le-Duc's view that architecture should harmonize with technology to reflect societal values[1]. This balance is critical for sustainable construction.

This research, originating from a graduate technology course, explores performative facade systems using computational design, digital fabrication, and robotic manufacturing. It extends terracotta tiles beyond roofing to enhance water management and sustainability. Unlike conventional gutter systems that prioritize rainwater removal, this project incorporates water retention within the facade.

The central research question is: How can robotic milling and 3D printing be utilized to develop customizable clay tiles with integrated planters that enhance water management and adhere to zero-waste principles? This study positions clay as a versatile material addressing ecological concerns, contributing to the BTES conference theme by demonstrating how technology can enhance architecture's performance, sustainability, and cultural relevance.

Literature Review

This project integrates planters into a modular facade system to optimize rainwater capture and support plant growth.

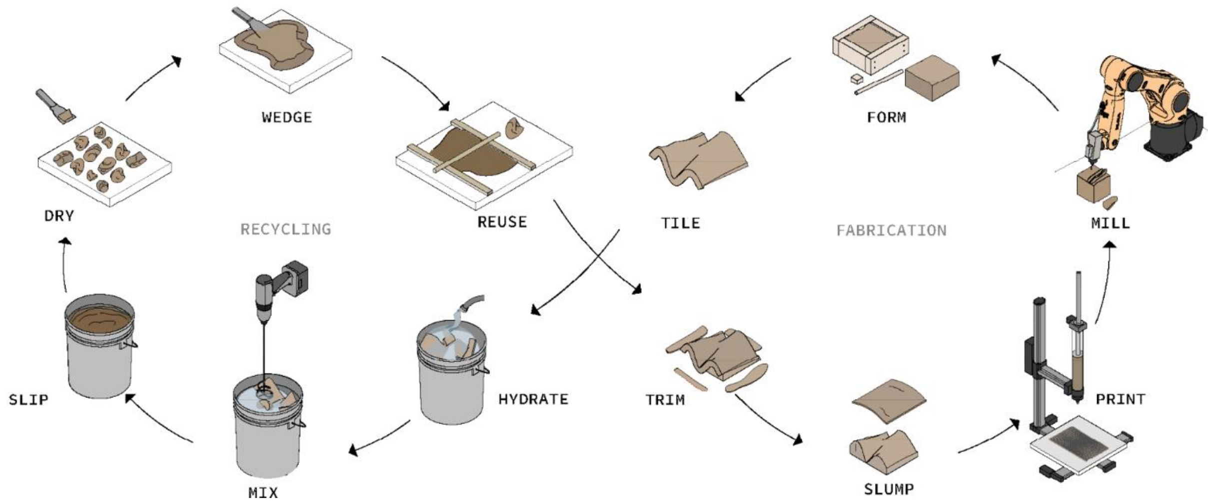


Fig. 1. The recycling workflow is on the left, and the fabrication workflow is on the right. Highlighting the closed-loop system.

Sustainable Architecture

The CO-MIDA[2] project offers a compelling example of an integrated system, utilizing 3D-printed clay modules as vertical gardens for edible plants in urban environments. This aligns with the broader trend in sustainable architecture, where materials like locally sourced clay are used, as seen in the Tile Nest House[3] in Vietnam.

Advanced Fabrication Techniques

The Cabin of 3D Printed Curiosities[4] highlights the potential for customized textures in 3D-printed ceramic tiles, but also reveals constraints, such as limitations in printer angles. The WAFT[5] project addressed similar challenges by printing flat tiles on plastic wrap and draping them over reusable foam molds—a strategy that influenced our choice to use robotic milling for mold creation. Projects like Woven Clay[6], Robosense 2.0[7], and Clay Non-Wovens[8] demonstrate the capability of robotic deposition combined with traditional reusable foam or plaster molds to achieve formal complexity. These precedents inspire our use of robotic milling for formwork. However, this study advances these methods by employing non-fired, robotically milled clay formwork as molds for flat clay tiles printed on plastic. This combination allows for leveraging the precision of robotic milling for complex mold geometries while using a straightforward and more efficient flat 3D printing process for the tiles. This approach aims for a fully recyclable system and performative logic, optimizing the tiles for water movement and the integration of plants. This research builds on the draping technique seen in WAFT[5] while utilizing robotically milled foam molds, while this research uses reusable, unfired clay to reduce waste.

This research explores new directions in performance-driven facade systems by integrating computational design, and additive manufacturing.

Methodology

This research adopts a systematic approach to develop a customizable clay facade system that integrates planters and enhances water management capabilities. The methodology comprises several key stages, each designed to optimize both the performance and sustainability of the clay tiles.

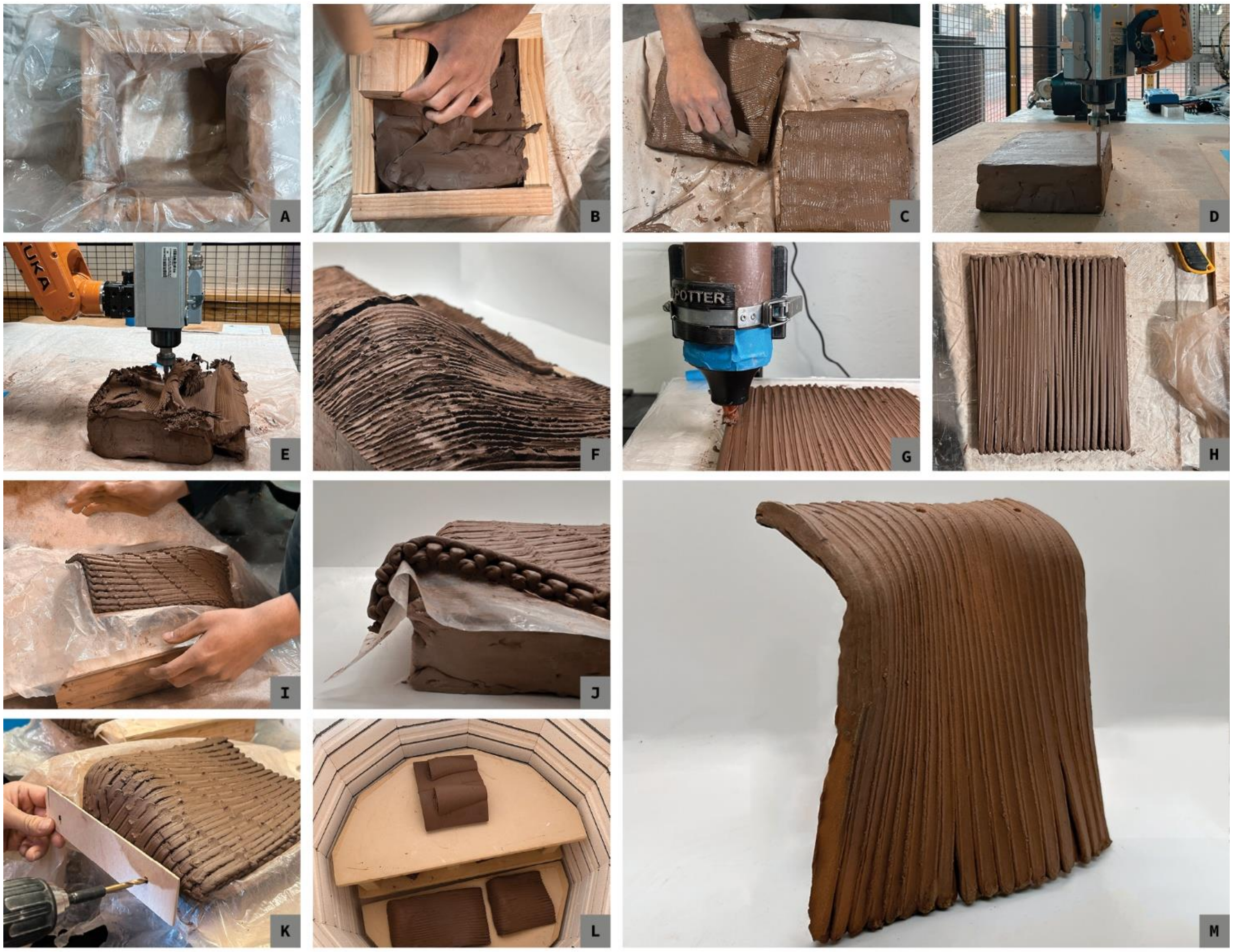


Fig. 2. (A) Plastic sheet placed in a wooden frame. (B) Pressing and molding clay for milling. (C) Combining two blocks into one. (D) Preparing block for milling. (E) Robotic milling. (F) Milled formwork. (G) 3D printing clay tile. (H) Finished slab. (I) Slumping slab onto formwork. (J) Aligning fastening edge. (K) Drilling precise holes. (L) Firing tiles. (M) Final tile.

Tile Fabrication Process

The fabrication process (Figure 1) begins with the formation of clay blocks within a reusable plywood formwork (Figure 2, Images A). The clay is loaded incrementally and carefully compressed using a wooden block and mallet (Figure 2, image B). This compression process eliminates air pockets, resulting in a solid material suitable for further processing.

Once the clay blocks are prepared, the next phase involves robotic milling. A KUKA KR10 R1100 robotic arm is utilized to mill the clay blocks using a quarter-inch end mill (Figure 2, image D). The choice of this specific end mill strikes a balance between detail and efficiency, enabling the creation of intricate mold geometries while maintaining reasonable material removal speed. This advanced milling technique allows for precise customization of molds, ensuring that the final tile shapes effectively respond to specific environmental conditions, such as shading, rainfall, and vegetation placement.

Subsequently, a 3D PotterBot 10 PRO clay printer fabricates the clay slabs on a plastic substrate (Figure 2, Image G), which is essential for facilitating the slumping process. During this stage, cross-laminated clay layers are printed, with the top layers oriented to optimize anticipated water flow. This design choice enhances both water movement over the tiles and the structural integrity of the slabs, mitigating cracking risks during the slumping process (Figure 2, image I).

The slumping process is crucial as the 3D-printed clay slabs are positioned over the milled molds to form the final tile shapes (Figure 2, image J). To prevent cracking during the drying phase, the clay is covered with plastic to slow desiccation. Depending on environmental conditions, the drying period ranges from two to four days.

After drying, precise holes are drilled using an eighth-inch drill bit and a custom plunging jig (Figure 2, image K).

The next step involves bisque-firing the clay at cone 5 in a kiln (Figure 2, image L). This initial heating process transforms the soft clay into a hard, porous material, ready for final assembly.

Material Considerations

Clay was chosen for its sustainability, low carbon footprint, and cost-effectiveness. As a renewable, locally sourced material, it reduces transportation emissions and supports local economies. The project embraces a zero-waste approach by recycling excess clay from milling and trimming, creating a closed-loop system (Figure 1).

At around 50 cents per pound, clay remains an affordable alternative to energy-intensive materials. 3D printing optimizes material use by depositing clay only where needed, significantly reducing waste while enhancing fabrication precision.

This sustainable approach maximizes efficiency while reinforcing clay's potential as a viable material for innovative facade systems.

Design Development of Water Channeling Tiles

The design development phase involved rigorous exploration of form and functionality. Initial inspiration stemmed from the curvature of traditional roof tiles and gutter designs, inherently suited for channeling water. Using Rhinoceros 3D modeling software and its visual scripting language, Grasshopper, tiles were crafted with variable sizes, textures, and intricate patterns tailored to optimize water flow.

Physical models were employed to assess water flow across different tile shapes. To simulate rainwater conditions, water was poured over a two-tile mockup mounted at an angle. The tiles were weighed before and after water application, and the volume of water was also measured pre- and post-test to determine absorption and runoff. This setup allowed for assessing each tile's performance in retaining and redirecting water. This iterative design process yielded critical insights into the relationship between form and functionality, culminating in the development of four key tile iterations (Figure 3).

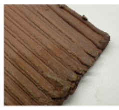
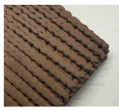
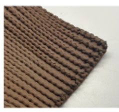
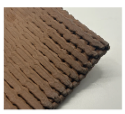
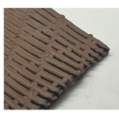
TILE TYPE		WATER WEIGHT BEFORE	WATER WEIGHT AFTER	TILE WEIGHT BEFORE	TILE WEIGHT AFTER	COLLECTION WEIGHT RATE
	VERTICAL TILE	54.4	49.8	85.1	83.4	7.16%
		54.4	50.5	85.1	88.7	
		54.4	51.0	85.1	89.2	
		54.4	50.7	85.1	88.9	
	LATTICE 00	73.4	70.7	100.6	101.8	4.63%
		73.4	69.4	100.6	104.7	
		73.4	69.8	100.6	104.1	
		73.4	70.1	100.6	104.6	
	LATTICE 01	54.4	49.8	86.8	89.1	6.75%
		54.4	50.3	86.8	88.7	
		54.4	51.4	86.8	90.9	
		54.4	51.2	86.8	88.3	
	DIAGONAL 00	73.4	70.7	76.8	77.6	4.66%
		73.4	70.3	76.8	80.8	
		73.4	69.5	76.8	80.3	
		73.4	69.4	76.8	79.7	
	DIAGONAL 01	49.8	49.8	75.7	83.4	7.98%
		49.8	46.5	75.7	79.1	
		49.8	45.7	75.7	78.8	
		49.8	46.9	75.7	79.0	
	DIAGONAL 03	63.3	55.0	84.1	86.2	6.97%
		63.3	60.0	84.1	85.7	
		63.3	60.1	84.1	87.7	
		63.3	59.2	84.1	86.8	

Fig. 3. Images of the tile designs with their performance evaluation regarding water retention.

First Iteration: This version utilized hand-rolled slabs, which proved less effective. Manual fabrication required significant time and expertise, limiting efficiency. Second Iteration: Fabrication shifted to 3D printing the tiles in a singular direction to better drape over the clay mold and direct water. However, this approach led to issues with tiles splitting due to steep slopes in the mold. Third Iteration: This iteration incorporated cross-laminated 3D-printed layers, providing lateral support to prevent tearing and enhancing structural integrity. Fourth Iteration: This phase investigated textured designs and patterns on the tile's top layer to augment both functionality and aesthetics.

Sustainability was a paramount consideration throughout the design process. The tiles not only collect rainwater but also channel it into integrated compartments for plants, fostering a self-sustaining ecological system. Moreover, decorative elements introduced through 3D printing enhance aesthetic value without compromising functionality.

Assembly Method

To test performance, a half-scale mockup was constructed using wood as a substitute for steel (Figure 4, 5). The tiles were slumped over milled molds, creating a fastening edge for easy attachment with minimal hardware. Precision-drilled holes ensured uniformity for effective water management and plant integration.

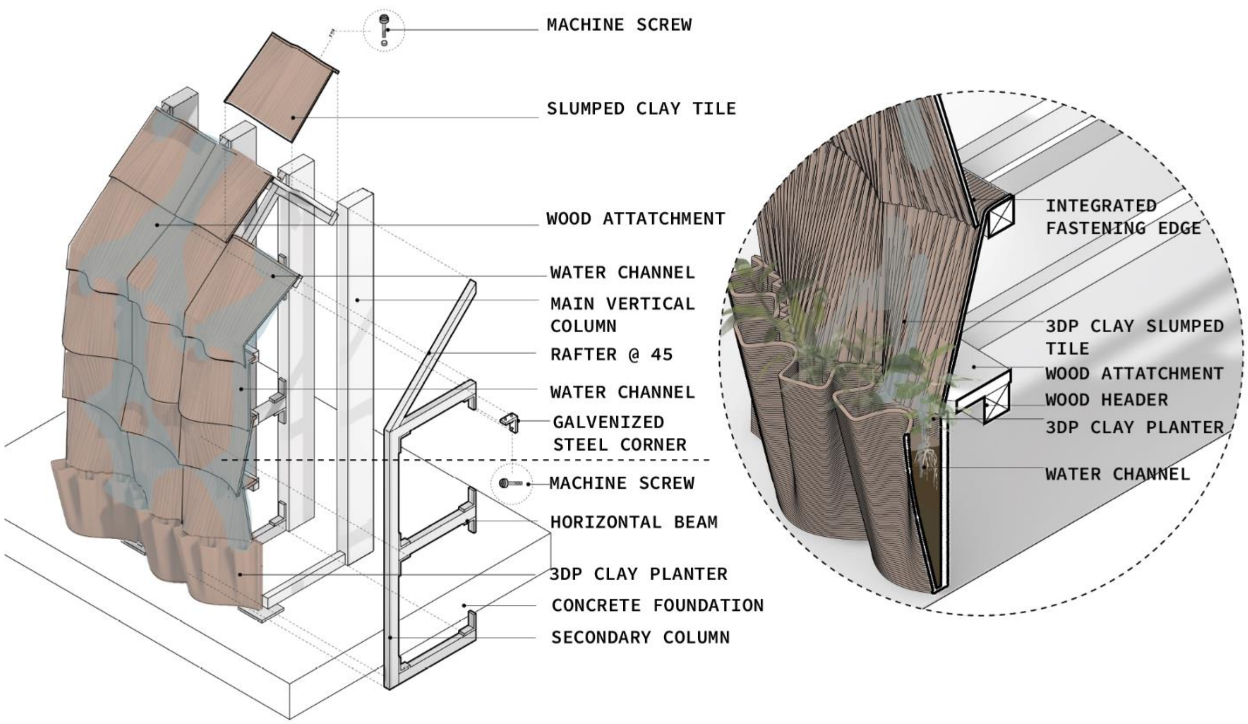


Fig. 4. Detailed drawing showing all materials used.

Tiles were systematically arranged to overlap, minimizing gaps and ensuring uninterrupted water flow. A total of 15 tiles were produced and tested, along with three 3D-printed clay planters to enhance ecological functionality.

This approach provided a realistic evaluation of both structural and functional performance, informing refinements for future iterations.

Sustainability and Aesthetics

This fabrication workflow aims for zero-waste production while enhancing aesthetics. The tiles collect and channel rainwater, and integrate planters, in an attempt to create a self-sustaining ecological system. 3D-printed decorative elements enrich the facade, merging function with artistry. This research demonstrates a customizable clay facade system that integrates water management and vegetation, advancing sustainable architecture and innovative building technology. It informs architectural practices and inspires future research on harmonizing ecology with design. Showcasing clay's modern potential, this work highlights sustainable practices in addressing environmental challenges.

Results and Discussion

The customizable clay façade system demonstrated significant potential in both water management and vegetation integration. The project successfully produced tiles that channel rainwater and support plant growth, employing advanced fabrication techniques such as robotic milling and 3D printing.

Water Management Performance

The tile system's water management efficiency was evaluated through controlled experiments measuring water collection and flow (Figure 3). The final iteration, featuring cross-laminated 3D-printed layers, demonstrated an average collection rate of 6.45% of poured water. Among the iterations, the diagonal 01 tile performed the best, retaining 7.98% of the poured water, while the lattice 00 tile—printed using a single-direction G-code—was the least effective, with a retention rate of 4.63%. These results highlight the impact of print pattern orientation on water performance.

The tiles' curvature and channels facilitated rainwater flow, minimizing pooling and maximizing drainage efficiency. The design's water retention features have the potential to reduce evaporation loss and maintain consistent soil moisture in the integrated planters, potentially lessening the need for external irrigation.

Integration of Vegetation

The system also successfully integrated planters, supporting initial healthy plant growth. Preliminary tests show that the system might support a variety of plant species and adapt to different climates, though more extensive, long-term testing is needed to verify these findings. The integration of vegetation offers aesthetic benefits and the potential to improve air quality and promote urban biodiversity.

Mockup Assembly Challenges

The initial assembly of the two-tile mockup utilized thin wood pieces shaped to conform to the tile curves; however, the need for precise cutting resulted in significant material waste, resulting in the current substructure. As the project scaled up to 15 tiles, a transition to a 3D-printed clay slab was made to enhance size and quality consistency. Despite this improvement, height variations from the milled surface emerged, necessitating the addition of support pieces. This experience underscores the critical need for meticulous fabrication planning and the importance of design refinements in subsequent iterations.

During bisque firing, an 11% shrinkage was observed, which misaligned the tiles with the pre-modeled substructure and prompted a redesign. Addressing shrinkage in the initial phases of the design process is expected to facilitate smoother assembly in the future and could potentially reduce build time by up to a week.

These challenges highlight the necessity of precise fabrication planning to ensure seamless integration and minimize material waste throughout the assembly process.

Fig. 5. Images of the assembly.

Overview

Robotic milling and 3D printing enabled extensive customization of tile design, allowing for unique

Fig. 7 (A) close-up of the tile attachment. (B) side view of the entire assembly. (C) water moving across the tiles. (D) front view of the tiles as they dry. (E) close image of the water passing over the tiles.

textures tailored to optimize water flow and enhance the composition of the assembly. Parametric design facilitated experimentation with patterns, ensuring both functionality and adaptability for complex facades.

3D-printed decorative elements improved the visual appeal while serving practical functions like water management and microhabitat creation. The project followed a zero-waste philosophy, utilizing locally sourced, recyclable clay to reduce its carbon footprint and support sustainable practices.

While integrating vegetation offers numerous benefits, ongoing maintenance and plant species selection remain key considerations. Future iterations will refine irrigation methods and adapt designs for varied climates, ensuring long-term performance.

This research demonstrates how customizable clay facade systems merge traditional materials with advanced fabrication, paving the way for innovation and sustainable architectural solutions.

Future Research and Development

Tile Fabrication and Design Improvements

The initial design lacked a consistent fastening edge for seamless attachment. Future iterations will refine the clay mold by milling a flat upper surface, ensuring uniform edges for easier assembly.

Following the 15-tile assembly, the clay 3D printer was used to explore intricate surface patterns that enhance water retention. Ongoing experimentation with G-code aims to optimize porous, cross-laminated, and diagonal 3D-printed layers for better water flow and structural integrity.

Advanced Planter Design

Future investigations will focus on innovating the design of the plant compartments within the facade system. This includes exploring optimized irrigation solutions, such as small perforations or channels that can direct water flow efficiently to the plant roots. Enhancing the planter's functionality will support healthier vegetation and improve overall ecological performance.

Integration of Smart Technologies

The incorporation of smart technologies is another vital direction for future research. By integrating sensors that monitor environmental conditions such as humidity, temperature, and soil moisture, the facade system can adapt dynamically to the needs of the plants and the surrounding environment. This data-driven approach will facilitate better water management and promote the longevity of the vegetation integrated within the facade.

Testing and Validation.

Further testing is essential to validate real-world applications of the customizable facade system. This will include evaluating the hydrodynamics of the water management system under various environmental conditions and assessing the performance of integrated vegetation over time.

Glaze Properties

Future iterations will investigate the application of glazes to improve performance, particularly concerning water flow and retention. The development of glazes that enhance the visual appeal of the tiles while adhering to sustainability principles will ultimately strive for an elegant balance between form and function.

Integration of Fauna

Future designs could also explore integrating habitats for fauna, such as birdhouses or other animal shelters, which could be contextually relevant and contribute to local biodiversity, particularly for endangered species.

Relating Channels to Plant Placement

Finally, a deeper examination of how channel dimensions and orientations correlate with the water needs of various plants will lead to more informed, ecologically sensitive design practices.

This student research will continue in a Spring 2025 independent study, refining fabrication techniques to enhance functionality, sustainability, and assembly efficiency.

Real-World Façade Implementation

Future research could explore the practicalities of integrating this system into building facades. This includes developing detailing for weatherproofing and structural attachment, potentially envisioning the system as a rain-screen facade. Considerations for integration with existing building envelopes and long-term maintenance strategies would also be valuable directions.

Conclusion

This research demonstrates a customizable clay facade system that explores enhanced water management and vegetation integration, contributing to the advancement of sustainable architecture. By combining traditional craftsmanship with advanced fabrication technologies like robotic milling and 3D printing, this study redefines clay as a viable material for modern, performative building envelopes. Preliminary evaluations indicate the system's potential for effectively directing rainwater. The implemented fabrication workflow adheres to zero-waste principles through clay recycling and optimized material deposition. The integration of planters suggests a pathway towards fostering biodiversity in urban settings and could help mitigate urban heat islands and improve stormwater management, although these benefits require further investigation and quantification. Future research will focus on refining tile fabrication techniques to ensure a consistent fastening edge and explore intricate surface patterns to enhance water retention. Advanced planter designs with optimized irrigation solutions will be developed to support healthier vegetation. The potential integration of smart technologies for environmental monitoring will also be explored. Additionally, future work may examine the feasibility of incorporating this system into building facades, considering its use as a rain-screen facade with detailed weatherproofing and structural attachment strategies. This study contributes to sustainable architectural practices, encouraging further innovation at the intersection of ecology, materiality, and digital fabrication.

Notes:

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3 H&P Architects. "Tile Nest House." ArchDaily, March 24, 2021. https://www.archdaily.com/1000475/tile-nest-house-h-and-p-architects.

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6 Harvard Graduate School of Design. "Weaving Buildings: MDes Students Push the Limits of Ceramic." Last modified July 2014. https://www.gsd.harvard.edu/2014/07/weaving-buildings-mdes-students-push-the-limits-of-ceramic/.

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