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 (Castellon 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).

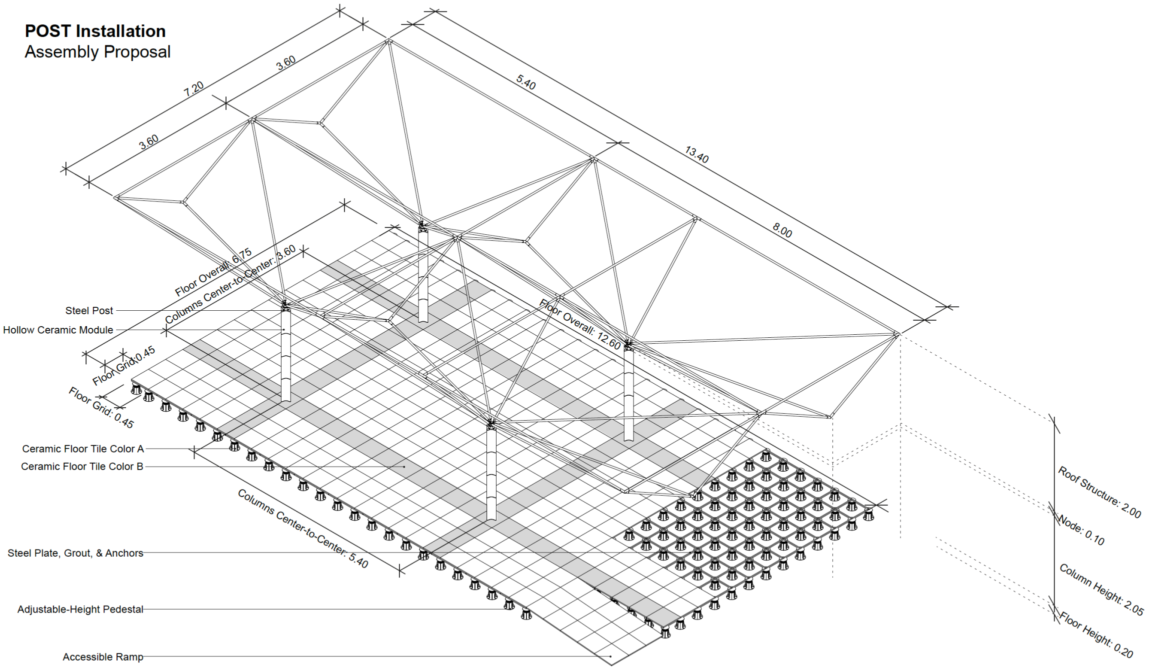

Figure 2: "Building Ecologies" Installation. Axonometric view. Source: (Juan José Castellón, 2022)

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 network[1]. 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 gardens[2]. 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 *Ceramica 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 heigh 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).

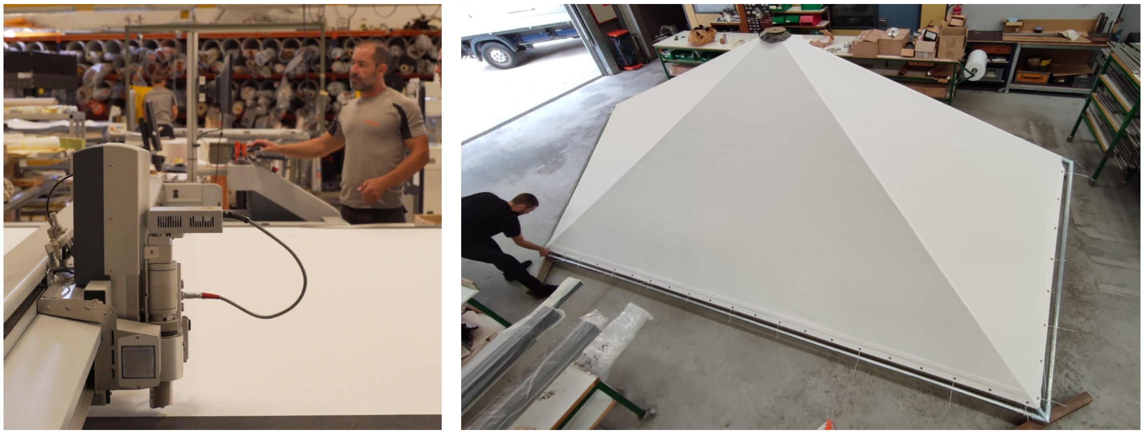

Figure 5: left: digital cutting process, right: attaching the membrane to the frame. Source: (Author, Frau Recerques 2022)

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 is13.40 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.

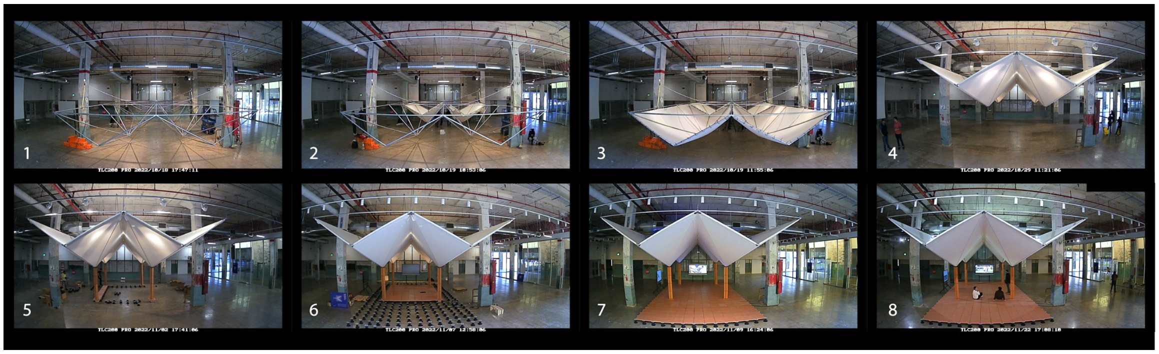

Figure 6: “Building Ecologies”, Assembly Sequence. Source: (Author, Juan José Castellón, 2022)

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)

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ENDNOTES

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