

FabriCity-XR: A Phygital Lattice Structure Mapping Spatial Justice – Integrated Design to AR-Enabled Assembly Workflow

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The research discussed in this paper centers around the convergence of extended reality (XR) platforms, computational design, digital fabrication, and critical urban study practices. Its aim is to cultivate interdisciplinary and multi-scalar approaches within these domains. The research endeavor represents a collaborative effort between two primary disciplines: critical urban studies, which prioritize socio-environmental justice, and integrated digital design-to-production, which emphasize the realization of volumetric or voxel-based structural systems. Moreover, the exploration encompasses augmented reality to assess its utilization in both the assembly process of the structures and the integration of phygital (physical and digital) data with the physical environment. Within the context of these research scopes, this paper introduces FabriCity-XR as an interactive phygital installation. In addition to presenting an overview of the integrated research driven and performative design to production methodologies, the project showcases the practical implementation of web-based augmented reality trails, eliminating the requirement for external applications for interaction. This approach allows users to seamlessly navigate and engage with phygital content overlaid on physical objects using their personal smart devices. The result is a captivating and immersive user experience that effectively merges the physical and digital realms.

1. INTRODUCTION

Emerging technologies, such as extended reality (XR) platforms, computational design, and digital fabrication, pave the way for new interdisciplinary and multi-scalar methodologies in architectural design and urban studies. This research integrates these technological advances within a framework that encourages collaboration between critical urban studies—emphasizing spatial justice and socio-environmental considerations—and integrated digital design-to-production (Mehan and Mostafavi, 2022), which employs voxel-based materialization of lattice structural

systems via data-driven solutions. Furthermore, this research explores the potential application of augmented reality (AR) in the assembly process of lattice structures and the incorporation of multi-media phygital visualization within a physical environment. The aim is to leverage the capabilities of AR to cultivate immersive, interactive experiences for users.

Drawing upon these three principal research domains, this paper introduces the physical outcomes of this interdisciplinary collaboration, realized in the form of an immersive and interactive pavilion installation furnished with integrated phygital trails within an indoor setting. As depicted in Figure 1, the pavilion has been showcased at an international exhibition, where user interactions and engagements will be documented and analyzed over six months. The subsequent sections of the paper will specifically discuss the Integrated Design to AR-Enabled Assembly Workflow.

2. RESEARCH SCOPES AND BACKGROUND

The installation combines three interconnected research areas and interdisciplinary investigations, namely Integrated Design Computation to Production, Urban Communities and Spatial Justice and the incorporation of Extended Reality and Gamification to establish an immersive experience. These research spheres are further elucidated in the subsequent sections, accompanied by a brief overview that situates the project within a broader disciplinary context.

2.1. Urban Community and Spatial Justice

Several researchers and practitioners have examined the concept of spatial justice, a prominent topic within critical urban studies and community development (Cuff, 2023; Kozlowski et al., 2020; Fraser & Howard, 2017; Harvey, 2009). Cuff (2023) discusses architectural manifestations of spatial justice, while Fraser and Howard (2017) delve into environmental justice as a process within contested urban landscapes. Harvey (2009) further adds depth to understanding social justice in urban

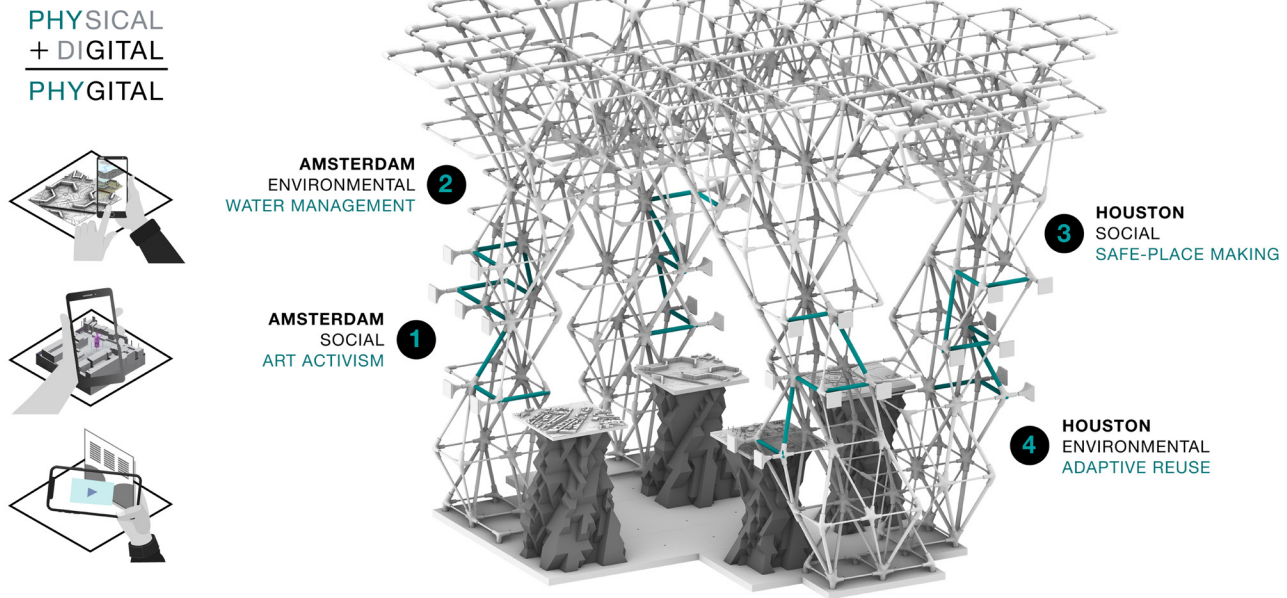


Figure 1. Isometric view of FabriCity_XR including Lattice Structures, 3D Printed Concrete Pedestals Holding Four Urban Models with four corresponding web-based AR trails highlighted in blue color. Image credit: Authors.

settings. Addressing these multifaceted urban-scale concepts poses considerable challenges in architectural design pedagogy and practice (Mehan and Abdul Razak, 2022a; 2022b), as highlighted by Kharvari and Kaiser (2022), who examine the impact of extended reality on architectural education and the design process.

This research explores the potential of interdisciplinary and multi-scalar approaches to navigate these complexities (Mehan, Odour and Mostafavi, 2023). The paper introduces FabriCity-XR, an interactive phygital installation within this interdisciplinary framework (Varış Husar et al., 2023). The project investigates the influence of sociopolitical norms on the shaping and control of urban thresholds, a notion extensively studied in the literature (Mehan, 2022; Mehan, 2020; Horvath, Thomassen, & Wydra, 2015; Mitchell, 1996). Checker (2005) provides insight into the paradoxical politics of urban sustainability, which is also considered in this research.

The project theorizes that the politics underpinning liminal urban spaces can lead to alternative methods for co-designing and co-producing urban thresholds, thereby challenging entrenched dichotomies between public and private urban spaces. The research aims to unravel the stark contrasts between the tectonics of public and private spheres and examine the impact of new tectonics and modalities on urban dwellers. Within the context of this study, there is a comparative analysis of socio-environmental justice in two prominent port cities, Houston, and Amsterdam, both of which are at the forefront of immigration, cross-cultural exchange, and environmental challenges (Mehan 2023a; 2023b; 2023c). Furthermore, the research brings to light

how power structures subtly homogenize social dynamics within the urban realm, a topic that resonates significantly with previous studies on spatial justice and environmental gentrification (Mehan, 2023d; Fraser and Howard, 2017; Mehan, 2015; Checker, 2005). The primary objective of the installation is to curate an immersive and interactive experience that provides diverse users with accessible and engaging access to researched and processed data on spatial justice (Mostafavi and Mehan, 2023).

2.2. Integrated Design to Production

The research undertaken in this project employs integrated design-to-production workflows on multiple scales. This project uses an integrated method to approach design and assembly, combining volumetric 3D printing with spatial lattice structures through a tetrahedron-based material system. The system is flexible, allowing users to create bespoke structures that respond to various contexts. Furthermore, the project promotes circularity and hybrid human-machine intelligence through resource and data-driven design workflows, which integrate robotic and numerically controlled production techniques with human craft and augmented reality-assisted assembly (Mostafavi, 2021). The installation acts as a liminal space, serving as an urban information hub that invites visitors to engage in an immersive experience, blurring the boundaries between physical and digital realms. Section three, as the core body of this paper, provides a comprehensive discussion and detailed presentation of the developed methodologies, accompanied by relevant reference projects that serve as precedents in the field of computational and digital fabrication.

2.3. Extended Reality (XR)

The FabriCity XR project introduces the XR Play (Extended Reality Play), a Phygital layer that fuses user interaction design, augmentation technologies, and gamification to shape captivating, augmented reality experiences. This effort is rooted in the concept of “phygital”—the convergence of the physical and digital worlds (DeMers, 2017). The project offers users an immersive experience as they explore physical environmental and digital data sets (Delgado et al., 2020).

Notable features like augmented reality trails, multiple data layers, and analytics ensure a comprehensive, interactive visitor experience (Mehan, 2024; Williams et al., 2020). Dynamic QR codes are employed to generate various augmented reality experiences, simultaneously gathering vital data on user engagement. This data informs a process of ongoing improvements, ensuring the XR experiences remain pertinent and adaptive to the evolving needs of users (Delgado et al., 2020).

The project’s use of gamification as a tool for promoting active participation and sustained engagement (Milovanovic et al., 2017). By integrating playful elements into exploring public art and urban landscapes, XR Play presents an engaging method of educating users about socio-environmental justice issues in two cities. Section 3.4 of this paper provides in-depth insights into the details and aspects of XR Play.

3. DESIGN, FABRICATION AND ASSEMBLY METHODS

Given the research scopes and objectives outlined above, the installation involved the implementation of various physical and phygital layers. This section presents the workflows and developed methods of the FabriCity_XR project, categorized into four subsections: Lattice Structure, Concrete 3D Printing, AR-Enabled Assembly, and ultimately, the Integration of Phygital Layers across the pavilion. The discussion of urban-scale data addressing socio-environmental justice is covered in a separate analysis (Mehan and Mostafavi, 2023a; 2023b).

This project is the product of a cooperative research and design initiative that engaged more than 60 individuals, including participants from a graduate-level design studio, faculty members affiliated with Texas Tech university, external collaborators, and industrial partners from both the United States and Europe. The project’s realization was made possible through the collaborative efforts of two primary studios: Design Computation Fabrication (DCF) and Urban Community Design (UCD), which worked together synergistically on various aspects of the collective work (Mehan and Stuckemeyer, 2023). The overall size of the pavilion fits within 12x12x9.15 feet bounding box. An overview of key elements and layers of the installation is illustrated in an exploded view diagram below (Figure 2 - Top).

3.1. Tetrahedral Lattice Structure - Resource Driven Design Materialization

Lattice structures are topologically ordered, three-dimensional open-celled structures composed of one or more repeating unit cells (Maconachie et al., 2019). Also known as 3D space frame systems in architecture and engineering, several researchers and design inventors have considered the benefits of lattice systems such as being lightweight, easy to assemble and disassemble (Bell, 1903; Fuller, 1961). Recent advancements in digital design and fabrication techniques have opened avenues for the creation of customized lattice structures featuring non-repetitive modules and elements (Naboni et al., 2020; Kontiza et al., 2018; Kladeftira et al. 2022, Chiang et. al, 2018). Building upon these precedents, this research presents an integrated approach to streamline the design-to-assembly process for the resource

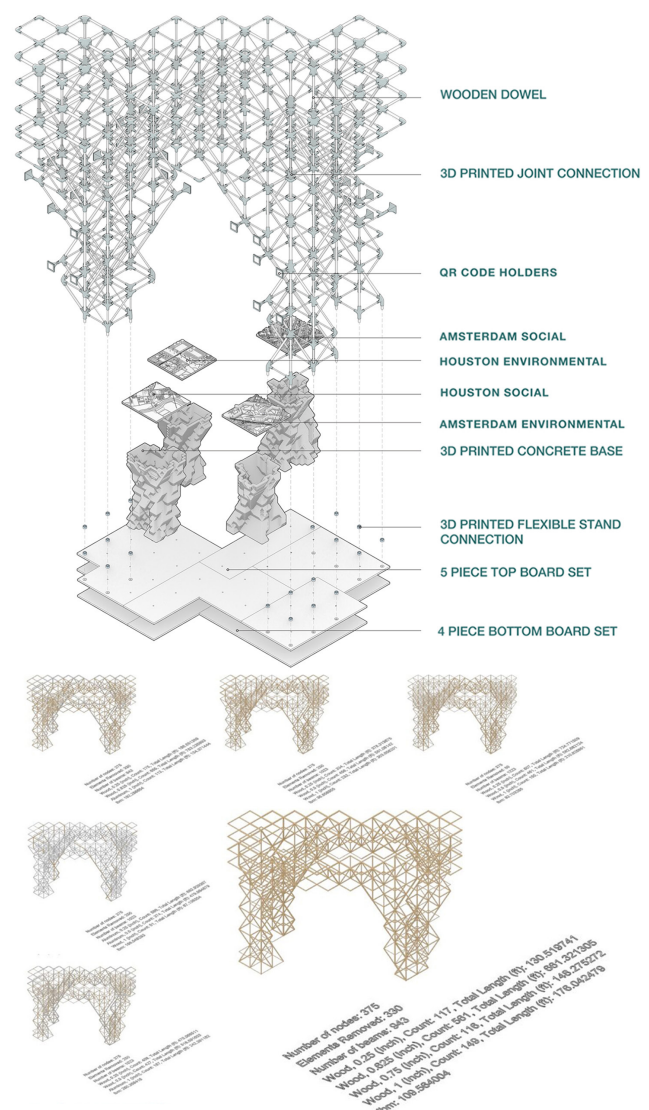


Figure 2. Top: Exploded isometric view of FabriCity_XR, highlighting its physical layers, Bottom: Resource Driven Design Materialization of Voxel Based Lattice Structure – Integrated Structural Analysis for Material and Profile Allocation. Image Credits: Authors.

and data-driven materialization of tetrahedral lattice structures. The research entails the development of a computational design system within the Rhino Grasshopper interface. The workflow begins with the voxelization of a free-form volume as the design input and progresses to the allocation of material profiles informed by parametric structural analysis utilizing Karamba 3D. In other terms, the collection of voxel edges serves as the input dataset for conducting structural analysis. This analysis informs the allocation of profiles for the placement of locally resourced material.

Various topologies have been explored for the voxelization techniques of the base module. Ultimately, a scaled tetrahedral module with a square base measuring 1 foot by 1 foot in length and 1.25 feet in height is selected, considering factors such as assembly, transportation, and structural buckling of each element. The materialization system incorporates data on the material properties of locally available wooden dowel profiles, as well as other materials like aluminum tubes. Eventually, four varying profiles of oak wood round profiles have been chosen, measuring 3/8, 1/2, 3/4, and 1 inch in diameter. The distribution of these profiles across the pavilion is determined through structural analysis, whereby unnecessary elements are removed, and thicker profiles are allocated as needed based on structural requirements (Figure 2 – Bottom).

The connections within the lattice structure are achieved using 3D-printed joints, capable of accommodating a minimum of 2 and a maximum of 12 receiving elements. Given the four selected wooden profile types, the potential typologies expand exponentially. To ensure structural integrity, the load distribution across the lattice structure is parametrically adjusted, which results in thicker joints where significant forces accumulate. Leveraging insights gained from prior projects and conducting a series of test prints in PLA, ABS, Carbon-Fiber and Wood materials, the final material infill configuration is established as 40% with a 3D honeycomb topology with PLA. This infill pattern exhibits exceptional stiffness, effectively addressing the multidirectional forces exerted on the joints. Each printed joint weighs approximately 120 grams and requires approximately 10 hours of printing time using a Prusa MK4 3D Printer. By optimizing the print bed and nesting multiple prints, the overall production time can be significantly reduced. In the final production version of the pavilion, joints are categorized into horizontal layers labeled A to H, all facing a consistent direction, which facilitated the assembly process. For each wooden dowel used in the joining process, a connection pin is inserted primarily to enhance resistance against tensile forces. Additional information regarding the assembly procedure can be found in Section 3.3 of this paper.

3.2 Urban Models Pedestals - Voxel Based Concrete 3D Printable Volume

Recent advancements in Concrete 3D Printing (C3DP) have demonstrated potential in achieving curved geometries, as

the incorporation of curvature can enhance structural stability throughout the printing process and subsequent stages (Anton, 2021; Ahmed, 2022). Additionally, the design of continuous toolpaths has been identified as a critical factor in enabling efficient workflows for concrete 3D printing (Ashrafi et al., 2022; Breseghello and Naboni, 2022; Mostafavi et al., 2015). With these challenges in mind, this research focused on developing an integrated computational design to robotic production workflow specifically tailored to voxel-based geometries characterized by sharp turn angles. Similar to the lattice structure, which relies on tetrahedral modules, the design of concrete elements also adopts a volumetric approach. However, in the concrete pedestal, the resolution or dimensions of the base tetrahedral modules are recursively reduced to enhance the stability of the printed surface where needed.

The outcome of this research is the creation of four concrete pedestals that serve as foundations for urban models, acting as the starting points for phygital trails. To address the limitations arising from the absence of curvature and to mitigate tension concentration on flat surfaces, the generative system incorporates a recursive subdivision technique in areas where tension accumulates, reducing the likelihood of buckling during and after the printing process. The developed design materialization system can accommodate various boundary representation forms as input. The system incorporates a voxelization algorithm that converts the input geometry into voxels, automatically removing the inner fill while retaining the necessary voxels. Subsequently, two strategies for continuous toolpath generation are developed and evaluated: the single-layer approach and the double-layer approach, both of which ensure uninterrupted printing trajectories (Figure 3 - Top).

While both the double-layer and single-layer methods exhibited favorable attributes, the single-layer approach was ultimately selected to produce the four concrete pedestals due to considerations related to logistics and overall weight. The voxel size of the base tetrahedron in concrete is matched with the voxel size of the lattice structure, ensuring a visually cohesive result in both the physical and phygital environments. This consideration was complemented by corresponding extended reality trails. To validate the effectiveness of the continuous path generation technique, one-to-one tests were conducted using a BigRep 3D printer. Subsequently, the workflow was adapted for the XtreeE system, which utilizes a KUKA 210 robotic arm for printing high-performance concrete (Figure 3 – Bottom).

3.3 Augmented Reality Enabled Assembly and Dis-Assembly

Recent studies have shown the promising potential of Augmented Reality (AR) and Human-Robot Collaboration (HRC) in the assembly processes of the Architectural and Construction sectors (Jahn et al., 2022; Mitterberger et al., 2020; Mostafavi et al., 2023). FabriCity XR incorporates a voxel-based modular system, enabling efficient assembly and disassembly of discrete

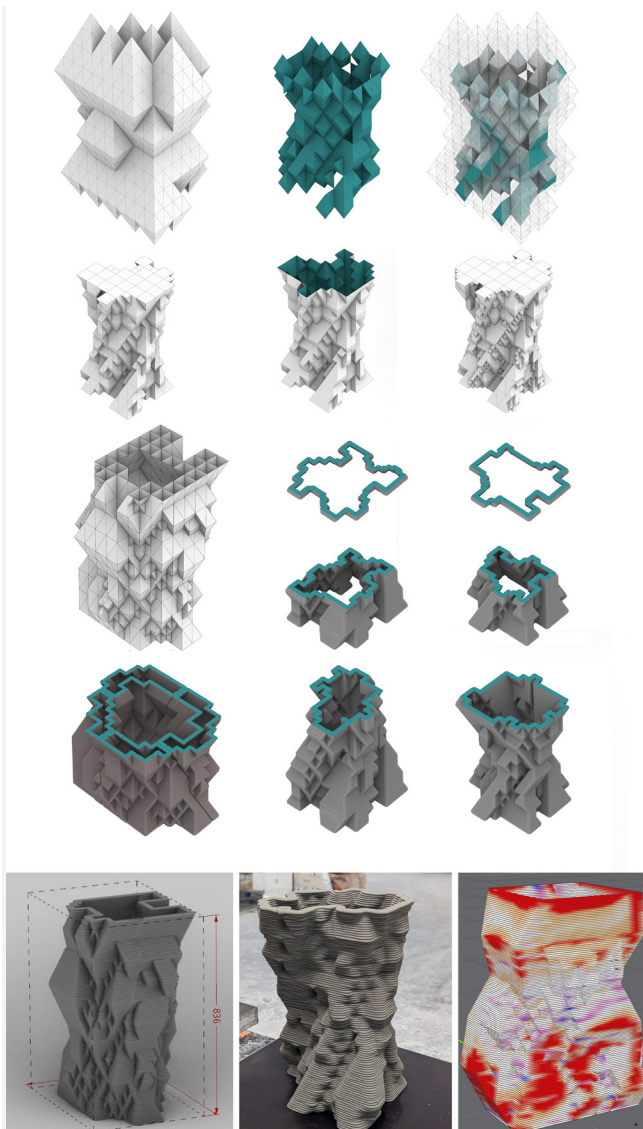


Figure 3. Top: Voxel-Based Tectonics and Toolpath Methods, Single- and Double-Layer Methods, Bottom: From left to right: Physical and Toolpath Specifications, and one of the final iterations printed in concrete, and Tension Analysis. Image Credits: Authors.

pieces. Augmented Reality, facilitated by Hololens 2, is utilized for the assembly process, with the Fologram platform serving as the interface between the parametric design model and the AR environment.

The assembly begins by connecting the wooden-based Tetris-like 3/4-inch boards layered in two levels to establish the foundation. The physical reference Fologram QR code was then synchronized with the digital reference model, serving as a guide for the assembly. Intermediate flexible PLA-printed cylinders are introduced to connect the support joints to the base, which prevents the first layer of joints from moving or breaking under pressure (Figure 2, Isometric View). Following a predetermined sequence spanning from layers A to H, the tagged joints will be positioned

in space with the assistance of the individual wearing the AR headset. The entire assembly, consisting of 377 joints and 921 wooden elements, required approximately two full working days or sixteen hours, involving one person wearing the headset and two to three additional assistants. This duration excludes the time dedicated to inserting the tension pins, which are 3/16-inch dowels used to secure the elements to the joints. Once each part is assembled, the tension pins are gradually employed to elevate the structure layer by layer until it achieves its desired rigidity. The whole structure is once assembled at the Texas Tech University and then des-assembled to be reassembled in the exhibition venue. All other elements such as concrete elements, urban models and dynamic QR codes for the physical trails are all assembled with the help of AR headset (Figure 4).

3.4 Interactive Web-Based XR, Integration of Physical Layers

The advancement of mobile and wearable devices has opened numerous possibilities for creative application of extended reality in built environments (Arth et al., 2015; Lopez Rodriguez and Pantic, 2023; Geopel et al., 2023). This research study delves into the convergence of user interaction design, gamification, and augmented reality technologies within the context of an exhibition design project. The primary objective is to establish a dynamic and immersive experience that effectively blurs the boundaries between the physical and digital realms. Furthermore, the phygital layer of the study integrates research findings on Socio-Environmental aspects through the incorporation of two scopes of research and design: Urban Community Design and Design Computation Fabrication. By engaging the audience in Extended Reality trails, the study aims to involve them in a comprehensive and multi-scalar exploration.

Through an exploration of various Augmented Reality platforms and apps compatible with personal smartphones and tablets, the MyWebAR platform was chosen as it eliminates the need for additional downloads as it utilizes webpages instead of the Operating System. The integration of phygital layers involves four trails, each starting from a physical model adjacent to one of the lattice structure's columns. Utilizing smartphone cameras, users can hover their devices over the urban model photos to reveal initial layers of digital information superimposed on models. Subsequently, an interactive process guides users along a multi-scene path, where they can follow dynamic QR codes corresponding to the model (Figure 5 - Top)

During the exhibition, user interactions are recorded to capture data on engagement levels and patterns, which will be analyzed to reveal insights for enhancing the installation. The dynamic nature of all 28 QR codes allows for the possibility of updating and expanding the content of the phygital layer over time. The bottom part of Figure 5 provides an overview photograph showcasing the final setup of FabriCity XR within the exhibition space.

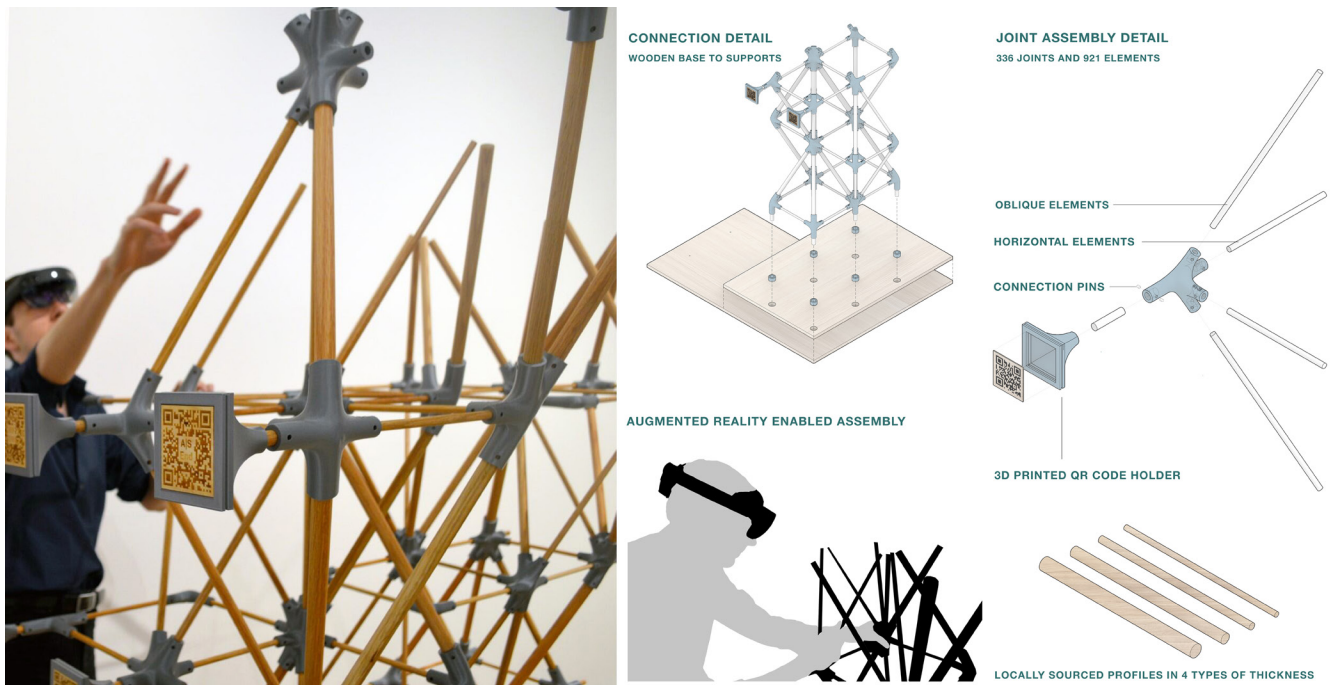


Figure 4. An Overview of Augmented Reality Enabled Assembly of the Fabricity XR project. Image credit: Authors.

4. DISCUSSION AND CONCLUSION

The FabriCity-XR project, resulting from our research, investigates the convergence of extended reality (XR) platforms, computational design, digital fabrication, and critical urban study practices. Our goal was to cultivate interdisciplinary and multi-scalar approaches by bridging critical urban studies and integrated digital design-to-production. By adopting an integrated design and assembly method, we combined volumetric 3D printing with tetrahedron-based material systems to create adaptable lattice structures. These structures serve as immersive spatial frameworks for phygital mapping, specifically focusing on spatial justice research and analysis in Amsterdam and Houston. Our objective is to provide a comparative lens for understanding socio-environmental justice in these distinct urban contexts.

The success of this project hinged upon the collaboration between diverse disciplines. The integration of critical urban studies, computational design, digital fabrication, and extended reality facilitated a dynamic exchange of ideas and expertise, enabling us to address intricate urban challenges and devise innovative solutions that prioritize socio-environmental justice within urban contexts.

In conclusion, the FabriCity-XR project serves as a testament to the transformative power of integrating digital design and fabrication technologies in the creation of spatially just and immersive environments. Through our embrace of circularity, hybrid human-machine intelligence, and augmented reality, we have not only expanded the boundaries of design and assembly workflows but also forged new frontiers in the exploration of

the interplay between the physical and digital realms. The result is an engaging user experience that exemplifies the potential for merging technology and design to shape more inclusive and interactive urban landscapes.

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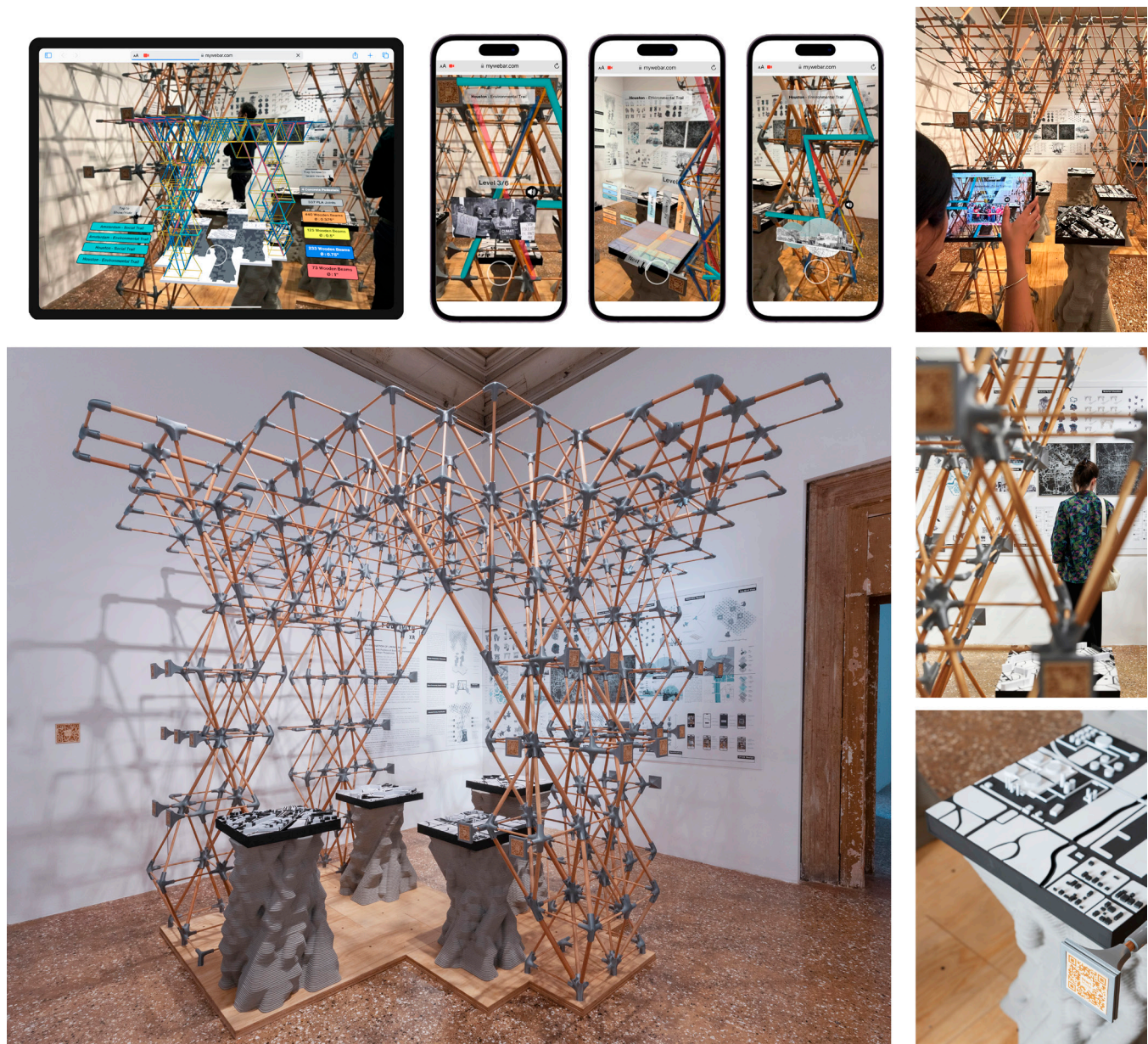


Figure 5. Overview of the final setup of FabriCity XR within the exhibition space. Top: Phygital Trails and interactions Image Credits: Authors, Bottom: Photographs of the Venue Photo Credit: ECC Venice Architecture Biennale, Federico Vespignani

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