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Design and fabrication of wooden grid shells using small-diameter timber

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Abstract

As the construction industry increasingly shifts toward sustainability, timber has emerged as a primary renewable building material. However, as timber consumption increases, exploring and optimizing wood value chains become essential. Here, a significant portion of harvested timber is still used for low-value applications such as thermal energy or fiber-based products. Small-diameter round timber, despite being abundantly available as thinnings from forestry management, remains largely underutilized—even though its continuous fiber structure provides higher and less variable bending strength compared to sawn beams of the same cross-section. To explore the architectural and structural potential of this material, a one-to-one case study had been pursued, resulting in a 6×6 m wooden grid shell that combines the geometric efficiency of Hypar structures with the inherent strength of small-diameter timber. The case study was realized during a one-week design-build workshop, whereas locally sourced logs were a) carefully debarked, b) assembled on-site, and c) using a digital-material workflow. In particular, Augmented Reality (AR) technology was employed to enhance construction accuracy and robustness. Overall, this paper discusses the potentials and feasibility of using irregular timber for geometrically-complex shell structures through digital planning and AR-assisted construction and assembly. The presented findings suggest a scalable approach to valorizing low-grade timber, potentially broadening its architectural and structural applications while reducing material waste and, at the same time, ensuring optimized wood value chains. Ultimately, the paper outlines a new architectural potential of roundwood when combined with contemporary digital tools and insights from historical construction methods, offering a scalable model for sustainable, low-impact timber architecture.

Keywords: timber construction, hypar grid shell, digital fabrication, non-standard construction, digital design, small-diameter timber, augmented reality, wood value chains, digital-material pedagogy

1. Introduction

We live in a world that is increasingly shaped by climate change. This is evident in more frequent climate extremes and, consequently, in geopolitical crises driven by competition for dwindling resources. Autochthonous construction—methods optimally adapted to local environments and materials—could be an important cornerstone in overcoming these challenges while enhancing social and cultural values. Timber, especially natural round timber, has long been fundamental to such construction, directly linking local materials with context-sensitive building traditions. Amid resource scarcity, revisiting these approaches is vital—not only to promote sustainability and resilience, but also to inspire innovative solutions by drawing on time-tested practices and integrating them with modern techniques.

This project investigates how small-diameter roundwood—a material typically excluded from conventional construction—can be integrated into resource-efficient timber architecture through digital-material workflows and hands-on experimentation. Digital tools such as 3D scanning, computational design and augmented reality make it easier to work with natural timber by accommodating the unique shapes and variability of each piece, enabling efficient, precise construction that leverages the material's inherent qualities.

The project was carried out as part of irreguLAB at Bauhaus University Weimar, collaborating with the University of Applied Sciences Erfurt and the City of Suhl. Digital tool-chains and workflows—including computational design, 3D scanning, and augmented reality (AR)—were first developed through research to address the challenges of natural timber's inherent geometry and variability. Students engaged deeply throughout the timber chain: researching historical and traditional round timber structures, proposing material-driven designs, sourcing and harvesting timber, pre-processing, and finally constructing on site. The culmination was a 6 × 6 m hyperbolic paraboloid (Hypar) timber grid shell, whose doubly-curved, straight-lined geometry is ideal for linear materials like round timber, enabling high spatial rigidity with minimal material. Despite using only simple hand tools, the complex form was realized within four days, with AR actively guiding on-site assembly and construction to ensure precision and maintain design intent.

2. Background

In this chapter, the background to the utilization of small diameter roundwood (thinnings) and the development of hyperbolic paraboloid shells is examined in more detail to demonstrate the traditions and possibilities, but also the constraints and difficulties, of building with low-value timber, specifically small diameter round timber.

2.1. Architectural precedents

2.1.1 Hyperbolic Paraboloid (Hypar) Grid Shell Structures

Hypar (hyperbolic paraboloid) shells have had a prevalent use in architectural contexts due to their self-supporting, anticlastic geometry, which enables wide spans with minimal material through double curvature. Despite their complex form, they can be built entirely from straight linear elements arranged along two intersecting directions, thanks to the doubly-ruled nature of the hyperbolic paraboloid [1]. In this context, architect-engineer Félix Candela, for example, helped popularize this system through projects like the 1958 *Los Manantiales* restaurant in Xochimilco, where he used straight timber boards for the formwork, aligned with the ruled lines of the surface (Fig. 1). This allowed for fast, low-cost construction of thin concrete shells with minimal labor [2].

Straight natural materials—such as bamboo or roundwood (specifically softwood forest thinnings)—are particularly well-suited for Hypar structures. Their inherent straightness, high axial and bending stiffness, and availability in long lengths make them ideal for forming the intersecting grids that define the Hypar surface, as demonstrated in multiple examples of bamboo Hypar roofs in Latin America [3].

Figure 1: Félix Candela's Los Manantiales Restaurant and its timber formwork structure [4].

2.1.2 Roundwood thinnings in Structural Use

Small-diameter roundwood, the result of thinning from forest management, wasn't always considered 'weak wood' or underutilized in construction. It has played a prominent part in vernacular architecture and traditional construction. However, since industrialization and standardization, its role in structural applications has diminished significantly [5].

In the 1980s, Frei Otto, together with British architects Ted Cullinan, Richard Burton and engineers from Buro Happold, carried out a series of experimental case-study buildings using 'weak' thinnings at Hooke Park, a non-profit educational and training center in the use of local roundwood, in Dorset, the UK [6]. At Hooke Park, experiments with small-diameter roundwood thinnings—typically low-value by-products of forest management—demonstrated their potential as a structural material in innovative timber construction. The thinnings, sourced directly from local managed forests, were harvested and processed with minimal intervention, often retaining their natural form and curvature. After felling, the roundwood was debarked and sometimes seasoned, but largely left un-milled to maximize material efficiency and sustainability [6].

Figure 2: Model, construction and the roundwood gridshell of Westminster Lodge at Hooke Park, Dorset [7]

For construction, these slender spruce poles were sorted and arranged into structural grids or lattice frameworks, exploiting their inherent strength in tension and bending. The most prominent example is the gridshell roof of *Westminster Lodge*, completed in 1998 (Fig. 2). Here, the thinnings were assembled into a double-layered gridshell, with the elements woven and fixed at their intersections to form a self-supporting, doubly-curved timber shell. The assembly process involved bending the slender poles into the desired curvature on site, then connecting them with shear blocks and oak dowels, and finally adding a solid roof covering above [6]. This approach allowed the use of irregular, small-diameter timber in a highly efficient structure, demonstrating that local thinnings could be utilized as integral structural members in complex architectural forms while promoting sustainable woodland management and the efficient use of locally available natural materials [5][6].

2.2. Material research

In forestry, small-diameter roundwood traditionally refers to logs with a diameter of 20 cm or less. This material typically results from thinning, a forest management practice that removes select young trees to reduce density and promote the growth of stronger, straighter specimens [5]. Despite its abundance, small-diameter timber is rarely used for structural building products today and is mostly relegated to thermal use or industrial fiber-based materials such as wood insulation boards [8].

Research has shown that unsawn timbers possess higher and less variable bending strengths than sawn timbers, due to unbroken fiber continuity around knots and the favorable bending properties of round cross-sections [5][6][9]. However, these advantages are offset by the complexity of joining round timbers, which is made more difficult by their irregular geometries and natural curvature. Earlier studies [5][8] concluded that an effective connection and fabrication strategy is essential for reliable use. For example, timber-to-timber joints—such as those used in the Westminster Lodge gridshell at Hooke Park—were used only in select cases due to their complexity, while most connections were achieved with simple screws to better accommodate variability [5].

In contrast to sawn beams, round timber must be debarked to prevent pest and fungal infestation and to promote faster drying, which increases durability; this process is discussed further in Chapter 3.4.

Recent advances in digital technology—such as 3D scanning, algorithmic modelling, and augmented reality (AR)—now enable efficient processing and precise assembly of irregular small-diameter roundwood, greatly expanding its structural applications. These tools transform an abundant, underutilized material into a viable resource for advanced construction.

2.3 Digital approaches

Continuing at Hooke Park, the *Biomass Boiler House* exemplifies the integration of digital tools with low-value, natural timber. Over 250 naturally curved Douglas fir thinnings were 3D-scanned to create a digital inventory of their unique geometries. Algorithms then determined the optimal placement of each log to form a complex, load-bearing wall that follows an organically curved profile. This process transformed the inherent irregularity of the timber into both a structural and architectural asset, relying on minimal processing and maximizing the direct use of local resources [10].

RUBI Lab (Rural-Urban Building Innovation Lab)'s *Timber De-Standardized* project at Cornell University further explores this intersection by employing augmented reality (AR) to guide the assembly of irregular, salvaged wood. AR overlays digital instructions directly onto the physical elements, enabling precise placement and joining without the need for standardized materials or conventional drawings. This workflow demonstrates how computational design, and digital guidance can enable innovative, resource-efficient construction using non-standard timber [11].

In contrast to these approaches, which often depend on advanced fabrication technologies and robotics, our project leverages the geometric properties of the hyperbolic paraboloid (Hypar) typology which allows natural round timber to be used in its relatively straight form, requiring minimal post-processing or specialized machinery.

3. Integrated digital-material workflow

3.1. Material-driven research and design

The project was structured around two interwoven phases: research-driven design exploration and hands-on building, both focused on the integration of small-diameter roundwood thinnings as primary structural elements. The initial phase examined historical and vernacular roundwood construction—from Chinese timber arch bridges to Frei Otto's case study buildings at Hooke Park—to critically assess traditional material sourcing, processing, and assembly methods. This empirical study deepened understanding of roundwood's natural geometry, fiber orientation, and variability, informing the development of novel design and fabrication strategies.

Iterative prototyping formed the core of the design process, progressing from conceptual sketches and physical models to full-scale prototypes of key connection joints. This scaled 'design and build' approach established a reciprocal feedback loop, where material testing and prototyping directly informed design refinements.

The physical exploration and iterative prototyping provided critical insights into the structural and practical performance of roundwood, highlighting the value of hands-on experimentation and real-world validation. The outcome was a series of comprehensive proposals that integrated roundwood thinnings across all stages of the design process—from material cataloguing and sourcing strategies to process chains and multi-scale prototypes.

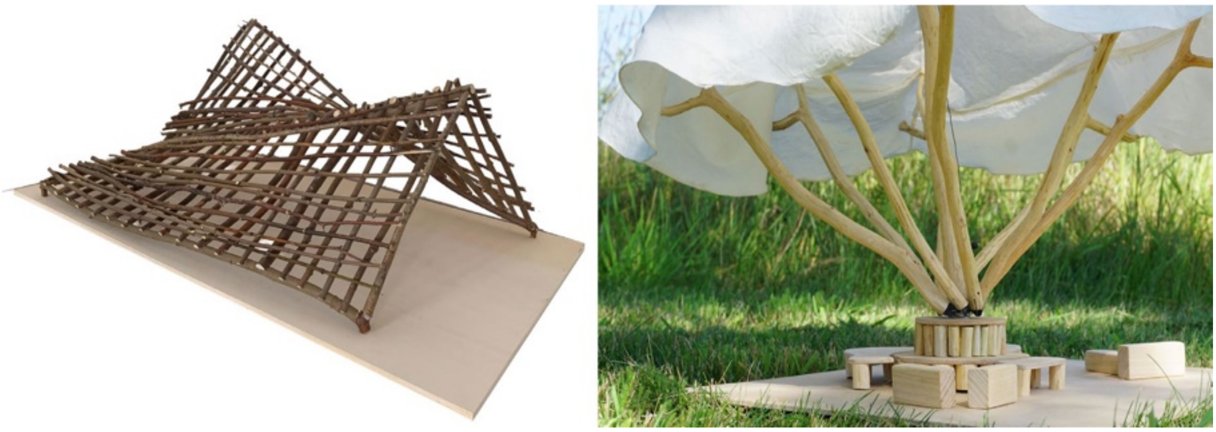

Figure 3: Student models in the design phase

Throughout the project, material exploration through physical experimentation and digital logic continuously informed one another, creating a symbiotic relationship between design and material understanding. This reciprocity advanced a methodology of design-through-materiality and materiality-through-design, expanding architectural possibilities by integrating historical knowledge, hands-on craftsmanship, and digital workflows.

3.2 Digital-material interaction

Building on the material-driven methodology outlined in Section 3.1, this phase established a feedback loop between digital tools and physical material processes.

Central to this feedback loop, augmented reality (AR) technologies—specifically a Microsoft HoloLens 2 head-mounted display and Fologram, an AR-Plugin for the CAD environment of Rhinoceros 7.0 — bridged digital design and physical construction across all stages, from timber sourcing to on-site assembly. During the research and design phase, AR enabled the overlay of digital 1:1 models onto the forest environment (Fig. 4), allowing for selective harvesting of roundwood pieces with specific geometries tailored to structural requirements. This approach drew inspiration from historical template-based timber selection in traditional craft and shipbuilding, establishing a direct dialogue between material source and design intent, thereby optimizing material efficiency and minimizing over-harvesting.

Figure 4: AR-assisted versus historic fork selection [12]

During construction, AR facilitated real-time visualization of the complex Hypar geometry, guiding precise placement of foundation points and providing step-by-step assembly instructions. This was achieved with a detailed 3D model of the structure and a layered construction sequence that visualizes each step of assembly (Fig.5). While AR precision is limited to about 0.5–2 cm depending on user skill and marker placement, its integration significantly improved accessibility and accuracy, particularly in complex assembly sequences [13].

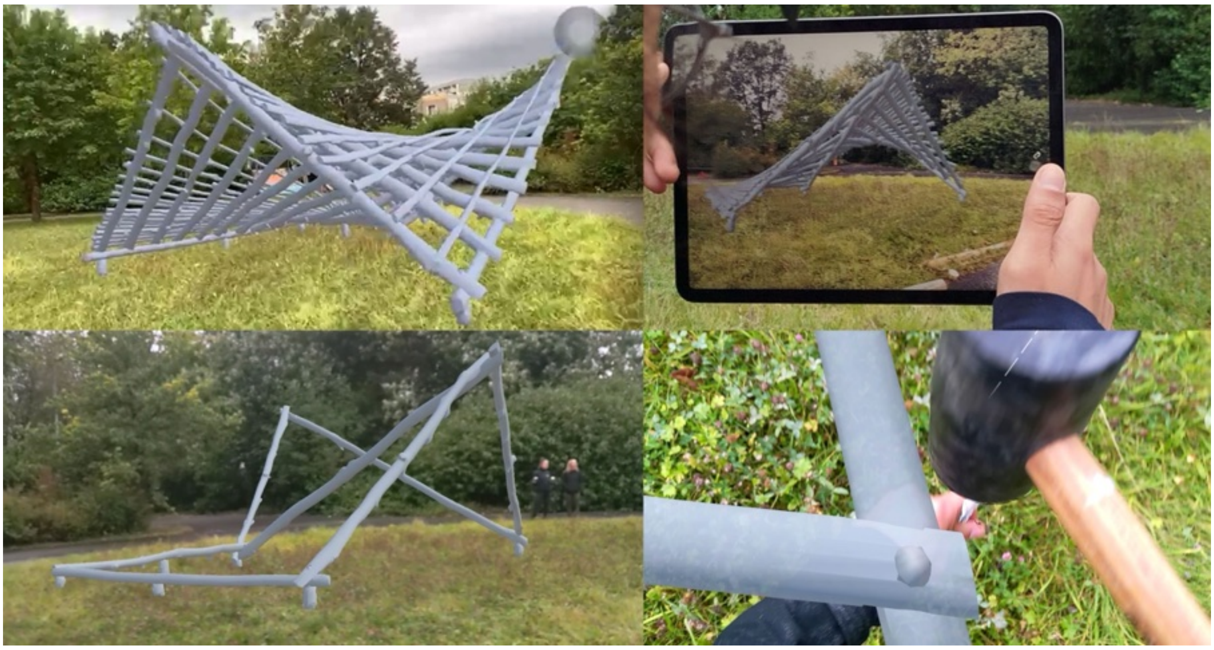

Figure 5: AR-Model placement for foundation pins

3.3. Design system

The overall design system emerges from a material-driven approach that prioritizes resource efficiency, structural integrity, and adaptability to material variability. Contextual constraints—such as log length and geometry—and criteria for construction feasibility are addressed through parametric modelling and structural calculations, building on the digital-material workflows established in prior sections. This integration ensures that material logic and computational design are directly linked to structural performance.

3.3.1 Structural system and calculations

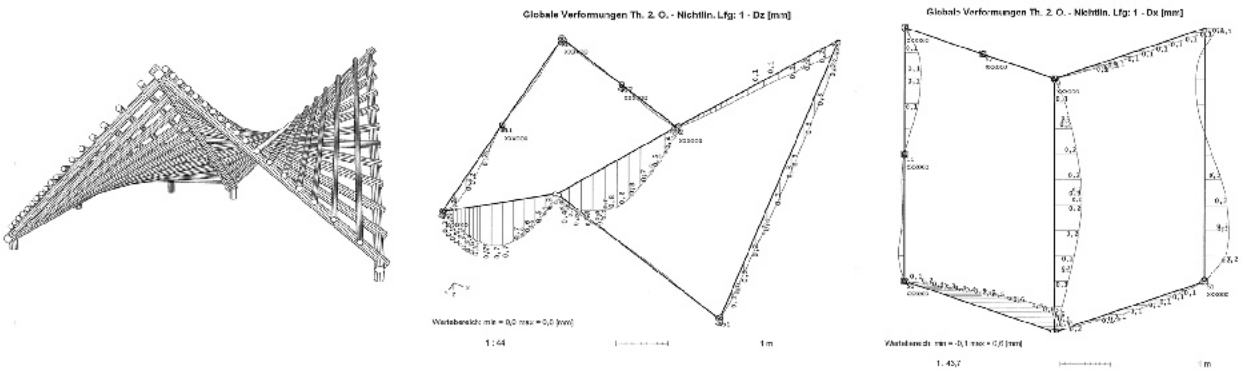

Figure 6: Structural models – Meshed model (left), analysis models showing overall deformations under vertical load (center), and lateral load (right)

Building on the material-driven design process, this phase addressed lateral stability and ground connection challenges specific to the Hypar geometry. The hyperbolic paraboloid's inherent resistance to compression enabled efficient load distribution but required targeted reinforcement for wind and snow loads. Structural analysis (D.I.E. Baustatik software) directly informed grid density and member placement, with higher-density zones concentrated at high-stress regions (e.g., edge beams, support nodes). Larger-diameter roundwood (≥120 mm) was prioritized for primary load paths, while smaller diameters (80–100 mm) were allocated to secondary elements.

Conservative joint detailing—washer-head timber screws (6–8 mm diameter, 100–200 mm lengths) scaled to member diameters—ensured force distribution aligned with structural requirements. Ground connections were optimized for the site's rubble subsoil, with six elastically clamped supports anchored via steel plates (300 × 500 mm) and three crosswise ground anchors (20 × 800 mm) to distribute loads without exceeding roundwood's bending capacity.

These structural decisions—grid density, member sizing, and joint detailing—directly shaped the construction workflow. The following section (3.4. Construction System) details how these engineering considerations were translated into assembly sequences, material handling, and on-site adaptations, ensuring alignment between computational design and physical realization.

3.4. Construction System

Building on the structural logic and material allocations established in previous sections, the construction system prioritized efficient use and assembly of small diameter roundwood thinnings. The roundwood was harvested from a forest near Ilmenau, located approximately 30 km from the construction site in Suhl-Nord, under the supervision of a professional forester.

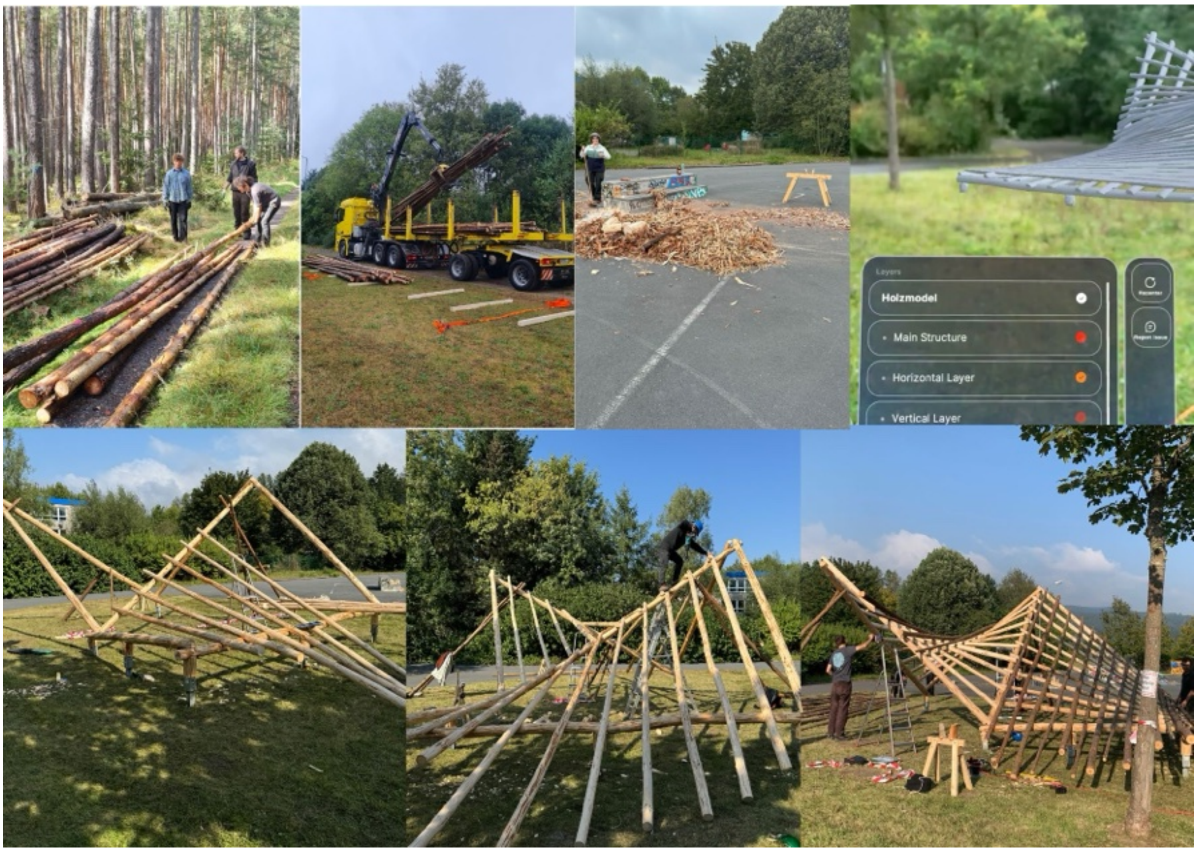

Figure 7: Harvest - Transport - Debarking - AR-model placement – Edge frame construction - First grid layer - Top grid layer (top left to bottom right)

After debarking and sorting by diameter, larger, straighter logs were directed to primary load-bearing roles, while smaller diameters were allocated to secondary and cladding layers. Construction commenced with precise site layout and foundation placement, guided by augmented reality (AR) overlays as explained in Section 3.2. Temporary scaffolding, also crafted from roundwood, facilitated the assembly of edge beams and columns using the largest available logs.

The Hypar gridshell's geometry enabled straightforward joinery: intersecting roundwood layers overlapped at regular intervals, allowing for simple, effective connections secured with stainless steel 8 mm × 200 mm timber screws. The uppermost grid layer, composed of the smallest-diameter roundwood, was intentionally left with bark on for aesthetic and design reasons, creating a deliberate contrast in texture that highlights the diversity and origin of the material from forest thinnings. To address natural taper, logs were alternately oriented head-to-toe along each span, equalizing structural depth and visual profile while ensuring uniform load distribution, as demonstrated in traditional blockhouse construction. The structure was finished by coating exposed end grains with natural oil to protect against moisture and weathering. These construction strategies and their outcomes are further analysed in the next section.

4. Results and reflections

Figure 8: Realized 1:1 Hypar grid shell spanning 6 x 6 m

Material Sourcing and Preparation

As described in Section 3.4, small-diameter roundwood thinnings were harvested locally, manually debarked, and sorted by diameter, curvature, and taper to optimize placement within the Hypar gridshell. High-pressure water jet debarking was tested but rejected due to excessive energy and water demands, underscoring the viability of manual processing for small-scale applications.

Structural Logic and Assembly

The Hypar's anticlastic geometry, as detailed in Sections 2.1.1, enabled efficient load distribution across intersecting roundwood grids. The self-supporting nature of the structure eliminated the need for temporary formwork, with each added layer incrementally stabilizing the assembly. Connections relied on robust screw fasteners, chosen for their compatibility with irregular geometries. AR, as described in Section 3.2, guided on-site assembly, overlaying digital instructions to clarify spatial logic and reduce errors inherent to complex geometries. It allowed for human intuition in handling the irregular timber while following a given general design through AR. In this respect, AR cannot replace the precision of computer-controlled manufacturing, but it allows for the complexity of three-dimensional designs to be conveyed better than 2D construction plans can. Instead of complex and time-consuming path planning for robotic assembly, AR assembly could therefore play a greater role in the future of construction, especially regarding the use of natural irregular materials, ultimately keeping the human in the loop.

Scalability and Environmental Considerations

The prototype's scale limited assessment of long-term environmental effects such as moisture exposure, thermal shrinkage, and thermal expansion. Maximum log length (~4 m) constrained upscaling, as splicing roundwood segments introduces inefficiencies absent in standardized materials. Semi-automated debarking and regional material networks could help address labor constraints for larger implementations. Historical precedents as explained in Section 2.1.2 demonstrate that larger spans are achievable with layered gridshells, but they require advanced jointing techniques or hybrid material systems [6].

Discussion

This project and approach are rooted in learning from traditional techniques and craftsmanship, which are thoughtfully complemented and extended by digital tools and workflows—with the completed structure validating this integrated methodology. Small-diameter roundwood proves viable as a primary structural material when paired with material-efficient geometry and adaptive digital workflows. AR's integration with manual processes democratized complex assembly, while local sourcing and minimal processing reduced embodied energy. The Hypar's design balanced analogue prototyping and digital analysis, adapting to material variability and ensuring safety through structural redundancy and conservative detailing. Together, these strategies advance a resource-conscious, locally grounded, and sustainable model for architecture.

5. Conclusion and Outlook

It should be stated that further testing and validation is needed to fulfill the requirements of a reliable, robust structure. Even though the wooden grid shell was able to carry the load of the whole project team standing on it and thereby demonstrating its basic performance capability, no more detailed load tests have been carried out in the course of the project to date.

This project confirms the viability of small-diameter roundwood as a primary structural material when paired with adaptive digital workflows and material-efficient geometries. By integrating traditional craftsmanship with augmented reality-guided assembly, the approach demonstrates how locally sourced, low-value timber can be transformed into resilient architectural systems in a quick and efficient way. A team of six students and two teachers was able to debark the logs and complete the structure in just four days. However, upscaling such methods to broader applications requires systemic shifts in both the timber supply chain and societal perceptions of material value. To transition from experimental prototype to mainstream practice, the industry must reorient toward regional material networks, prioritize semi-automated processing, and challenge entrenched norms that equate structural reliability solely with standardized industrial products.

Outlook

Achieving this shift demands technical and methodological advancements: automated timber grading using non-destructive scanning to assess stiffness and defects; life-cycle assessments to quantify environmental benefits; and integrated design-to-fabrication workflows that optimize material use. Policy frameworks incentivizing low-carbon construction could further help redefine timber architecture in an era of climate extremes and resource scarcity. Ultimately, hybrid systems combining roundwood with other natural materials like bamboo or engineered timber products could further expand structural possibilities. Ultimately, this approach charts a resilient, resource-efficient trajectory for timber architecture, grounded in the integration of local ecosystems, digital innovation, and traditional craft.

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