

Article

iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological

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Abstract: Raw bamboo, a biomass building material with ecological degradability and rapid growth, is crucial for promoting a circular economy and sustainable environments. However, its non-standard nature limits standardized design and mass production. To overcome this, our study introduces a modular bamboo design workflow utilizing digital design technology to address geometric variability. The workflow incorporates 3D scanning to convert raw bamboo forms into precise geometric data, analyze their geometric parameters and connection methods for modular design, and apply discrete–topological shape-finding and aggregation for iterative optimization in batch production. We explore how XR assists in visualizing bamboo furniture designs, the benefits of 3D scanning, discrete design principles, and strategies for material integration. Our methodology includes material analysis, form finding, optimization, and a parametric workflow to enhance adaptability and innovation. The process covers 3D scanning raw bamboo, designing discrete units and connection rules, and aggregating units via topological optimization. This study highlights how modern digital technologies and innovative methodologies can enhance bamboo furniture design. These approaches promote more effective and diverse solutions while addressing the inherent limitations of the material.

Keywords: raw bamboo; non-standard materials; 3D scanning; discrete design; sustainable design; furniture design; circular economy; extended reality (XR)



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1. Introduction

Influenced by the current state of greenhouse gas emissions and resource constraints, there have been calls from all parts of the world to actively utilize biomass resources and increase the utilization of biomass materials. Bamboo is a fast-growing alternative to wood and offers designers and engineers a reliable alternative to green, low-carbon materials. According to David Trujillo, in parts of the world where there is no significant commercial forestry, one cannot wait 30–50 years to plant trees to meet market demand, whereas bamboo forests can be cultivated from scratch in less than 10 years and can be followed by a stable and continuous supply of bamboo timber [1]. Bamboo's rapid growth and high strength offer a viable solution for sustainable biomass construction, particularly in developing countries, addressing challenges like global warming and urbanization.

However, bamboo furniture faces several challenges. The non-standard geometry of materials is one of the biggest challenges for designers when designing raw bamboo structures [2,3]. In daily life, there are many non-standard raw materials around people

that are difficult to be utilized, including recyclable wood waste, solid construction waste, and raw bamboo. The efficient utilization of these raw materials will promote low carbon energy and sustainable development [4,5]. Currently, the construction industry is one of the industries with the highest carbon emissions (39%) and energy consumption (35%) in the world [6]. Due to the increase in labor costs, the construction industry is undergoing a digital transformation where all aspects of a building project are controlled through digital platforms from the start of construction to completion and maintenance and even demolition [7–9]. The utilization of digital technologies will drive the development of sustainable structure design. Ngai Hang Wu [10] of the Bartlett School of Architecture led his team to develop a system for digital construction of bamboo (Figure 1), where they extracted information on real bamboo materials in the physical world, followed by calculating the data in a series of digital tools to transform the bamboo into digital inputs. Finally, the digital information is combined by matching the digital information to the raw material through augmented reality during the construction phase. This system showcases the design potential of digital technology in leveraging sustainable, unconventional bamboo materials, inspiring architects to rethink the role of sustainable materials in architectural innovation.

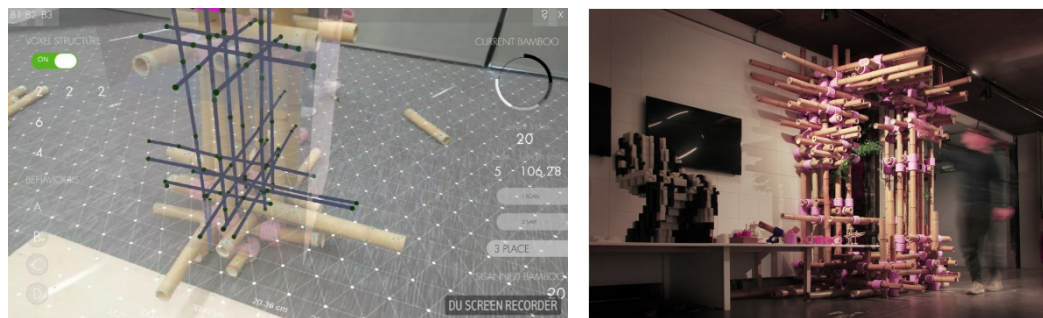


Figure 1. A digital system for AR fabrication of bamboo structures through the discrete digitization of bamboo.

Despite its superior properties, including resistance to bending, light weight, fast growth, and biodegradability, bamboo's full application in the furniture design remains limited by these challenges. This poses a critical research problem: how to reconcile bamboo's inherent geometric variability with industrialized construction demands while preserving its ecological value. Addressing these issues is imperative to introduce bamboo into the architectural market, particularly under the current environmental crisis, to provide better solutions for contemporary architecture [11–13]. To overcome this, our study introduces a modular bamboo furniture design workflow utilizing digital design technology to address geometric variability with the dual aim of establishing a scalable framework for mass production and advancing bamboo's role in sustainable architectural innovation.

By transforming raw bamboo into optimized structural components through precise digital fabrication, the workflow ensures that every part of the material is used efficiently, reducing offcuts and scrap. Furthermore, the ability to design and fabricate customized bamboo elements encourages modularity and reusability, enabling structures to be disassembled, repurposed, or recycled at the end of their lifecycle. This approach not only extends the material's usability but also reduces the demand for virgin resources. Additionally, the workflow promotes local sourcing and production, cutting down on transportation emissions and supporting regional economies. By integrating bamboo into a digitally driven, circular design process, the proposed workflow demonstrates how sustainable materials and innovative technologies can work together to create environmentally responsible and economically viable solutions, ultimately advancing the goals of the circular economy.

2. Background

Raw bamboo has gained prominence as a key sustainable material, thanks to its rapid renewability and low carbon footprint. However, its adoption in industrialized architecture remains constrained by inherent geometric irregularities, which challenge conventional standardization methods. To bridge this gap, digital design technologies are critical enablers: 3D scanning captures bamboo's organic morphologies as precise digital twins, transforming natural variability from a liability into a dataset for systematic analysis. Discrete algorithms decompose these irregular forms into modular, recompilable units, enabling mass customization through parametric shape-finding and topological optimization. XR visualizes and tests modular assemblies in virtual environments, ensuring functional and aesthetic coherence before physical fabrication. These technologies collectively operationalize this study's research framework, a workflow that harmonizes ecological materiality with industrial scalability, by digitizing, discretizing, and dynamically validating bamboo's unpredictable geometries. This integration not only addresses standardization barriers but also redefines bamboo's role in circular economies, where digital precision enhances material efficiency without erasing its biomorphic essence.

2.1. Three-Dimensional Scanning

Three-dimensional scanning technology helps engineers obtain digital information about bamboo poles. Converting materials from the physical world into data enables designers and engineers to utilize non-standard bamboo. In a reconstruction project of bamboo houses in Lombok, Indonesia, researchers digitized the individual structures of bamboo elements through reverse engineering to make the bamboo culms compatible with modern data management platforms and used Building Information Modeling (BIM) to coordinate structural design, construction, and maintenance [14]. This digital workflow increases compatibility between the organic nature of bamboo culms and modern design and construction procedures, enabling digital management of irregular building materials. However, 3D scanning has its drawbacks, including the challenge of capturing the precise geometry of bamboo, which can be irregular and inconsistent. This can lead to difficulties in achieving accurate digital representations and can complicate the design and construction processes.

2.2. Enhanced Design with Discrete Algorithms

Discrete algorithms enhance prefabricated assembly design systems for bamboo structures, helping overcome limitations associated with 3D scanning. A discrete bamboo structure is composed of repetitive and reconfigurable discrete bamboo elements. Discrete Automation considers every element as a piece of data that can be computed [15], which aligns with the purpose of 3D scanning bamboo. These bamboo elements can be assembled through traditional joining practices such as lashing, bamboo bolts, and bamboo wedges. Designers and users make preliminary designs for these combinations, and based on these assembled structural units, computer programs digitally simulate and combine these elements using discrete algorithms. This approach enhances the digital fabrication process by providing more accurate and mechanically sound designs. The designer can set growth boundaries for the bamboo components, giving realism and practical value to the bamboo structures. AUAR has utilized Discrete Automation to frame the platform approach [15,16]. Discrete algorithms allow users to explore countless personalized combinations of styles, but the structural soundness of these aggregated bamboo units needs further verification. To make the morphology of the discrete unit aggregates more mechanically sound, the structure needs to be topologically optimized.

Topology optimization was developed as an advanced structural design methodology for generating innovative, lightweight, and high-performance structures that are difficult to obtain through conventional concepts [17,18]. Topology optimization tools allow the form and structure of discrete bamboo structures to be optimized together, rather than as separate parts of the design [19].

2.2.1. Modular Design

Discrete design generation technology offers significant advantages for modular design. By using prefabricated and standardized discrete units, designers can create highly flexible and adjustable building systems. For example, Gilles Retsin's 2017 Tallinn Architecture Biennale pavilion, composed of 83 modular discrete units, demonstrates the flexibility of discrete technology in design and assembly. These units can be used under various design boundary conditions, functioning as load-bearing columns, beams, ceilings, or staircases. Gilles Retsin's design also illustrates how changing connection rules and design boundaries can generate large-scale design schemes, such as the London residential block design. This method, based on the same discrete units, achieves diversified spatial results and enhances the modularity and reusability of buildings.

2.2.2. Temporary Structure Design

Discrete generation technology also shows great potential in temporary building design. In 2021, Chen Daoyuan and Wang Guoen applied discrete generation technology to design post-disaster temporary buildings, emphasizing "convenience" and "recyclability" as crucial features. By flexibly combining and quickly assembling discrete units, they provided an efficient and economical solution. For instance, the SUP system can organize and construct spatial units of various scales, such as booths, partitions, seats, and corridors, meeting diverse functional requirements. Furthermore, all materials can be fully recycled after use, enhancing economic recovery efficiency. Despite some issues with building sealing and waterproofing, researchers proposed using membrane systems as a "skin" attached to the SUP "skeleton" to achieve waterproofing and insulation, improving the performance of temporary buildings.

2.2.3. Digital Assembly

The rise of digitalization and automation has brought new opportunities to the construction industry, especially through discrete design, which demonstrates significant potential in modular design and digital assembly via fully automated processes. For instance, Walid Anane [20] constructed a digital assembly research framework based on discrete generation technology for prefabricated modular housing. In this project, discrete modules are assembled by industrial robotic arms and then transported to the site for assembly. Discrete design not only reduces labor costs and improves construction efficiency but also enhances construction accuracy and the manufacturing precision of discrete units. Through digitally iterative generation and simulation models, architects can adjust designs according to user needs and realize efficient modular assembly by combining robotic manufacturing technologies.

2.3. Extended Reality (XR)

XR technologies, including AR, VR, and MR, play a crucial role in our workflow by promoting participatory design, fostering creativity, and enhancing user engagement. By integrating gamification and user-centered design principles, XR transforms traditional design processes into interactive and immersive experiences. This approach democratizes design, allowing non-professionals to actively participate in the creation process, thereby equalizing power relations and promoting mutual learning. XR also addresses

the limitations of traditional bamboo structure design, which often lacks innovation and fails to engage younger audiences. Through intuitive simulations, XR enables users to interact with both specific (e.g., size, material) and non-specific (e.g., spatial perception, usage scenarios) design data, providing rich feedback for designers to refine their work. This immersive environment bridges the gap between human–computer interaction and human–environment interaction, reducing cognitive burdens and improving operational efficiency. Ultimately, XR fosters a more inclusive, creative, and sustainable design process, attracting broader attention to the use of bamboo in design.

2.3.1. Enhancing 3D Scanning

XR platforms, encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), significantly enhance the 3D scanning process in bamboo furniture design. Leveraging XR technologies allows designers and engineers to visualize and interact with 3D scans of bamboo poles in immersive environments. For instance, AR overlays digital information onto physical bamboo, enabling real-time visualization of geometric inconsistencies and aiding in the accurate capture of irregular bamboo shapes. This immediate feedback loop improves the precision of 3D scanning, addressing primary drawbacks of traditional methods. Furthermore, VR enables designers to explore detailed 3D models in a virtual space, ensuring comprehensive data capture before proceeding to the design phase. This immersive experience leads to more accurate and efficient data collection, ultimately enhancing the digital representation of bamboo poles.

2.3.2. Integration of 3D Scanning Data into Discrete Design

XR platforms seamlessly integrate 3D scanning data into the discrete design process for bamboo furniture. Using MR, designers visualize how scanned bamboo elements fit within a digital design framework in real time. This integration allows for the immediate adjustment and optimization of bamboo components within a digital twin of the intended furniture design. For example, AR projects scanned bamboo elements into a virtual design space, enabling testing of various configurations and joinery methods before finalizing the digital model. This hands-on approach ensures that digital representations are accurate and practically viable, streamlining the transition from physical scanning to digital design.

2.3.3. Facilitating Collaboration and Iteration

XR platforms enhance collaboration among designers, engineers, and other stakeholders in the bamboo furniture design process. VR and AR create shared virtual spaces where team members interact with 3D scanned models and discrete design elements in real time, regardless of physical location. This collaborative environment fosters better communication and quicker decision-making, as all participants see and manipulate the same digital objects. Moreover, iterative design becomes more efficient with XR, as changes to the digital model are immediately visualized and assessed in an immersive environment. This capability reduces the time and cost associated with multiple design iterations, making the process more agile and responsive to feedback.

2.3.4. Optimizing Digital Fabrication

XR technologies significantly optimize the digital fabrication of bamboo furniture by bridging the gap between digital models and physical production. The Timber De-Standardized framework by RUBI Lab (Figure 2) reimagines digital fabrication by merging mixed reality (MR) with sustainable material use, enabling users to co-design and assemble structures from irregular logs through an immersive, iterative process. By integrating real-time structural feedback and a digital archive of 3D-scanned logs, the system balances user creativity with viability, salvaging non-standard materials typically discarded in

conventional workflows. The successful prototype demonstrates that complex timber assemblies can be achieved without robotic tools, prioritizing accessibility and sustainability. This approach advances resource efficiency in architecture, empowering users to redefine design possibilities through intuitive, hands-on interaction within a hybrid digital–physical environment. Furthermore, AR guides the assembly of discrete bamboo elements by overlaying digital instructions onto the physical workspace, ensuring precise alignment and connection of components. This approach minimizes errors and enhances the accuracy of the assembly process. Additionally, XR platforms simulate the structural performance of bamboo furniture in a virtual environment, allowing designers to test and refine their models before fabrication. By integrating real-time data and visualizations, XR helps optimize the design for both aesthetic and functional performance, leading to more robust and reliable bamboo furniture products.

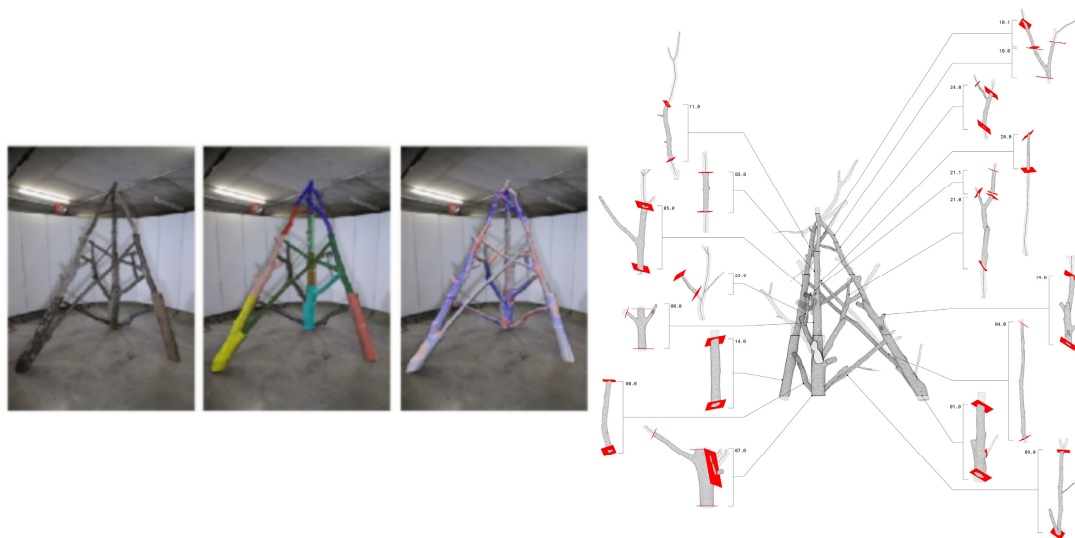


Figure 2. Timber De-standardized 1.0, a mixed-reality framework for the assembly of irregular tree log structures by RUBI Lab, directed by Leslie Lok [21].

2.3.5. Educational and Training Applications

The XR workflow in this research (Figure 3) begins with the integration of XR technology to create an interactive, immersive design platform. Using Unity (2022.3.53f1c1) software as the development platform, Rhino-Grasshopper is linked to Unity to enable dynamic scene creation and entity behavior simulation. This platform allows users to explore and interact with virtual environments, providing real-time feedback on design choices. Gamification is introduced to enhance user engagement, with mechanisms such as logical storytelling, interactive dialogues, and task nodes that make the design process more enjoyable and accessible. For bamboo structure design, the workflow involves iterative switching between physical and virtual environments, where non-standard bamboo components are digitally cataloged and optimized. This process ensures that even irregular bamboo pieces are utilized, reducing waste and promoting sustainability. In urban furniture design, XR simulates real-world scenarios, enabling users to visualize and interact with designs in context, while virtual human models test ergonomic compatibility. This approach not only improves design accuracy but also empowers users to contribute creatively, ensuring that the final products are both functional and appealing. By combining XR, gamification, and participatory design, the workflow fosters innovation, inclusivity, and sustainability in bamboo-based design.

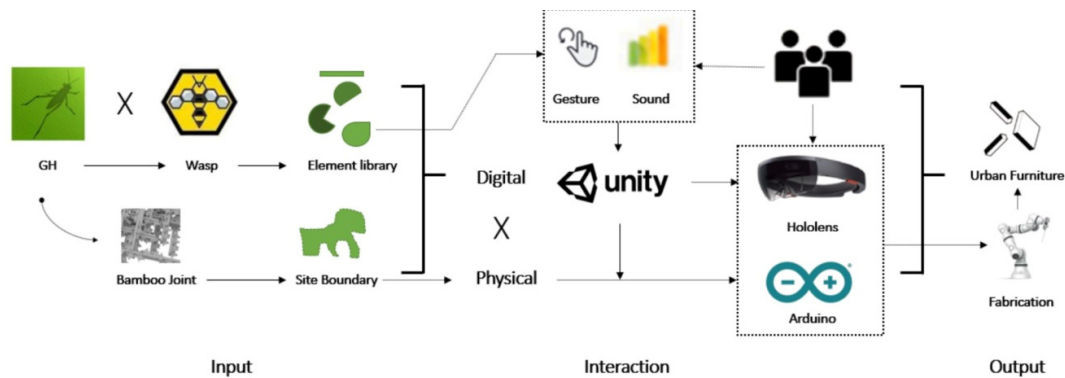


Figure 3. Proposed workflow from discrete design input to XR collaborative interaction to digital fabrication output.

The experimental results demonstrate the transformative role of XR technology in the design and manufacturing process, particularly in enhancing participatory design, improving precision, and fostering sustainable practices. By integrating XR into the workflow, users were able to interactively engage with bamboo structure designs in immersive virtual environments, providing real-time feedback on spatial perception, material usage, and ergonomic compatibility. This participatory approach not only democratized the design process but also generated innovative ideas from non-professionals, addressing the traditional limitations of bamboo design. In the manufacturing phase, XR-enabled simulations allowed for the precise cataloging and optimization of non-standard bamboo components, significantly reducing material waste and improving resource efficiency. Furthermore, the gamification elements incorporated into the XR platform increased user engagement and creativity, making the design process more accessible and enjoyable (Figure 4). These results highlight how XR bridges the gap between design and manufacturing, enabling a more inclusive, efficient, and sustainable workflow that aligns with circular economy principles. Future research will further explore the structural performance and scalability of XR-integrated bamboo designs to validate their practical applications in mainstream construction and furniture industries.



Figure 4. Interface of the XR platform to engage the audience in bamboo furniture design.

Overall, the synergy of XR, 3D scanning, and discrete design technologies provides a powerful and flexible approach to bamboo furniture design. By leveraging these tools, designers can overcome the inherent limitations of bamboo, integrate it with other materials, and create innovative, sustainable, and aesthetically pleasing furniture. This new work-

flow not only democratizes the design process but also drives the construction industry towards greater flexibility, efficiency, and sustainability. As these technologies continue to evolve, their combined application will undoubtedly lead to even more groundbreaking developments in bamboo furniture and beyond.

3. Developing the Structure of Workflow

The basic logic of this technology can be summarized in three key steps: discrete unit design, definition of connection rules, and aggregation of components. This process begins with an in-depth study of the simplest raw bamboo rods. Using 3D scanning and other technologies, the geometric data of the bamboo rods are obtained and quantitatively analyzed. This allows for the study of the discrete generation of bamboo rods, addressing the material limitations of bamboo and providing corresponding solutions (Figure 5).

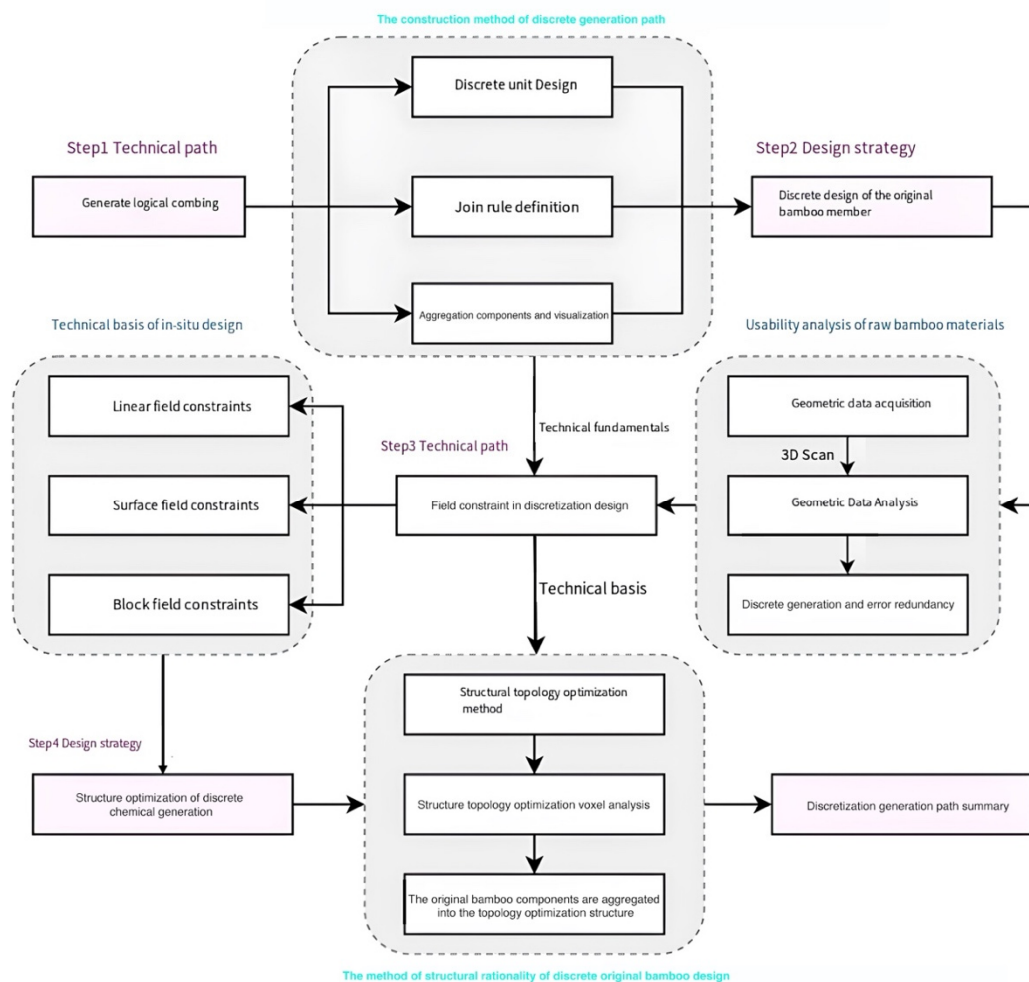


Figure 5. The workflow of a new aggregation approach for discrete bamboo component.

Following this, the technology investigates field constraints on discrete generation involving complex bamboo nodes. This is explained through three levels of constraints: linear field, surface field, and volume field. These field constraints provide technical pathways for the local design of bamboo landscape architecture.

Lastly, the application of discrete components in structural rationality is analyzed. Through topological optimization, a new aggregation approach for discrete bamboo components is proposed, addressing the limitations and usability of this path. This analysis provides technical references for subsequent empirical research.

3.1. Material Analysis

A very critical challenge is the non-standardization of the geometric characteristics of bamboo poles and the variability of their physical and mechanical properties [22–25]. Compared to other materials suitable for construction, bamboo poles are difficult to standardize in terms of design and modular production [26]. According to the statistical data analysis of more than forty bamboo materials (Figure 6), the growth cycle of bamboo takes only 2–5 years, which is much faster than that of timber. The growth height of bamboo poles can reach up to 30 m, and the diameter of bamboo ranges from a minimum of 1 cm to a maximum of 30 cm. These statistics show the excellent potential of bamboo as a sustainable building material, which can be used in a variety of building designs.

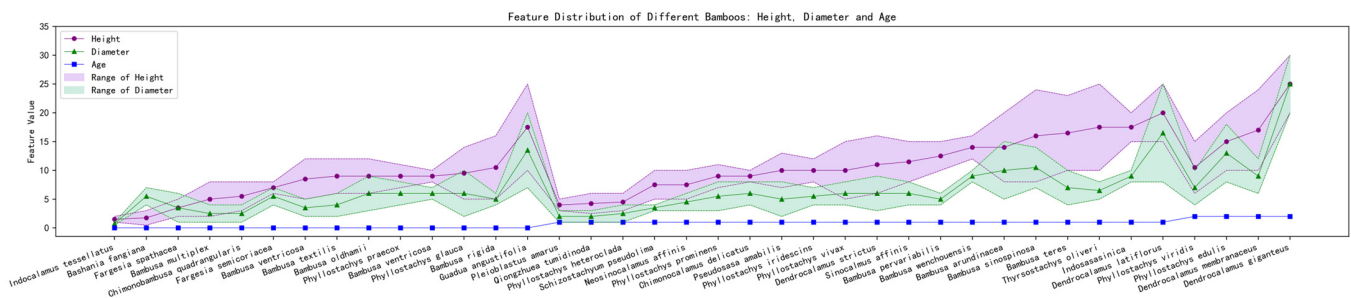


Figure 6. Feature distribution of different bamboo: height, diameter, and age.

The variable nature of bamboo culm's geometry and mechanical properties makes it unique rather than standard, which not only prevents its use in the construction industry but also its integration into digital platforms. This gap can be addressed by utilizing digital methods of 3D scanning and reverse engineering to address the challenges associated with the non-standard nature of bamboo culms, while integrating digital information about bamboo culms into modern platforms.

After the scanning is completed, the digital information of the bamboo needs to be extracted and analyzed for better design strategies. The geometry of the original bamboo is processed using Rhino built-in plugins Grasshopper [27] and Cockroach [28]. Rhino (version 7) is a powerful modeling software that can analyze and reconstruct irregular shapes. Elements reconstructs the point cloud to obtain an STL file that is a mesh surface model, which needs to be converted into NURBS for the analysis of the cross-section. To analyze the cross-section data, it needs to be transformed into a NURBS model. Since NURBS surfaces cannot directly generate bounding boxes for further development, a conversion step is required in the workflow. Therefore, we use Cockroach to convert the mesh surface model into a point cloud, and then convert the point cloud into a NURBS surface model in Rhino. Then, we intercepted the original bamboo in 5 mm increments and obtained the maximum and minimum circumferential values to analyze the differences in bamboo diameter (Figure 7).

3.2. Form Finding and Optimization

In the traditional design process, it is very difficult to apply non-standard materials to buildings, and they often use customized processes to process raw materials into standardized components for use. When raw bamboo is processed into integrated or reconstituted bamboo, it increases energy consumption and CO₂ emissions. We aim to consider the errors between non-standardized bamboo materials at the design stage. Therefore, we need to obtain digital information about the bamboo, and converting the physical material into digital data is beneficial for determining the use and location of each bamboo pole at the design stage to minimize the systematic errors caused by the material itself. By

embedding raw bamboo rods within a larger voxel, the shape discrepancies caused by the non-standard geometric characteristics of the bamboo can be mitigated. Utilizing flexible connection methods such as binding to connect the bamboo rods allows these non-standard components to participate in the discrete generation workflow. This approach reduces system errors inherent to the material itself.

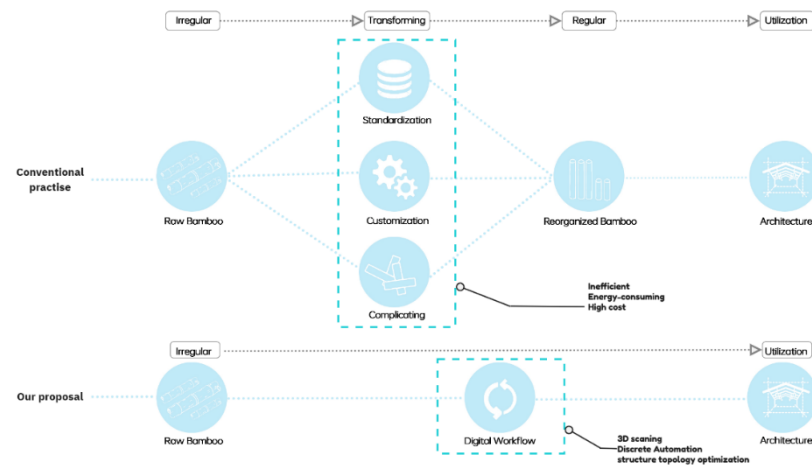


Figure 7. The difference between conventional practice and our proposal.

3.3. Discrete Generation

On the one hand, discrete generation technology expands the diversity of design solutions and improves design efficiency. On the other hand, the randomness inherent in the aggregation of components generated by this technology poses significant challenges to design control. To address this, it is essential to incorporate field constraints into the aggregation process to help designers and users achieve the desired outcomes. Fields can be categorized into curve regions, surface regions, and volume regions (Figure 8).

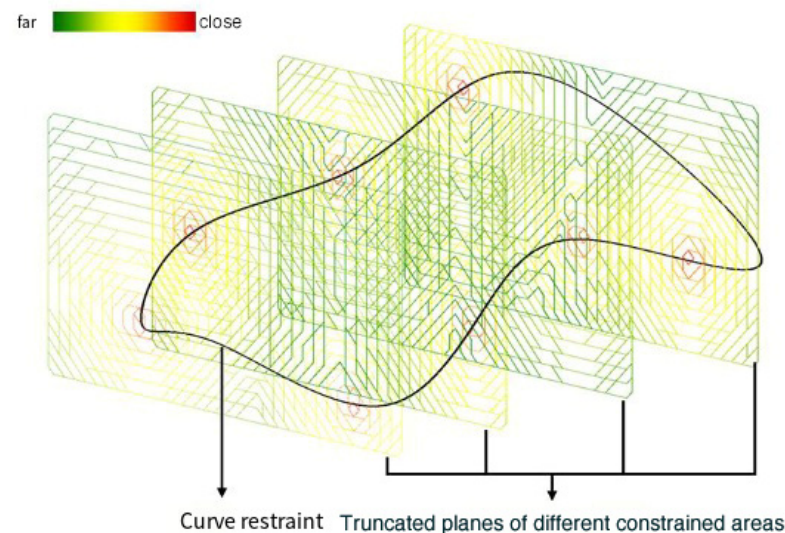


Figure 8. Curve constraint area section plane.

In the context of curve region constraints, discrete generation can be understood as creating design solutions along specified paths. Designers only need to specify one or more curves, and discrete units will generate designs that follow these paths driven by algorithmic scripts. This section introduces the curve region constraints in discrete generation from three aspects: algorithmic logic, relevant computational tools, and the

resulting designs. It also compares different design forms under various parameters and analyzes the potential of curve-constrained designs.

Surface region constraints involve generating aggregation components near a defined surface (Figure 9). Designers can define any surface, and discrete units will cluster around this surface to form a design. For example, when designing container homes on a hilly terrain, surface region constraints can be used to optimize the placement of containers. Using software like Ladybug (Version 1.7.26) [29] for light analysis can enhance the preliminary design phase, and generative algorithms can significantly boost efficiency in conceptual design. This section discusses the surface region constraints in discrete generation, focusing on the algorithmic logic and resulting designs.

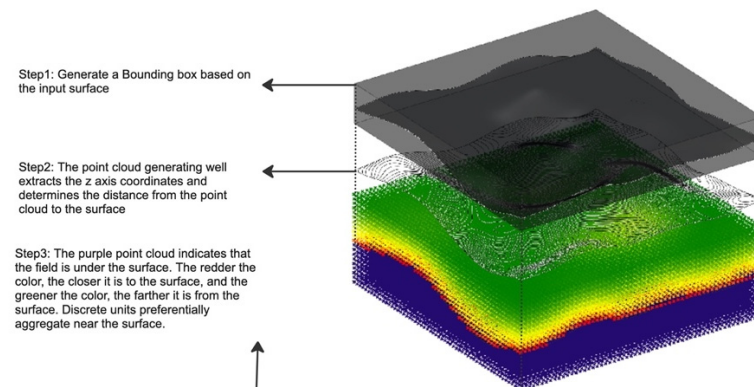


Figure 9. Field generation with surface area constraints.

Volume region constraints pertain to generating design solutions within a specified three-dimensional geometric space. Designers need to define a closed region or mesh, and discrete units will form aggregated components within this volume driven by algorithmic scripts. This section explores volume region constraints in discrete generation, detailing the algorithmic logic and resulting designs, comparing different design forms under various parameters, and analyzing the potential of volume-constrained designs (Figure 10).

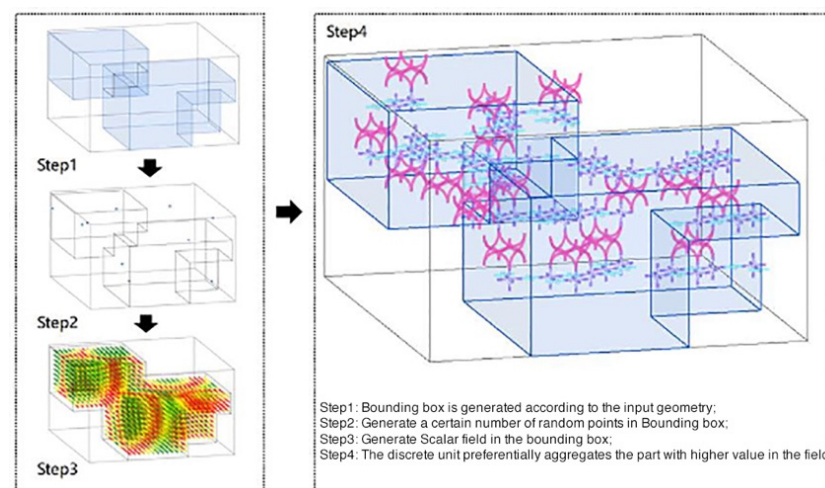


Figure 10. Algorithmic logic of volume constraints.

When working with raw bamboo materials, embedding bamboo rods within a larger voxel can mitigate shape discrepancies caused by their non-standard geometric characteristics. Using flexible connection methods like binding allows non-standard bamboo rods to participate in the discrete generation workflow, reducing system errors inherent to the

material itself. Discrete generation technology not only expands design possibilities and efficiency but also necessitates the integration of field constraints to manage the randomness of aggregated components, ultimately aiding in achieving the desired design outcomes.

4. Digital Workflow

The focus of our research is how a range of digital design tools can be used to achieve innovative design and direct utilization of raw bamboo without having to go through the tedious process of fabrication (Figure 11). During our experiments, we employed 3D scanning techniques, discrete algorithms, and topology optimization. Three-dimensional scanning techniques were used to obtain digital information about the physical material, and the geometric data of the raw bamboo helped to analyze the bamboo nodes, which also served as inputs for subsequent research. Discrete algorithms focus on the way modules are connected and aggregated, which can explore the aggregated forms of discrete bamboo nodes and provide more ideas for the innovative design of raw bamboo. Topology optimization can optimize the structure while optimizing the form, so that the discrete bamboo units can be aggregated into a structurally superior solution to support the design solution.



Figure 11. Digital workflow of steps: from scanning to discrete to topological.

To better utilize biomass sustainable bamboo materials, their non-standard material properties need to be overcome. Currently, the commonly used method is to process raw bamboo into integrated or recombinant bamboo for construction, which unifies the shape of the bamboo poles in terms of geometric parameters, but also limits material properties such as air permeability and bending resistance and brings more carbon emissions during processing. Therefore, this paper proposes a digital design workflow to improve the design possibilities of non-standard bamboo materials. Firstly, we scan the bamboo poles using 3D scanning technology to obtain geometric parameters such as bamboo diameter, node spacing, number of nodes, and length of the poles. Then, we study the modular connection between the construction nodes and bamboo poles of the original bamboo and aggregate the discrete bamboo units based on the wasp plugin [30] in grasshopper. In addition to this, the building boundaries are defined by the user and the designer, and the bamboo structure is optimized by topological algorithms. In this paper, the author analyzes the pain points of raw bamboo design and explains the help of multiple digital technologies in combination with experimental simulations to increase the possibilities and diversity of non-standard raw bamboo architectural design (Figure 12).

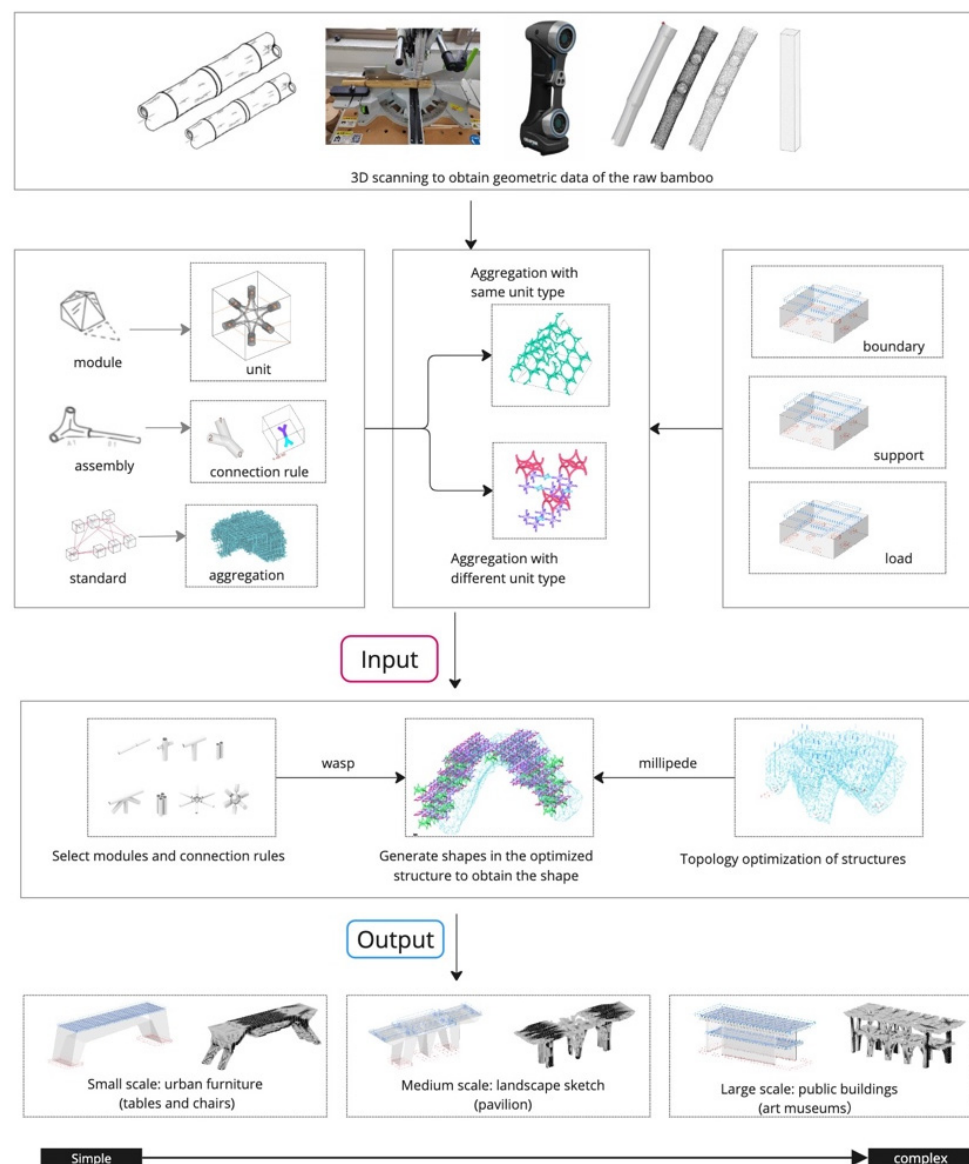


Figure 12. The diagram of data flow with operators.

Especially in furniture design, the workflow supports the creation of lightweight, durable, and aesthetically versatile bamboo products that can be mass-produced with minimal environmental impact. By optimizing material usage and enabling local production, the workflow reduces transportation costs and carbon emissions, further enhancing its economic and ecological benefits. For construction, the workflow enables the precise customization of bamboo components, allowing for modular and prefabricated systems that can be easily assembled, disassembled, and reused. This modularity not only reduces construction time but also facilitates the adaptation of structures to changing needs, extending their lifecycle and minimizing waste. Additionally, the integration of bamboo into mainstream construction and furniture design promotes the use of a rapidly renewable resource, reducing reliance on non-renewable materials and supporting sustainable supply chains. Exploring the economic viability of this workflow in these industries could demonstrate its potential to drive innovation, reduce costs, and contribute to a circular economy, where materials are kept in use for as long as possible, and waste is systematically minimized.

The experimental part was carried out around three main aspects, firstly, the geometrical data collection of the original bamboo was completed by using reverse engineering, and the data were processed and analyzed by combining with parametric design tools. Then, the node structure, geometrical relationship, and connection rules of the discrete bamboo structures were investigated. Lastly, the aggregation mode of the discrete bamboo design was investigated, and it was applied to the topology-optimized structure (Figure 13).

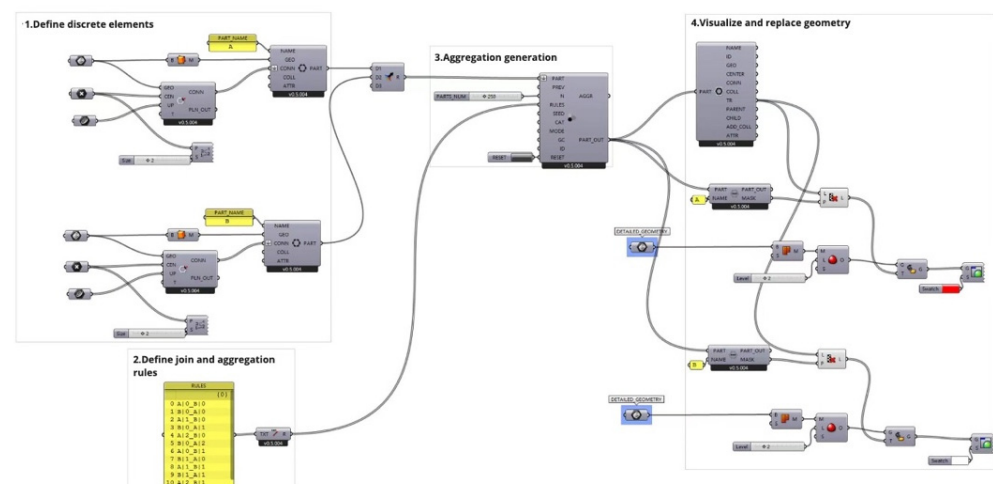


Figure 13. The diagram of discrete generation in Rhino 3D-Grasshopper.

4.1. Three-Dimensional Scanning of the Raw Bamboo

4.1.1. Material Pre-Processing and 3D Scanning

During the pre-processing stage of the raw bamboo material, the experiment was analyzed on twenty 40 cm long sections of raw bamboo poles, which were intercepted from the same batch of five bamboos. The parameters of the bamboos for this scanning were 4 cm in diameter and 4 m in length each. According to the experience provided by the bamboo master, the available length of each raw bamboo in southern Fujian is about 4 m, so the bamboo selected for the experiment is the raw bamboo that can be used as a building material. When scanning the raw bamboo (Figure 14), we used a laser 3D scanner Handyscan700 (Creaform, Levis, QC, Canada), which is an industrial-grade high-precision handheld 3D scanner with a scanning range of up to 0.1–4 m and a scanning accuracy of 0.03 mm. The scanning speed of the scanner is fast, the operation is simple and convenient, and the scanning range is large, which meets the demand for scanning of the scale of the bamboo components. The scanning speed of this scanner is fast, the operation is simple

and convenient, and the scanning range is large, which meets the demand for scanning the scale of bamboo components. The software used for 3D reconstruction of the scanned point cloud is VX (version 11) elements, which provides excellent accuracy and data quality to minimize errors caused by hardware and software equipment during the scanning process.

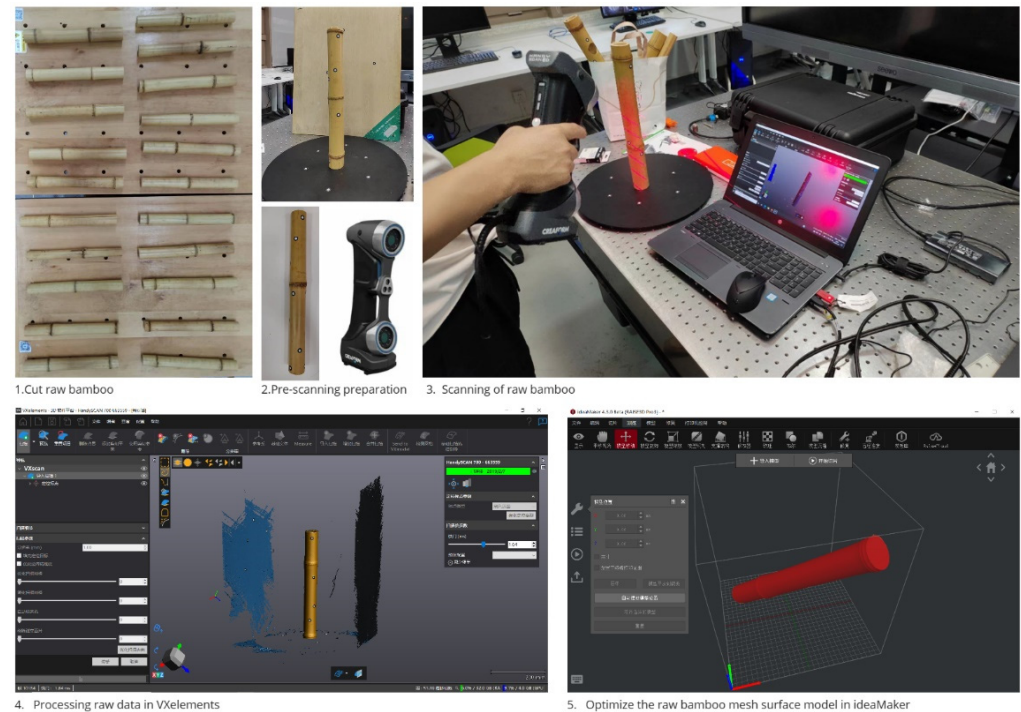


Figure 14. Cutting 20 pieces of 40 cm raw bamboo and its 3D scanning.

The geometric shapes were captured using an Eva scanner from Artec 3D [17] to generate point clouds [19] of the outer bamboo surface and portions of both ends' cross-sections. Figure 14(4) shows the 80 bamboo rod-shaped clouds obtained at the end of the geometric data acquisition. This point cloud was then processed using proprietary software Artec Studio 12 [17] to create 3D polygon mesh models of individual bamboo stalks. The average precision of the 3D polygon mesh created by the scan has a sectional dimension accuracy of 1% and a stalk length accuracy of 1/1000 compared to manual measurements [15].

4.1.2. Geometric Data Analysis of Raw Bamboo (NURBS Model and Geometric Properties)

Bamboo is a tall, rapidly growing grass-like plant with woody stems. It is distributed in tropical, subtropical, and warm temperate regions. The highest concentration and variety of bamboo species are found in East Asia, Southeast Asia, and the islands of the Indian and Pacific Oceans. The above-ground stem of bamboo, which is woody and hollow, is referred to as a bamboo pole and is the primary material used in traditional bamboo construction. The large, sturdy stems of Moso bamboo make it suitable for construction purposes, such as beams, columns, trellises, and scaffolding. Its flexible strips can be used to weave various bamboo utensils and handicrafts. The main geometric features of bamboo culms are their nodes, internodes, and nodal diaphragms (Figure 15).

This study follows a previously developed approach (Figure 16) for the digitization of bamboo culms based on initial 3D polygon mesh models. These mesh models are further processed into 64 lighter non-uniform rational basis spline (NURBS) models from which geometric properties are computed and analyzed.

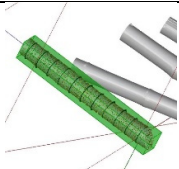
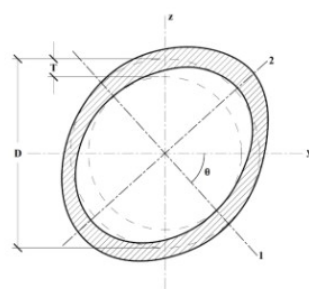
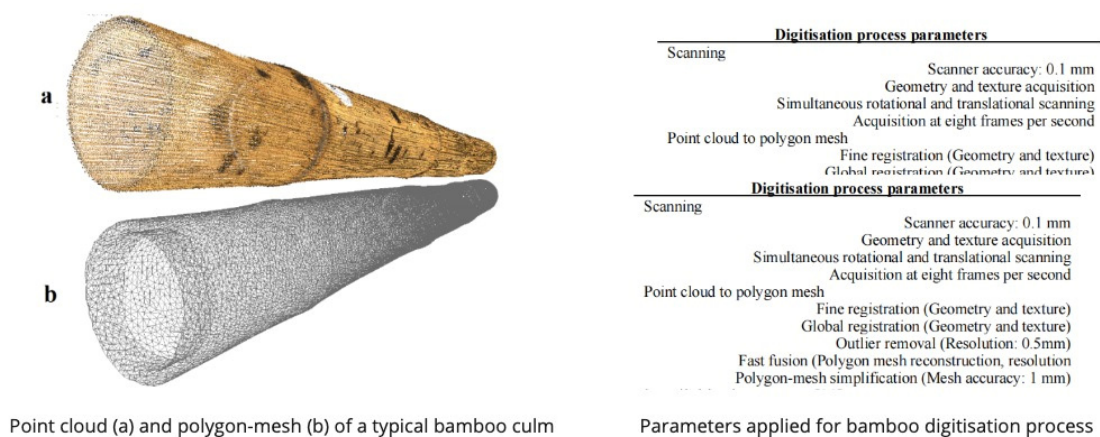
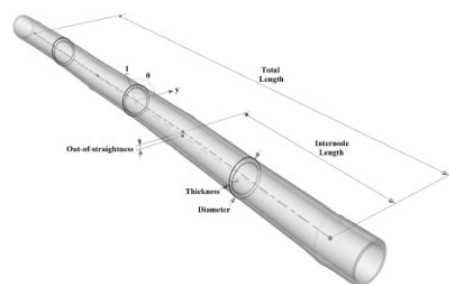
3D Bamboo Expression					
Format	Raw bamboo	Point cloud	Mesh	Nurbs	Voxel grid
Characteristics	Easy to recognize and has physical properties	The original geometric information in the three-dimensional space is retained	Some geometric data can be extracted, which is highly controllable	Controlled by functions, the surface is smooth and easy to perform geometric data analysis on	Define the geometric boundaries of raw bamboo materials
	Difficult to analyze and quantify	Irregularity and disorder, lack of texture information	Accuracy has declined compared to point cloud	It must be further optimized and generated by mesh, and the accuracy of geometric data is further reduced	Convenient to use wasp plugin to generate designs

Figure 15. Original bamboo models with different geometric data.



Typical asymmetric sections and their corresponding equivalent sections



Typical NURBS model of a digitised bamboo culm and basic geometric properties extracted from it

Figure 16. The developed process of mesh models.

4.2. Discrete Units and Connection Rules of Bamboo Nodes

The Characteristics of Raw Bamboo Nodes

One of the main reasons hindering the large-scale promotion of raw bamboo is the variability of its nodes, which makes it difficult to standardize and mass-produce bamboo structures. Different node structures result in different node units being designed. To better design raw bamboo modules, we first studied the types of nodes in various bamboo structures. Common node types in modern bamboo structures include screw connections, metal fittings, rope bindings, bamboo dowel connections, and 3D-printed component connections (Figure 17).

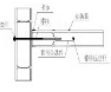
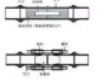
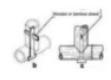
Fabrication Method	structure diagram	case	strength	Thermal Properties(°C)	water resistance	Durability	reusability& sustainability	cost	Flexibility (Elasticity)
Screw (bolt) connection			poor	350°C	poor	3-7	poor	¥ 0.2-1	poor
Sleeve connection			fair	550°C	poor	3-7	fair	¥ 0.5-5	high
metal belt or U-shaped iron plate connection			fair	900°C	good	5-10	fair	¥ 2-10	fair
prefabricated metal connection			ultra-high	1150°C	good	10-20	good	> ¥ 50	high
cast-in-place cement connection			ultra-high	700-1200°C	excellent	>15	poor	> ¥ 50	poor
groove connection& Bamboo nail connection			poor	70°C	poor	2-5	excellent	¥ 2-20	poor
Hemp rope binding			fair	150°C	poor	3-10	fair	¥ 5-20	ultra-high
3D printing			high	180-200°C	excellent	3-7	good	> ¥ 20	ultra-high
Combined connection			high	>180°C	good	4-10	good	> ¥ 50	high

Figure 17. The characteristics of different fabrication method.

4.3. Aggregation of Discrete Units Based on Topological Optimization

To facilitate assembly and processing, we define the connection methods of raw bamboo nodes as vertical connections and parallel connections. Connections at arbitrary angles are more complex, slower to process, and not conducive to the mass production of bamboo materials, so we do not study them. Besides distinguishing the nodes by type and material, we also analyze the types of connections between nodes.

The junctions of raw bamboo structures can be seen as pairs of bamboo pieces connecting with each other and then connecting with other bamboo pieces in a similar manner (Figure 18). The methods of connecting pairs of bamboo pieces include “end-to-end connection”, “end-to-pole connection”, and “pole-to-pole connection”.

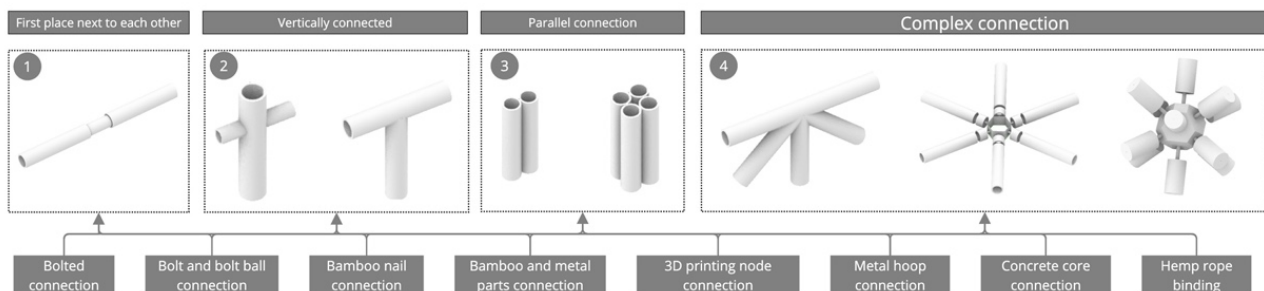


Figure 18. The framework of topological discrete units.

In digital models, we can determine the connection method between two bamboo pieces using vector products. We name the normal vectors of the bamboo end sections as $\times 1$ and $\times 2$, and the center of the bamboo ends as A, A1, B, and B1. The normal vectors parallel to the bamboo poles are named Y1 and Y2.

4.3.1. Discrete Aggregation of Identical Raw Bamboo Nodes

As shown in Figure 19, we selected a “Y”-shaped geometric relationship to demonstrate the discrete aggregation method of the same bamboo nodes. This node can be composed of three individual raw bamboo poles and a metal sleeve. The advantage of this node design is that by changing the length of each raw bamboo pole, the corresponding voxel of the component can be adjusted. This allows the node to be flexibly applied to different voxels without needing to change the connection method and angle.

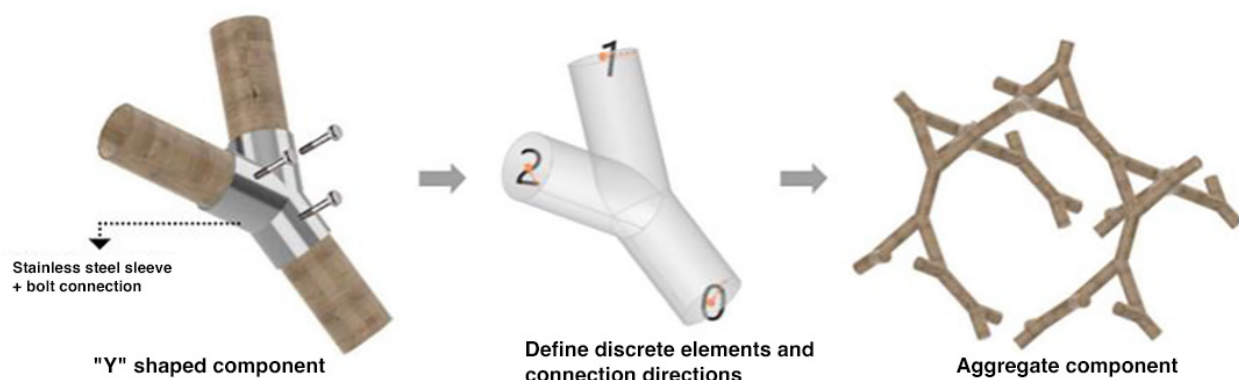


Figure 19. Original bamboo node design.

4.3.2. Discrete Aggregation of Different Raw Bamboo Nodes

A bamboo structure is often composed of various assembly units (Figure 20). We selected three different bamboo nodes and simulated the discrete aggregation of different geometric units. The connection nodes of Unit B are set in the xy plane, the connection

nodes of Unit C are set in the xz and yz planes, and the connection nodes of Unit D are set in the xy, xz, and yz planes. This configuration allows for the connection and generation of discrete units in different directions along the x, y, and z axes (Figure 21).

Original bamboo node	Geometric model	Define discrete elements	Define connection nodes
			 Type D Connection direction: xy,xz,yz
			 Type C Connection direction: xz,yz
			 Type B Connection direction: xz,yz

Figure 20. Three kinds of original bamboo discrete units.

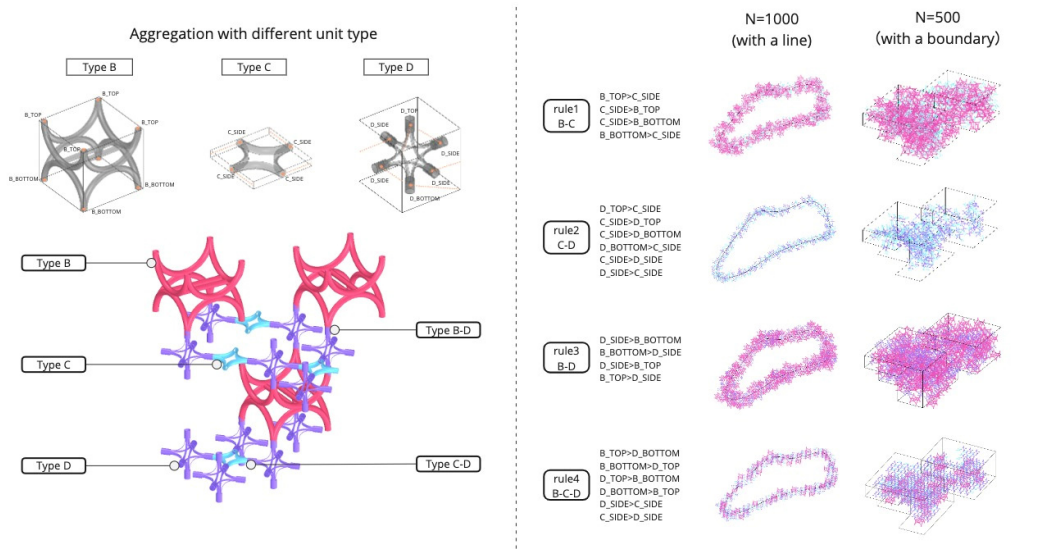


Figure 21. Aggregate components of linear region constraints.

4.3.3. Discrete–Topological Optimization–Aggregation

Discrete units represent the basic components that are identical or similar in shape in discrete design and are the smallest elements in this design methodology. In discrete generative design, voxels are symbolic elements that define a single unit of a discretized three-dimensional object. To achieve more efficient combinations between different elements, the hierarchical concept of “Partice–Part–Metapart” is introduced, like the structural relationship of “atom–molecule–polymer”.

Moreover, to better explore the relationship between parts and the whole, the concept of voxels is often introduced into the relationship between discrete units and voxels, where

voxels act as the “parts” capable of containing multiple discrete units. By defining the connection rules between voxels, they can aggregate into a whole, thereby enabling the discrete units nested within the voxels to combine into a larger overall structure.

Previous studies examined the connection rules and field constraints of discrete generative design and explored the generative effects from single raw bamboo poles to complex raw bamboo nodes, clarifying the usability and limitations of different types of raw bamboo components under discrete generative techniques. Under field constraints, discrete structures exhibit characteristics such as geometric diversity and locality. However, the aggregated components formed by raw bamboo elements are structurally weaker. Therefore, this section will combine structural topology optimization to study the structural characteristics of raw bamboo aggregate components.

Topology optimization algorithms can achieve size optimization and shape optimization of structures, finding the optimal material distribution scheme that meets design requirements through iterative optimization processes. According to Martin P. Bendsøe [31], shape optimization is the process of determining where material should be present or absent at each point in a given space. The topology optimization method involves discretizing a specified “domain” into a finite element grid, filling each element with material where needed and emptying the material from each element where it is not.

In this study, we apply topology optimization technology to explore a discrete generative design method for raw bamboo structures. The Topos plugin, a topology optimization tool based on the SIMP method [32], was utilized to optimize the structural form of raw bamboo. The plugin features a simple and user-friendly interface, requiring only an initial model design, applied loads, and constraints to generate optimized results. As illustrated in Figure 22, we began with a cubic model, applied cross-shaped loads, and distributed constraints at the base. Through computational processing, a spatially rich “pavilion” design was generated.

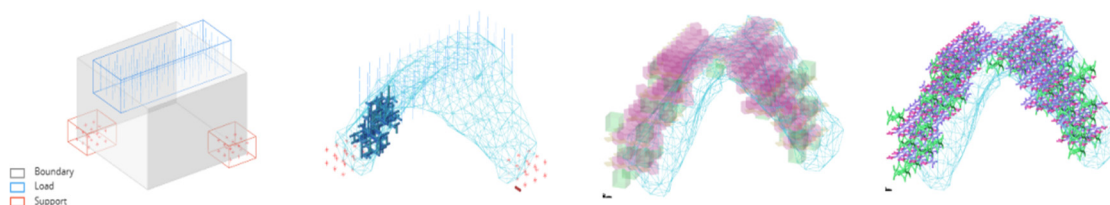


Figure 22. Relationship between voxels and discrete units.

It is important to note that topology optimization in this study is employed exclusively for form design, focusing on the aesthetic and spatial qualities of the structure. While this method significantly influences the overall geometry, its impact on the structural performance of the final design, such as load-bearing capacity, stability, and material efficiency, has not been thoroughly evaluated. The structural performance of the final design will be rigorously investigated as part of future research, ensuring a comprehensive understanding of its feasibility and functionality in real-world applications.

5. Discussion

This study is currently in the preliminary research phase, where the primary focus has been on developing and proposing the optimization method for bamboo construction. The findings presented so far are based on theoretical and computational models, focusing on the conceptual framework and preliminary design generation.

The next phase of this research will involve collecting and analyzing empirical data to evaluate the optimization results quantitatively. Key performance indicators, such as mate-

rial utilization efficiency, structural stability, and weight reduction, will be incorporated to assess the effectiveness of the proposed method. Additionally, a comparative study will be conducted to benchmark the proposed approach against traditional bamboo construction methods. This comparative analysis will help to clearly identify the advantages, limitations, and potential areas for improvement of the proposed method, thereby providing a more comprehensive understanding of its feasibility and practical relevance. Furthermore, this research will also focus on the development of an XR platform, which will serve as the final component of the integrated workflow.

5.1. XR Platform-Enhanced Bamboo Furniture Design

The XR platform offers a transformative approach to bamboo furniture design, characterized by its participatory, interactive, and visualization capabilities. By integrating advanced technologies like the Meta Quest 3, designers and users can immerse themselves in a virtual environment where they can interact with and manipulate digital representations of bamboo furniture in real time. This enhances the design process by making it more intuitive and collaborative, allowing for better decision-making and innovation.

5.1.1. Participatory Design with XR Platforms

The participatory nature of XR platforms allows users to become an integral part of the design process. Using devices like Meta Quest 3, users can visualize and interact with 3D models of bamboo furniture, providing instant feedback and suggestions. This level of engagement ensures that the final product meets the specific needs and preferences of the user, fostering a more personalized and satisfactory design outcome. The immersive environment of XR also enables users to experiment with different configurations and designs, promoting creativity and innovation.

5.1.2. Interactive and Visual Aid in Design

The interactive features of XR platforms facilitate detailed and precise adjustments to bamboo furniture designs. Designers can use hand gestures or voice commands to modify dimensions, materials, and structures, immediately seeing the impact of these changes in a virtual setting. This instant feedback loop helps in identifying potential issues and optimizing designs before moving to the fabrication stage, reducing time and resource wastage.

5.1.3. Visualization of Multi-Material Integration

XR platforms excel in visualizing how different materials can be integrated into bamboo furniture designs. For example, automated weaving machines can combine bamboo strips with metals or synthetic fibers to create hybrid components. The XR environment allows designers to visualize these combinations in real time, adjusting and optimizing the material integration for enhanced strength and aesthetics. This capability is crucial for overcoming the inherent limitations of bamboo, enabling the creation of more durable and versatile furniture pieces.

5.1.4. Step-by-Step Visualization and Production Assistance

During the production phase, XR platforms assist by providing detailed, step-by-step visualizations of the assembly process. Designers and manufacturers can use Meta Quest 3 to overlay digital guides onto physical components, ensuring precise assembly and reducing the likelihood of errors. This guidance is particularly beneficial when integrating bamboo with other materials, as it ensures that all elements fit together perfectly and function as intended.

5.1.5. Post-Design Visualization and Optimization

After the initial design phase, XR platforms continue to support visualization and optimization. Designers can simulate different environmental conditions and use cases to test the durability and functionality of the bamboo furniture. This helps in making any necessary adjustments before final production, ensuring that the furniture not only meets aesthetic standards but also performs well in real-world scenarios.

5.1.6. Holistic Workflow Integration

By incorporating XR, 3D scanning, and discrete design technologies, a holistic workflow is established that enhances every stage of bamboo furniture design and production. Starting with precise 3D scanning to capture the unique geometry of bamboo poles, the process moves to interactive and participatory design through XR platforms, and finally to optimized production using discrete design principles. This integrated approach ensures that the final product is not only innovative and sustainable but also tailored to the user's needs and preferences.

5.2. Limitations

Combining modular raw bamboo units through discrete generative technology to form a landscape architecture that responds to the terrain is a fundamental goal in the empirical research stage. The bamboo structures of raw bamboo landscape architecture typically include arched, umbrella-shaped, dome-shaped, and space grid forms. These different structural forms can be assembled from discrete units and can also be considered as discrete units participating in generative design. Aggregating scattered discrete units into a structural module and further combining them into a functionally complex landscape architecture can weaken the structural stability.

6. Conclusions

In conclusion, the integration of XR platforms, 3D scanning, and discrete design offers a comprehensive and innovative approach to bamboo furniture design. The participatory, interactive, and visualization capabilities of XR technologies, exemplified by tools like the Meta Quest 3, enable designers and users to collaboratively create optimized, sustainable, and aesthetically pleasing bamboo furniture. By visualizing and integrating different materials within the XR environment, designers can overcome the limitations of bamboo and expand its applications, driving the furniture and design industries towards greater flexibility, efficiency, and sustainability.

However, our research has also revealed several challenges and drawbacks associated with this approach. While the ecological degradability and rapid growth of raw bamboo make it a promising biomass material for promoting a circular economy and sustainable environments, its non-standard nature poses significant challenges for standardized design and mass production. To address these issues, we propose a modular bamboo furniture design workflow that leverages digital design technology to manage geometric variability. This workflow includes 3D scanning to convert physical bamboo forms into precise geometric data, analyzing geometric parameters and connection methods for modular design, and employing discrete-topological shape-finding and aggregation for iterative optimization in batch production.

Despite these advancements, there are inherent limitations to this approach. The reliance on 3D scanning and XR technologies can be resource-intensive and may require specialized equipment and expertise, which could limit accessibility for smaller design firms or individual designers. Additionally, the iterative optimization process, while effective, can be time-consuming and may not always yield immediate results.

To mitigate these drawbacks, we recommend the following design solutions and typologies as guidelines for architects and interior designers:

1. Hybrid Material Integration: Combine bamboo with other sustainable materials to enhance structural integrity and design flexibility. For example, integrating bamboo with recycled plastics or metals can create composite materials that leverage the strengths of each component.
2. Simplified Modular Systems: Develop simplified modular systems that reduce the complexity of geometric variability. This can be achieved by standardizing certain components while allowing for customization in other areas, making the design process more accessible and efficient.
3. User-Friendly XR Tools: Invest in the development of more user-friendly XR tools that require less specialized knowledge and equipment. This could involve creating more intuitive interfaces and providing comprehensive training resources for designers.
4. Scalable Production Techniques: Explore scalable production techniques that balance the benefits of digital design with the realities of mass production. This might include the use of CNC machining or other automated manufacturing processes that can handle the variability of bamboo more efficiently.
5. Collaborative Platforms: Establish collaborative platforms where designers, manufacturers, and end-users can share insights and feedback. This can help streamline the design process and ensure that the final products meet the needs and expectations of all stakeholders.

Addressing these challenges and implementing the proposed design solutions can further unlock bamboo's potential as a sustainable and versatile material in furniture design. Future work should focus on refining these methodologies, further exploring the integration of bamboo with other materials, and developing more advanced XR applications to facilitate even greater precision and efficiency in bamboo furniture design.

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