RETHINKING TRADITIONAL INDONESIAN ROOF BAMBOO FRAME STRUCTURES BY UTILIZING PARAMETRIC TOOLS AND AUTOMATED FABRICATION TECHNIQUES: A SYSTEMATIC REVIEW

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Abstract. In traditional Indonesian architecture, bamboo and timber-frame structures are essential elements, with roofs being a prominent feature. This is due to the tropical climate conditions that demand such a design. However, the traditional Indonesian hyperbolic-paraboloid roof is at risk of extinction due to modern construction demands, and traditional craftsmanship is gradually being lost. To address this issue, our research investigates which existing parametric design tools and fabrication techniques are suitable for a digital workflow and assembly production of Indonesian traditional roof structures. Through a systematic review and analysis of 19 selected articles, we have categorized the various workflows, tools, and techniques and their suitability to propose and be integrated into a novel Indonesian bamboo-based roof structure fabrication workflow, making it accessible to contemporary architecture.

Keywords: *parametric bamboo, bamboo fabrication, bamboo frame, bamboo roof, bamboo structures.*

1. A brief description of a typical traditional Indonesian house

Indonesian architecture is known for the diversity of its traditional housing typologies and construction methods. Inherited from the noble ancestral culture, the traditional houses were constructed using non-rigid timber and bamboo frameworks with a notable emphasis on the distinctive roof geometry (figure 1). The diverse forms of the roofs share a common thread in the expression of roofing steepness, which embodies local wisdom's response to solar radiation and the tropical climate (Prasetyo *et al.*, 2017). They are spread over several islands (figure 1) and follow a particular rule in their local tradition or are driven by culture (Toe and Kubota, 2015). Traditional Indonesian houses have vital elements in ornamentation, symbiosis with external space, transitional, inner space, breathing walls, non-rigid structure, and roof domination (Prasetyo *et al.*, 2017). It has been described terminologically as "*roof-based architecture*" because the name of the traditional house is given based on the shape of the roof (Hardiman, 2005). The roof is linked to the head of a building, showing its dominant proportion compared to the element of the body or building base (stilt houses); using *pilotis* (ground-level supporting columns or stilts) gives the impression of lightness, especially to the heavy roofs.

The roof is a critical element in recognizing and processing building figures, and each tribe represents a different form and shape of houses, especially conspicuously in the roof shape (Nurdiah, 2001). A very sharp upper slope causes the roof to buckle, thereby reducing the absorption of solar energy (Supriatna and Handayani, 2021). Despite the variety of roof shapes in traditional Indonesian houses, the common thread in climate consideration is essential in creating its geometry (Rajendra, 2021) to express the roof's steepness (Prasetyo *et al.*, 2017). Gadang Houses in west Sumatera have a roof that is tapered on both left and right sides, curved inwards on both sides, low in the middle, and elongated in the shape of a buffalo horn (Supriatna and Handayani, 2021). Generally, a traditional house's roof structure is made of bamboo or timber rods and sheets connected through rattan rope and a pin-a-hole join system. It uses bamboo as frame roofing structure material and palm tree fiber or *ijuk* (palm fiber) as covering material affecting thermal conditions inside the house for tropical climate friendly.

However, to limit the scope of this research, three traditional houses representing the west and east of Indonesia are chosen as case studies due to their similarity in the basic roof geometry. The houses are the Gadang House Minangkabau tribe in West Sumatera, the Tongkonan House Toraja Tribe in South Sulawesi, and the Bolon House Batak tribe in North Sumatera. The Bolon (A), Gadang (B), and Tongkonan (C) Houses have similar roof shapes protruding at the end like buffalo horn (Nurdiah, 2001).

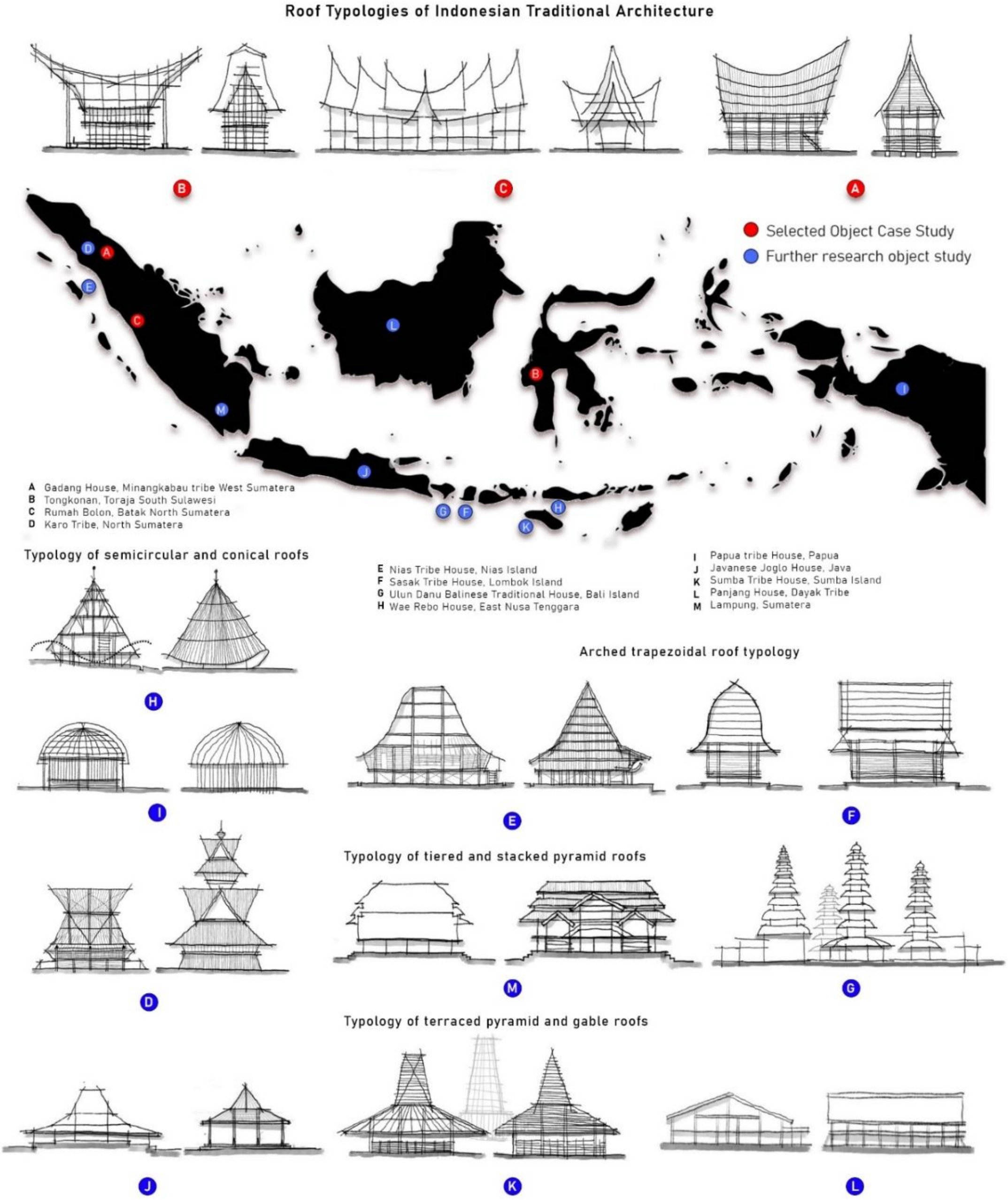
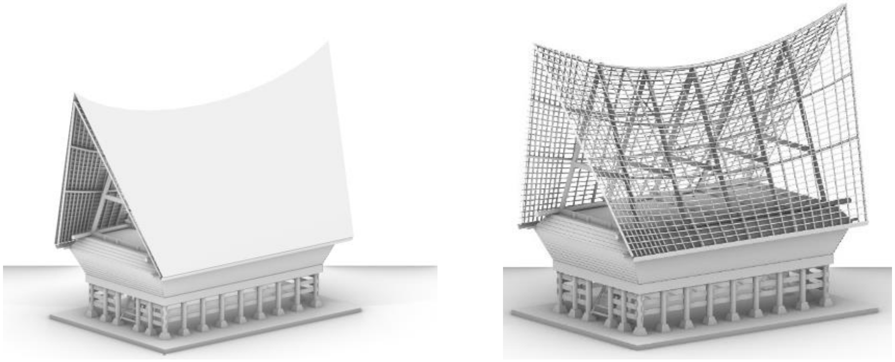
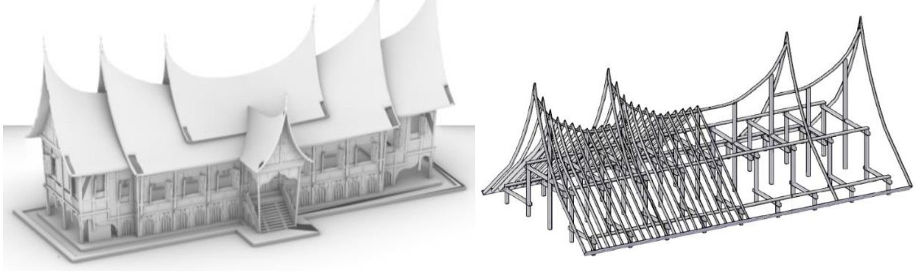


Figure 1. Typological grouping of traditional Indonesian roof shapes spread in the Indonesian Archipelago (Source: authors)

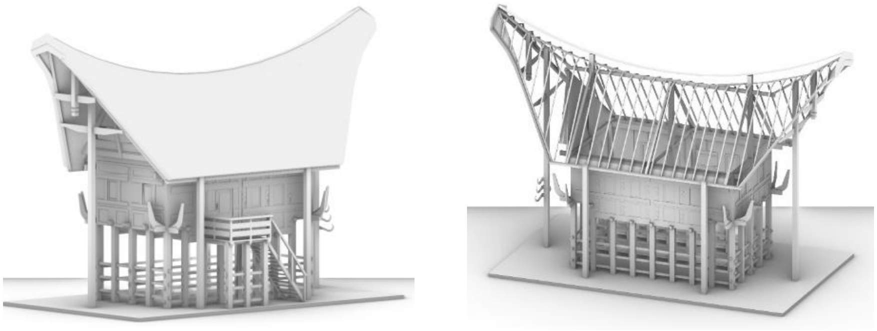
Batak, Gadang, and Tongkonan houses have similar roof shape typologies, and these three tribes are well-known for their protruding shapes, with high-raised roof arches and curving at the top end of the roof. Regardless of their similarity in basic shapes, each has its differences in symmetry and asymmetry of their curve ridge (figure 2). The basic roof geometry has been adopted and translated into many contemporary architectures as new vernacularism, especially in public facilities and local government services office buildings, as the cultural symbolism and architectural representation.



A *Bolon House*, Batak North Sumatera



B *Gadang House*, Minangkabau tribe West Sumatera



C *Tongkonan House*, Toraja South Sulawesi

Figure 2. Selected object case study of traditional Indonesian houses (Sources: authors)

2. Materials and Methods

This systematic review focuses on integrating traditional bamboo frame construction techniques with parametric design and robotic fabrication technologies to make them applicable in contemporary architecture. Consequently, this research answers the following questions:

1. What are the most useful and applicable parametric design, optimization, and fabrication tools that can be utilized in the design process of Indonesian bamboo hyperbolic paraboloid structures?
2. What design and fabrication workflow would be the most suitable to potentially revolutionize Indonesian bamboo-based traditional architecture and make it accessible to contemporary architecture?

We conduct a systematic review to answer our research questions, following a method that consists of three phases, as seen in Figure 3. This includes 1) data collection and filtration by searching specific keywords in the Scopus and CuminCAD databases, selecting journal and conference articles, and 2) analyzing and reviewing selected research of bamboo-related digital architecture and automated fabrication techniques. The selection process filters the most suitable design and fabrication methods by looking into structure type, tools, and techniques. Finally, in stage 3) we categorize the articles according to: a) material and structural system b) the workflow of digital/parametric design and optimization c) digital automated fabrication or assembly methods.

We utilized the databases CuminCAD, which contains papers of conferences; ACADIA, CAADRIA, eCAADe, SIGraDi, ASCAAD, CAAD, and ISARC international academic conferences are summarised and Scopus, which contains journal papers from architecture, engineering, and structural science-related fields, such as Automation in Construction, Construction Robotics, Visualisation in Engineering, and Journal of Building Engineering. The search was conducted using the keywords "bamboo architecture", "parametric bamboo", "bamboo fabrication," bamboo form-finding", and "bamboo structure".

The articles were filtered in phase two by removing the review publications and low-relevance articles. The first filtering took place using the database's filtering tools, whereby 256 articles were found. The 256 remaining articles were reviewed by reading their abstracts. The articles not dealing with the robotic fabrication of bamboo structures, materials, and joints were also removed. An additional 238 articles were removed, resulting in the remaining 19 articles we present. In phase three, the remaining 19 articles were systematically categorized and analyzed into three categories: 1) Material and structural system, 2) The workflow of digital/parametric design and optimization 3) Digital automated fabrication/assembly methods.

The final 19 selected articles include one book, five journal articles, and 13 conference papers. Eleven articles examined parametric tools in the design stages, four articles only presented the application of parametric modeling and simulation in bamboo material without fabrication, eight articles applied hand bending, manual assembly, and fabrications in the construction process, three articles explored Mixed Reality (AR and VR) during the fabrication process, one article showcased the hybrid augmentation between robot and human collaboration by using mobile robotic arms and AR-based mobile devices, one article demonstrates the use of robotic tools in fabricating flexible and bendable structures, and one article uses mobile robots in constructing bamboo rods structure. These categorized articles are analyzed and compared in the final phase to answer our research questions.

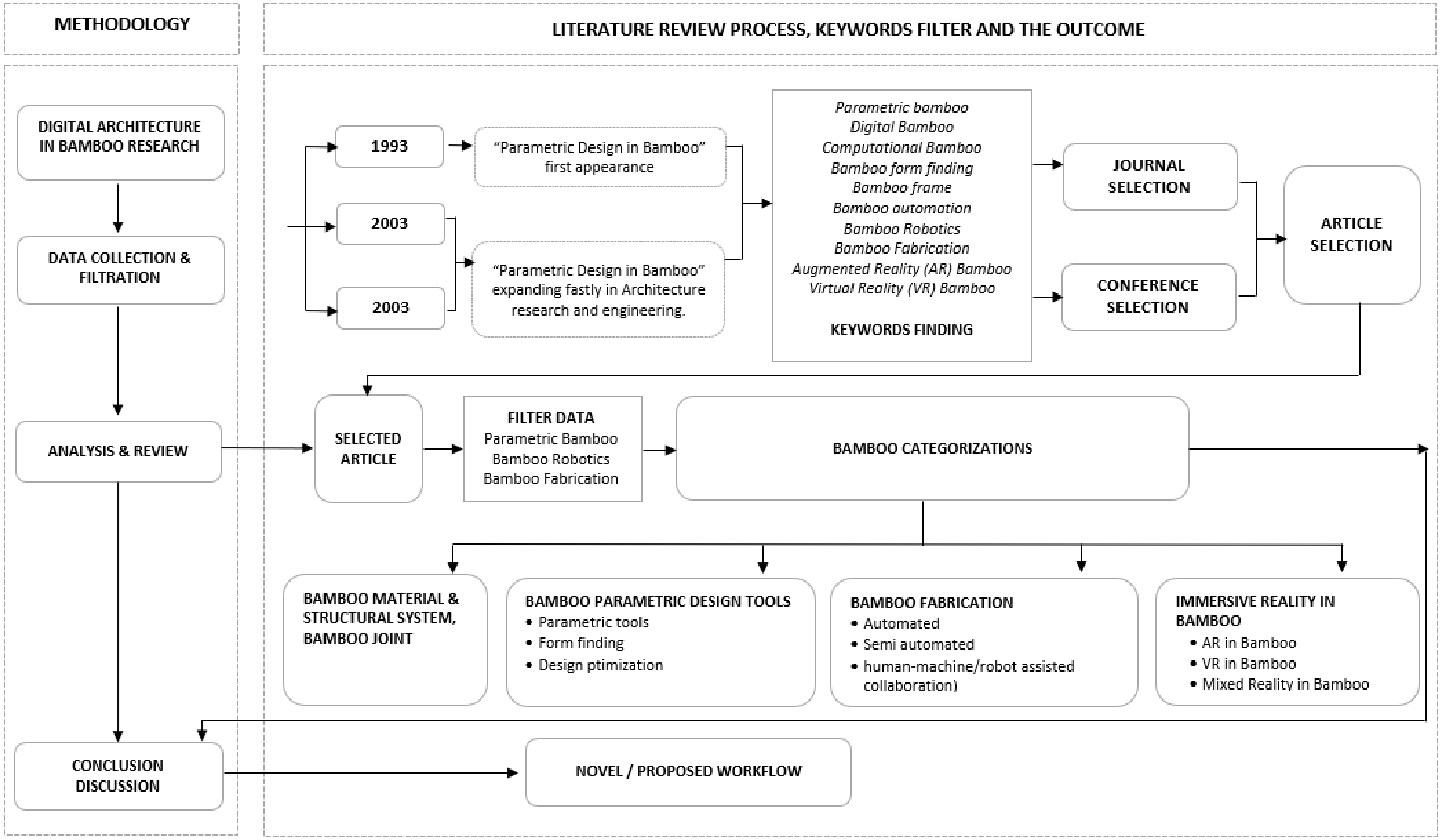


Figure 3. The structure of the systematic review methodology

4. Analysis of the Filtered Papers

4.1 PARAMETRIC DESIGN AND OPTIMIZATION TOOLS

Crolla (2017) showcased the use of parametric design tools for producing complex bamboo geometries in the ZCB Bamboo pavilion, a long-span, bending active bamboo grid shell in CUHK Hong Kong. He used the Kangaroo plug-in for Grasshopper in the form-finding process to simulate physical forces. The digital model geometry is used to extract conventional architecture plans and section and elevation drawings to provide digital data and communicate the bamboo structure application in construction (figure 4).

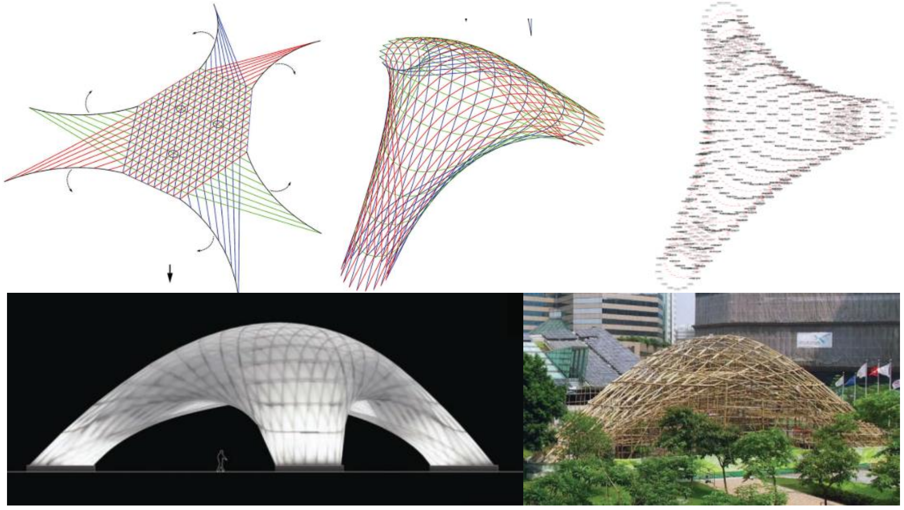


Figure 4. Parametric tools application in ZCB Bamboo Pavilion (Crolla, 2017)

In this research, the parametric model automatically produces the graphic representation of drawings, coordinates, and the dimensions of each element. These data are useful building information used for the construction process, reducing its complexity.

Naylor, J.O et al. (2022) applied parametric tools in Rhinoceros and Grasshoppers to design a full-culm hyperbolic paraboloid bamboo structure. The form-finding process involves changing the parameters, such as pole length and diameter, adding poles to the grid, and modifying the upper point. Changing the parameters allows the hyperbolic paraboloid bamboo geometry to transform. This allows the overflow of the rainwater to fall towards the two lower points without requiring the additional expense of guttering (figure 5).

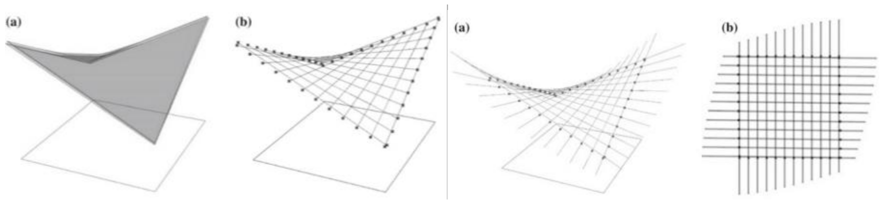


Figure 5. Hyperbolic paraboloid bamboo roof for rain collection strategy using parametric tools (Naylor, J.O., 2022)

Wallisser et al. (2018) designed a tropical bamboo grid shell pavilion as a parabolic hyperboloid grid shell at Rio de Janeiro Federal University utilizing Grasshopper and load simulations with the Karamba Plug-in. They stimulated hands-on empirical testing to predict bamboo structural behavior and explore the geometry through tension and compression. To generate the bamboo cell division in a freeform structure, a grid shell structure is created instead of polygonal meshes or planar surface, and the surface is divided into a structural tessellation grid shell (figure 6), allowing flexible joints to enable the assembly process.

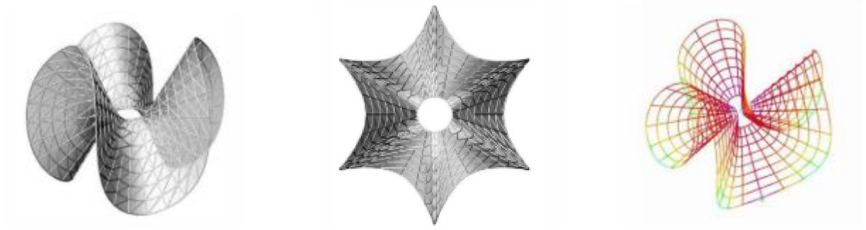


Figure 6. Tropical bamboo grid shell form-finding (Wallisser et al., 2018)

Huang (2022) integrated parametric tools to reinvent the bamboo structure of a traditional Chinese umbrella inspired by cultural values and conventional Chinese craftsmanship. He utilized the Karamba3D and Kangaroo optimization plug-ins for Rhinoceros/Grasshopper. The traditional Chinese bamboo umbrella is transformed into a dynamic and open space geometry (figure 7) but is still rooted in traditional craftsmanship, linking the idea of basic umbrella geometry with novel design tools and new fabrication technology. He argued that to connect traditional material principles with global practice, the new approach of computational tools can enhance the value of local material performances by proposing a new design framework.

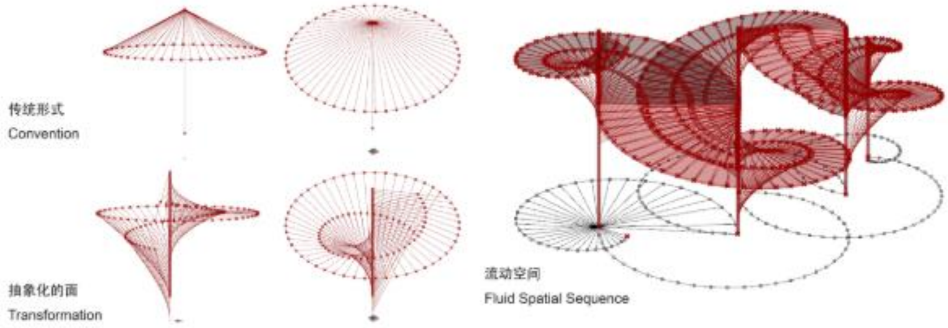
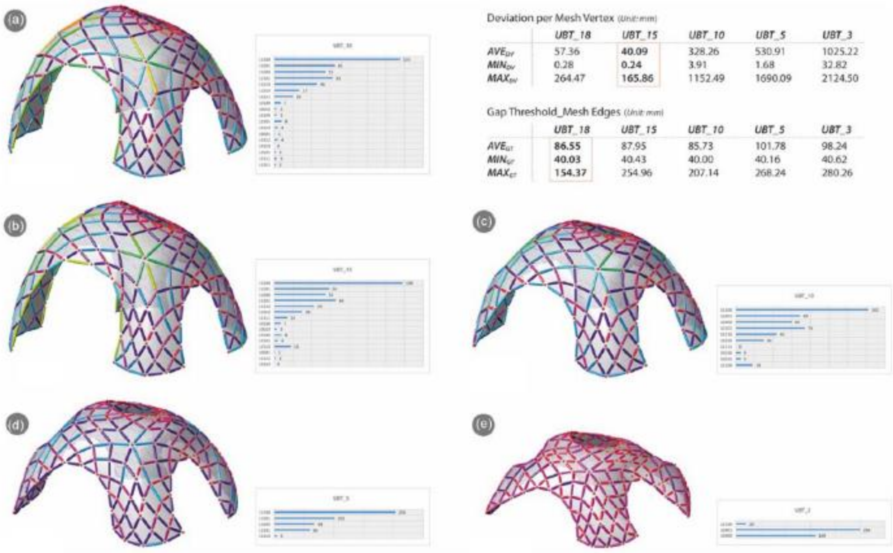


Figure 7. Parametric tools application in designing the bamboo structure of a traditional Chinese umbrella (Huang, 2022)

Wang et al. (2017) investigated the design of a freeform bamboo structure and how parametric tools can systematically be used to deal with the irregularities and joint challenges in bamboo material. A two-stage optimization was applied to support the fabrication of the freeform structure through encoding material properties and freeform shape optimization. This research facilitated direct feedback to the architect on how the cost efficiency of bamboo construction can be achieved by reducing the material used and optimizing the elements of the final structure assembly. The optimization took place using different types of tessellations from the quadrilateral, triangle, and diamond-like patterns. These tools inform how these discrete geometrical elements can be further evaluated and rationalized for fabrication to achieve efficiency and minimum use of material (figure 8). This research displayed that parametric tools can be applied to encode bamboo structures' physical and geometrical attributes. It demonstrated the integration of design optimization, which can simultaneously facilitate the form-finding process systematically and iteratively.



Deviation per Mesh Vertex *(Unit: mm)*

	UBT_18	*UBT_15*	*UBT_10*	*UBT_5*	*UBT_3*
AVE_{DV}	57.36	**40.09**	328.26	530.91	1025.22
MIN_{DV}	0.28	**0.24**	3.91	1.68	32.82
MAX_{DV}	264.47	**165.86**	1152.49	1690.09	2124.50

Gap Threshold_Mesh Edges *(Unit: mm)*

	UBT_18	*UBT_15*	*UBT_10*	*UBT_5*	*UBT_3*
AVE_{GT}	**86.55**	87.95	85.73	101.78	98.24
MIN_{GT}	**40.03**	40.43	40.00	40.16	40.62
MAX_{GT}	**154.37**	254.96	207.14	268.24	280.26

Figure 8. Parametric tools in generating joint system and surface tessellation in freeform bamboo structure (Wang et al., 2017)

Estrada Meza et al. (2022) used parametric tools in the design exploration of a bamboo shell structure. Specifically, they used the NSR-10 Colombian code for seismic design and construction, analyzed and solved the mechanical behavior design of double-curved shells, and then compared the result calculation with the values deriving from the Karamba3D, Rhinoceros/ Grasshopper plug-in. Figure 9 illustrates the structural behavior of two double curvature geometries simulated with parametric software, which has the potential to be applied in the early structural bamboo design process.

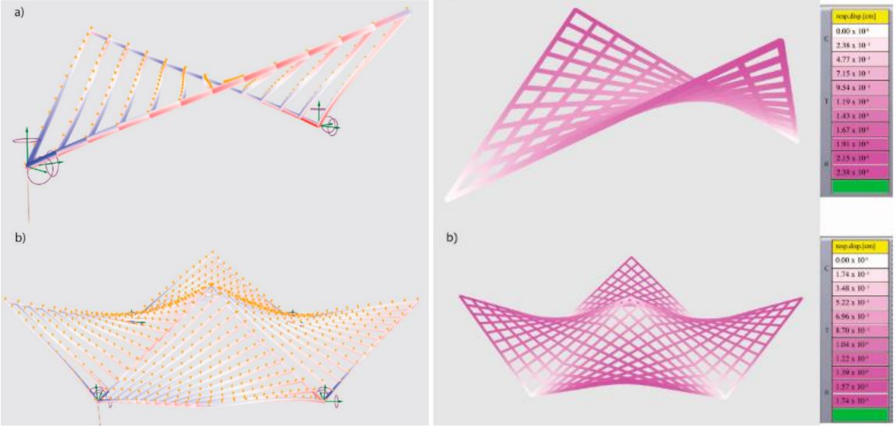


Figure 9. Parametric tools for design exploration of bamboo shell structures (Estrada Meza at al., 2022)

4.2 AUTOMATED FABRICATION TOOLS AND TECHNOLOGIES

Robotic construction has allowed faster and more precise production with the advantages of customization, accuracy, and reliability in various work environments and scales (Adel et al., 2018). Along with it, the progression in bamboo integration with digital fabrication has introduced a variety of approaches and methodologies using multiple tools and techniques in several projects, ranging from bamboo pavilion structures using 3D printing joints (Tanadini et al., 2022) to parametric augmented injection in ZCB Bamboo Pavilion (Crolla, 2017) Mixed Reality Collaboration in Bamboo structure (Goepel and Crolla, 2020) 3D Scanning and Augmented reality Bamboo Fabrication (Crolla, 2017)(Wu et al., 2019) and expanding the collaboration process between human-robot cooperation in digital design framework of bamboo culms (Lorenzo et al., 2017).

Nevertheless, bamboo, characterized by its non-standardized nature and distinctive traits of flexibility and versatility, encounters obstacles and challenges when it comes to achieving complete automation in fabrication. The bamboo structures still depend on manual and human labor assembly (figure 10) to address and navigate unpredictable disruptions from a human-free workforce exclusivity in automated robotic construction. Specific bamboo fabrication is still a prominent feature that employs manual techniques and hand bending to construct bamboo structures and installations, both on-site and offsite construction scenarios.

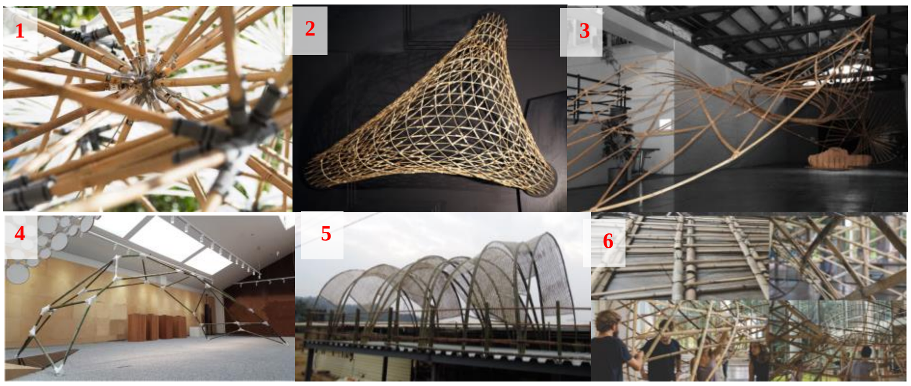


Figure 10. The progression of research in bamboo fabrication: 1) bamboo pavilion in ETH Zurich (Tanadini *et al.*, 2022), 2) the ZCB Bamboo Pavilion in CUHK Hongkong (Crolla, 2017), 3) Bamboo Lightweight Active bending structure in ITKE Stuttgart (Suzuki, Slabbinck and Knippers, 2020)0, 4) Bamboo[3] project in SUTD Singapore (Amtsberg and Raspall, 2018), 5) the Bamboo Bend Project in NCTU China (Chen and Hou, 2016), and 6) Trefoil Pavilion, a parabolic hyperboloid grid shell (Wallisser, Henriques and Menna, 2019).

Crolla (2017), in the ZCB Bamboo Pavilion in CUHK Hongkong, three layers of bamboo culms were bent and hand-tied into a bending-active triangulated diagrid on-site (figure 11). The pavilion's structure is formulated and validated through digital and physical models, encompassing bamboo prototypes at different scales. In this project, Metal wires were manually used to tie the bamboo culms together, as they offer fire resistance in contrast to conventional knots.

Figure 11. The construction process of ZCB Bamboo Pavilion CUHK (Crolla, 2017)

Achieving full automation in bamboo construction is challenging. Bamboo, as a natural and organic material, exhibits variations in dimension, shapes, and mechanical properties, which make it challenging to automate the fabrication process entirely. On the other hand, bamboo structures also rely on well-designed connections and joints for stability. Hence, in unstructured and non-static environments, especially in construction sites, the robustness and autonomy of such robotic processes are still remarkably low (Edsinger and Kemp, 2007), specifically if applied in fully automated bamboo fabrication. Therefore, during bamboo fabrication, robotic and digital tools still rely on human power assistance in operating, getting involved in fabrication stages, and making critical decisions during the robotic fabrication process (Moniz and Krings, 2016). The assembly and handling of bamboo elements still require skilled human intervention because on-site adjustments and adaptations make it challenging to achieve full automation.

On the other hand, the lack of autonomy limitation in robotic vision will leverage complementary skills and tools that can be integrated with traditional bamboo construction, such as human collaborations and mixed reality, in enhancing the digital construction and fabrication process. The digital environment can provide more intuitive interfaces for robotic fabrication, providing seamless communication and data exchange in collaborative human-robot construction (Aryania et al., 2012), and it can potentially be applied in bamboo fabrication. The constraint limitation in bamboo fabrication will be inclined to expand and openly leverage cooperation in a semi-autonomous manufacturing system between humans, digital tools environment, and robots working together.

A similar scenario was demonstrated in a study by Mitterberger et al. (2022). He explored human-robot collaboration scenarios in assembling wooden structures using rope joints. This experiment employed digital tools and workflows to facilitate augmented human-robot collaboration between two humans and two 6-DoF mobile robotic arms (UR10e) with custom 3D-printed pneumatic grippers. Human operators manually placed the wooden structure and established rope connections with dexterity, while robots assisted in the assembly cycle by accurately placing elements and stabilizing overall structures. This experiment (figure 12) highlights how hybrid human-robot teamwork can enable new pathways toward bamboo automated fabrication.

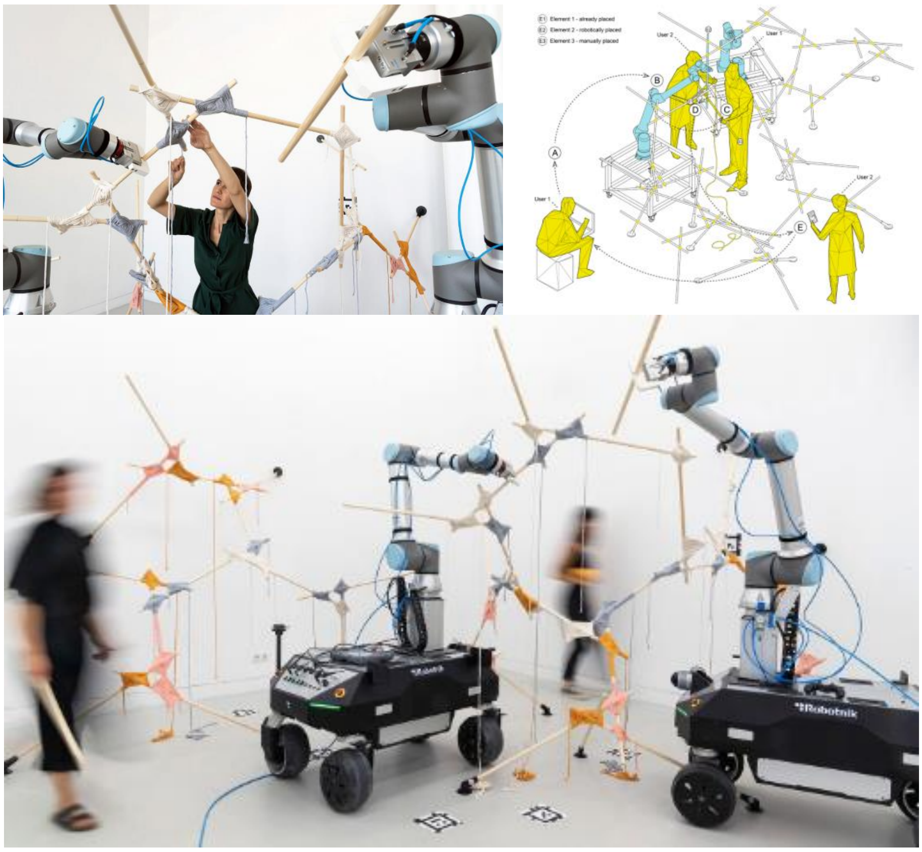


Figure 12. Hybrid human-robot collaboration in assembling wooden structures (Mitterberger et al., 2022)

Brugnaro, Vasey, and Menges (2008) demonstrated a research project titled Robotic Softness, incorporating robotic tools in a bendable and flexible material to assemble woven structures that can be adapted and extended to bamboo structures. The research was inspired by behavioral fabrication logic used by the weaverbird during the self-making of its nest. A 6-axis industrial robot (KUKA KR 125/2) fabricated three-dimensional woven structures with rattan material (figure 13), and it was operated with an online agent-based system, a custom weaving end-effector, and 3D scanning for coordinated sensing strategy.

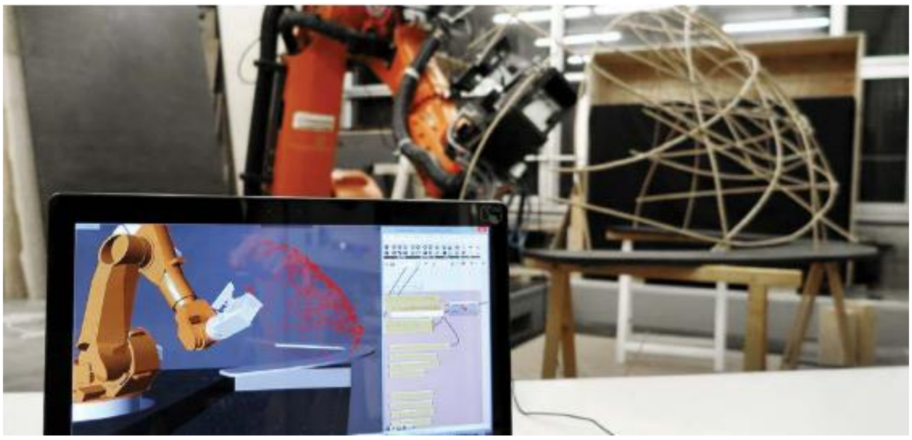


Figure 13. Robot technology applications on bendable material fabrication (Brugnaro, Vasey, and Menges, 2008)

This technique is particularly tailored for the weaving process. It showed that natural materials with organic geometry can be fabricated with robotic technology (figure 14). However, this strategy needs deeper exploration to determine whether this framework adapts to bamboo fabrication scenarios. This research indicated that integrating computational design and innovative fabrication techniques with natural material and organic construction processes can be implemented.

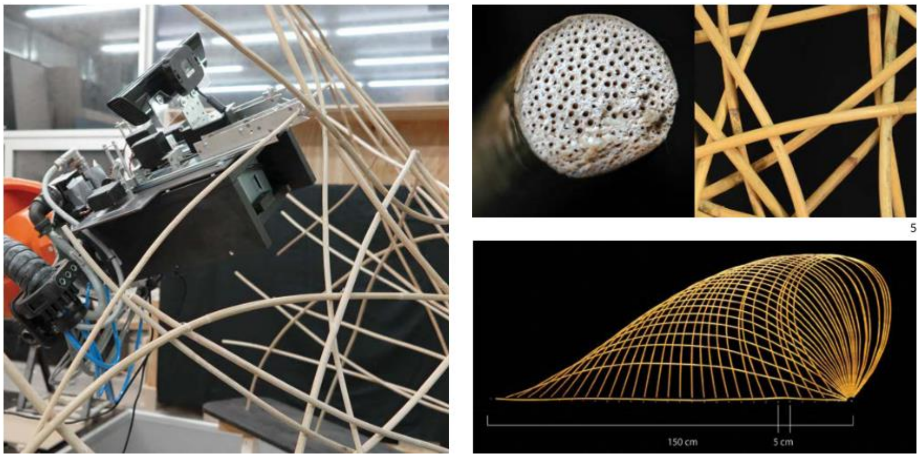


Figure 14. Employing Robot technology for the assembly of bendable materials (Brugnaro, Vasey, and Menges, 2008)

Another robotic system utilized in bamboo rod construction was presented by Lochnicki et al. (2021) in an active-bending light touch assembly for a bamboo bundle structure project. They used mobile robots that behaved toward bamboo dynamic characteristics and assembled the frames by teaching the robots with a particular control policy to bend bamboo bundles (figure 15) using deep reinforcement learning (DRL) algorithms. They constructed bamboo bundles with metal zip-tie joints and steel anchor base foundations. This research showcased the potential to unlock robotic building practices with bamboo as a rapidly renewable material and promote sustainable construction.

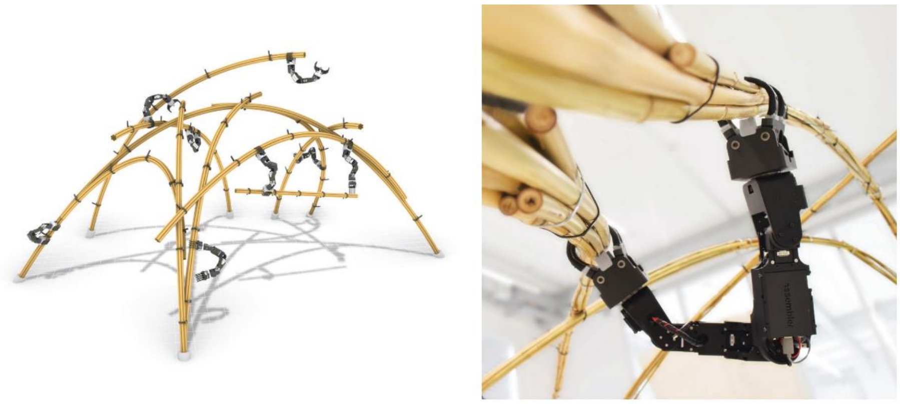


Figure 15. Mobile robot prototypes used in feasibility studies assemble lightweight bamboo bundle structures (Lochnicki et al., 2021)

During the physical assembly, the mobile robot could use its weight and momentum to bend the bamboo rod bundle element into the determined position. The robot could adjust its swinging even when external factors influenced the bending response from the material. The ability of robots to connect bundles was achieved by hard-coding the mobile robots to grasp and connect them to the other existing bundles in the structures (figure 16).

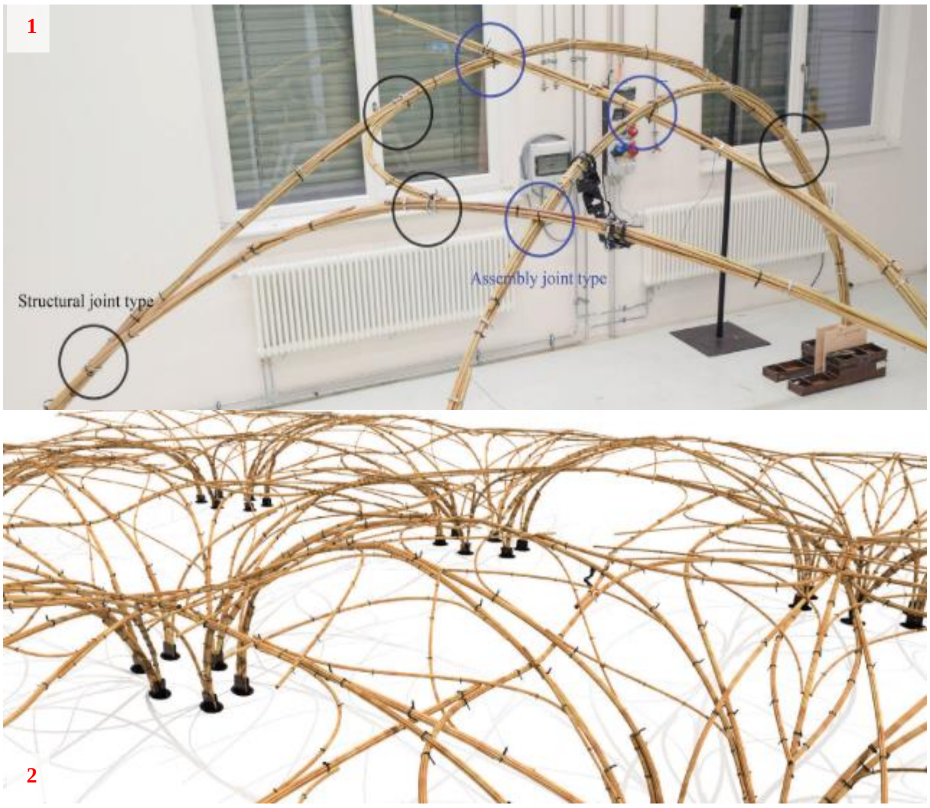


Figure 16. The assembly process of bamboo rod bundle structures with mobile robots: 1) join types of the construction system. 2) The speculative outlook of the whole structure of active bending bamboo structures ((Lochnicki et al., 2021)

In addition, mixed reality tools (AR and VR) technologies can also assist in visualizing and experiencing bamboo structures before, during, and after their physical construction. These technologies provide an immersive environment to explore geometry during the design stages, assess spatial qualities, and make informed decisions during the design and fabrication stages. Several bamboo projects have applied to incorporate AR for fabrication stages (figure 17). Mixed reality tools in Bamboo fabrication can stimulate dialogue and collaborate in creative production and augmented craftsmanship, providing a greater mechanism and diverse design output (Goepel and Crolla, 2020).

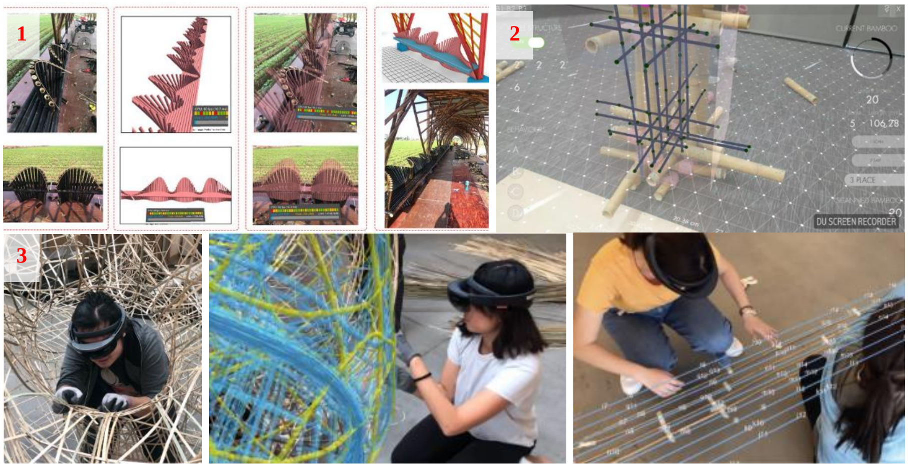


Figure 17. Mixed reality applications in the fabrication of bamboo structures: 1) Bamboo Pavilion Diecui Gallery in China (Kenan Sun, Tian Tian Lo, Xiangmin Guo, 2022), 2) Rawbot Bamboo project, a Mobile AR Assembly in UCL: United Kingdom (Wu *et al.*, 2019), 3) Argan Bamboo installation project in CUHK Hongkong (Goepel and Crolla, 2020)

Lorenzo et al. (2017) used a 3D scanner attached to a robotic arm to get bamboo culms' physical and geometric properties as digital data for bamboo pavilion construction (figure 18). They utilised sensor technology to monitor bamboo materials' performance and structural behaviour as a supporting tool for bamboo fabrication. This tool provided real-time data on factors such as stress and movement to ensure structural integrity and longevity of bamboo construction. Various sensors can be employed to monitor and analyze the performance behaviour of bamboo structures, such as strain sensors for measuring deformation strain in bamboo elements, accelerometers for measuring acceleration or vibration, and load cell sensors to measure loads on bamboo components or connections.

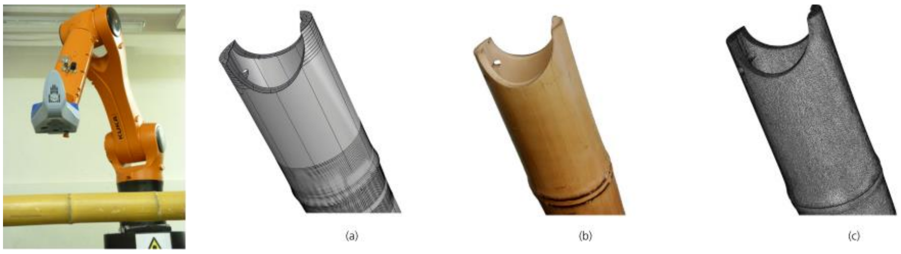


Figure 18. Robotic tools and 3D sensing applications in bamboo fabrication (Lorenzo et al., 2017)

In summary, we present a table (Table 17) categorizing all 19 research projects according to their publication type, materiality, structural system, digital design, optimization tools, and fabrication methods. By analyzing and evaluating them, we propose a novel bamboo fabrication workflow to bridge the gap between traditional architecture and utilizing the latest technology.

NO	**BAMBOO & DIGITAL FABRICATION RESEARCH**	**TYPE OF PUBLICATION**	**MATERIAL**	**STRUCTURAL SYSTEM**	**DIGITAL DESIGN & OPTIMISATION TOOLS**	**FABRICATION METHODS**	**REFERENCES**
1	Exploring the potential of equilibrium-based methods in additive manufacturing: the Digital Bamboo Pavilion	JOURNAL	Bamboo small poles as an ultra-lightweight structure with 3D Printing Join	Spatial truss with post-tensioned cable	Not mentioned	Manual assembly with 3D printing Joint	(Tanadini *et al.*, 2022)
2	Computational Bamboo: Digital and Vernacular Design Principles for the Construction of a Temporary Bending-Active Structure	CONFERENCE	Bamboo laths and jute cords	Lightweight Active bending structure	Rhinoceros & Grasshopper. ElacticSpace for numerical form-finding	On-site assembly, Hand bending	(Suzuki, Slabbinck and Knippers, 2020)
3	Building indeterminacy modelling – the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials	JOURNAL	Bamboo triangulated diagrid shell, lightweight translucent glass-fibre reinforced polymer membrane.	Bending active grid shell structure,	Rhinoceros & Grasshopper Plugin, Kangaroo for phisical force simulation engine	Various scales of 3D scan prototyping before building a full-scale model	(Crolla, 2017)
4	Bamboo 3	CONFERENCE	Bamboo poles and 3D printing joint and connectors	Truss structures	Not mentioned	Visual sensing for material properties and applied in a digital model Manual assembly	(Amtsberg and Raspall, 2018)
5	Design with a bamboo bend, bridging natural material and computational design	CONFERENCE	Bamboo strips	Bending and curvature construction	Parametric tools Rhinoceros & Grasshopper Plug-in	Manual bending and assembly	(Chen and Hou, 2016)
6	Digital construction of bamboo architecture based on multi-technology cooperation	CONFERENCE	Bamboo Pole	Force bearing stricture	Not mentioned	AR, 3d scanning, robot-aided construction, 3d printing and design rules	(Kenan Sun, Tian Tian Lo, Xiangmin Guo, 2022)
7	Rawbot, A digital system for AR fabrication of bamboo structures through the discrete digitization of bamboo	CONFERENCE	Bamboo pole with custom joint	Pole Bamboo Structure	Not mentioned	AR Assembly	(Wu *et al.*, 2019)
8	Tie a knot:human–robot cooperative workflow for assembling wooden structures using rope joints.	JOURNAL	Wood stick and rope joint	Wood frame structure	Not mentioned	Hybrid Augmented Human-Robot, two mobile 6-DoF mobile robotic arms (UR10e) with custom 3D-printed	(Mitterberger *et al.*, 2022)

NO	BAMBOO & DIGITAL FABRICATION RESEARCH	TYPE OF PUBLICATION	MATERIAL	STRUCTURAL SYSTEM	DIGITAL DESIGN & OPTIMISATION TOOLS	FABRICATION METHODS	REFERENCES
						pneumatic grippers and two humans	
9	BIM Bamboo: a digital design framework for bamboo culms	CONFERENCES	Bamboo pole	Bamboo pole gridshell	BIM Modelling, Numerical simulations	3D scanning Attached to a robotic arm, performance monitoring robotic prototyping	(Lorenzo *et al.*, 2017)
10	Protection by Generative Design, designing for full-culm bamboo durability using sunlight-hours modeling in Ladybug	CONFERENCE	Full culm bamboo	Only simulation for solar roof protection	Rhinoceros 3D & Grasshopper, Ladybug plug-in	No Fabrication Only simulation	(Naylor, 2021)
11	Augmented Reality-Based Collaboration Argan, A Bamboo Art Installation Case Study	CONFERENCE	Bamboo splits	Free form Art bamboo Installation	Rhinoceros 3D & Grasshopper	Holographic with Microsoft Hololens, AR tools-based assisted manual assembly, Smartphone.	(Goepel and Crolla, 2020)
12	Applying Design Tools for Full-Culm Bamboo	CONFERENCE	Bamboo pole	Hyperbolic paraboloid, bamboo grid shell structure	Rhinoceros 3D & Grasshopper, NURBS geometry, Kangaroo Plug in	Manual assembly Full-scale prototyping	(Naylor, Stamm and Vahanvati, 2022)
13	Encoding bamboo's nature for freeform structure design	JOURNAL	Bamboo	Free form structure	Rhinoceros 3D & Grasshopper, Galapagos Plug-in	Only modeling and simulation	(Wang *et al.*, 2017)
14	The Opportunities and Challenges of Using Parametric Architectural Design Tools to Design with Full-Culm Bamboo: Case Study: A Design for a Hyperbolic Paraboloid for Gutter-Less Rainwater Capture Using Full-Culm Bamboo	BOOK	Full-culm bamboo	hyperbolic paraboloid	Rhinoceros 3D & Grasshopper Galapagos Plug-in	Only modeling and simulation	(Naylor, 2020)
15	Weaving physical-digital networks: Brazil-Germany integration experience	CONFERENCE	Bamboo poles and strips	Bamboo freeform a parabolic hyperboloid grid shell	Rhinoceros 3D & Grasshopper Karamba Plug-in for loads simulations	Manual assembly Full-scale prototyping	(Wallisser, Henriques and Menna, 2019)
16	Integrating Computational Design and Traditional Crafts, A Reinvention Of Bamboo Structures	CONFERENCE	Bamboo	Umbrella free-form structure	Rhinoceros 3D & Grasshopper, Karamba Plug-in for Structural analysis, Kangaroo Plug-in	Manual fabrication	(Huang, 2022)

NO	BAMBOO & DIGITAL FABRICATION RESEARCH	TYPE OF PUBLICATION	MATERIAL	STRUCTURAL SYSTEM	DIGITAL DESIGN & OPTIMISATION TOOLS	FABRICATION METHODS	REFERENCES
17	Design Exploration of Bamboo Shells Structures by Using Parametric Tools	JOURNAL	Bamboo structures	double-curved shells	Rhinoceros 3D & Grasshopper, Karamba 3D Plug-in for Structural analysis, Parametric design, and optimization for the early structural design stage	Only modeling and simulation	(Estrada Meza *et al.*, 2022)
18	Robotic Softness: An Adaptive Robotic Fabrication Process for Woven Structures	CONFERENCE	Rattan woven structure	3-dimensional freeform woven structures	Rhinoceros3D and Grasshopper/RhinoPython	6-axis industrial robot, a KUKA KR 125/2	(Brugnaro, Vasey and Menges, 2008)
19	Co-Designing Material-Robot Construction Behaviors: Teaching distributed robotic systems to leverage active bending for light-touch assembly of bamboo bundle structures	CONFERENCE	Bamboo rods bundle structures (diameters 1.0 to 1.8 cm) Joint: metal zip-tie joints and steel anchor.	Active Bending structure	Not mentioned	Mobile Robots with Deep Reinforcement Learning (DRL)	(Lochnicki *et al.*, 2021)

Table 1. The scope of digital design, optimization, and fabrication methods is examined across the 19 articles.

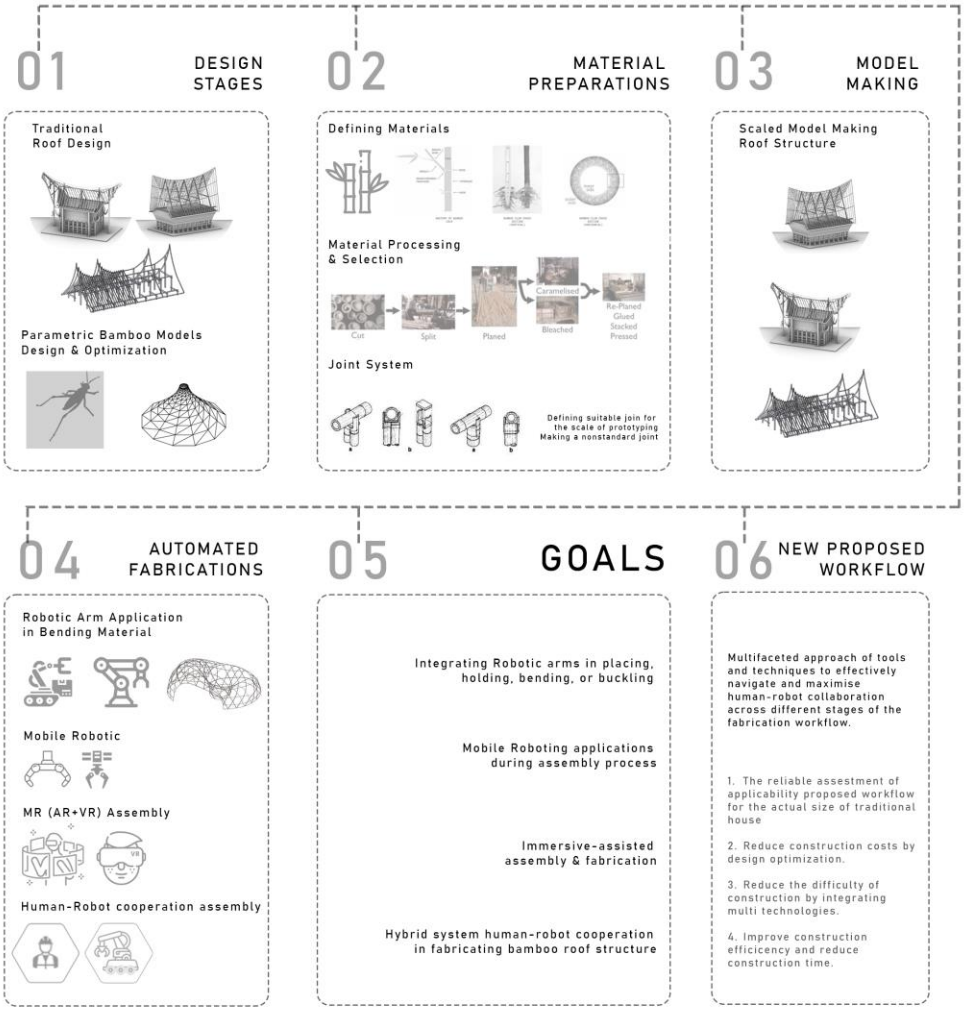
5. Findings and Conclusions

Our conclusion focuses on answering our initial research questions: What are the most useful and applicable parametric design, optimization, and fabrication tools that can be utilized in the design process of Indonesian bamboo hyperbolic paraboloid structures? Of the 19 chosen articles, 12 employ parametric design tools as digital design strategies, with Rhinoceros and Grasshopper being the most prevalent and practical choices. Supplementary plug-ins such as Kangaroo, Ladybug, Karamba, and Galapagos find utility in structural, environmental, optimization, and simulation tasks. Solely one article integrates BIM Modeling alongside numerical simulations for bamboo digital design.

What design and fabrication workflow would be the most suitable to potentially revolutionize Indonesian bamboo-based traditional architecture and make it accessible to contemporary architecture? Eight of the eighteen selected articles utilize manual fabrication and assembly, including hand bending and on-site manual assembly. Four articles demonstrate the application of mixed reality (VR and AR) cooperation during the fabrication and assembly process, and three articles applied robotic technology consisting of mobile robotic arms (UR10e) with custom 3D-printed pneumatic grippers, 6-axis industrial robot, a KUKA KR 125/2, and the mobile robots with deep reinforcement learning (DRL) algorithms during fabrication of the structures. Additionally, one article shows the potential use of robotic tools attached to

3D scanning sensors during the material selection. Furthermore, our findings show four articles about bamboo digital and parametric design that were only conducted in the modelling and simulation phase without fabrication stages. These projects relied on manual fabrication and assembly indicating that it is the most popular, pragmatic, reliable, and effective approach. Using mixed reality tools can enrich the various digital fabrication strategies in bamboo structures. Three articles have demonstrated the potential use of robotic technology involvement during the fabrication and assembly stages; however further investigation is required due to the challenges of stability and unpredictable disturbances to achieve full automation in bamboo fabrication. Our deduction indicates that achieving our fabrication research objectives will require integrating a multifaceted approach of tools and techniques to effectively navigate and maximize human-robot collaboration across different stages of the fabrication workflow.

5.1 PROPOSED WORKFLOW



Multifaceted approach of tools and techniques to effectively navigate and maximise human-robot collaboration across different stages of the fabrication workflow.

1. The reliable assestment of applicability proposed workflow for the actual size of traditional house
2. Reduce construction costs by design optimization.
3. Reduce the difficulty of construction by integrating multi technologies.
4. Improve construction efficicency and reduce construction time.

Figure 17. The review leads to a proposed novel workflow to reimagine the digital design and fabrication of traditional Indonesian roofs.

The research question also touches on our research methodology's potential to move beyond traditional Indonesian bamboo architecture. Hence, we propose a new workflow (figure 17) based on the literature review findings. We start with applying parametric design and optimization for traditional roof structures based on collecting and analyzing data about the dimensions and conventional roof geometry frame structures. Once we identify the basic original principle of the traditional roof frame structure, we will design a new scalable roof and apply the proposed workflow for digital design and fabrication of traditional roof frame structures. We optimize the roof structure and fabrication parameters during the design phase to achieve efficient fabrication by evaluating and verifying the entire process scenarios and performances. Regarding the fabrication process, we intend to deploy a hybrid system involving collaborative efforts between humans and robots to construct bamboo roof structures. This is achieved by integrating various technologies at distinct stages of the fabrication workflow.

Our systematic literature review underscores the opportunities and challenges in achieving automation in bamboo construction. As Huang, Z. (2019) has mentioned, the fabrication and assembly of bamboo frame structures historically have been highly dependent on manual operations in construction and difficult to integrate with other standardized building materials. As emphasized by Edsinger and Kemp (2007), in unstructured and non-static environments, especially in construction sites, the robustness and autonomy of such robotic processes are still remarkably low, especially in bamboo material with organic and flexible geometry. However, in this case, the lack of autonomy will encourage complementary skills and tools by providing seamless communication and data exchange in collaborative scenarios between humans and robots (Aryania et al., 2012). Our future work will focus on verifying our proposed framework through design experiments.

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