Adaptive Bamboo Joinery: Robotic-Assisted Assembly of Traditional Indonesian Roof House Typologies

Ahmad Mansuri[1], Asterios Agkathidis[2], Davide Lombardi[3], and Hanmei Chen[4]

Abstract. Traditional bamboo construction relies on a joinery system for structural integrity. Bamboo's heterogeneity and non-standardized nature challenge its integration in computational modelling and structural optimisation, particularly to address its natural flexibility, tensile strength, and lightweight properties for active bending applications. Integrated computational design and digital fabrication have the potential to modernise and enhance vernacular and heritage architecture. This study proposes adaptive joinery systems tailored to traditional Indonesian house typology to substitute conventional joints compatible with robotic assembly. The method integrates parametric design and structural optimisation for the proposed fabricable elements and joint design prototype. Key joint design criteria include mechanisms, adjustability, and angular systems. The findings highlight the feasibility of digitally fabricated joint systems in robotic assembly scenarios and digital fabrication as an alternative to traditional craftsmanship. The research provides insight into the suitability and compatibility of bamboo joint techniques for robotic assembly, bridging the gap between heritage architecture and technologies and offering solutions for contemporary bamboo architecture.

---

[1] A. Mansuri (✉)
University of Liverpool, Liverpool School of Architecture
25 Abercromby Square, Liverpool, L69 7ZN
e-mail: ahmad.mansuri@liverpool.ac.uk

[2] A. Agkathidis (✉)
University of Liverpool, Liverpool School of Architecture
25 Abercromby Square, Liverpool, L69 7ZN
e-mail: a3lab@liverpool.ac.uk

[3] D. Lombardi (✉)
Xi'an Jiaotong - Liverpool University, 111 Ren'ai Road, Suzhou, Jiangsu Province
PR China 215123, South Campus, Office DB428
e-mail: Davide.Lombardi@xjtlu.edu.cn

[4] H. Chen (✉)
University of Liverpool, Liverpool School of Architecture
25 Abercromby Square, Liverpool, L69 7ZN
e-mail: hanmei.chen@liverpool.ac.uk

Keywords: bamboo architecture, bamboo joint design, additive manufacturing, structural optimisation, robotic assembly, robotic fabrication, human-robot collaboration.

1 Introduction

Developing bamboo joints compatible with robotic assembly involves understanding and integrating traditional joinery principles and advanced digital fabrication methods. Recent research advancements in digital and robotic fabrication have fundamentally linked how to overcome the main challenge in bamboo structure, including the complexity of joint design systems. Traditionally, bamboo joinery systems require human dexterity for tasks such as binding and bolting, making their adoption in robotic fabrication challenging. The significance of connection systems may limit the possible geometric configuration that can be created, as their connections play a significant role in determining the structural typology and complexity of the structure [1]. Therefore, the success of the bamboo structure is highly determined by its ability to overcome the main challenge of the complexity of the jointing design. [2]. The development of the tailored and adaptive joint system is essential to accommodate bamboo's unique physical properties in its hollow structure and diameter variation [3]. Recent research has addressed these limitations by integrating robotic 3D scanning technologies to obtain bamboo digitisation and investigate material mechanical properties. [3] [4] [6] developing parametric modelling and designs for bamboo joint systems [6] [7] and engineering bamboo 3D-printed joinery [1] [8] [9] [10] [11] [13]. These efforts aim to overcome the challenges and adapt bamboo joint systems to digital fabrication. However, the literature indicates that this joint design system is intended for manually constructed structures. Only a few similar research uses of wooden sticks have been discovered in applying the joint system in a robotic assembly scenario [14] [15] which is a relevant and insightful reference for our case study? Building on our prior research on systematic literature review [16] and proposed automated fabrication techniques [17]It is suggested that no prior research has attempted to incorporate robotic technologies for bamboo assembly, especially for bending operations and joint installation in a human-robot collaborative framework.

Designing an adaptive joinery system compatible with robotic assembly requires both bamboo material constraints and automation feasibility. The human-robot collaboration (HRC) approach is a viable strategy, as bamboo joinery techniques are intricate and considered a skill that robotic fabrication is still struggling to automate fully. The joinery is critical because bamboo construction relies on well-designed connections, and highly traditional craftsmanship skill labour is required [12] [18]. Human participation remains crucial for joinery execution and depends on manual operation, particularly during material handling and bending [19]. Therefore, adaptive and compatible joinery systems are needed to make it suitable with robotic assembly and meet several criteria such as simplicity, repeatability, and a fast assembly process. This study aims to investigate and propose a design for adaptive joinery systems tailored to traditional Indonesian roof typology, compatible with robotic assembly workflows as an alternative to conventional joints. The joint systems must be a balance between structural strength, fabrication efficiency, and assembly precision while still allowing human adaptability for manual alignment, force control, and fine-tuning in a hybrid HRC scenario. Building on prior research, we aim to develop a workflow for the robotic assembly of bamboo structures based on Indonesian roof house typology within a human-robot collaboration scenario, where an adaptive joinery system will be integrated into the workflow. Adaptive bamboo joinery for robotic assembly is crucial for dynamic adjustment and sharing tasks between humans and robots, ensuring a flexible and efficient HRC assembly process.

Building on prior research and literature review, this study explores how to develop adaptive joinery for bamboo structures compatible with robotic fabrication within the HRC framework. The research explores key questions.

1. How can adaptive joinery systems support the robotic assembly of irregular bamboo structures while preserving traditional Indonesian roof typologies?
2. How do adaptive joinery systems address active bending mechanisms in bamboo joint structures for robotic assembly scenarios?
3. What are the strengths and limitations of proposed adaptive bamboo joinery systems for robotic assembly that can support their structural integrity?

1.1 Background and Context

Indonesian traditional houses feature distinctive architectural elements: the protruding roof geometry, which dominates the house figure, symbolising the head of the house and showcasing dominant proportions. The roof shape aims to show the impression of the lightness of a stilt house, which balances the heavy roof with a lighter and elevated body and is deliberately designed to be more striking and prominent compared to the body. The roof geometry is an architectural element with deep symbolic meanings and practical functionality. Key characteristics of traditional Indonesian roof shapes include: 1) high-pitched and steep roofs, 2) layered or multi-tiered roofs, 3) extended roof overhang for climate adaptation, 4) curved and symbolic roofs, 5) natural roof materials, and 6) stilt houses with raised roofs. This design element reflects local wisdom in adapting to harsh weather conditions such as heavy rainfall, intense solar radiation, and tropical climate [20]. In this study, we focus on the Bolon house of the Batak tribe in North Sumatera, Indonesia, as the object of study, and its distinctive features are the soaring and highly curved roof. It features two large cut hyperbolic paraboloid surfaces that rise steeply with the curve outward at the tips, resembling the boat or buffalo horns. The roof extends beyond the walls, providing shade and protection from the tropical climate (Fig.1). The overall structure is symmetrical, and the curvature is carefully designed to distribute loads and withstand heavy rainfall efficiently. The steep pitch and pointed roof edges allow better airflow circulation to maintain a cool interior. Traditional roofs use lashing and binding techniques to join systems with rattan lashing or ropes. However, in modern adaptations, particularly in restoration projects or incorporating new materials, nails and screws are commonly used.

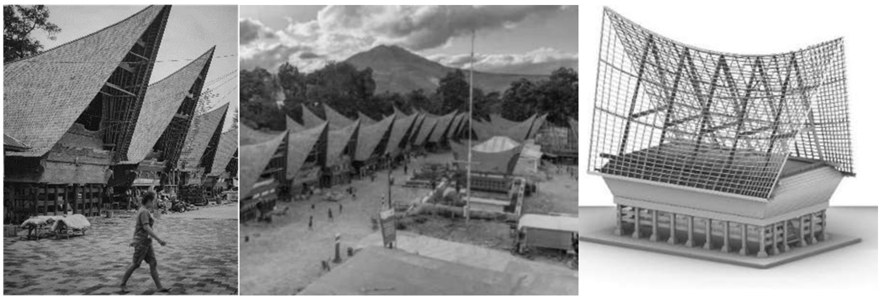

Fig. 1 shows a Traditional Bataknese tribe house known as Bolon House, which was chosen as an object study in North Sumatera, Indonesia.

Our focus on choosing the Bolon House (Fig.1) as a case study for the prototype is due to its cultural significance, and the curvilinear shape has structural challenges in terms of its applicability for human-robotic workflows. The Bolon house, characterised by soaring, highly curved geometry, consists of a dual hyperbolic paraboloid surface, which is architecturally challenging due to its multidirectional curvatures and extended overhangs. From the technical standpoint, the roof typology requires joints for overlapping intersections of member units where curvature and angular deviation vary. The surface continuity and geometric simplicity are other reasons for the study case justification, as the roof frame consists of repeated curvilinear elements and can be translated into regular modules, simplifying the robotic task planning. For robotic applicability, the roof geometry is also more exposed and accessible for robotic arms to operate from both sides. The Bolon house roof relies on overlapping and rope joint techniques, which easily alternate with clamp-based or swivel-based adaptive joints and make it well-suited for robotic placement. The roof geometry also aligns with the scenario of human-robot collaborative assembly for robotic element handling and positioning. Human agents employ micro-adjustments during bending operations, joint installation, and post-joint fine-tuning. The layer separation between horizontal and vertical element units facilitates step-by-step robotic handling and simplified task sequencing in HRC workflows.

In terms of geometry, Bolon house curvature can be adjusted parametrically without losing the topological essence, making it ideal for simulation, optimization, and adaptive joint fitting. The behaviour compatibility with bamboo active bending and design intent can showcase the role of joint systems in a simple curvilinear roof surface where the curvature varies, demonstrating the role of joint systems in locking flexible units after deformation as a core objective of the research within the Human-Robot Collaborative framework.

The challenges in transitioning manual joinery techniques to robotic assembly in our framework are the material variability due to the uniqueness of every member and the need to balance joint precision and accuracy. Robotic systems typically work best with standardised and predictable forms. Meanwhile, developing algorithms capable of replicating this highly variable material and customising joints is challenging. Programming robots to assist humans in assembling complex joints may require real-time adjustment for fitting, which can be fastened quickly, allowing tightening and loosening. It must also account for tolerances during bending operations that may impact structural integrity. Adapting to the bamboo active bending material behaviour can also be challenging, particularly in designing a joint system that performs well under bending operation while securing the joint with good adjustability for post-assembly structure stabilisation.

1.2 Review of Digital Bamboo Joinery Systems

Based on the literature review of bamboo joinery systems utilising digital fabrication and robotic assembly techniques, we identified various types of contemporary bamboo joinery, which are summarised in the table. 1 and Fig. 2. In this study, we define the scope of our case study by focusing specifically on contemporary bamboo joinery systems that incorporate digital fabrication techniques to ensure their applicability for robotic assembly. We focus on selecting and analysing this joint system as a basis for analysis, comparison, and critical evaluation. Observing their design approach, the objective is to explore their adaptation for seamless integration with the robotic assembly workflow.

Fig. 2 Various bamboo joinery systems found in the literature review

Joint Mechanism	Connecti on Systems	Adjustabilit y	Angular system	Material	Technol ogy	Reference
clamp joint	bolt	Adjustable	overlap joint	Steel/alumi nium	SIP	(Vasiliki et al. 2024)
clamp joint	bolt	Fixed static	overlap joint	PLA	AM	(Vasiliki et al. 2024)
Interlocking joint	mechani c	Fixed static	multiaxial joint	Nylon-Based Steel Joint	AM DMLS	(Kladeftira et al. 2022)
Interlocking joint	bolt	Adjustable Fixed static	End-to-end joint	Metal	AM	(Matson and Sweet, 2016)
Interlocking joint	glue and a metal bolt	Fixed static	multiaxial joint	PLA Nylon and Metal	AM	(Amtsberg and Raspall 2018)
Interlocking joint	Glue	Fixed static	multiaxial joint	PLA	AM	(Amtsberg, Mueller, and Raspall 2022)
clamp joint	bolt	Adjustable	overlap joint	Not mentioned	AM CNC machine	(Qi, Zhong, Kaiser, Tahouni, et al. 2021)
Interlocking joint	bolt	Adjustable	multiaxial joint	PLA	AM	(de Oliveira, Pauletti, and Meneghetti 2020)
Interlocking joint	bolt	Fixed static	multiaxial joint	PLA	AM	(Di Paola and Mercurio 2020)
Interlocking joint	bolt	Fixed static	multiaxial joint	PETG filament	AM	(Condezo De La Vega et al. 2024)
Interlocking joint	bolt	Adjustable	overlap joint	PLA	AM	(Qi, Zhong, Kaiser, Nguyen, et al. 2021)
Rope Joint	Tied winding	Fixed static	overlap joint	Rope	SM	(Mitterberger et al. 2022)

SIP = Standardized Industrial Product
AM = Additive manufacturing (3D-printed)
DMLS = Direct Metal Laser Sintering
PLA = Polylactic Acid
PETG = polyethylene Terephthalate Glycol-modified
SM = Standart Material

Table 1: Case study and comparative analysis of bamboo joinery systems and digital fabrication identified in the literature.

Based on our analysis in Table 1 and Fig.2, we identified three joint systems that are suitable for our roof prototype with overlap elements: clamp joint mechanism [15], interlocking joint [21], and rope joint [14]. The clamp joint mechanism is more favourable because it can secure and cover more friction with the tube's circular bamboo surface through clamping force and adjustable tightening systems. It allows disassembly, reassembly, and adjustability to accommodate joint fit tolerances, offering reusability and post-assembly stabilisation for final tightening and fine-tuning adjustment. In contrast, the interlocking join provides a fixed structure with a predefined direction, making it less suitable for robotic assembly due to its inability to adjust to multi-angle directions. Meanwhile, the rope join offers strong tensile strength, ideal for dynamic loads, and is sustainable and biodegradable. However, it requires skilled humans to use knot-tying techniques, is time-consuming for manual processes, and may be inconsistent in repeatability, as each joint may vary in thickness and position. Securing knots with ropes is also challenging for humans, requiring complex, dexterous, consistent movement. Considering these strengths and limitations, we conclude that clamp joints manually assembled by humans in the robotic workflow are highly compatible and practical as they provide quick, strong, and adjustable connections, enhancing the HRC construction scenario. In our case study on Indonesia roof typology, where bending elements are required for the shape, the clamping join must tolerate movement during iterative robotic assembly. Once the clamp is secured, the manual bending will continue at the subsequent overlapping joint point to achieve the hyperbolic paraboloid deformation surface.

4 Methods

The adaptive joinery systems methods in our object study utilised parametric design workflows for form-finding, followed by genetic algorithms with two-stage optimisation to generate the dataset intersection point of elements as the joint prototype's location (Fig.3). Key design criteria include joint mechanisms, adjustability, and angular systems. It is tested to perform active bending structural performance to achieve the intended roof shape. In this case, the manual bending of bamboo elements enables deformation to create curvilinear structures. At the same time, joints are placed to lock the bamboo in its bent position and maintain the desired form. To showcase feasibility, we limit the scope to a reduced-scale prototype and optimise the bamboo prototype size compatible with the UR10 robotic arm's size and reachability. The physical demonstration will be tested in the Indonesian traditional roof typology with overlapping bamboo joint systems in a double surface hyperbolic paraboloid shape. The study evaluates the adaptive joint that allows elastic deformation while maintaining structural integrity. Ultimately, the study explores the integration between robotic handling and manual bending within active bending elements and observes any positional shifts in the bamboo element during joint placement within the human-robot collaboration (HRC) workflow.

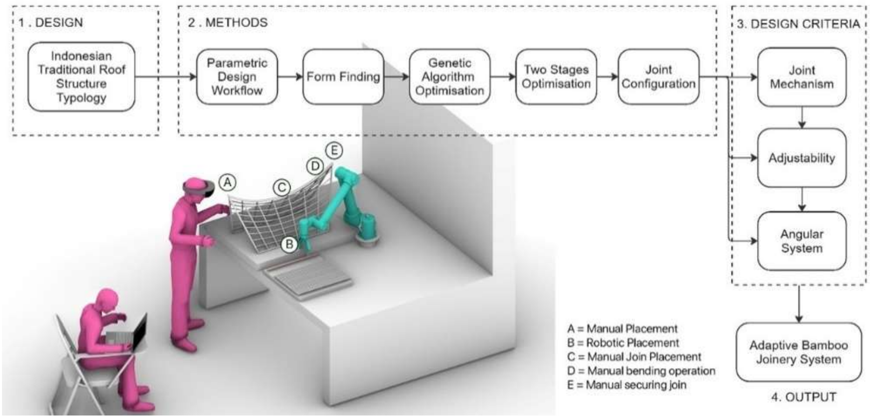

Fig. 3 Methodology, generative steps of the parametric modelling system, and joint design criteria

Our anlysis summarises the three main key design principles (Fig.4) for adaptive bamboo joinery to overcome: 1) material variability adaptation, 2) robotic compatibility, and 3) post-assembly adaptation. It is illustrated in Figure 4

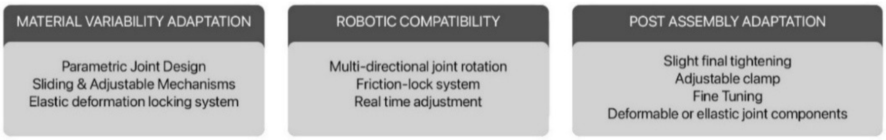

Fig. 4 Bamboo adaptive joinery key design principles for robotic assembly

5 Results and Discussion

5.1 Parametric design workflows, form finding and optimisation.

To define a joinery system compatible with our prototype and framework, the process starts by designing an Indonesian traditional roof house typology into a parametric design workflow. Parametric tools allow irregularity in the form-finding process and are addressed in the modelling process. The steps of the form-finding and optimisation process are illustrated in Fig.5. It starts with form-finding utilising Kangaroo to generate a mesh surface. Following the design principle of roof dimensional typology, we set the proportion of the roof shape by following the original size proportional composition. To realise the roof shape, the pattern of elements is adapted from the original frame arrangement into U and V isocurves of the generated mesh. The structural bamboo element is then generated into three layers: the mainframe, vertical lines (VE), and horizontal lines (UE). The cross-sectional size of the bamboo element is gradually reduced, as the element with a smaller cross-section will be on top of the element with a bigger cross-section. In this study, we choose the overlap joint systems following the traditional roof frame rules; by generating overlapping elements between these vertical and horizontal curve lines, we define the point of intersection joint as a dataset generated to be the joint placement position.

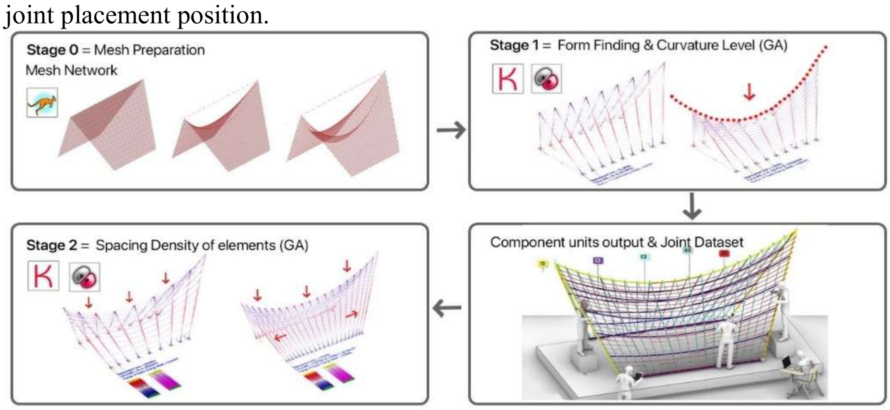

Fig. 5 The steps of the form finding and optimisation process

The post-design rationalisation process is investigated by examining the relationship between mesh shape, form-finding, and the spacing frame distance with structural performance. The first objective of optimisation is to modify the initial mesh to ensure the initial design constraints are fulfilled, to the original shape of the traditional roof. The form-finding surface optimisation seeks the level curvature of the top roof line that results in the minimum displacement value. We investigate the influence of the width curvature of the top roof line elements and see its behaviour on the structural displacement performance. By understanding the form-finding process (Fig.6) for optimisation, we intend to investigate the original design's refined shape and better understand the balance of the top-width line curvature into the overall form surface performance. During this step, we discover that the higher or the bigger width curvature of the top line on the roof will increase the displacement value.

The mesh preparation is created by a computational logic form-finding process that starts from a simple 2D spine graph, which acts as the roof shape's conceptual frame line or layout. A base polygonal mesh is generated from this spine and defines the roof surface. To achieve a smooth and structurally viable form, the mesh undergoes subdivision, refining it into a Subdivision (SubD) mesh with more control points for detailed shaping. The process continues by applying vertical force, simulating gravity, and the expected load across the mesh surface. These forces cause the mesh to deform and settle into a minimal energy state, which optimizes the shape structurally. The resulting guided mesh represents an organic, load-responsive roof form that can be further developed for fabrication and assembly, particularly suited for flexible bamboo materials.

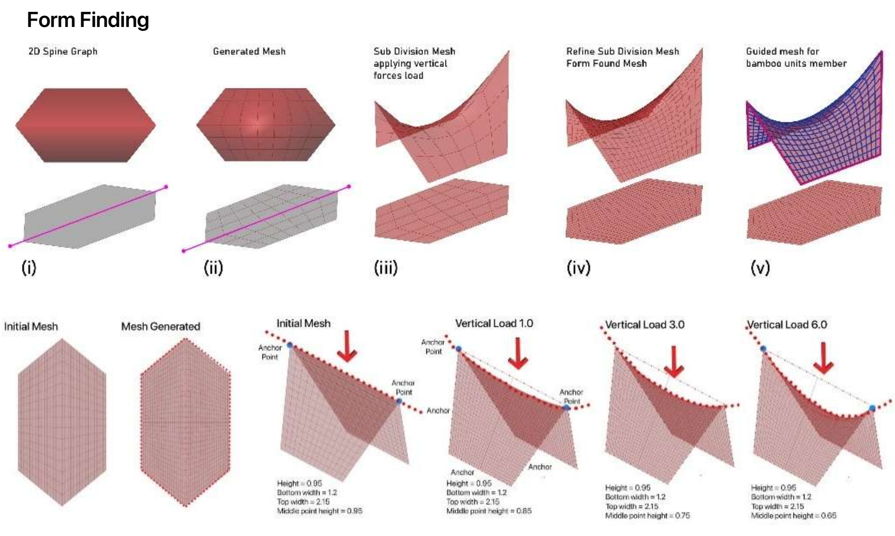

Fig. 6 The form-finding process of mesh to generate a minimal and relaxed surface

In the form-finding process, multiple vertical loads are applied to vary the magnitude and distribution of these loads on the mesh surface and explore how the roof geometry responds to the displacement simulation. Increasing or decreasing the vertical force gives the ability to control the width and curvature of the roof's upper levels. Their variation allows generations of a range of roof shapes from the same base mesh and spine graph, providing flexibility for form-finding, structural, and fabrication considerations. We define curvature level as a controllable parameter that influences the bending and shape of the roof surface. Increasing or decreasing this curvature provides the exploration of various forms, ranging from gently curved to sharply arched roofs (Fig.7). Similarly, the cantilever distance at the roof's tip is another parameter that controls how far the roof extends beyond its supports. This affects both the spatial coverage below and the structural demands on the bamboo elements. By parametrising these two variables, we study their impact on the form finding and the structural performance.

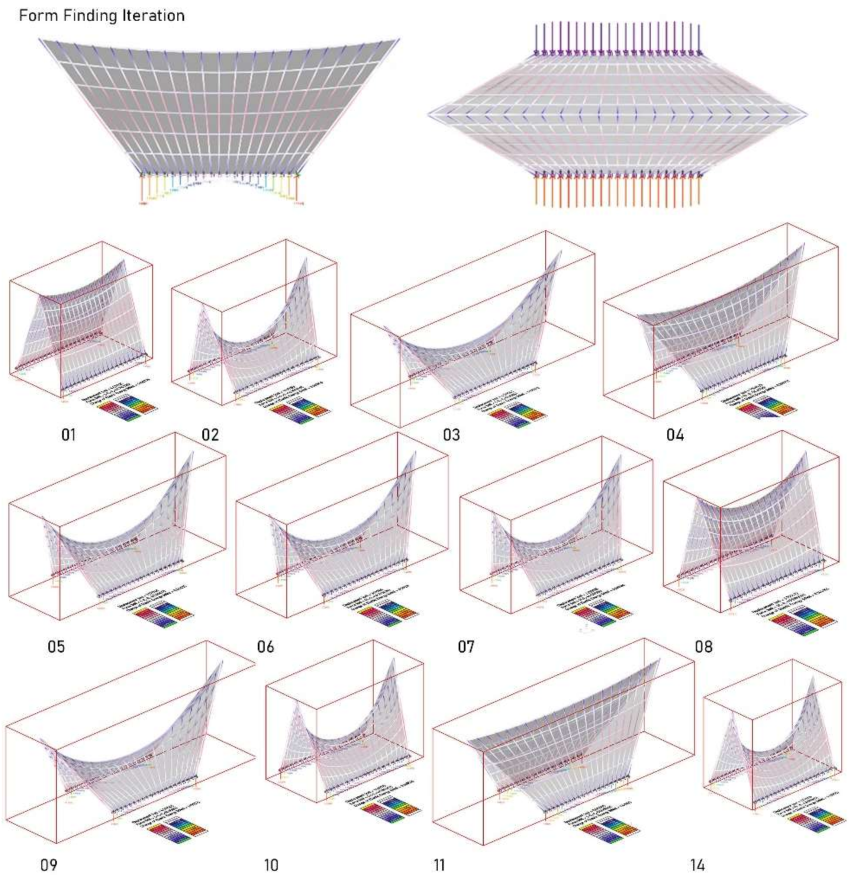

Fig. 7 The form-finding iteration process, assessing minimum displacement of roof shape based on height, top point distance, and level of curvature width with GAO and Karamba3D

After the first optimization stage, the number of bamboo element-type layers is determined from the mesh obtained into vertical and horizontal units from the isocurves mesh. Structural optimisation is conducted by examining the layer arrangement parameters in overlapping vertical and horizontal line elements, utilising a genetic algorithm optimisation solver with Galapagos (Fig.8). The spacing distance range of vertical and horizontal element parameters is explored for optimisation to see which configuration has minimum displacement to shape as structural roof surfaces with Karamba3D for an optimal solution that satisfies the minimum target fitness of the structural displacement. Based on this optimisation, the internode of joints is then defined as a dataset for bamboo joint location. This data setpoint joint coordinate is then used to determine the joint design based on the overlapping internode joint, angle, and components. Based on this joint configuration, we categorised the type of joint based on its position.

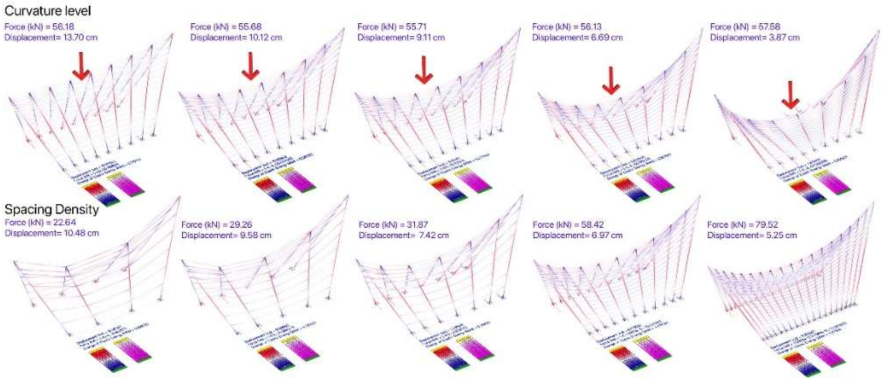

Fig. 8 Form Finding and structural optimisation process with two object optimisations: curvature level and spacing density

The next stage after optimisation is translating mesh elements to curvilinear units and constructible components, consisting of horizontal units (UE) as U elements, vertical units (VE) as V elements from the mesh isocurves, and joint coordinate points. During the initial modelling, the robotic tools pick the UE units as a straight element, placing them into a targeted coordinate at the middle point. The bending curvature level varies and becomes higher or increases gradually towards the top position to achieve the desired surface. The UE level curvature is achieved by the division of equal distances of the main frame, and this will be distributed into the distance of joint placement at the end of the structure into equal distances. The joint placement operated by humans will be located in a zig-zag pattern, and the desired curvature bending is achieved by attaching and securing the joint in the overlapping point units of the UE and VE elements. The elements of the structure will maintain their position at the desired curvature level by relying on the joint connection. The joint coordinate dataset is generated into a set targeted at joint placement (Fig.9), and the number of joints required is calculated. Based on this single unit point, the adaptive joinery design coordinates are defined. To adapt to bending operations requiring adjustability, we design a joint with a level of adjustability and fine-tuning during the robotic assembly process and post-assembly stabilisation.

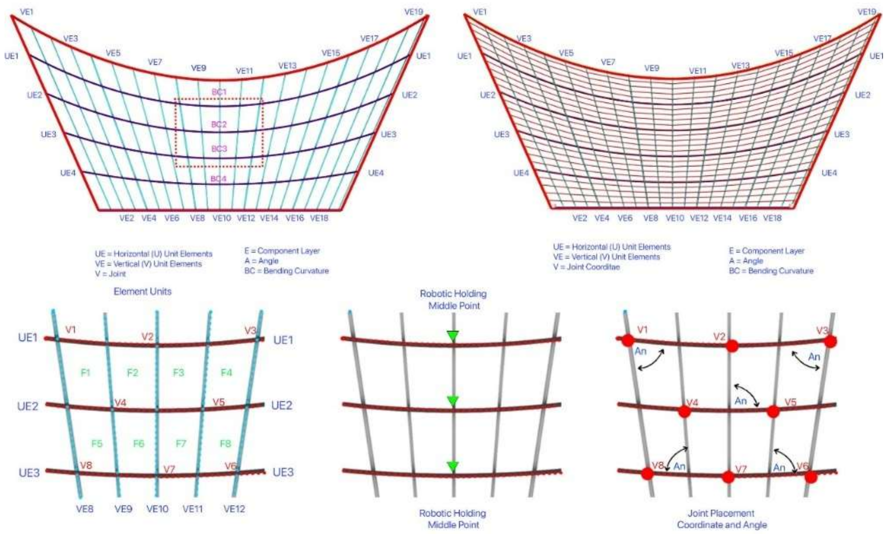

Fig. 9 Translating the component units' output and the joint dataset from mesh elements.

The last stage defines and proposes the adaptive joinery systems based on the generated point coordinate. As the overlapping configuration of UE and VE elements is unique in the angular systems for the whole point, and for this case, we define the main criteria of the adaptive joints as their ability to work with the units that have a good level of real-time adjustment in direction and rotation. The second criterion is the joint with good friction to grasp and maintain the targeted joint coordinate location. During the subsequent jointing process, the connection can maintain its structural position and remain in its initial location.

Our concern for the HRC framework during the manual bending operation by human agents is that the units of the bamboo elements may shift, experiencing deformation and changing their position because of human intervention during the joining process. Finding an adaptive joint is a good balance between adjustability to achieve precision of the joint process while minimizing missed changes in the location of the joint position to achieve the desired roof surface. This study proposes two joint mechanisms adaptable for robotic assembly in bamboo structures. First are the Swivel Couples joints with clamp mechanisms with adjustable bolts, and second are the rope joint mechanisms (Fig. 10). Our future work will test the joinery system proposed to see its strengths and limitations for evaluation.

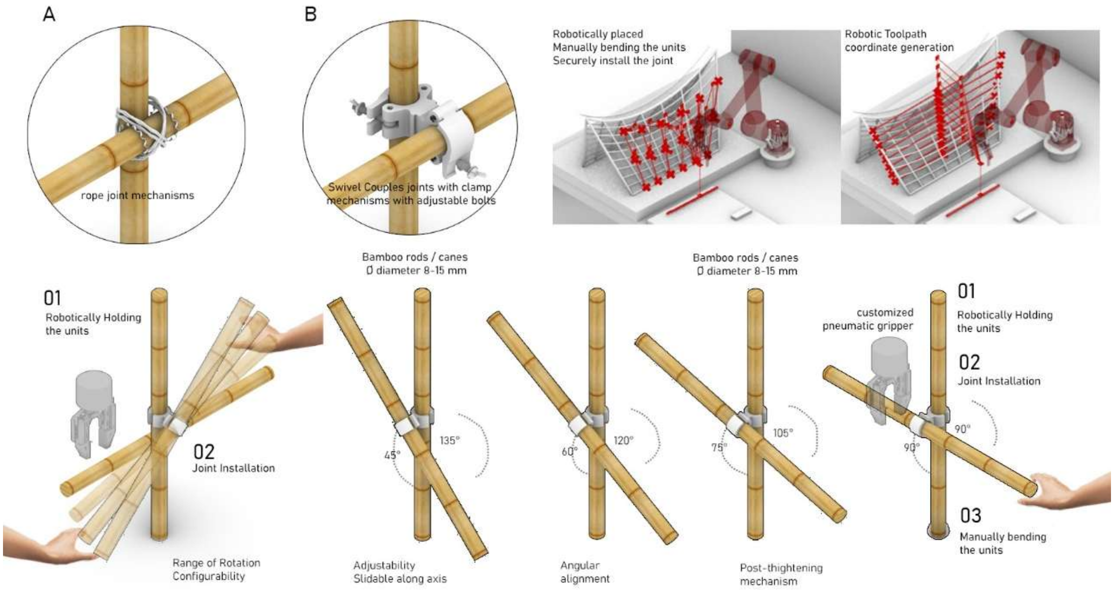

Fig. 10 Adaptive joinery system proposed with criteria.

5.2 Robotic Workflows

To ensure compatibility with robotic-assisted construction, the roof prototype is scaled within the operational limits and reachability of the UR10e robotic arms. The UR10 has a payload of 10kg and a maximum reach of 130mm, which influenced the physical size of the roof prototype. These constraints require the overall structure to be scaled down proportionally to ensure that the joint installation point and bamboo elements are within the effective radius of the robotic setting. The robotic placement strategy is adapted by allowing sequential pickup and precise placement of the elements at the centre points of the roof for sequential robotic task planning. Their isoplanar position also generates precise alignment of different angles of vertical member units without repositioning. The horizontal units and overlapping joints could be positioned through controlled, repeatable robotic paths. A human agent will manually operate the bending task while securing the joint installation during robotic holding. By operating within this constraint, the initial test showcases the feasibility of the prototype demonstrated in the robotic system for material handling, holding the units, stabilizing the structure, joint alignment, and positioning tasks in the human-robot collaborative workflow. The robotic assembly fabrication plan and HRC workflow are illustrated in Fig. 11 and Fig. 12. The HRC framework includes the design process, model registration, material preparation for feeding the unit assembly, and the assembly process, which consists of sharing tasks between humans and robots in a sequential loop assembly..

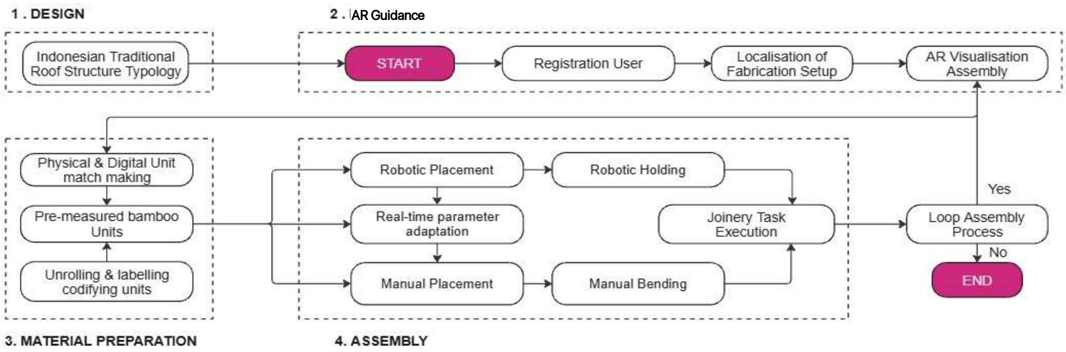

Fig. 11 Human-Robot Collaboration (HRC) Workflows, defining task sharing (human & robot)

5.3 Limitations

While the proposed HRC workflows demonstrate promising results in controlled and lab-scale settings, we consider several limitations for full-scale implementations. First, transitioning from a small-scale prototype to a full-size structure poses challenges regarding robot reachability, payload, workspace settings, and logistics. A robot system with a rail or mobile platform may extend or increase reachability for assembly. A mounted or movable robotic system could be used for larger assemblies and introduce new complexities in task coordination and spatial planning of robotic settings. Second, bamboo irregularities on the diameter surface and thickness potentially affect structural performance and alignment during micro-adjustment, as it is performed with active bending behaviour. Therefore, the structural integrity relies on the strength of joinery systems. Third, in the HRC workflows, coordination concerns depend on human precision during joint installation and micro-adjustment for final tightening and alignment after robotic placement. Manual bending and joint sequence deviation could lead to cumulative geometry deviations or the member units' desired curvature. These limitations highlight how HRC could contribute to better intuitive integration between human actions and robotic operations in bamboo construction.

However, our objectives for the proposed workflow are not only to achieve perfect precision but also to explore tolerance and adaptability in Human-robot collaborative (HRC) settings. Rather than achieving exact and absolute precision outcomes, this study prioritizes the exploration of tolerance thresholds for the assembly following the irregular nature of bamboo materials. The nature of the HRC workflow with manual operations for joint tightening and bending adjustment inherently introduces variability. This study embraces that variability to allow controlled misalignment for on-site adaptability. Further work is needed to define the limits of acceptable deviation during assembly and an improved feedback mechanism that can assist human agents in fine-tuning the operation output during joint installation for improved assembly.

6 Conclusion

This research is developed to explore how adaptive bamboo joinery systems can support and be compatible with the robotic assembly while preserving traditional roof typologies. For our prototype purpose, the findings demonstrate the conclusion for adaptive joinery in a human-robotic collaboration scenario, as rather than focusing on high-precision customized joinery, the joinery systems must be adaptable for tolerance and adjustability to accommodate bamboo material irregularities. The proposed clamp-based joint mechanism to substitute repetitive rope winding can be more efficient with an adjustable system that allows overlapping bamboo units and is adaptable for flexible angular adaptation. The tolerance of bamboo diameter irregularities can be addressed by a joint system that allows the tightening process for post-structural stabilisation. This approach not only facilitates the alignment of the units but also replicates the traditional bolon roofs joint logic that is compatible with the fast pace of robotic workflows scenario. By allowing rapid assembly and the presence of human operators in the loop, the system addresses the balance of fabrication techniques and craftsmanship. These answers the first research question on how adaptive joinery systems support robotic assembly of irregular bamboo while preserving traditional indonesian roof typologies.

Additionally, the research examines how adaptive joinery systems for bamboo respond to active bending mechanisms applied in a robotic assembly scenario. The study discovered that successful robotic assembly under these circumstances requires joints capable of securing elements after deformation of their final position. The joint must tolerate varying forces during active vending and allow for post-placement adjustment by a human agent to maintain the curvature accuracy position. The clamp and swivel joint proposed in this research can accommodate positional shifts and angular deviations caused by the bending process for structural stability. Post-thickening for active bending material like bamboo is necessary to compensate for material relaxation and maintain elastic deformation. These answer the second research question on how joinery systems address the active bending mechanism in bamboo joints for robotic assembly scenarios.

In answering the third research question, we identified strengths of our approach in the human-robotic collaborative (HRC) workflows and cooperative process of assembling and bending bamboo and joint executions. These aspects facilitate intuitive interaction between the robot and manual adaptation of traditional bamboo construction. While the joint systems are a key critical point for bamboo structural integrity, it is inevitable not to integrate humans for joinery techniques, which are the skills that robots may struggle to adapt to. The adaptive bamboo joinery systems for a purpose prototype require a joint that facilitates rapid installation for the relatively fast pace of robotic assembly without disrupting the robotic sequence. While the research promotes joint system potential for scalability, our current experiment with a collaborative UR10 robot or a KUKA robot will face challenges for full-scale implementations. Our research emphasizes the human-robot collaborative process in bamboo construction and showcases its feasibility. Further development of future adaptations or full-scale implementations may require system modifications based on the same joinery principles. However, the limitation identified in our research is the absence of a real-time feedback mechanism, particularly during the manual bending execution of the human operators with robotic holding. This may introduce bending inaccuracy of the targeted curvature desired in the prototype to precisely align with the digital models. To address this limitation, further research will explore incorporating sensor-guided systems or AR-assisted tools to assess the bending deviation tolerance and ensure improved geometry assembly.

The study contributes to the growing application of hybrid human-robot collaboration that addresses natural traditional material logic like bamboo with robotic assembly workflows. Integrating computational design and digital fabrication research on bamboo promotes sustainability for contemporary applications of traditional and culturally responsive Indonesian architectural solutions.

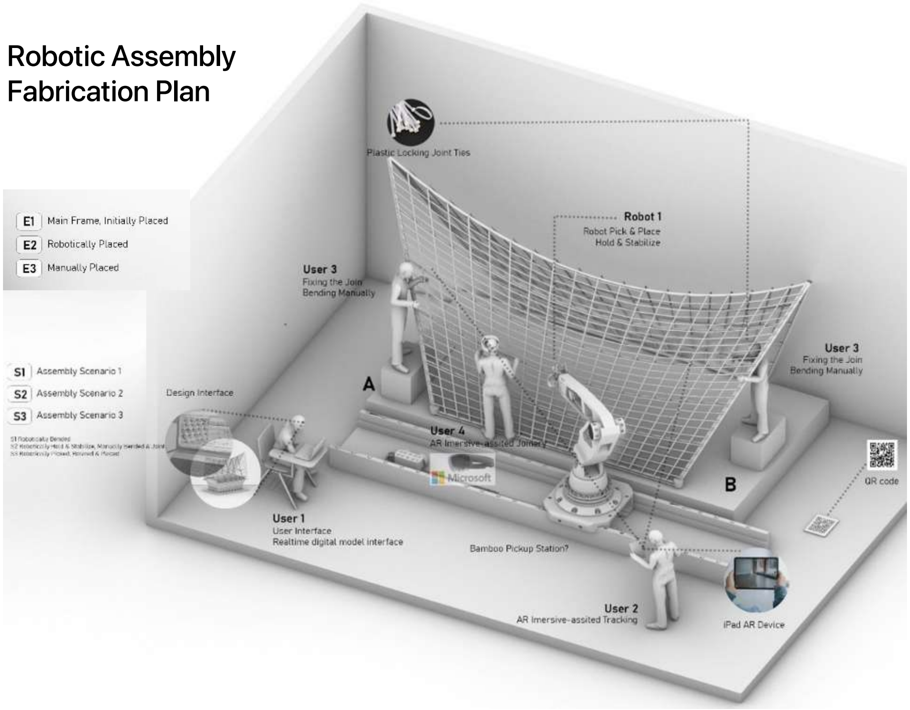

Fig. 12 Human-Robot Collaboration (HRC) fabrication plan and shared task scenario for the bamboo prototype

Acknowledgements

The authors would like to express appreciation to the Indonesian Education Scholarships / *Beasiswa Pendidikan Indonesia* (BPI) Ref. Number: 0973/J5.2.3/BPI.LG/VIII/2022, Ministry of Education, Culture, Research, and Technology, and the Indonesian Endowment Fund for Education / *Lembaga Pengelola Dana Pendidikan* (LPDP), Ministry of Finance of the Republic of Indonesia, for financial support of the full scholarship.

7 References

1. Davide Tanadini, Ohlbrock PO, Kladeftira M, Leschok M, Skevaki E, Dillenburger B, et al. Exploring the potential of equilibrium-based methods in additive manufacturing : the Digital Bamboo pavilion. In: Proceedings of the IASS 2022 Symposium: Innovation Sustainability Legacy [Internet]. 2022. Available from: https://doi.org/10.3929/ethz-b-000594566
2. JJA J. Designing and building with bamboo. Eindhoven: The Netherlands: International Network for Bamboo and Rattan; 2000.
3. Amtsberg F, Mueller C, Raspall F. Di-terial – Matching Digital Fabrication and Natural Grown Resources for the Development of Resource Efficient Structures. In: Proceedings of the 2021 DigitalFUTURES. Springer Singapore; 2022. p. 330–9.
4. Lorenzo R, Lee C, Oliva-Salinas JG, Ontiveros-Hernandez MJ. BIM bamboo: A digital design framework for bamboo culms. Proceedings of the Institution of Civil Engineers: Structures and Buildings. 2017 Apr 1;170(4):295–302.
5. Lorenzo R, Godina M, Mimendi L, Li H. Determination of the physical and mechanical properties of moso, guadua and oldhamii bamboo assisted by robotic fabrication. Journal of Wood Science [Internet]. 2020;66(1). Available from: https://doi.org/10.1186/s10086-020-01869-0
6. Lorenzo R, Mimendi L. Digitisation of bamboo culms for structural applications. Journal of Building Engineering [Internet]. 2020 May 1;29(February 2019):101193. Available from: https://doi.org/10.1016/j.jobe.2020.101193
7. Wang TH, Espinosa Trujillo O, Chang WS, Deng B. Encoding bamboo's nature for freeform structure design. International Journal of Architectural Computing. 2017 Jun 1;15(2):169–82.
8. Trujillo OE, Wang TH. Parametric modeling of bamboo pole joints. Communications in Computer and Information Science. 2015;527:272–90.
9. Wu NH, Dimopoulou M, Hsieh HH, Chatzakis C. A digital system for AR fabrication of bamboo structures through the discrete digitization of bamboo. In: Proceedings of the International Conference on Education and Research in Computer-Aided Architectural Design in Europe. 2019. p. 161–70.
10. Kladeftira M, Leschok M, Skevaki E, Tanadini D, Ohlbrock PO, D'Acunto P, et al. Digital Bamboo: A Study on Bamboo, 3D Printed Joints, and Digitally Fabricated Building Components for Ultralight Architectures. In: 41st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Hybrids & Haecceities [Internet]. 2022. p. 406–17. Available from: https://doi.org/10.3929/ethz-b-000667377
11. Di Paola F, Mercurio A. Design and digital fabrication of a parametric joint for bamboo sustainable structures. In: Advances in Intelligent Systems and Computing. Springer Verlag; 2020. p. 180–9.

12. Matson CW, Sweet K. Simplified for Resilience: A parametric investigation into a bespoke joint system for bamboo. In: Sociedad Iberoamericana de Gráfica Digital (SIGraDI). Blucher Design Proceedings, 3(1); 2016. p. 405–11.
13. Amtsberg F, Raspall F. Bambooˆ3. Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019. 2018;1:245–54.
14. Mitterberger D, Atanasova L, Dörfler K, Gramazio F, Kohler M. Tie a knot : human-robot cooperative workflow for assembling wooden structures using rope joints. Construction Robotics. 2022 Dec;6(0123456789):277–92. Available from: https://doi.org/10.1007/s41693-022-00083-2
15. Vasiliki E, Joseph A, Kenny C, Atanasova L, Casas G, Dörfler K, et al. Cooperative augmented assembly (CAA): augmented reality for on-site cooperative robotic fabrication. Construction Robotics [Internet]. 2024; Available from: https://doi.org/10.1007/s41693-024-00138-6
16. Mansuri A, Agkathidis A, Lombardi D, Chen H. Rethinking Traditional Indonesian Roof Bamboo Frame Structures By Utilizing Parametric Tools And Automated Fabrication Techniques: A Systematic Review. In: International Conference of the Arab Society for Computation in Architecture, Art, and Design (ASCAAD). Arab Society for Computation in Architecture, Art, and Design. 5000 THAYER CTR STE C, OAKLAND MD 21550-1139, USA. ISSN: 2994 – 9777; 2023. p. 110–33.
17. Mansuri A, Agkathidis A, Lombardi D, Chen H. Rethinking Bamboo Roof-Based Architecture of Indonesian Traditional House Using Parametric Design and Automated Fabrication Techniques. In Nicosia; 2024 [cited 2025 May 30]. p. 203–12. Available from: http://papers.cumincad.org/cgi-bin/works/paper/ecaade2024_367
18. Arce Villalobos OA. Fundamentals of the design of bamboo structures. Eindhoven: Technische Universiteit Eindhoven; 1993.
19. Huang Z. Model Study on the Application of Bamboo in Building Envelope. In: Green Energy and Technology. 2019. p. 81–118.
20. Prasetyo YH, Astuti S, Perumahan PL, Badan P, Kementerian L, Umum P, et al. Tropic Climate Form of Nusantara Traditional Architecture's Expression in Regionalism. Settlement Journal. 2017;12(2):80–93.
21. Qi Y, Zhong R, Kaiser B, Nguyen L, Wagner HJ, Verl A, et al. Working with Uncertainties: An Adaptive Fabrication Workflow for Bamboo Structures. In: Proceedings of the 2020 DigitalFUTURES. Springer Singapore; 2021. p. 265–79.