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ADDRESSING CHALLENGES IN MANUFACTURING IRREGULAR WOODEN POLES: A PRACTICAL EXPLORATION ON ACCURACY, EFFICIENCY, AND COST

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ABSTRACT: The primary challenge in advancing the practical application of wood-wood connections lies in addressing the deficiency in performance metrics of manufacturing irregular wooden poles, such as accuracy, efficiency and cost. This study aims to address the above challenges. Initially, a comparative experiment was conducted between robotic and manual workflow to evaluate the performance differences of manufactured irregular wooden poles. A series of improvement strategies based on the evaluation results was formulated, including optimization of connection details, integration of machinery and craftsmanship, and pre-planning of workflows. These strategies effectively addressed the challenges associated with manufacturing irregular wooden poles through verification in a practical timber dome project, aligning with the growing trend of design for manufacture and assembly strategies, timber modular construction, and mass customization. Moreover, this study served as a reference for fabricating wood-wood connections with irregular poles and indicated a potential integrated application of appropriate machinery and craftsmanship.

KEYWORDS: irregular wooden poles, wood-wood connection, performance metrics, improvement strategies, manufacturing workflow

1 – INTRODUCTION

Due to the difficulties in manufacturing, assembly and cost-effectiveness, irregular wooden poles and wood-wood connections are rarely utilized in modern architectural practices [1]. With advancement of manufacturing technologies and the increasing demand for sustainable building solutions, there has been a resurgence of interest in irregular wooden poles and wood-wood connections [2]. In curved surfaces and dome structures, employing irregular wooden poles and wood-wood connections to achieve precise curvature necessitates the accurate fabrication of components with complex joints. Thus, it is crucial to address deficiencies in the manufacturing performance metrics, such as accuracy, efficiency and cost. This study proposed improvement strategies for the above metrics and has effectively validated them through a timber dome project, corresponding to three subsequent practical experiments.

2 –DOME DESIGN

The project *Bonda Dome* investigated in this study was conceived as a sustainable timber structure utilizing renewable materials. Its structural system integrates wood-wood connections with irregular wooden poles as primary joint components. The prototype design synthesizes anthropometric considerations, landscape integration, and recreational functionality, with key dimentional parameters comprising a 1.80 m radius, 10.18 m² footprint, and 2.90 m vertical clearance (Fig. 1). The design principles are articulated as follows:

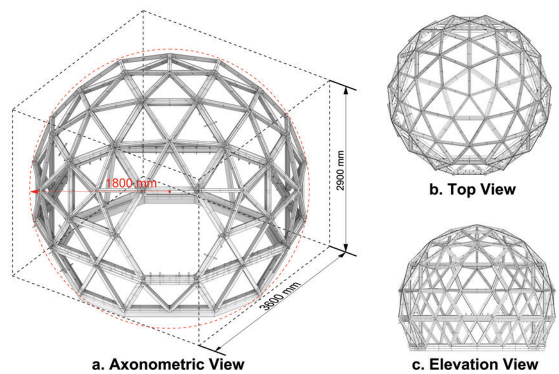

Figure 1. Design drawings of Bonda Dome.

Structural system. The strcture prototype is derived from the geodesic dome, which is favoured by architects for its excellent stability, durability and the advantage of not requiring internal support [3]. By adjusting the main parameters of the topology, e.g., subdivision frequency, division type, platonic polyhedral, and sphere radius, this

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lightweight truss system can achieve varying load-bearing capacities, component lengths, and polygonal module types. By optimizing the geospatial structure through finite element analysis in Karamba3D, the *Bonda Dome* prototype has been decided on ortho icosahedron with frequency of 3v subdivision, i.e., the structure is comprised of three lengths of poles and two module types.

Connections. Component connections play a crucial role in ensuring the timber structure's integrity and strength [4]. Owing to the ease-machinability, joint-concealability, and manufacturing cost-effectiveness, wooden dowels were utilized for connections. They were capable of preventing detachment without any metal fasteners, leveraging the substantial frictional forces between components. Besides, utilizing specialized joints facilitates reversible disassembly [5]. Considering the ubiquitous accessibility of dowels and woodworking tools in the market, it was practicable to utilize dowels of same dimension to assembly the entire dome structure.

Material. After comparing the divergent physical attributes and processing complexities of different wood species, lightweight Scots pine was selected for the main sturcture. Besides, polywood panels and beech dowels were ultilized at the central joints of the modules to ensure stability. Beech can provide dowels enhanced load-bearing capacity due to its superior stiffness.

Prefabrication and modularization. The standardized dimensions of components of the dome were well adapted to digital modelling and modularization fabrication. It allowed enhanced control over the entire prefabrication process as the majority of modules were fabricated in an off-site environment, which enhanced assembly efficiency and minimized waste.

3 – METHODOLOGY

To facilitate precise assembly, the difficulty of connecting curved surface was shifted from intricate connectors to irregular wooden poles, which allowed their end joints in conjunction with simple dowels. This study analytically compared the performances of three different workflows for manufacturing hexagonal modules of *Bonda Dome*, and explored effective improvement strategies to enhance the performance metrics. The study encompasses four steps (Fig. 2): First, two distinct workflows of *Initial Design* were established: robotic workflow (*Experiment I*) and manual workflow (*Experiment II*). Each workflow was designed to follow the planned process of manufacturing a hexagonal module. Second, the two experiment's results were analytical compared in terms of accuracy, efficiency, and cost. Other relevant factors were also evaluated, such as flexibility, operator knowledge, tool types, machine maintenance, and auxiliary devices. Based on the evaluation analysis, improvement strategies were proposed. Third, to accommodate the strategies, *Initial Design* and workflows were targeted optimized into *Optimized Design* and a new workflow (*Experiment III*). Finally, the performance metrics of the third experiment's results were evaluated and discussed to verify the effectiveness of the strategies.

4 – WORKFLOW AND EXPERIMENT

4.1 INITIAL DESIGN

The geometric modules of *Initial Design* is illustrated in Fig. 3. There are 12 poles intersecting at the center of the hexagonal frame, projecting upwards to form the dome curvature. The wooden poles are characterized by two

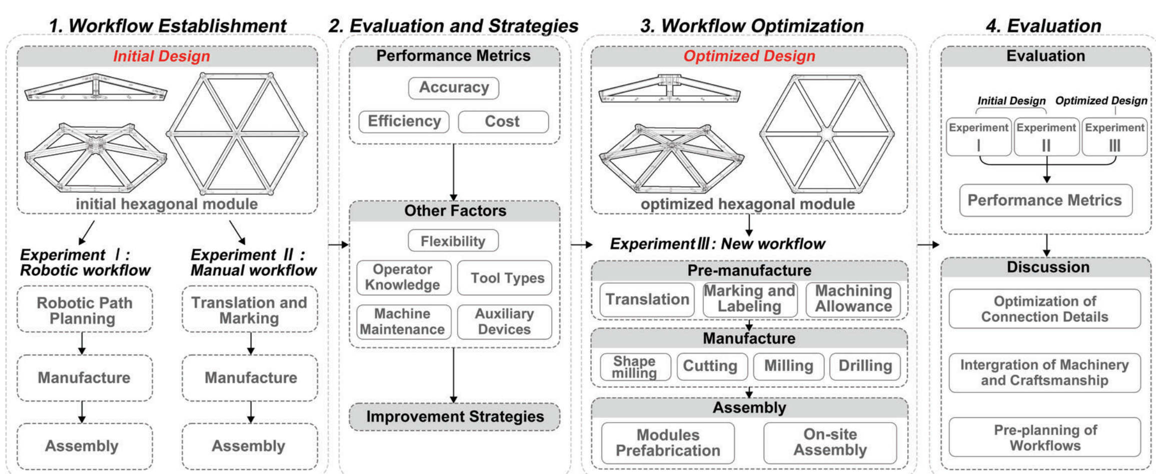

Figure 2. Research methodology.

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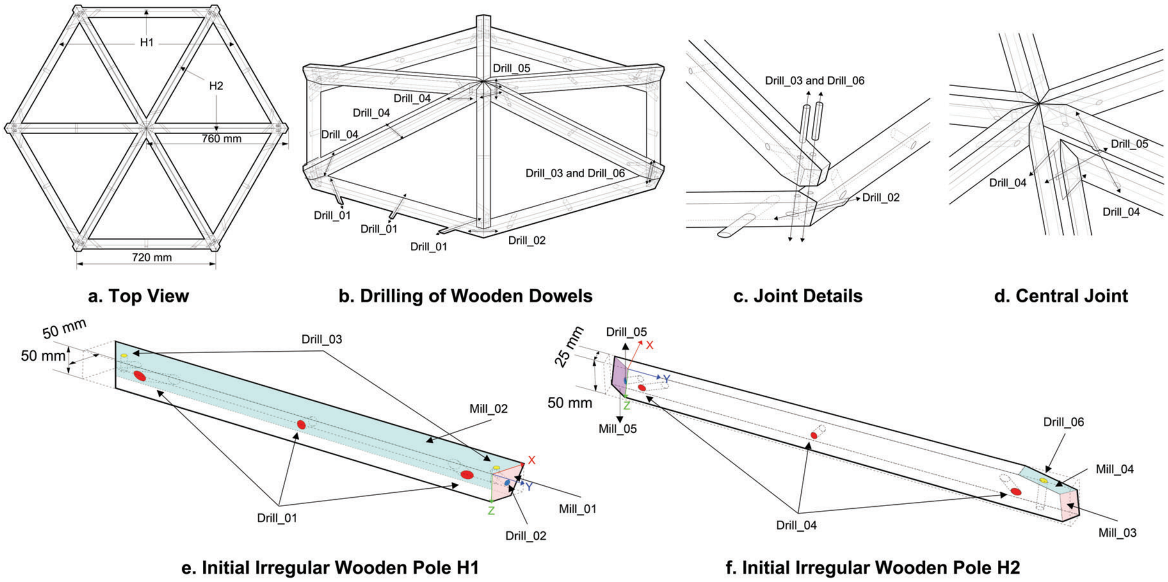

Figure 3. Geometry of the hexagonal module of Initial Design.

cross-section dimentions: H1 poles measure 50mm by 50mm, while H2 poles measure 25mm by 50mm. To achieve accurate curvature and the mortise holes, each pole is characterized with high geometric complexity, such as non-orthogonal penetration and irregular bevelled ends (e, f in Fig. 3). Theoretically, the central joints can connect 12 poles, leaving no gaps (d in Fig. 3). To accommodate robotic and manual machinery, detailed manufacture steps for different workflows are as follows.

4.1.1 Experiment I: robotic workflow

According to the robotic workflow, one KUKA six-axis robot (KR 120 R2500 pro) was deployed for fabrication, operated by one engineers and two students. Equipped with a motor spindle capable of tool switching, the robot was able to manufacture within a working radius of 2496 mm. The experimental machining setup consisted of the robot and a fixture platform. The detailed manufacture steps are showed in Fig. 4. Digital model was initially created with Rhinoceros3D and Grasshopper software to establish a foundation for subsequent requisite simulation information. Then, the robotic procedures were generated by Robim software, converting 3D models to digital information recognizable by the robotic control system. To minimize errors associated with manual intervention, each procedure was executed in one single programme without repositioning or recalibration, along with seamless transition between tools. A commissioning cycle was designed before manufacute, containing three steps: toolpath planning, code generation, and parameters modification. The toolpath planning also involved three main operations: a) Rough milling. Corn milling cutter was used for initial roughing of lumber surfaces. Additionally, the large bevelled sides (Mill_02 of e in Fig. 3) were rough milled to ensure surface smoothness. b)

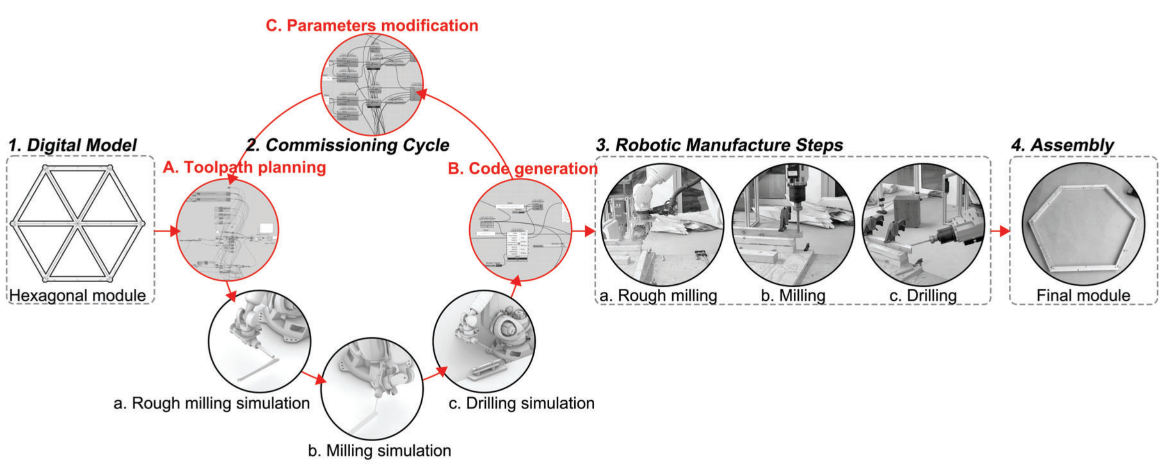

Figure 4. Steps of Experiment Ⅰ.

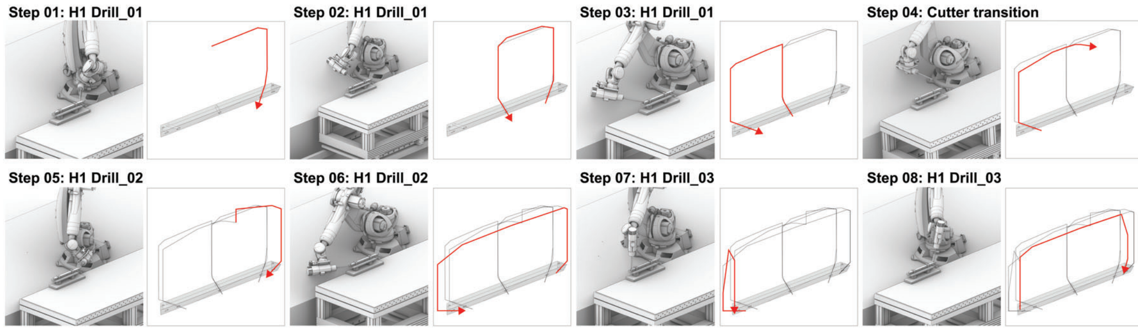

Figure 5. Drilling path planning and simulation of pole H1.

Milling. Smaller milling cutters were selected to manufacture other bevelled surfaces (Mill_03, 04, and 05 of f in Fig. 3). c) Drilling. Several holes with different angles and diameter needed to be done in one programme. Prior to the practical manufacture, it was crucial to give visual inspection to the toolpath planning and simulations. This is essential to mitigate potential collisions and reachability among the spindle, fixtures, and workbench [6]. Computational simulations of each operation were conducted iteratively, with necessary modifications made over multiple cycles. This was particularly crucial for drilling operations, which involved repeated round-trip motions. Every virtual collisions or system errors in the simulation could be monitored and inspected, as depicted in Fig. 5, where the red lines represented the tool path of current step. By observing the trajectory, potential issues, such as paths that bypass the intended drilling locations, collisions with other objects, and abnormal twists of the robot's arms, could be resolved within minutes.

4.1.2 Experiment II: manual workflow

The manual workflow was executed by two professional carpenters, utilizing ordinary joinery machines (Fig. 6). The carpenters initially translated the design drawings and positioned all the intricate details in lumbers, providing essential guidance for subsequent steps with markings. A planer and a thicknesser were used to rough mill the lumbers to desire sizes. Subsequently, the carpenters continuously adjusted the blade angles of table saws and tension miter saws to ensure smoothness and precision of the cutting surfaces. Finally, they utilized a bench drill and a handheld drill for non-orthogonal penetration. The final assembly process was assistanted by two students.

4.1.3 Experiment results and evaluations

After finishing the practical experiments, this study then analytical compared the accuracy, efficiency, and cost between the two results, along with further analysis of other relevant factors (Tab. 1). Upon summarizing the results, it was found that the manual workflow exhibited superior performance in certain aspects:

Accuracy. The lack of considertation of dimensional tolerance in both workflows has led to cracks on the poles surfaces after thickness processing. Additionally, the hygroscopic warping has prevented adjacent H2 poles from fitting tightly together. Due to the datum plane calibration errors, all H1 poles in *Experiment I* have exhibited a 2mm machining error of in the x-y plane (e in Fig. 3). However, the drilling spacing remained sufficiently precise, aligning with the relative positions of the digital model. Conversely, the carpenters were unable to ensure the high consistency of non-orthogonal penetration with the digital models in *Experiment II*. The ultilization of electric handheld drills has resulted in visible gaps at the central joints of 12 poles, failing to match the digital model. This mismatch resulted in potential detachment.

Efficiency. After code programming, the robot could work continuously to reduce fabrication time. However, considering the entire process, the duration of the commissioning cycle must be accounted for, which involved toolpath planning, code generation, and parameters modification. In comparison, the manual pre-manufacturing phase was more concise and streamlined. The total duration of *Experiment I* was 456 mins, nearly 10% longer than the 415 mins in *Experiment II.*

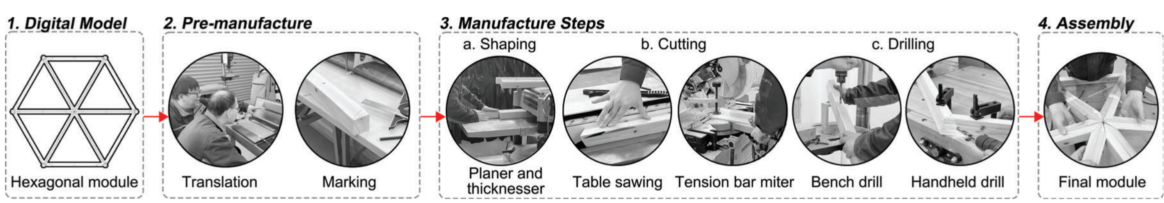

Figure 6. Manufacture steps of Experiment Ⅱ.

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Table 1. Experiment results and comparison of Experiment I and Experiment II of Initial Design.

Accuracy	Milling	Drilling	Assembly gap	Dimension error	Hexagonal module
I					
II					

Efficiency	Pre-manufacture	H1 Manufacture	H2 Manufacture	Assembly	Total
I	180 mins	126 mins	120 mins	30 mins	456 mins
II	20 mins	125 mins	240 mins	30 mins	415 mins

Cost	H1 Manufacture	H2 Manufacture	Assembly	Other cost	Total
I	315.00 yuan	300.00 yuan	75.00 yuan	robot rental: 2000.00 yuan, operator: 150 yuan / hour	2690.00 yuan
II	416.67 yuan	800.00 yuan	100.00 yuan	operator: 100 yuan / hour	1316.67 yuan

Other	Flexibility	Operator knowledge	Tool types	Machine maintenance	Auxiliary devices
I	low	robotic knowledge, carpentry knowledge	robots and cutters	high frequency	specialized fixture
II	high	carpentry knowledge	joinery machines	low frequency	supporting bases, angled drilling templates

Cost. Considering the expense of electricity, robot rental and professional operators, the total expense was 2690.00 yuan of *Experiment I*. In contrast, the cost of *Experiment II* was 1316 yuan, much lower than the former experiment. Moreover, the investment and maintenance cost for robots, tools, and other auxiliary devices far exceeded to the cost of joinery machines.

Other relevant factors. To perform initial rough milling of the lumber, both workflows necessitated fundamental knowledge for joinery machines. In *Experiment I*, operators were required for additional specialized robotic knowledge and adhere to laboratory safety protocols, which necessitated prior training. As for fabrication flexibility, joinery machines have exhibited superior performance. Robots required extra procedure for commissioning cycle and position recalibrating, as the practical environment was more complex than the simulation environment. Moreover, to prevent safety incidents, It was required to fabricate specialized fixtures and base for irregular poles. In *Experiment II*, the carpenters could flexibly apply craftsmanship experience to avoid potential issues. When confronted with intricate details, employing auxiliary supporting bases and angled drilling templates could fulfill the requirements without generating complex robotic procedures.

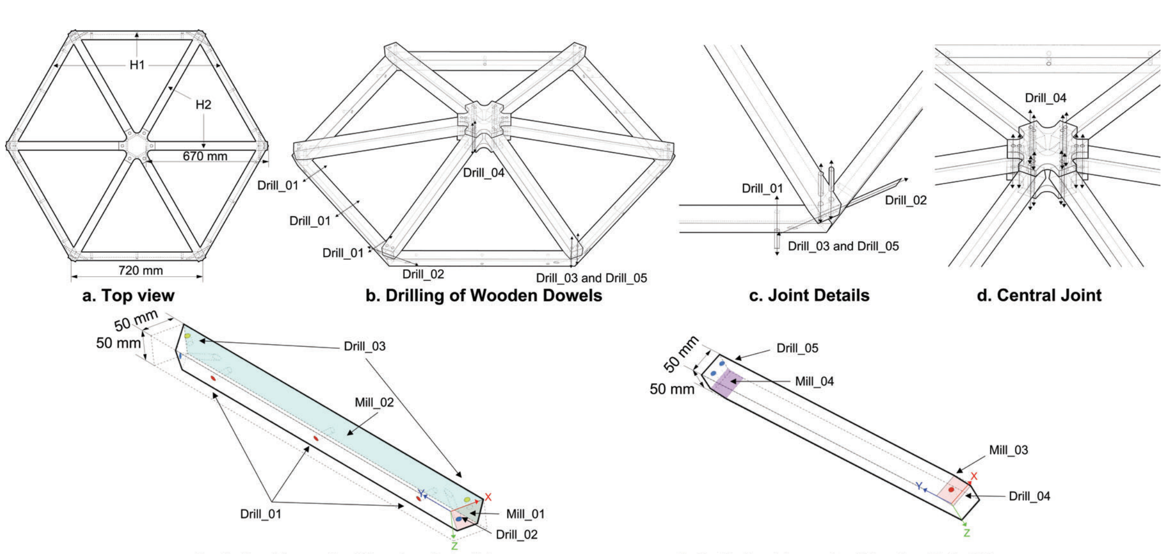

Figure 7. Geometry of the hexagonal module of Optimized Design.

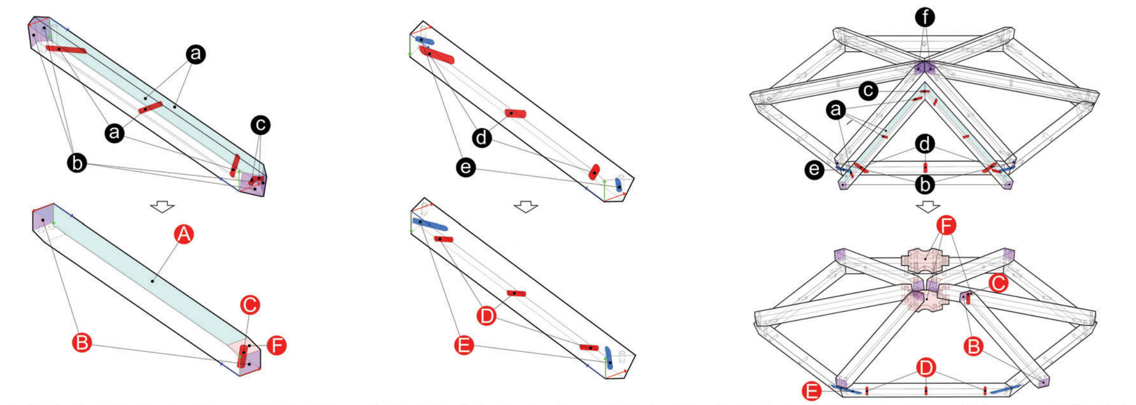

Figure 8. Optimization of connection details.

4.2 OPTIMIZED DESIGN

In light of the above experimental results, the manual workflow demonstrated superior performance in most aspects and has been ultilized in *Optimized Design*. Accordingly, multi-objective improvement strategies have been proposed, aiming at enhancing the key performance metrics and adapting to joinery machines. The geometric modules of *Optimized Design* are depitcted in Fig. 7.

Optimization of connection details. The connection details of both designs are compared in Fig. 8, with optimization changes denoted by letters. The H2 poles have been combined in pairs (1 a → 1 A), eliminating superfluous assembly steps. The complex of bevelled surfaces, sections, and end joints of H2 poles has been simplified for ease of connection (1 b →1 B), requiring minimized manufacture operations. Moreover, the non-orthogonal penetrations of H1 poles have been standardized for vertical drilling (2 d → 2 D). To ensure strength and precision of the central joints, the connections are modified from using only dowels to incorporating polywood panels and dowels (3 f → 3 F). Furthermore, the wood dowels in the central joints and each pole's end have been lengthered and thickened (1 c → 1 C, 2 e → 2 E).

Integration of machinery and craftsmanship. Taking into account the advantages of different craftsmanship and machinery, *Optimized Design* did not solely pursue the use of machines that require high-standard operating environments and specialized technical skills. Instead, manual joinery machines with high flexibility were employed. Due to the orthogonal penetration, *Optimized Design* has eliminated the need for angled drilling templates, which were required in the manual workflow of *Initial Design*. Besides, to ensure accuracy and efficiency, laser cutting machines were utilized to fabricate the central polywood panel joints.

Pre-planning of workflows. The operating datum planes of each component were pre-planned, enabling poles with trapezoidal cross-sections to be stably placed without auxiliary supporting bases or being twisted to special angles. Furthermore, by treating the polygonal modules as the basic assembly units, the integrated manufacture and assembly sequences have been predetermined to minimize assembly errors attributable to the irregular wooden poles.

4.2.1 Experiment III: new workflow

The detailed steps of *Experiment III* are depicted in Fig. 9. Similar to the carpentry procedures in *Experiment II*,

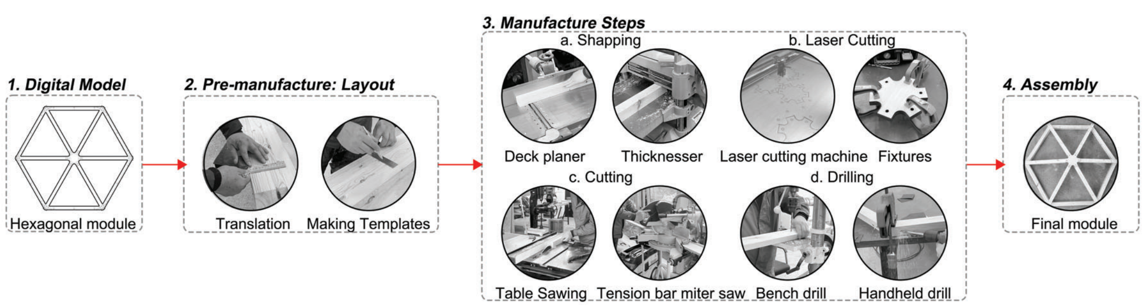

Figure 9. Steps of Experiment III.

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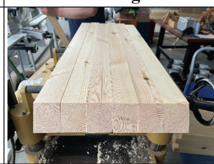
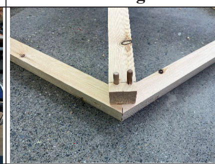
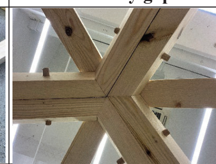
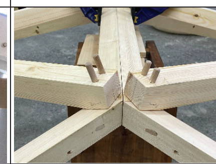
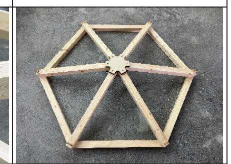
Table 2. Experiment results of Experiment II of Optimized Design.

Accuracy	Milling	Drilling	Assembly gap	Dimension error	Module
III					

Efficiency	Pre-manufacture	H1 Manufacture	H2 Manufacture	H3 Manufacture	Assembly	Total
III	10 mins	81 mins	57 mins	20 mins	12 mins	180 mins

Cost	H1 Manufacture	H2 Manufacture	H3 Manufacture	Assembly	Other cost	Total
III	135.00 yuan	95.00 yuan	40.00 yuan	20.00 yuan	operator: 100 yuan / hour laser cutter: 40.00 yuan	290.00 yuan

Other	Flexibility	Operator knowledge	Tool types	Machine maintenance	Auxiliary devices
III	high	carpentry knowledge	joinery machines and laser cutter	low frequency	positioning templates

one carpenter initially translated the design drawings and made a plan for processing the components, along with the assembly assistance of one student. To expedite manufacturing, wood templates have been created for drilling and cutting positioning. This step have ensured the accuracy of markings and labels on the same type of components. Deviating from *Experiment II*, the central polywood panels have been cut precisely by laser cutting machines.

4.2.2 Experiment results and evaluations

Tab. 2 illustrated the experiment results of *Experiment III*. This section conducted a comparative evaluation of the experiment's results for new and old designs, with a particular focus on *Experiment II.* The improvement strategies have effectively mitigated the challenges in manufacturing irregular wooden poles:

Accuracy. Incorporated with component standardization and dimentional tolerance, components of *Experiment III* exhibited lower degrees of deformation, reduced warping, and tighter connection. As for drilling, the results of the two manual workflows were relatively similar. In terms of dimension errors and assembly gaps, the module in *Experiment III* were assembled with high precision, eapecially at the central joints.

Efficiency. Including the pre-manufacture time, the dutation in *Experiment III* was reduced by approximately 50% to 180 mins in comparison to the total time of 415 mins in *Experiment II*. Despite the relatively short time in translating and marking, the carpenter confronted challenge of reworking the components due to misunderstanding of the digital model and drawings.

Cost. Compare to the robotic workflow, the rental expence of conventional joinery machines employed in *Experiment III* significantly reduced the total cost. In comparison to *Experiment II*, the optimized connection achieved by laser cutting machine in *Experiment III* resulted in a reduction of the work hours and labour costs.

Other relevant factors. Compared with robotic workflow, both manual workflows have showed the value and flexibility of skilled labor and craftsmanship, allowing for effective management of wood defects and the joinery machines limitations. When dealing with similar components, it revealed diverse decisions on machinery and auxiliary devices can impact the fabrication flexibility and final precision. For instance, to address the issue of unstable placement of irregular poles, carpenters in *Experiment II* needed additional effort to fabricate auxiliary supporting bases. The use of laser cutting machine and positioning templates in *Experiment III* have expedited the fabrication process.

After a comprehensive evaluation of the results from the three experiments, the new workflow in *Experiment III* has been selected to fabricate modules of *Bonda Dome*. The entire structure included six pentagonal modules, ten hexagonal modules, and fifteen flattened trapezoidal modules. All modules were prefabricated with satisfactory accuracy in a carpentry shop and then were assembled with beech dowels on-site in Shanghai, China (Fig. 10).

Figure 10. Bonda Dome.

5 – DISSCUSION

5.1 OPTIMIZATION OF CONNECTION DETAILS

Connection errors and precision directly impact the load-bearing strength of the entire timber structure. In *Initial Design*, components and connections were susceptible to accumulating errors during manufacturing processes such as layouting, sawing, drilling, and milling. *Optimized Design* has considered the adapbility of wood-wood connections to minor errors, which can further eliminate additional manual labor, minimize waste, and enhance flexibility of manufacturing and assembly through the following strategies:

Simplification of connection geometry. Each pole's end in *Initial Design* required multiple bevelled cuts, which could lead to minor errors, thereby possibly causing potential detachment or assembly gaps in central joints. Simplifying the connection geometry can reduce multiple operations to one single operation, thereby effectively minimizing the cumulative errors.

Standardization of component connections. Standardization has been achieved by unifying the drilling and milling angles within the components in *Optimized Design*, accelerating the mass production of components and streamlining manufacturing process. By standardizing component connections, the manufacturing process becomes more predictable and controllable, allowing for better resource utilization and management.

Introduction of dimensional tolerance. To mitigate manual errors and assembly difficulty caused by positioning and measurement, *Optimized Design* has incorporated dimensional tolerances for the components. For instance, by adding extra spacing at the ends of each poles, the central joints of hexagonal modules prevented end-to-end contact, reducing machining tolerance issues caused by compression and deformation (3 f → 3 F in Fig. 8). Moreover, the consideration of these tolerance facilitates subsequent replacement of new components, ensuring the structure remains maintainable over time.

5.2 INTEGRATION OF MACHINERY AND CRAFTSMANSHIP

Efficient intergeration of machinery and craftsmanship in the manufacturing process not only has addressed the limitations of robotic and manua workflows, but also met higher demands for manufacturing performance metrics of irregular wooden poles. The strategy lowered the technical skill requirements, allowing operators flexibly apply craftsmanship experience to address assembly errors and equipment limitations. *Optimized Design* has successfully leveraged the integration of appropriate machinery and craftsmanship experience through several considerations:

Reduction of investment costs. Reducing reliance on specific high-tech machinery can effectively lower the costs of machinery investment and operator training. In certain countries and regions, the high initial outlay and stringent environmental standards of robotic systems and automated production lines are not suitable for small-scale enterprises and immature markets. In light of the prevailing economic conditions in certain developing countries, such as China, the low expences of manual workflow and joinery machines offer greater market competitiveness, especially when production precision is maintained.

Significance of manual intervention. Inlight with the special characteristics of woodworking, current automatic timber manufacturing is still tightly bound to human interventions, such as spontaneous decisions, supervision, and adjustments of operators. In *Experiment I*, the toolpath planning and operational procedures of robotics were typically based on standardized digital models and parameters, necessitating extensive time for recalibration of irregular surfaces and drilling angles. The commissioning cycle, which involves toolpath planning, code generation, and parameters modification, was repeated until the desired outcome was achieved. The unforeseen errors could still emerge in the complex practical environment, such as the abnormal torsion of multi-axis robotic arms. Furthermore, the operators were also tasked with executing physically demanding and inefficient auxiliary works, including manual calibration for datum plane positioning, replacement of cutters, check for abnormal torsion of robotic arms. The works are not only time-consuming but also reliant on the operator's skill for accuracy. To lower the operational costs for specialized technical expertise in *Experiment III*, joinery machines were ultilized. It augumented flexibility to incorporate craftsmanship experience for addressing assembly errors, equipment limitations, and wood defects.

Application of flexible HMI. After comparing the performance metrics of automated robotic and entirely manual workflows, the experiment results have showed the importance of application of appropriate machinery and craftsmanship. Achieving efficient human-machine intervention (HMI) is regarded as an effective solution to

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enhance fabrication flexibility and task coordination [7]. To concurrently harness the positioning accuracy of advanced mechinerys and the flexibility of manual workflow, there is a need to develop a new integrated manufacturing method for timber craftsmanship. With the continuous improvement of sensor technology in precision and adaptability, advancements in head-mounted display, voice and gesture recognition, and various mixed reality (MR) technology devices can bridge the gap between digital and physical spaces, providing intuitive guidance for convey design intention [8]. Under the guidance of the MR devices, operators can navigate inevitable errors in complex manufacturing processes. By providing real-time analysis and iterative decision-making, MR devices can supplant the fabrication of auxiliary supporting bases and positioning templates in manual workflow, thereby enhancing efficiency and reducing additional task. Moreover, compared to automatic workflow, integrating woodworking craftsmanship, joinery machines, and immersive devices could actively intervene and steering manufacture workflow. In this instance, fabrication process can achive higher levels of robustness and efficiency, especially for irregular wooden components.

5.3 PRE-PLANNING OF WORKFLOWS

Pre-planning of workflow is crucial for establishing a sequential design-manufacture-assembly workflow in advance, ensuring high efficiency, low cost, and good quality. Regardless the type of workflow and machinery employed, the pre-planning stage for timber components fabrication necessitates a comprehensive consideration of datum planes and manufacturing sequences. This approach can facilitate the productization and modularization of wooden components, thereby better aligning them with the trend of mass customization in the construction market.

Continuity of digital chain. In pre-manufacture phase of robotic workflow, it is essential to employ robotic program plugins and self-detection system to support the commissioning cycle, thereby detecting potential errors. When manually replacing cutting tools or components, there is still a risk of discontinuity in the digital planning chain and loss of datum coordinate system information. Such interruptions could lead to reduced workflow efficiency. To ensure the continuity of the digital chain, it is necessary to employ advanced visual recognition and machine learning technologies to enhance the robotic system.

Design for component datum plane. To accelerate the manufacture process, comprehensive design for datum plane of irregular poles were made in *Optimized Design*. It encompassed the specific content of each fabrication step, required time, equipment, potential inefficiencies, and allocation of human resources, adapting to joinery machines and manual workflow. For instance, each manufacture step has been smoothly executed on the workbench without the need for additional auxiliary supporting bases, and the blades or drilling bits can perform the operations without being deflected to special angles, ensuring the safety of subsequent manual process.

Sequencing of manufacture and assembly. Take account to manufacture sequence in *Experiment III*, irregular wooden poles were processed through shape-milling, end-cutting, side-milling, and hole-drilling, thereby enhancing the stability of the clamping and positioning. Moreover, the assembly sequences were anticipated based on forms and positions of various polygonal modules in *Bonda Dome*. The components have been preliminarily assembled into separated modules off-site and then transported to the project site for secondary assembly, which simplified on-site assembly procedures.

Design for manufacture and Assembly (DfMA). The above mentioned pre-planning strategies have accommodated the growing need of timber construction industry for shorter product life cycles, sustainable manufacture processes, and individualized production, aligning with the DfMA concept advocated in the manufacture industry. DfMA strategies employ highly backward-compatible prefabricated components to streamline the manufacturing preocess and enhance assembly efficiency [9]. However, current DfMA practices are predominantly based on the guidelines from the manufacturing industry, lacking guidance tailored to timber construction. To adapt to the trend of mass customization and modular timber construction, and to extend the DfMA concept to timber construction, there is a need to establish comprehensive integrated optimization strategies for manufacturing and construction industries. It warrants further investigation for addressing the limitations of integration the DfMA concept with timber construction sector.

6 – CONCLUSION

This study has comprehensively investigated the challenges associated with manufacturing irregular wooden poles with wood-wood connections, focusing on enhancing accuracy, efficiency, and cost-effectiveness.

The improvement strategies proposed in this study included the optimization of connection details, the integration of machinery and craftsmanship, and the pre-planning of workflows, which have demonstrated significant enhancements in the mentioned metrics. After a series of experiments, the effectiveness of these strategies were ultimately validated through the practical construction of *Bonda Dome* project. The results have underscore the importance of a flexible and adaptable manufacturing approach. The integration of machinery and craftsmanship not only met the demands of personalized production but also simplified the assembly process. Looking forward, future research will be dedicated to fully leveraging the advantages of MR devices and HMI methods, and further exploring integration of DfMA concepts into the timber construction industry.

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