

A Time-Based Comparison of Manual and Robotic Manufacturing Processes for Nail-Laminated Timber Panels

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Abstract -

Manual fabrication of Nail-Laminated Timber (NLT) panels relies on repetitive operations and visual judgment, which can limit consistency, productivity, and process repeatability. This study presents a comparative time-based analysis between manual and simulated robotic fabrication of full-scale NLT panels. Manual assembly was examined through video-based time studies, decomposing the workflow into principal assembly stages and complementary activities. In parallel, a robotic manufacturing cell composed of an industrial serial robot, a multi-functional pick-and-nail end-effector, and an automated assembly table was modeled and simulated to replicate the NLT fabrication process. The robotic workflow was structured to mirror the manual assembly stages, enabling a direct stage-level comparison while accounting for parallelized operations inherent to automation. The analysis highlights fundamental differences in workflow structure, time lapses, and process variability between manual and robotic fabrication. The results provide insight into the potential of robotic manufacturing cells to improve efficiency, repeatability, and process control in NLT panel production, supporting the transition toward automated timber construction systems.

Keywords -

Nail-Laminated Timber; Timber Nailing; Robotic Fabrication; Construction Automation; Time Study

1 Introduction

In the construction industry, timber assembly plays a crucial role, as wood remains one of the most widely used structural materials [1, 2]. The construction industry, like many others, is seeking to achieve ever-higher levels of automation. Despite this trend, the construction industry has been comparatively slow in adopting automated solutions [3, 4]. Within this context, timber assembly represents a particularly promising domain for automation, owing to material properties such as low weight, and ease of handling, which make timber components well suited for robotic manipulation.

At present, automated timber assembly is predomi-

nantly implemented in controlled off-site manufacturing environments. In such settings, robots operate collaboratively with other robotic systems [5, 6], in conjunction with automated devices such as CNC machines and saws [7, 8, 9], or through the use of integrated multi-tool robotic end-effectors [10]. These manufacturing cells are commonly used to prefabricate products including frame walls [8], timber structures [7], facades [11], panels [12], and Glue-Laminated Timber (GLT) elements [13, 14].

In contrast, other timber construction products—such as Nail-Laminated Timber (NLT) panels—are rarely produced within automated manufacturing cells. One reason for the limited adoption of automation in NLT manufacturing lies in the nature of the process itself. NLT fabrication consists of repetitive operations applied to simple geometries within a well-defined workspace, relying primarily on standard timber members and mechanical fasteners (nails). These characteristics have historically made NLT panels well-suited for manual fabrication by human workers and may have reduced the perceived need for automation.

However, simplicity of execution does not imply optimal efficiency. While manual fabrication remains feasible, it inherently limits production speed, repeatability, and scalability. Autonomous systems, by contrast, can exploit the repetitive and structured nature of the NLT manufacturing process to achieve significantly higher productivity, while simultaneously reducing worker safety risks and improving product quality consistency [15, 16, 17]. From this perspective, the automation of NLT panel manufacturing represents a logical and timely opportunity rather than a redundant one.

Existing attempts to automate NLT production are limited and typically rely on large-scale, highly customized machinery designed to fabricate panels [18] or columns [19]. While effective, such solutions are accessible only to a small number of manufacturers due to their high cost, limited flexibility, and lack of reconfigurability. This motivates the exploration of alternative approaches based on compact robotic manufacturing cells that leverage industrial robotic arms. Such systems may offer modularity, scalability, and adaptability, making them particularly attractive for medium-scale or evolving production environ-

ments.

In this context, it is essential to quantitatively evaluate the feasibility and benefits of robotic NLT manufacturing relative to conventional manual processes. This paper presents a detailed time-based comparison between manual and simulated robotic NLT panel manufacturing. Time data for manual production were obtained from the fabrication of several NLT panels at ACQBuilt Corp. The robotic manufacturing process was analyzed using a simulation environment developed in RoboDK. The proposed robotic manufacturing cell consists of a KUKA KR 250 R2700-2 industrial robot equipped with a multi-functional pick-and-nail end-effector, as well as an automated table for panel positioning during the nailing process.

The main stages of the NLT manufacturing process are identified, described, and analyzed for both manual and robotic workflows. Time durations for each stage are reported and compared. The results demonstrate that robotic NLT panel manufacturing offers a significant reduction in production time as well as repeatability and control on the fastening process. These findings support the viability of implementing robotic manufacturing cells for NLT panel production, both in terms of productivity, repeatability, and process efficiency.

The remainder of this paper is structured as follows. Section 2 describes the manual NLT manufacturing process. Section 3 presents the proposed robotic manufacturing cell. Section 4 details the time analysis and comparative results between manual and robotic processes. Finally, discussion and concluding remarks are provided in Sections 5 and 6, respectively.

2 Manual NLT Panel Manufacturing

NLT is a structural solid wood panel constructed by placing dimension lumber on edge and fastening the boards together with nails driven through the face of each lamination. Panels are formed by multiple parallel members, typically 38 mm, 64 mm, or 89 mm in width and between 89 mm and 286 mm in depth [20]. The main geometric parameters (panel depth, lamination depth, panel width, and lamination width) are illustrated in Figure 1. NLT panels are commonly used as one-way spanning systems in floors and roofs, and can also be applied in vertical elements such as walls and shafts when a solid structural section is required.

The panels analyzed in this study are constructed using nominal 2×6 SPF lumber, with actual dimensions of 38.1 mm by 140 mm. Each panel has overall dimensions of 2438.4 mm in width and 3000 mm in height and consists of 64 laminations, as shown in Figure 2.

Regarding the fastening configuration, the panels employ an alternating nailing pattern using 3.7 mm × 76 mm nails, installed in accordance with the prescribed spacing

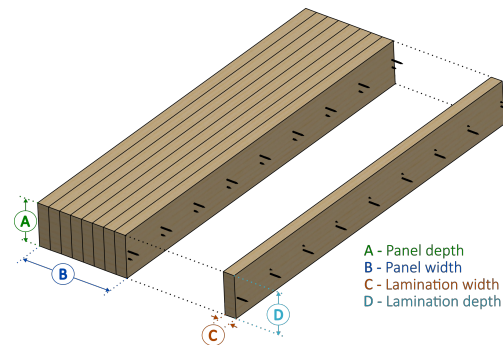


Figure 1. NLT main geometric parameters

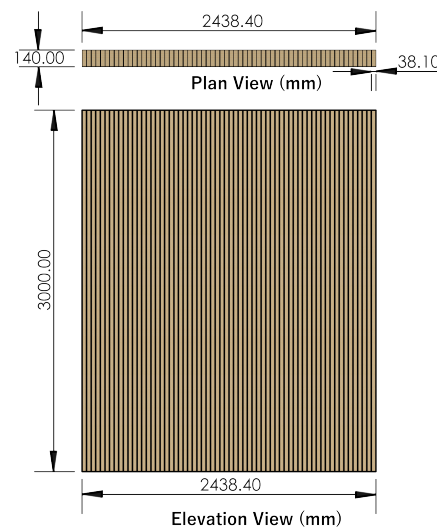


Figure 2. Complete NLT panel layout.

and offset requirements for NLT fabrication [20]. The complete fastening layout, including minimum nail spacing and designated installation zones across the panel face, is illustrated in Figure 3.

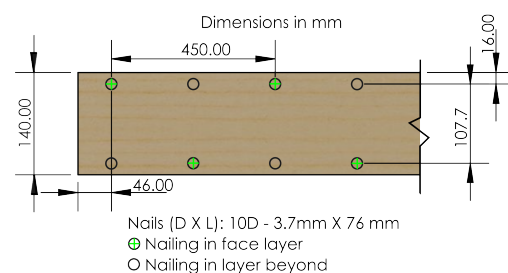


Figure 3. Fastening pattern and nail spacing

2.1 Manual Assembly Process

The description of the manual process is based on observations made at ACQBuilt Corp. The manual fabrication of the NLT panels involves a sequence of four recurring

stages: material handling, alignment, fastening, and correction. These stages structure the workflow during panel assembly, from material preparation through to all laminations being. A schematic overview of these stages is presented in Figure 4, which illustrates the overall sequence.

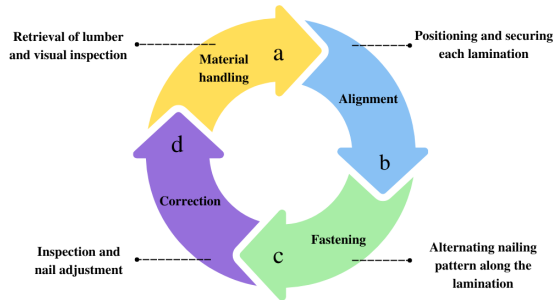


Figure 4. Manual NLT assembly sequence

The process begins once the tools, workspace, and fabrication drawings are prepared. In the material handling stage shown in Figure 5(a), the worker retrieves lumber from a designated storage area and transports it to the assembly station. There is no standardized procedure for this task, and the approach varies between workers. Some carry a single lumber at a time and immediately complete all subsequent stages before returning for the next piece. In contrast, others prefer to bring several lumbers at once and keep a small working stock beside the panel. After each piece of lumber is selected, the worker performs a quick visual inspection to identify defects. Most pieces are acceptable, whereas boards with excessive imperfections are discarded.



Figure 5. Manual assembly stages of the NLT panel: (a) material handling, (b) alignment, (c) fastening, and (d) correction

Once the lumber reaches the workbench, the alignment stage is performed, as shown in Figure 5(b). The worker manually adjusts the lamination in both directions to establish a straight reference edge along one side, while the opposite side remains irregular due to dimensional variability and is trimmed later. A clamp is applied at a reference position along the top edge to secure the lamination before fastening.

The fastening stage, shown in Figure 5(c), follows an alternating pattern depending on the lamination position within the panel. Reference marks placed every six laminations provide visual guidance for nail placement. Nailing begins from one side, with temporary screws used near the edges to maintain compression of the laminations. The worker completes the fastening in segments, repositioning the clamp and working location as the process progresses along the panel length. Interruptions may occur due to tool-related issues, worker coordination, or fatigue.

No measuring instruments are used during the nailing process, resulting in non-uniform nail spacing and limited repeatability, as illustrated in Figure 6. The fastening pattern shown in Figure 3 serves primarily as a visual reference, with nail placement governed by visual judgment and reference markings.



Figure 6. Observed variability in manual nail placement, illustrating non-uniform spacing along a timber stud (D1, D2, and D3)

The final stage is correction as shown in Figure 5(d). After the lumber has been nailed, the worker removes the temporary screws at the edge of the panel and inspects the fasteners along the lamination. Nails that are misaligned, protruding, or not fully driven are adjusted using a hammer. This inspection and correction step helps ensure that each lamination meets the fastening requirements before the next piece is installed. Once this stage is complete, the worker either retrieves new lumber from the storage area or continues with the remaining studs previously brought to the station. The sequence of feeding, alignment, nailing, and correction is then repeated until the panel is fully assembled.

2.2 Time Lapses During Assembly Stages

Time lapses during the four-stage assembly process, including material handling, alignment, fastening, and correction, were extracted from video recordings of the panel

construction. For each stage, individual task durations were recorded and organized to capture variations, repetitions, and disruptions inherent to the manual process. The sequence of the four main stages analyzed in this study is shown in Figure 5.

The three workers involved in the manual fabrication process have practical experience in timber construction, with varying levels of familiarity with NLT panel assembly. The workers were selected to capture the inherent variability of the manual fabrication process. Although individual execution times are reported, the purpose of this study is to characterize the behavior of the process under realistic operating conditions rather than to assess individual performance. This approach provides a representative baseline for comparison with the robotic alternative, highlighting differences in production time and consistency across the repetitive stages of NLT panel assembly. The corresponding average time lapses for these four stages, obtained from three different workers, are summarized in Table 1.

Table 1. Average time lapses of the main assembly stages per timber stud

Stage	W1 (s)	W2 (s)	W3 (s)
Material handling	19.00	18.86	32.57
Alignment	25.86	17.14	33.43
Fastening	139.67	117.71	150.00
Correction	26.50	26.00	36.57

The total time required to fabricate a complete NLT panel by each worker is reported in Table 2, while the cumulative time spent on the four main assembly stages during full panel fabrication is summarized in Table 3. In all cases, the panel was assembled following the same sequence of material handling, alignment, fastening, and correction operations. A representative example of a manually fabricated NLT panel after completion of the full assembly process is shown in Figure 7, illustrating the final outcome.

Table 2. Total panel assembly time per worker

Worker	Time (hh:mm:ss)
Worker 1	06:42:55
Worker 2	04:05:24
Worker 3	07:47:28

Table 3. Total time spent on the four main assembly stages during full panel fabrication per worker

Worker	Time (hh:mm:ss)	Total (s)
Worker 1	03:45:06	13506
Worker 2	03:11:42	11502
Worker 3	04:29:25	16165



Figure 7. Manually fabricated NLT panel after completion of the full assembly process.

Beyond the four main assembly stages of the workflow, several complementary activities were observed during fabrication that also contributed to the overall process duration and explain part of the variability observed across workers. These activities include time spent reloading the nail gun, clearing occasional equipment jams, marking the lumber to identify the correct fastening pattern, and brief consultations between workers while becoming familiar with the procedure. In addition, complementary time encompasses short rest periods, tool changes, reading technical drawings, and informal decision-making during execution. The cumulative duration of these complementary activities over the complete panel fabrication process is reported in Table 4. It should be noted that this time component is highly variable, as it depends on individual worker experience, workstation layout, tool placement, and personal working habits.

Table 4. Time spent on complementary activities per worker

Worker	Time (hh:mm:ss)	Total (s)
Worker 1	02:57:49	10669
Worker 2	00:53:42	3222
Worker 3	03:18:03	11883

3 Robotic Manufacturing Cell for NLT Panels

The robotic manufacturing cell was designed and simulated using RoboDK software. The system is centered on an industrial serial robot, the KUKA KR 250 R2700-2, equipped with a multi-functional end-effector capable of performing both pick-and-place operations and automated nailing tasks. Due to the current development stage of the robotic manufacturing cell, a simulation-based approach was adopted to evaluate the feasibility and expected performance of the system, particularly in terms of execution time. The robotic platform used in the simulation cor-

responds to the actual industrial robot and end-effector available in the laboratory, whose motion parameters were validated against real robot operation. In this context, simulation also supports the ongoing development of the automated assembly table by enabling the evaluation of system behavior and coordination strategies before full physical implementation.

An automated assembly table operates in coordination with the robot to support the NLT panel manufacturing process. The table receives, secures, and incrementally displaces the panel, enabling the robot to place timber studs and perform nailing operations at a fixed spatial location as the panel progressively grows. The table integrates two main subsystems: clamping and displacing. The clamping system, composed of three upper pneumatic pistons and four front post clamps, secures, compresses, and aligns the laminations from above and from the leading edge, respectively. The displacing system translates the entire panel backward after each stud is fastened, creating space for the placement of the next lamination. This subsystem consists of lateral jaws that grip the first two studs and pull the panel rearward as it increases in length. Additionally, moving conveyor bands and rolling rails are incorporated to facilitate smooth and controlled panel motion during displacement.

The overall layout of the robotic manufacturing cell, along with the main operational zones considered during the simulation, is shown in Figure 8. The key processes developed include timber stud picking, positioning, and automated nailing following predefined fastening patterns.

The simulation parameters were calibrated to match the operating conditions of the physical robot available in the laboratory. The same nominal velocity settings were used for both the real robot and the simulation environment. Cartesian linear motions were executed at a TCP velocity of 1 m/s, corresponding to 50% of the robot's maximum allowable speed. For joint-based motions, RoboDK allows the definition of a single global joint velocity. A representative value was therefore selected based on the maximum velocity of the fastest joint (Axis 6, 206 deg/s), applying a 50% scaling factor, resulting in a global joint velocity of approximately 103 deg/s. This configuration provided the closest agreement with the real robot behavior.

The simulation was validated through a representative pick-and-place operation performed with the physical KUKA KR 250 R2700-2 robot under the same spatial configuration as defined in the simulation. The same operation was then replicated in RoboDK using identical motion parameters. The measured execution time for the real robot was 9.54 s, while the simulated execution time was 9.56 s, resulting in a difference of less than 0.2 s (approximately 0.2% of the total execution time). This close

agreement confirms that the simulation provides a reliable approximation of the kinematic execution time of the real robot for the scope of this study.

3.1 Robotic NLT Manufacturing Simulation

The simulation video illustrating the assembly processes for each operation and the complete robotic panel fabrication is available at the following link.¹ The simulated operation of the robotic manufacturing cell follows a repetitive and structured sequence that reflects the intended industrial workflow. The complete process is divided into two main functional blocks: material handling and automated panel assembly.

At the beginning of the process, a batch of 36 timber studs is located on the right-hand side of the cell, serving as the initial material supply area. The robot sequentially picks each stud and places it onto the automated NLT assembly table. After placing the second stud, the clamping system is activated. Then, the robot initiates the automated nailing operation following the fastening pattern. Upon completion of the nailing sequence, the process transitions into a parallel execution phase. While the robot moves to retrieve the next timber stud, the clamping system releases the assembled laminations, and the displacing systems shifts the panel backward to prepare the workspace for the subsequent lamination.

This sequence is repeated iteratively, with the fastening pattern alternating, as described in Figure 3. After completing the placement and fastening of the 36 studs from the right-hand supply area, the robot continues the same procedure by retrieving the remaining 28 studs from the left-hand side of the cell, completing a total of 64 laminations for the full-scale NLT panel.

The coordinated parallel execution of robot motions and table mechanisms allows for efficient utilization of the cell components and minimizes idle time. The total simulated execution time for the complete fabrication process is reported in Table 5. In addition, the simulated execution times of the individual operations composing the overall process, namely pick-and-place, clamping, nailing, unclamping, and panel backward displacement, are summarized in Table 6.

Table 5. Total simulated execution time for full NLT panel fabrication

Process	Time (mm:ss)
Complete NLT panel fabrication	51:21

¹<https://youtu.be/7-MWA-wvv98>

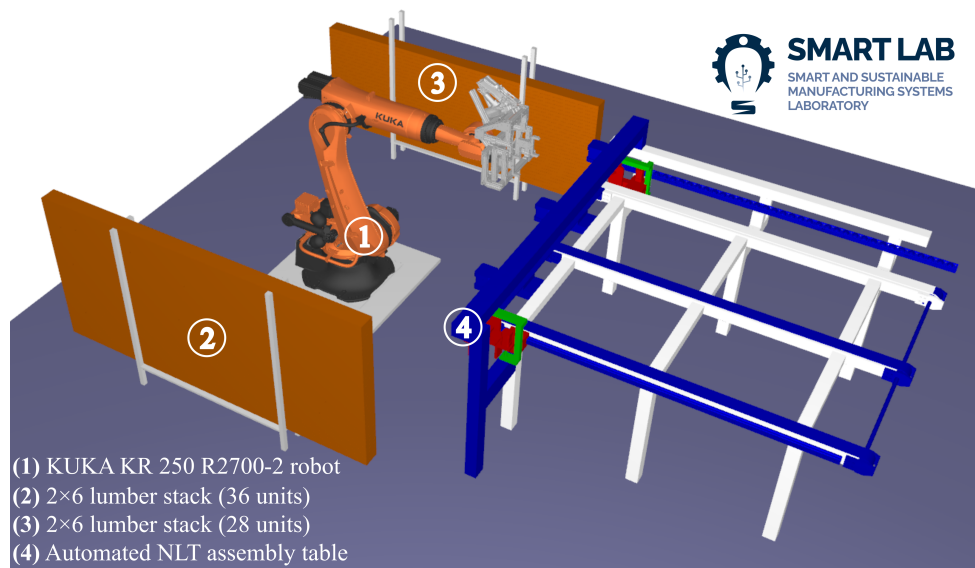


Figure 8. Simulation-based overview of the robotic manufacturing cell for NLT panel fabrication

Table 6. Simulated execution time of individual operations

Operation	Time (s)
Pick-and-place	10.09
Clamping	6.16
Nailing	32.96
Unclamping	6.16
Backward displacement	1.90

4 Time Study and Results Comparison

Figure 9 presents a comparison of the average time per timber stud for manual and robotic fabrication across the four main assembly stages: material handling, alignment, fastening, and correction. To enable a consistent comparison, the robotic workflow was mapped onto the manual stage definitions as follows: robotic pick-and-place operations were associated with material handling, the clamping operation was associated with alignment, and robotic nailing was associated with the fastening stage. The correction stage was assigned a zero-time value for the robotic cell, as no corrective actions were required during automated operation. Unclamping and backward panel displacement operations, reported separately in Table 6, are not shown as independent stages in Figure 9, since these actions are executed in parallel with the pick-and-place process.

Figure 10 illustrates how the total fabrication time is distributed between value-adding assembly stages and auxiliary activities for each worker, together with the total simulated execution time of the robotic manufacturing cell.

The key quantitative improvements achieved by the robotic manufacturing cell are summarized in Table 7.

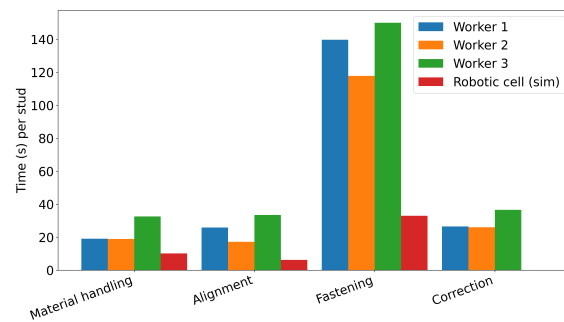


Figure 9. Average time per stage per timber stud for the manual process and the robotic manufacturing cell (simulation).

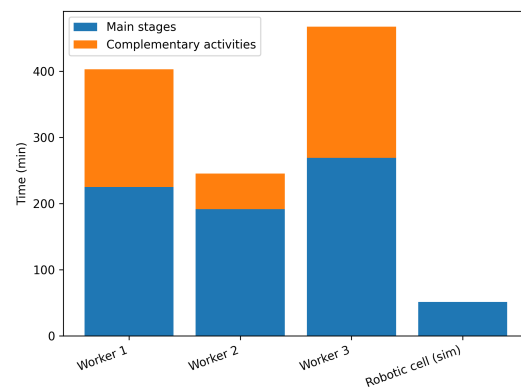


Figure 10. Time distribution of manual assembly stages versus total simulated robotic cell time.

The results show that the robotic system reduced the total panel fabrication time by approximately 86.2%, decreasing the process from 22,315.7 s to 3,081 s, corresponding to a productivity increase of approximately 7.2 times compared to manual assembly. At the stage level, reductions of 57.0%, 75.8%, and 75.7% were observed for material handling, alignment, and fastening, respectively, while the correction stage was eliminated (100% reduction).

Table 7. Summary of key quantitative improvements achieved by robotic NLT panel fabrication

Metric	Value
Total time reduction	86.2%
Productivity increase	7.2×
Material handling reduction	57.0%
Alignment reduction	75.8%
Fastening reduction	75.7%
Correction elimination	100%
Non-value-added time (manual)	38.5%
Process variability reduction	~90%

5 Discussion

The results highlight clear differences between manual and robotic fabrication of NLT panels, particularly in terms of process variability, repeatability, and overall manufacturing efficiency. Although manual assembly follows a defined sequence of operations, its execution time and quality are strongly influenced by worker-dependent factors such as individual practices, workstation layout, tool handling, and accumulated physical fatigue.

The robotic system achieved an 86.2% reduction in total fabrication time, significantly increasing production capacity and enabling faster and more consistent panel manufacturing compared to manual processes. These improvements are primarily driven by reductions across all main assembly stages and the complete elimination of corrective operations. In addition, coordinated and parallel execution of tasks, such as clamping and panel displacement, minimizes idle time and further enhances overall efficiency.

Manual fabrication also includes a substantial proportion of non-value-adding activities, accounting for approximately 38.5% of the total production time on average. These activities, including tool adjustments, repositioning, and corrections, introduce inefficiencies that are largely eliminated or integrated within the robotic workflow.

Furthermore, manual fabrication exhibits high variability, with total production times differing by up to approximately 90% between workers, whereas the robotic system operates with near-deterministic cycle times. This consistency is particularly advantageous for industrial applications, where predictable throughput and reliable scheduling are essential.

In addition to time-related improvements, the robotic process achieves greater consistency in fastening quality. Manual nailing relies primarily on visual references, leading to non-uniform nail spacing and limited repeatability. In contrast, the robotic cell executes predefined fastening patterns with high positional accuracy, ensuring uniform nail placement across all laminations. The simulation-based workflow incorporates simplifying assumptions, notably the absence of corrective actions and the use of pre-screened timber studs. While these assumptions idealize the automated process, they remain appropriate for evaluating the intrinsic performance differences between manual and robotic fabrication.

6 Conclusion

This study presents a time-based comparison between manual and robotic fabrication of NLT panels. The results show that the robotic manufacturing cell reduced the total fabrication time by approximately 86.2% and increased production throughput by a factor of 7.2 compared to manual assembly. In addition, corrective operations were eliminated, and substantial reductions were observed across all primary assembly stages.

The robotic system operates with a deterministic cycle, reducing variability associated with worker-dependent manual processes and enabling consistent production performance. The integration of parallel robot and table motions further enhances time efficiency, resulting in a predictable process suitable for industrial production.

Despite these advantages, this study focuses primarily on temporal performance. Other factors, including initial investment cost, system maintenance, long-term reliability, and structural performance of the finished panels, were not addressed and warrant further investigation. In particular, future work could examine how variations in manual nail placement affect the mechanical behavior of NLT panels compared to the highly uniform fastening patterns produced robotically.

Overall, the findings demonstrate that robotic manufacturing cells represent a promising pathway toward more efficient and scalable NLT panel fabrication, supporting the broader adoption of automation in off-site timber construction.

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