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INDUSTRIAL ROBOTS FOR GLT MACHINING: BASICS AND BEYOND

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ABSTRACT: With the growing share of timber construction driven by environmental benefits, coupled with a shortage of skilled labour in the industry, the development of more efficient production processes is essential. A promising approach is digitalising the process chain and implementing new production methods. Currently, specialised joinery machines process glued laminated timber beams This paper examines potential benefits over joinery machines, machining quality and possibilities to enhance production efficiency of standard multi-axis industrial robots for timber machining. An analysis of the current technology is followed by the identification of the industrial robots' capabilities including machining trials for comparison with state-of-the-art production. Furthermore, multi-part stacks are calculated by a specifically developed solving model. Subsequently, the stacks are machined employing a laser tracking workpiece location system. The analysis reveals that applicability for machining tasks depends significantly on the end effector specifications. Hence, the study focuses on milling operations using the industrial robot of the BOKU University, showing that machining quality in terms of surface quality and dimensional accuracy is competitive with joinery machines. The large workspace is utilised effectively, mostly without exceeding accuracy requirements, presenting opportunities such as stack machining. Ultimately, the developed workpiece-stack-optimisation model reduced the machining time by up to 16%.

KEYWORDS: CNC Machine, Automation, Digital Construction, Prefabrication in Wood Construction, Glued Laminated Timber

1 – INTRODUCTION

In recent years, timber construction has gained significant momentum as a sustainable building solution, driven by both economic growth and environmental policies. The global Compound Annual Growth Rate of timber construction is projected to rise by 6% between 2021 and 2031 [1], reflecting a shift toward renewable materials in construction. This trend is particularly evident in Austria, where the share of timber construction has steadily increased from 14% in 1988 to 24% in 2018. The proportion of multi-storey timber construction in residential construction increased from 1.6% to 3.0% between 2009 and 2019.[2] As the industry continues to grow, revenues rise, housing completions increase, and the backlog of flat construction projects shrink [3], [4], [5]. A similar pattern can be observed in Germany, where timber construction increased from 17% in 2018 to 21% in just four years. This upward trend across the German-speaking Central European region highlights a clear and broader shift toward wood-based building solutions [6]. While economic factors contribute to this development, political and environmental policies play a crucial role as well. On the European Union (EU) level, efforts to combat climate change have led to policies promoting long-lasting wood products as means to enhance carbon storage [7], [8]. To meet this growing demand, digitalisation and automation are demanded by the industry due to a shortage of skilled workers [9]. Looking back at Austria, surveys show that 82% of the surveyed companies report a deficiency of skilled workers, with 29% indicating a significant shortage [10]. Moreover, a high rate of workplace illness, coupled with the demand for reduced working hours and enhanced work-life balance, poses significant challenges for enterprises. This is further complicated by the limited number of school leavers in the labour market [11]. In response to these evolving market trends, 33% of surveyed companies have adopted automation to streamline their processes [10]. Furthermore, larger components and smaller batch sizes are increasingly demanded, necessitating high flexibility and automation in production. One mitigation is the development of more advanced tools and production techniques which result in a shift from on-site production to off-site prefabrication [12]. In this context, joinery machines (JM), automated machines with cutting, drilling and milling units are most established. However, high delivery times and costs make them uneconomical for small businesses [9]. This point is of particular importance as a predominant portion of enterprises within the timber construction sector in Austria and Germany are categorised as small and medium-sized enterprises (SMEs) [6], [12]. Moreover, the shortage of skilled workers and vacancies has had a significant impact on SMEs. Conclusively, these challenges present an opportunity to enhance the productivity of the sector through increased automation, with the utilisation of industrial robots (IR) suggested as a potential solution. However, unlocking the full potential of this technology requires addressing the following key question:

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- Are IRs capable of meeting industry standards and genuinely enhancing efficiency of the sector?

To answer to this primary research question, a series of subsidiary questions emerge:

- What are the capabilities and limitations of existing machine types such as JMs and IRs concerning tools, equipment, flexibility, workspace and machining power?
- Do IRs introduce new opportunities, particularly in enhancing automation efficiency and flexibility?
- What is the machining accuracy of IRs and how does it compare to that of JMs?
- What is the machining accuracy of IRs along their advantageously larger workspace?
- Is it possible to increase the machining efficiency by utilising the entire workspace of IRs?
- Can the efficiency be increased by machining stacks of multiple workpieces?

2 - METHODS

This paper aims to outline the fundamental application of IRs for machining glued laminated timber (GLT) while also exploring possibilities of efficiency increase. The study structure, illustrated in Figure 1, comprises three main parts: (1) a systematic literature review on the state of the art, discussing the advantages and disadvantages of JMs and IRs [13]; (2) experimental trials examining the machining parameters of IRs and their impact on the machining quality [14], [15], along with comparative experiments assessing the machining accuracy of JMs and IRs [9] and evaluating the utilisation of the IR's large workspace, including an accuracy assessment within the workspace [16], [17]; and (3) an investigation of efficiency through modelling and machining workpiece stacks [18].

2.1 LITERATURE REVIEW

In part (1), as a first step, various IR and JM machine types were defined and categorised based on key parameters, including machine size, workspace dimensions, maximum workpiece cross section, material flow, moving machine elements, equipped machining units and end effectors (EEs), and machining power, with specific examples provided to each category. Thereafter, a rating system was developed that allows for an objective analysis of the reviewed publications. The system is based on the following parameters:

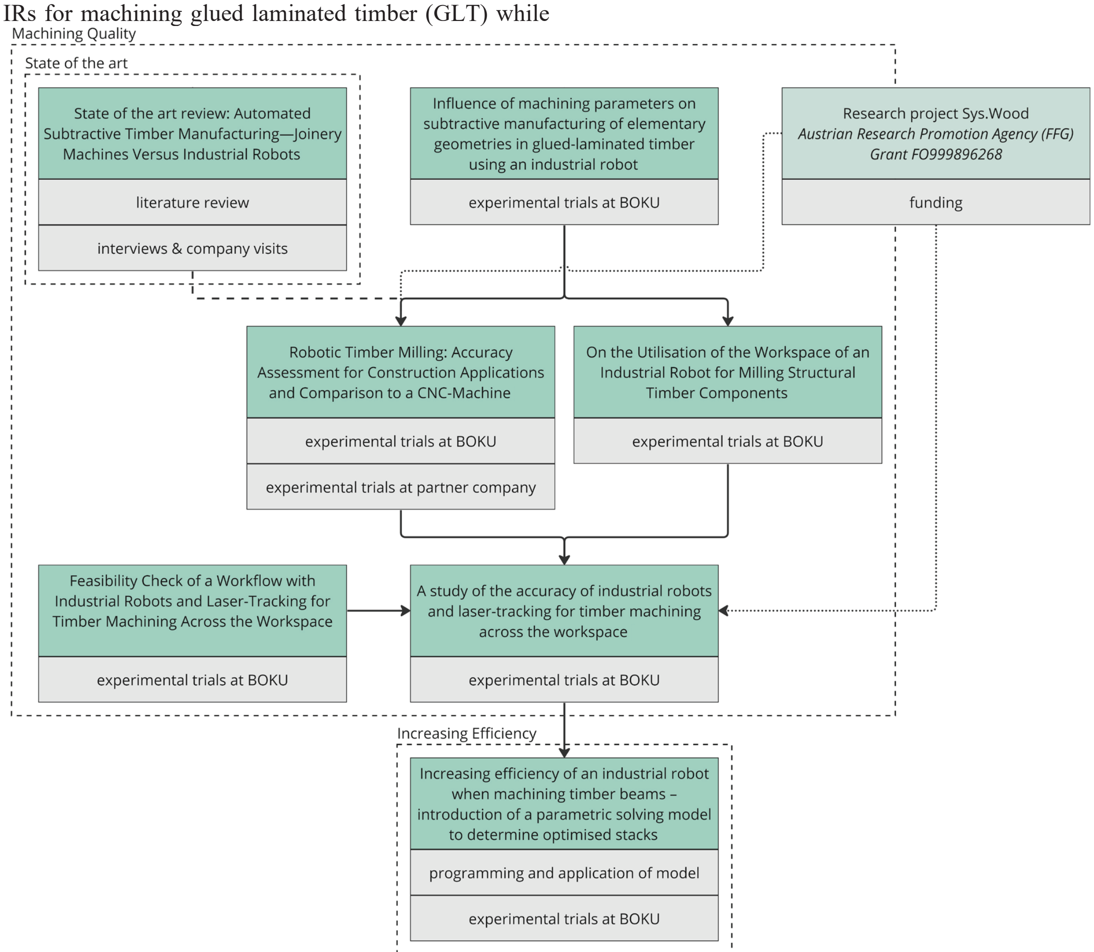

Figure 1: Study structure.

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- Quality parameters: dimensions; surface.
- System parameters: accuracy and kinematics; stiffness, payloads and vibrations; workpiece placement and robot position; programming and computer aided design/computer aided manufacturing (CAD/CAM).
- Machining Parameters: tool types and machining units; feed rate and spindle speed; material removal rate (MRR), radial depth of cut (RDOC) and axial depth of cut (ADOC).
- Economic Parameters: market share; acquisition costs; efficiency, production time and batch processing.

All parameters were weighed equally when calculating an assessment score for each machining system. To gather data, the following search engines and databases were used: IEEE Xplore, Google Scholar, Science Direct, Open Knowledge Maps, and Research Gate. A broad array of keywords, encompassing both German and English renditions of the following formulations, was investigated: accuracy, automation, carpentry, construction, digitalisation, economic, engineering, industrial robot, joinery, joinery machine, machining, manufacturing, milling, process, production, quality, robot, wood, subtractive, systems, and timber. The search yielded 300 + publications which were non-exclusively refined and the most relevant were selected for the study. Additionally, market scans and interviews with companies from timber engineering and processing to machine and tool manufacturers were conducted. [13]

2.2 EXPERIMENTAL TRIALS ON MACHINING QUALITY

The experimental trials (2, 3) were conducted, at the BOKU University Robot Laboratory. The machining was performed by an ABB robot of the type IRB 7600-325/3.1 mounted on an ABB IRBT 6004 external linear axis with the length of 8.7 m to increase the workspace [19], [20]. The IR is combined with a HSD ES 951 A 1112 S machining spindle as EE that offers 13.2 kW maximum power at spindle speeds between 12,000 1/min an 15,000 1/min and maximum torque of 10.5 Nm at 12,000 1/min [21]. The specimens were GLT with specification of GL24h made from Norway Spruce (Picea abies L. Karst.) according to EN 14080 [22].

The literature review revealed a research gap in the field of machining parameters for IRs and GLT. Hence, the machining quality was assessed in order to identify optimal settings and gain understanding on the interaction between IRs and the mechanics of machining. [14]

The first experimental trials examined the impact of machining parameters axial depth of cut (ADOC), radial depth of cut (RDOC), as well as acceleration and jerk on the machining quality. A test series of 43 elementary geometries including lines, rings and pockets was machined using three distinct tool types and sizes (diameter 125 mm and 40 mm insert cutters and diameter 14 mm end mill by Leitz). As already stated by Fujiwara et al. [23] and Gurau and Irle [24], there is no applicable objective evaluation system for surface quality in woodworking. Hence, a new evaluation system, the quality deviation value (QDV), was developed, incorporating the following criteria: tactile measurements of surface roughness using the stylus method, optical and haptic inspection of the surface roughness, optical and haptic inspections in a scale of magnitude beyond surface roughness inspecting imperfections caused by fluttering tools and the identification of wood surface defects such as protruding fibres and fuzzy grain. For the assessment, a MarSurf PS 10 device (PHT 350, 2 µm probe) was utilised [14]. All assessments were performed by at least two scientists to ensure objectivity with a higher QDV score corresponding to a lower quality. [25] In addition to the QDV, a high-resolution three-dimensional (3D) scan was conducted in corporation with the Research Unit of Engineering Geodesy at TU Wien to visualise the results.

Following the analysis of the cutting parameters and the determination of optimal settings, the machining accuracy was assessed. This was achieved by high-resolution 3D scans of the samples, enabling a CAD-based nominal-actual comparison with a Leica AT960 laser tracker and Leica AS1 laser scanner [9], [16]. For the assessment, the following simplified steps were performed: (1) Manual scan of a specimen generating a point cloud; (2) Automated best-fit alignment with the reference CAD-model; (3) Automated dimensioning and protocol generation. [25]

The defined requirements for machining accuracy were set to ±1 mm by the project partner Rubner Holzbau GmbH, in accordance with ISO 18202 [26] as no specific normative regulations exist for manufacturing tolerances of timber-timber joints. Additional accuracy benchmarks were set by the most widely used JMs including Hundegger [27], [28], [29], Weinmann HOMAG [30], TechnoWood [31] and Krüsi [32] who, in a lack of independent scientifically resilient data, claim high accuracy machining results. In regard to IR accuracy the industry differentiates in path and position repeatability, which for the used IR are specified by the manufacturer with 0.10 mm and 0.59 mm [19], respectively. Due to the lack of scientific data the present study assessed the machining accuracy based on 45 specimens with four geometries as presented in Figure 2.

Eight specimens per geometry were machined by the BOKU IR with the cutting parameters previously identified as optimal [25], while a total of thirteen specimens were machined with the JM Hundegger k2i (production year 2011, firmware version 9.16.19.38788-F19) of the partner company. To include the machining parameters of the JM in the evaluation, two of the geometries were processed at three different trajectory speeds. For the machining with the IR two cutting tools, a diameter 125 mm and diameter 30 mm insert cutter by Leitz, where used. The JM required two machining units, the 5-axis universal mill and the blade saw, wielding the following tools: (1) a diameter 350 mm insert cutter by Hundegger, (2) a diameter 30 mm end mill by Leitz, (3)

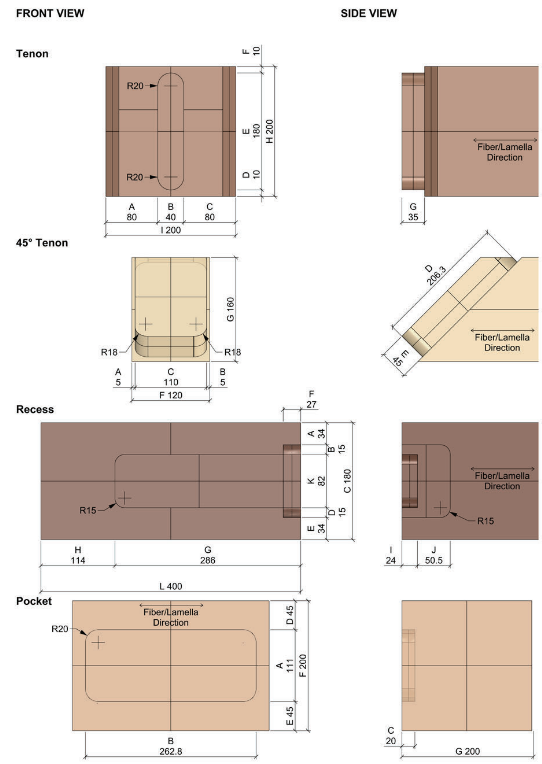

Figure 2: *Selected workpiece geometries as subject to the experimental trials. Measured lengths A-L.*

a diameter 40 mm end mill by Hundegger and (4) a diameter 800 mm saw blade. The final step of the accuracy assessment, which already points towards an increased efficiency, involved examining machining accuracy within the expansive workspace of IRs. The aim of this part of the study was to identify the machining accuracy for workpiece positions aligned to a grid within a vertical plane intersecting the spherical workspace of the IR as shown in Figure 3. The test setup consisted of a heavy-duty rack, used to mount the workpieces at any desired position inside the grid, with dimensions of 1,100 mm x 4,810 mm x 3,800 mm (length x width x height) and a field load of 6,600 kg. Lateral stabilisation was achieved through angular supports anchored to the ground and supplementary reinforcements attached to the wall.

After assembly, the structure was aligned to gravity using the Leica AS600 laser-tracking system [33]. The IR was able to reach 50 of the predefined 81 fields and machined three specimens per location, resulting in a sample size of 150. The process goal was to use the same machining code for every grid field by only adjusting the work coordinate system in RAPID to the actual workpiece position based on the semi-automated digital measuring method. To enable this, a suitable method was developed in preliminary studies comparing two different solutions, a laser profile scanner of the type Keyence LJ-X8900 [34] mounted to the IR and a Leica AS600 stationary laser tracker [33] with 1.5" red ring target [16], [17], [35].

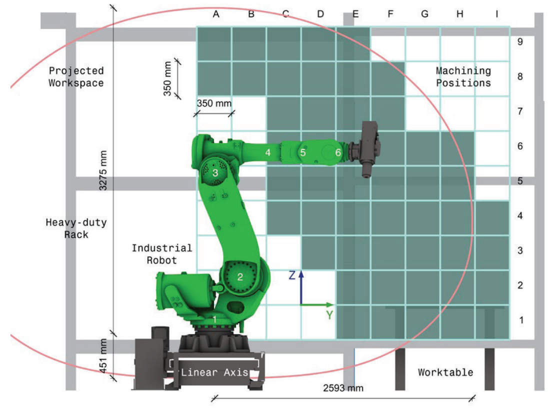

Figure 3: *Test setup for accuracy examinations along the workspace.*

The laser profile scanner provided sufficient results for two-dimensional (2D) displacements and rotations of the workpiece when the workpiece was placed on a flat machining surface and scanned from above. However, for the 3D application in the vertical plane required for the current trials, the laser tracker was better suited.

Within the accuracy assessment the workpiece was first placed roughly in the centre of the designated grid field before the accurate workpiece position was measured with the Leica AS600, feeding the positional data to the IR. Following this, the work object coordinate system ${}^{Workobject}T_{Workpiece}$ was transformed as shown in Figure 4. To prevent singularities the robot wrist configuration was manually adjusted if necessary (required for a total of eight configurations as indicated in Figure 5). With the positioning fixed the specimens were machined and laser scanned. The entire processes ended with post-processing and data gathering. [16], [17]

For the machining, the previously introduced diameter 125 mm insert cutter was used, and the machining parameters identified as optimal were applied.

The quality assessment was conducted with a Leica AT960 [36] in combination with Leica AS1 laser scanner [37] to capture point clouds with up to 1.2 Mio points per second with a minimum density of 0.037 mm along the profile while recording profiles with 300 Hz, resulting in an accuracy of 0.016 mm. [16], [17]

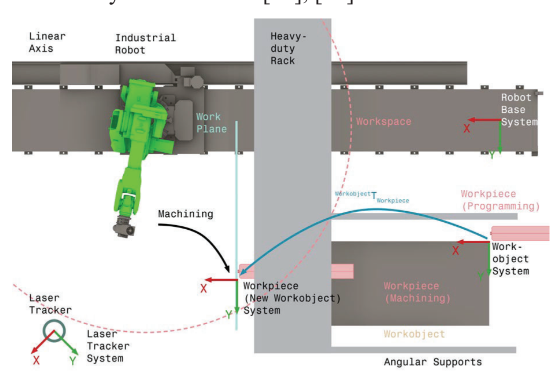

Figure 4: *Top view on the trial setup highlighting the coordinate transformation and test setup for accuracy examinations along the workspace.*

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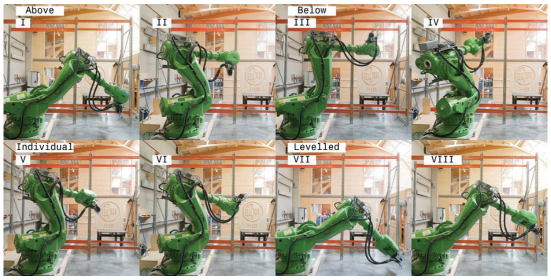

Figure 5: Wrist configurations required to reach the defined positions.

2.3 EFFICIENCY INCREASE

Based on the literature review and analysis of factory processes at Rubner Holzbau GmbH, it was observed that stacks of workpieces were frequently found in buffer zones, idling while awaiting machining. The IR's larger workspace compared to the JM, particularly in the vertical dimension, was identified as the key advantage, indicating its potential to enhance efficiency. The increase of efficiency was pursued by creating a model to generate optimised workpiece stacks as compact as possible yet machinable by adjusting the number, spatial arrangement and spacing of the workpieces. The model's outcome was validated by machining trials including time measurements that allow the comparison of three scenarios: (1) IR stack machining, (2) IR individual workpiece machining of an equivalent number of specimens and (3) JM individual workpiece machining.

The optimisation model was created in Rhinoceros 3D's parameterised graphical programming plug-in Grasshopper and employs either one of the two tested evolutionary solver algorithms Galapagos or Opossum. In a first step, boundary condition parameters including the maximum stack size, the workpiece dimensions, tool type and size, machining clearance, distance between individual workpieces as well as stack position in relation to the IR, are set. In a second step, the solver algorithm varies the parameters of the workpieces including number, position to each other and position in the stack within user-specified margins leading to an optimised stack solution until one or more termination criteria are fulfilled. The termination criteria are set to a maximum time limit of 120 minutes and a maximum of 40 calculated generations. The operating principle of the optimisation model is based on intersecting volumes of necessary machining clearance and workpieces as shown in Figure 6. For each workpiece in the stack a set of three intersection volumes is calculated: intersection volume of the workpiece with the exterior volume boundary (exceeding the IR workspace), intersection volume of the workpiece with every other workpiece in the stack (stacking not possible) and intersection volume of the machining clearance with all other workpieces in the stack (robot collision with other workpiece). The total intersection value for each stack configuration is calculated. The presence of an intersection increases the value and consequently compromises the ranking of the stack. A stack is deemed physically feasible and machinable when the total number of intersections equals zero. One of the resulting optimised stacks was then chosen for the three previously mentioned machining scenarios with the process times measured for all three. The process times were subdivided in machining time, traversing time and chip ejection, idle time, first and last lead-in/out or conveying time and IR tool change. For a final assessment, the machining times of the IR and JM were compared. [18]

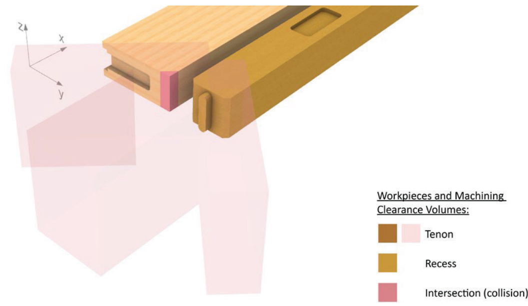

Figure 6: Operating principle of the optimisation model based on penalties for intersecting volumes. An intersection volume of the machining clearance and recess workpiece is shown.

3 – RESULTS

3.1 LITERATURE REVIEW

At the meta level, the literature review (1) found that existing literature contains no data on the use of IRs and JMs for machining timber construction elements. Additionally, the level of automation, particularly applying robotics, in the timber construction industry is currently limited but steadily increasing. Therefore, further research is needed to explore the characteristics of both machine systems to advance in this field. Based on the introduced ranking system, the literature review resulted in the highest favourable score for IRs followed by the JM although they equalled in the quality parameters category. This can be attributed to the enhanced dimensional quality attained by the JMs and the superior surface quality achieved by the IRs. A more detailed analysis reveals benefits of IRs including lower acquisition costs, greater availability, higher flexibility and universal application. This has the potential to grant SMEs access to more affordable automation. Furthermore, a larger workspace was identified as key benefit ultimately allowing to facilitate 3D stack processing. However, deficits were noted in CAD/CAM processes and work preparations that are very labour intense. The study concluded that a data-driven assessment of IR's potential is necessary. It can be anticipated that JMs would predominate in larger companies characterised by a high volume of standard operations. However, it is predicted that IRs will complement JMs in larger companies and will be introduced solely to SMEs. [13]

3.2 EXPERIMENTAL TRIALS ON MACHINING QUALITY

The investigation of machining parameters found that the tool manufacturer's recommendations can be applied directly to the IR, which can then achieve a workpiece surface quality comparable to that of JM-produced specimens [25]. Based on the newly introduced QDV, it was further revealed that all examined machining parameters significantly affect the quality. The ADOC and RDOC were found to be of particular importance in this context. Typically, higher values, resulted in a reduction in quality. Increases in ADOC have been shown to generate heightened deflection forces, enacting the tool more prone to flutter. This phenomenon often leads to a deterioration in the quality of the side face, an effect that was reduced when larger diameter tools were used. Increased RDOC resulted in reduced bottom surface quality. ADOC had a higher impact on the quality of the result than RDOC. It was found that both, ADOC and RDOC were constrained by the dimensions of the tool and the power of the EE. Furthermore, it was determined that the stiffness of the robot was the primary factor influencing machining quality, as evidenced by the increasing values of ADOC and RDOC. [14] It was demonstrated that the kinematic configurations of the robot acceleration and jerk exerted a more pronounced impact when smaller-diameter tools were employed. Additionally, it was observed that surface areas where the trajectory of the tool changes direction (vertical planes perpendicular to the tool path trajectory) exhibited comparatively reduced surface quality when smaller-diameter tools were employed. Furthermore, 3D scans proved to be a valuable tool for tracing machining irregularities as shown in Figure 7 [15]. Ultimately, applicable machining parameters were identified, paving the way for further research. [14]

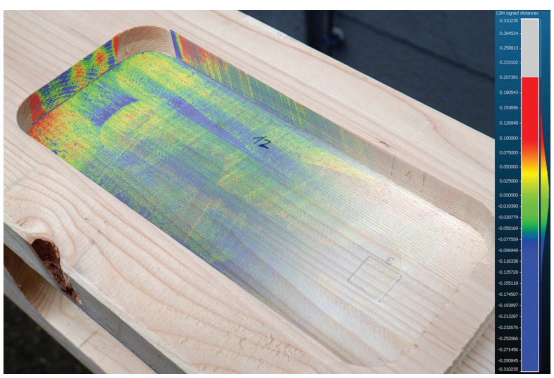

Figure 7: Surface quality inspection visualised by an high-resolution 3D scan [15].

Incorporating the previous findings and identification of suitable machining parameters, the mean machining accuracies of the IR and JM were determined and compared based on high-resolution 3D scans of the samples. Based on the assessment of 45 specimens comprising four distinct geometries, it was found that the cumulative median absolute machining accuracy of the IR was 0.13 mm, only 0.01 mm higher than that of the JM, as shown in Figure 8. Note: the sample size of the IR was 32, while the sample size of the JM comparably smaller, with 13 specimens. The resulting IR accuracy closely aligned with the position repeatability specifications reported by the robot's manufacturer (0.10 mm) and even exceeded the repeatability of 0.59 mm [19]. Even though, the accuracy of the IR was below that of the JM, the former showed greater consistency of the results, therefore making it the more consistent machine. [9]

When evaluating the various feed rates of the JM, it was found that the slowest speed was not necessarily the most accurate, contrary to expectations. The tenon geometry was machined most accurately at the medium speed setting, which is preferred by the machine operator for its optimal balance of speed, accuracy and tool wear. However, it is important to highlight that the adjustments of the machining parameters were research-based for the IR and experience-based for the JM. The results indicate the presence of patterns within the data, suggesting the effect of external factors with significant influence on the machining accuracy of the IR. The most predominant factors are the alignment of the workpiece to the worktable and robot reference coordinate system as well as the deviation of the raw workpiece cross-sectional dimensions, as permitted by the standard EN 14080 [22].

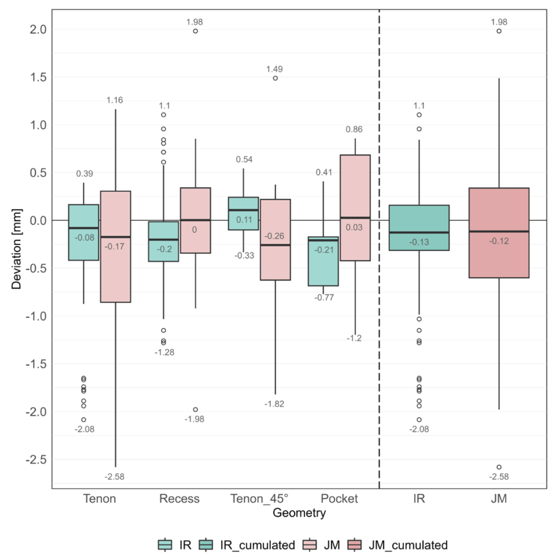

Figure 8: Machining accuracy of the ABB IRB-7600 at BOKU Robot Laboratory and Hundegger k2i at Rubner Holzbau GmbH [9].

When external factors were excluded, the accuracy of the IR was inspected independently and revealed smaller deviations compared to the accuracy including external factors and the accuracy of the JM. In summary, this research addresses a gap by identifying external factors as sources of inaccuracies and provides future readers insights into the machining accuracies of IRs in timber construction. [9]

Within the assessment of the larger workspace, which is seen as one of the key benefits of IRs, a mean nominal-actual deviation of $y_{M;abs}$ = 0.383 mm and $z_{M,abs}$ = −0.392 mm (due to face milling of the front end in x-direction, there is no data for the absolute x-accuracy) was assessed. Achieving this accuracy, the industrial tolerance requirement of ≤ 1 mm was achieved. When only robot effects are included, by calculating the accuracy based only on machined surfaces, the relative accuracy is yielded as $x_{M,rel}$ = 0.072 mm, $y_{M,re}$ = 0.084 mm and $z_{M,rel}$ = 0.100 mm. To visualise the results, accuracy maps, as displayed in Figure 9, were

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created. Additionally, the centre of accuracy (COA), a calculated point with the highest accuracy, was determined at y = 1.701 m and z = 1.565 m which is close to the centre of the two-dimensional workspace. This suggests that the ideal mid-range working area of previous studies can be confirmed [38], [39]. Based on these results, the robot manufacturer's repeatability specifications were applicable to the expected milling results. The knowledge gained from this study can be implemented to the machining of large, complex parts, multi-workpiece stacks and even mobile robot platforms - an approach that would clearly enhance the possibilities and efficiency within timber construction. [16]

	A	B	C	D	E	F	G	H	I
9	0.111	0.095	0.199	0.130	0.123				
8	0.156	0.079	0.039	0.045	0.046	0.248			
7			0.048	0.062	0.166	0.253			
6			-0.007	0.115	0.086	0.147	0.219	0.252	
5			0.045	0.058	0.042	CoA 0.011	0.208	0.212	
4			0.099	0.059	0.058	0.086	0.145	0.143	0.113
3				0.107	0.053	0.052	0.102	0.191	0.115
2					0.116	0.143	0.166	0.178	0.114
1					0.196	0.152	0.136	0.160	0.101

Figure 9: Accuracy map of the relative accuracy calculated based only on machined surfaces indicating robot-only effects. The point with highest accuracy - centre of accuracy (CoA) located at y = 1.701 m and z = 1.565 m is displayed in the bottom right diagram. [16]

3.3 EFFICIENCY INCREASE

The developed model is a valuable tool to generate physically possible, machinable volume-optimised stack configurations. Despite its efficacy, the model is not without its limitations. Primarily, the workpiece spacings are not calculable as individual values, but rather as a group of workpieces sharing the same geometry. This does not allow the adjustment of the position of a single workpiece and therefore restricts the model's performance. It is important to note that certain parameters, such as vertical displacement, exert a greater influence on the physical applicability of the resulting stacks.

Of the tested solvers, Galapagos and Opossum CMAES1 generated compact and machinable stack configurations of identical quality in contrast to the Opossum RBFOpt algorithm. The Opossum CMAES1 algorithm was found to be the most efficient calculation method, with a calculation time that was approximately one-sixth of that of the Galapagos solver. For this research, the RAPID code was generated semi-automated. However, with the automated stack generation model at hand, the fully automated generation of the RAPID code for IR machining should be explored in future research to further advance automation.

In pursue of this approach additional points, such as collision prevention and optimised transition movements must be considered. Machining trials including process time measurements with one of the calculated stacks lead to the following result: The process time can be reduced by 16% when machining the same number of workpieces with the stack approach when compared to individual machining (IR). The assessment also showed that stack machining with the IR did not outperform the benchmark process time set by the JM. It is worth noting, that this observation does not include material handling times, which are likely to be higher for JM's individual part machining. A multi-stack rotary principle allowing one stack to be machined while other stacks are assembled and disassembled should also be considered within the next assessments. It is also important to highlight that, when stack machining by IR, the relative proportion of machining time within the entire process was significantly higher. Summing up, the developed model is an important tool to exploit the advantageously large workspace of IRs and the machining trials clearly showed the benefit of reducing production time and increasing machining efficiency.

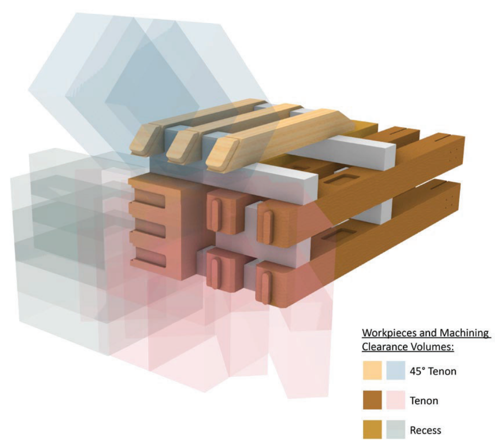

Figure 10: Workpiece stack as optimised by the parameterised model consisting of ten workpieces including their machining clearance volumes.

5 – CONCLUSIONS AND FUTURE RECOMMENDATIONS

This paper offers a foundational overview for the implementation of IRs for machining GLT, from an overview of the state of the art to machining parameters, milling accuracies, and efficiency increase aiming to expand their application in timber construction and underscore future potentials. IRs represent a promising alternative to JMs and mark the next stage in the technological evolution of subtractive machining and automation in the timber construction industry. In alignment to the structure of this manuscript, the research questions stated at the beginning were addressed:

- The IR is capable of meeting the required standards in terms of surface quality and dimensional accuracy.

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- Based on the lower acquisition costs, higher flexibility and high production efficiency when machining stacks IRs truly positively affect the efficiency of the sector, inheriting particular potential for SMEs.

To complement the primary research question even more particular conclusions can be drawn:

- Overall, the level of automation employing IRs in the timber construction sector is relatively low.
- Based on the literature review, IRs and JMs performed equally in the quality category. However, IRs present great potential due to their flexibility and large workspace.
- The primary benefit of IRs is their larger workspace and greater flexibility, which both enhance efficiency through the possibility of 3D stack machining.
- The tools and machining parameters established for JMs proved to be applicable to robotic utilisation, thereby ensuring the fulfilment of industry-standard machining quality. It was possible to identify suitable machining parameters at mid-range settings for subsequent test programs.
- The median machining accuracy of IRs was found to be 0.13 mm, which was only 0.01 mm below that of the JMs. It was demonstrated that both machines achieved accuracy levels that fell within the tolerance being less than 1 mm set by the industry. The IR exhibited greater consistency of results in comparison with the JM.
- The median machining accuracy of IRs, measured at 0.13 mm, is close to the robot specifications for positional repeatability of 0.10 mm and below the path repeatability of 0.59 mm. This finding suggests that manufacturer datasheets can be used when facilitating a decision over IRs regarding machining quality.
- The mean absolute accuracy of positions inside the analysed grid fields within the workspace was below the specified industry tolerances of 1 mm.
- Accuracy maps were generated, thus indicating the accuracy in the workspace. These maps are valuable tools for the placement of workpieces in machining operations when the highest possible accuracy is required. The position of the centre of accuracy (CoA) was determined to be in close proximity to the midpoint of the inspected vertical plane.
- A model to generate optimised workpiece stacks was developed and found suitable.
- Machining trials revealed that the machining time was reduced by 16% when machining optimised stacks with an IR compared to individual workpiece machining, thereby increasing the efficiency of the process. When compared to the benchmark machining time measured at the JM while machining the same number and geometry of workpieces, machining by IR required more time. It is worth noting, however, that this does not include material handling times, which are likely to be higher for JM's single part machining.
- A thorough investigation into the processing time revealed that stack processing exhibited the highest proportion of processing time and the lowest proportion of idle time.

Based on these findings the following topics remain unaddressed and are recommended for future research: To draw more generalised conclusions from this work, it would be beneficial to extend the tests to other IR systems as well as other commonly used construction timber species and engineered wood products. At the software level, there is a considerable need for robot CAD/CAM solutions tailored specifically for timber machining. Strategies need to be developed to counteract external accuracy factors in order to increase accuracy. The development of a universally applicable software solution is advised, one which adheres to the principles of stack machining, with an emphasis on its industrial applicability. From an economic standpoint, the potential of automation through the implementation of IRs for subtractive machining necessitates closer examination.

It is asserted by the authors that this work has established a substantial foundation for the utilisation of IR in the subtractive processing of timber construction elements and there is optimism that this will lead to advancements in robotic machining processes.

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