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Commercialisation Potential for Scanners in Wood Processing. Cross-Cutting Optimizing Scanner for Aspen and Black Alder

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***Abstract*—Increased competition in the international wood export markets, is vitally important for European wood processing companies. To ensure further competitive advantages digitalisation of wood processes is one of the contemporary strategies to ensure higher efficiency (reducing losses of useful material and improving quality), but also increasing productivity in order to reduce manual labour costs and eliminate "bottlenecks" in the overall production process. Findings reveal significant adoption of Industry 4.0 technologies enhancing processing speed and quality through AI-driven defect detection and robotic automation, achieving cycle time reductions exceeding 45% and defect remediation time cuts up to 60%. Material innovations and additive manufacturing improve mechanical properties and support sustainability, though scalability challenges persist. Circular economy principles are increasingly integrated via digitalisation of wood processing and waste valorisation, yet practical implementation faces economic and technology barriers. The aim of the paper is the commercialisation of cross-cutting optimizing scanner for aspen and black alder allowing to optimize order real-life parameters improving material combination and reducing waste. In addition, it is necessary for the company, using the statistical value of the material, to be able to determine what the possible costs of any order are. The findings are underlining the promotion of the digital transformation and increased competitiveness: enhanced useful yield of high-value material/reduction in material losses, reduction in manual labour associated with physical effort (the physical work of operators has been facilitated, and the sawing speed has been increased by 20%). The expected digital transformation impact has significant commercialisation potential, the development of such a new technology is contributing to the competitiveness and technological base of the forestry sector in European Union.**

Keywords*— *aspen, black alder, cross-cutting, forestry sector, machine learning, order optimization, scanner, quality control, wood processing, 3D computer vision.

I. INTRODUCTION

Research on the newest cutting technologies to enhance processing efficiency by improving quality of output and increasing speed for wood raw materials in Europe has emerged as a critical area due to the growing demand for sustainable and efficient wood manufacturing processes. The European Parliament recently announced the use of cascaded wood to promote the circular economy and mitigate climate change [1], [2] .

The wood industry, a key economic sector in many European countries, has evolved from traditional manual operations to increasingly digital and automated systems, integrating Industry 4.0 (recently 5.0) technologies [3]. Industry 5.0 most popular technologies in wood processing could be traced to its footprints – virtual factory concept first introduced in 1993 by Onosato and Iwata [4] and later known as a Digital Twin concept when production line is integrated with the real production processes using a simulation model.

Main operations of the manufacturing industry are cutting operations that produce changes in shape, dimensions, and surfaces. In order to control wood quality it is common to use artificial vision techniques like industrial scanners to determines internal and external defects [5], [6]. In the wood processing industry scanners are making parts classification, yet data is non stocked for analysis or to create prediction models [3].

As for more contemporary attempts to integrate Machine Learning (ML) and technics like Convolutional

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Neural Network (CNN) to train in wood defects recognition.

Professional scanning systems are often used in industrial or scientific applications where the highest accuracy and reliability are emphasized [7]. In addition to price, an important factor of scanning technologies is the difficulty to operate them. Some require specialized knowledge and experience to use them: training to use the software, setting parametric values, or properly positioning and calibrating the equipment [8].

Current practices in wood industry often rely on manual expertise and conventional scheduling, limiting scalability and efficiency [9]. In contrast to the conventional job-shop scheduling problem, flexible job-shop scheduling involves the use of processing equipment that is not predetermined but rather unknown for each operation [10].

Moreover, the integration of digital technologies such as AI, machine learning, and robotics remains uneven in the engineered timber sector and has notably lagged behind in adopting such practices as real-time quality control, defect detection, and adaptive manufacturing workflows [11], [12]. As a result, the wood industry is one of the least advanced industries in R&D and innovation compared to the computer and electronics industry, the automotive industry, or the aerospace industry [13].

Failure to address these gaps risks continued inefficiencies, increased waste, and reduced competitiveness in the European wood sector. The conceptual framework for this project is established in the intersection of Industry 4.0 technologies, digital fabrication, and sustainable wood processing. Key concepts include digital transformation through AI for quality optimisation for proper management and commercialisation. Commercialisation potential for scanners in wood processing is projected and implemented, particularly the cross-cutting optimizing scanner for aspen and black alder as a high-quality wood niche.

The purpose of this research is to synthesize recent research on emerging cross-cutting technologies that enhance processing efficiency in European wood material industries by improving output quality and increasing speed. This research aims to investigate the innovation gap, the findings are organized thematically to reflect advancements in digital transformation, AI-driven quality control, and circular economy integration within wood processing industries

II. Research Design and Specification of Environment.

The main aim is to examine the existing research on newest cross-cutting technologies to enhance processing efficiency by improving quality of output and increasing speed for wood raw materials in Europe in order to provide an applied finding and their practical implications within the European wood processing sector.

For wood manufacturing processes, influencing factors are the material, the operation, and the transformation technology. In cutting processes, factors are combined, the cutting tool being important. These impact on assets, rotating mechanisms, landings, materials, motors, auxiliary systems, and other devices. Heat, vibration and mechanical power impact machine availability. [14].

For our process, initial "as is" situation is presented:

- Operators manually take each board from the lumber package, based on the instructions, assess its defects, mark the wood defect areas with a luminescent crayon and place the marked boards on the conveyor belt (conveyor) in front of the cross-sawing machine.
- An automated cross-sawing machine, according to the lumber specifications, values set in it and the defects marked by the operators, performs the lengthening of the board into lumber of exact or "floating" length.
- The shortened boards, after being shortened in the cross-sawing machine, slide along the conveyor belt and are mechanically pushed into the "pockets" of the boards of the appropriate length.
- The operators manually stack the boards that have fallen into the "pockets" into the board packages. The sawn-off wood defects (wood waste during production) are automatically forwarded to separate conveyors and directed to the wood chipping machine –for circularity raw materials.

Initial system was allowing to select the most economically justified cross-cutting solution for each board, according to the defects marked by the operator. However, despite this, board lengthening process still requires both significant manual labor (low productivity) and errors, which result in inefficient work and losses of high-quality material (For example, when marking defects with a hand chalk, there is a large lengthening tolerance, because defects cannot be marked very accurately). In addition, this process still requires physically demanding work by at least two marking operators per shift. Another challenge for high quality wood is shortage of proposals. There are digital solutions (lumber scanner technologies) developed by various manufacturers on the market, however, taking into account the size of the market, they are mainly created for coniferous wood processing companies or other wood processing areas.

In the processing of aspen and black alder into a high-value-added product, the scanners solutions available on the market are unable to ensure full compliance with the specific needs of the company and the industry. Because, basic wood defects recognition such as, for example, branches, cracks (which are basically necessary for mass production of coniferous wood production companies), it is also very important for high-quality wood to be able to digitally correctly and accurately assess defects such as wood coloration in the production of specific products (e.g. oak [15]). The scanner technologies available on the market need to optimally assess special species of wood such as aspen and black alder wood coloration defects, therefore it is justified to conduct research into the development of a special and rare recognition system.

In addition, one of the reasons why it is justified to conduct contemporary research into the development of a new digital system is that modern computing capabilities have changed significantly. In connection with the emergence of new, high-power graphics processors and Machine Learning capabilities, there are new opportunities in the longitudinal optimisation of the material, i.e. there are new quality computing opportunities in making a decision on how to process order optimisation.

The value of the cut material is determined by the market and the order. Currently, this problem is basically solved by excluding from the possible scanner results the material that is sufficient for the execution of a specific order. As a result, the real optimisation of the order and materials does not actually work, because the optimisation no longer receives real-life parameters. By excluding products that are produced in large quantities, the optimisation has a limited number of possible material combinations, which means that it no longer uses all the possibilities. In addition to abovementioned factors, it is necessary for the wood processing company to use the statistical analysis of the material, to be able to determine what the possible costs of any order are, expressed in terms of the amount of raw material.

If the scanner system is able to be integrated to computational system with accumulated statistical parameters of scanned material quality and raw material units, it can, based on the volume of ordered products and their quality indicators, model the potential amount of raw materials required to fulfil such an order. Data engineering methodologies are important to validate complex problems having many variables and non-lineal relations [16]. Such AI modelling systems that allow estimating the costs of order fulfilment are very crucial for competitive advantages and sustainability.

Below is a description of production tasks with justification of the discussed needs for testing the created prototype in a production environment:

1. Board scanner - the main component for providing/implementing a digital solution in the cross-sawing process. With the help of this equipment, as the board moves through the scanner, all faces of the lumber are digitally evaluated and based on the defined parameters (specification of the materials to be obtained and price criteria), the software compiles the most optimal sawing algorithm for each board, as well as in some cases directing the board for re-processing (sawing in width) or thermal treatment (a separate post-processing process of processing lumber in a special dryer at high temperature, as a result of which completely dry lumber is obtained, a brown tint throughout the lumber cross-section and providing the material with improved physical and mechanical properties). As a result, following prototype was created Fig.1.

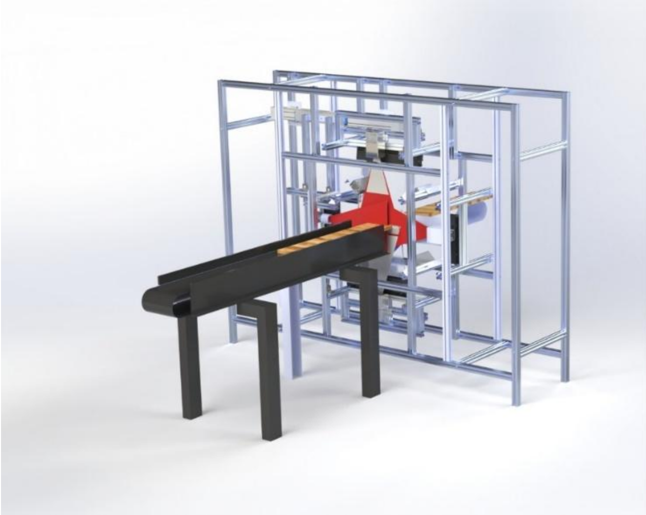

Fig. 1. Cross-cutting optimizing scanner for cross-cutting and quality (*source: company LV Timber SIA data*).

1. Preparation of an optimisation task, taking into account the order volume, warehouse volume and product values. Statistical analysis
2. Mechanisation of board feeding from the four-sided longitudinal milling machine to the scanner and from the scanner to the feed to the existing cross-sawing machine. Automatic and efficient operation of the cross-sawing line requires a conveyor system for feeding calibrated and scanned boards to the cross-sawing machine, thus ensuring fully automatic operation of the line.
3. Cross-sawing machine with discharge conveyors.
4. Increasing the efficiency of the existing cross-sawing machine, mechanical and digital adjustment with feed mechanisation in the existing cross-sawing machine. In order to adjust the sawing line and ensure automatic loading of boards, it is necessary to adjust the board loading mechanisation in the existing cross-sawing machine.

III. Specifications of Established Solution

A cross-cutting system was developed for wood processing plant. For the assessment of a possible order optimisation and surface defect data accumulation, the machine learning models were trained on a variety of images. It provides necessary quality control regarding the processing of the size, diameter, eccentricity, height, thickness and other parts of the non-contact numerical parameters of detection based on 3D scanner results.

Often, workers manually carry surface quality control. Wood processing companies train workers to identify complex surface defects due to their wide variety and sophistication in requirements. For wood processing companies, we have applied advanced 3D scanners that not only detect defects in products, but also offer the most optimal solution for obtaining maximum value from each product, as well as ensure autonomous operation of the product line with waste sorting advantages. The company's scanner captures images and topographis images of the boards from both sides, obtaining complete information about each board. Next, the artificial intelligence algorithm divides the boards into segments with good and defective wood. This data goes through an optimisation algorithm that divides each board into a predefined range of products and already places the blades of the next circular saw according to our algorithm data. All the company's experiences were used in the implementation of our product, and new knowledge on data analysis, artificial intelligence and Computer Vision was developed. We propose an upgraded system with high recognition of wood defects and analytics to overcome the optimisation problem caused by rising number of sophisticated data especially for high quality wood materials. As a result, we present acceptable strategies for dealing with 3D data that allowing to establish an integrated management network (Fig.2)

Fig. 2. Actual prototype of the scanner system with 4 triangulation and 4 visual cameras and a translation system for optical alignment (*Source: authors created based on SIA LV Timber data)*

Management will consist of several layers (based on quality requirements) with different zoom ratio, to increase the rate of precision during the defect recognition. As for the decision algorithm, the analytical system performs recognition of raw material required for the order. Wood constantly exchanges moisture with the ambient air, tending to an equilibrium moisture content so recognition of proper quality and estimation of order capacity is important [17].

The design of the decision-making system is appropriate for capacity for large complex order, it is proved to using several parts of processing board. This enables the management to capture not only the available materials, but also the costs and waste of the board (Fig. 3). The decision network uses not only output volume of the available raw materials, it calculates supply inputs and improves utilisation to avoid shortages with processing and over capacity issues. It also reduces the oversupply to a large number of orders and helps to confirm associated costs.

In the AI *decision network* learning is also allowing to created several layers of quality requirements thus decreasing issues with inventory waste management. For circularity management improvements in utilisation of maximums raw materials are playing vital role. Projections indicate that wood production will fall short of societal needs by 2030, therefore, efficient wood resource utilisation and waste wood management are essential, necessitating collection, recycling, and reuse of idle wood [18]. In recent years, a growing body of research has focused on design strategies aimed at promoting sustainability. One prominent model proposed as a strategy for achieving circular design, as discussed in the study conducted by Moreno et al. [19]. In order to promote wood further utilisation in the future, the usage of raw materials for digital manufacturing is a new opportunity. One of reasons is the recent development of digital fabrication technologies, such as 3D scanners and automatic cutters especially with the help of Machine Learning technologies with fast recognition are giving a lot of opportunities for circularity management [20].

Aspen and black alder defect solution consists of 2 parts - image acquisition and image segmentation (quality sorting), with the help of 3D scanner, a high-resolution image with dimensions of more than 18k is obtained. The image is then reduced in size and divided into smaller areas to not only expand the range of images available, but also to increase defect detection results. The resulting data set is allowing to create management report with precise cost and waste output for further analysis. During the prototype training of the model, a wide range of wood quality parameters was reviewed and tested, from which the best ones were selected. Accordingly, the best model was implemented, which was implemented for recognition in the production line and management system. A prototype of the most advanced scanner is located in a medium-sized wood processing company in Latvia. The board optimisation results for wood production line are shown in Figure 3.

This is the basic information about the optimisation algorithm uses to make further decisions on quality sorting. Once the board has passed through the four scanners, it is transported to the positioning process. Meanwhile, the optimisation algorithm, is taking into account the size of the board and the image information, processes it via a neural network (CNN) and labelling through the user interface for future order optimisation.

The neural network is able to recognize different classes of defects from the board image. It uses the sliding windows methodology to scan different areas of an image of the same size, where the segment belongs to a specific defect class. As a result of the segmentation model, we obtain boards that are already divided into parts, separating the white or valuable wood from the defective one. The optimisation algorithm then processes this board information until it reaches the positioning stage. The optimisation algorithm takes into account the individual defect information of each board, the defect quality class and the assortment of products produced every day - product widths and their prices to create cost estimation and future added value for each board. Using these parameters, it is able to position the manufactured products in such a way that the value of products on each board is maximized and material waste and equipment utilisation are minimized.

After optimisation, the next step for the board is positioning. It is part of the production line where the position of the board is fixed before it is cut into products according to the order requirements. At this stage, using the industry's most modern scanner systems, positioning cameras and high-precision chain conveyor, we are able to turn the optimisation result into a real position according to a planned prototype results. When the positioning algorithm is satisfied that the optimisation results match, the board is locked and launched for sawing. The end result is an automated full board sawing cycle for precise cut, obtaining the maximum value from the material used.

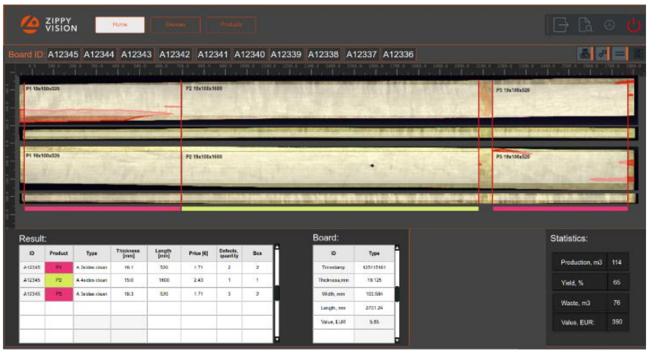

Fig. 3. Management system for detection of wood surfaces defects and capacity utilisation (*Source: authors created based on SIA LV Timber data*)

As a results, the following main benefits of speeding up the production line with greater quality, sustainability and optimisation are here. Before that we have manually looked at the board before it reaches the saw, evaluated it and decided how to get the maximum value from it before it enters the positioning step. Compared to manual human approach, which evaluates only one board at a time and only then adopts the optimal sawing solution with manual labelling, we can plan the next steps ahead with greater analysed stock, evaluate several boards at the same time and save them until they reach the saw. We not only reduce the time it takes for a person to make a decision and make all the necessary adjustments, but we also reduce the potential risk of human error. A person's attention and care for details can decrease in an 8-hour cycle which in ergonomics commonly known as vigilance fatigue. In turn, an automated process will always return an identically accurate and valuable result for the same boards while having future challenges with more sophisticated defects. Additional benefits can be seen in reducing the workload for other processes and positions on the production line, as the sawing process is autonomous.

IV. Discussion, Scalability and Commercialisation Approach

The key goal of this paper is to present a commercialisation potential for scanners in wood processing. We present a cross-cutting optimizing scanner for aspen and black alder wood with Machine Learning with CNN vision competency for manufacturing. Computer Vision is an encompassing term which includes the integration of both hardware and software for practical application.

TABLE I. Improvements after introduction of the scanner system

966,65	Production of high quality aspen boards, m^3
6490	Total raw materials (aspen logs) consumed, m^3
14,89%	Yield (boards / logs)
9,76%	B grade as a share of total high quality boards (the rest is A grade)
2500	Average monthly input of aspen logs, m^3
1050	Average A grade aspen board selling price, EXW 08.2025-10.2025, EUR/m^3
30%	Average discount for B grade aspen boards
15,39%	Yield (boards / logs)
0,50%	Yield improvement in comparison to operations without the scanner system
8%	B grade as a share of total high quality boards
1,76%	Reduction of B grade products in the total output, calculated as 9,76% - 8%; the same improvement of A grade board output generates additional revenue.

In order to confirm our CNN productivity, we have examined the customer's production reports over three months, August to October 2025, when the prototype scanner system was not yet developed. For comparison, we use 2026 data, after the introduction of prototype cross-cutting optimisation scanner (Table 1).

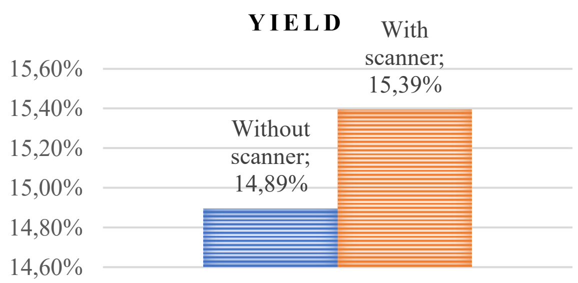

Fig. 4. Cross-cutting optimizing scanner for aspen and black alder efficiency results (*source: authors created based on SIA LV Timber data*).

The new scanner system improves output and reduces the manual labour of two employees. As confirmed to us by the customer, the main speed benefits come from the elimination of manual correction, human error and decision making (Figure 4).

Another noteworthy indicator is the decline in the amount of lower-grade material, which has fallen from 1,4% of raw material volume to 1,2%. The scanner has been able to find better solutions for optimizing each board and has achieved a reduction in material waste (Figure 5).

The scanner has been able to improve efficiency not only in the recognition of defect material, but also quite significantly in the production of useful material due to better optimisation. 92% of high-quality aspen boards are now marked as “A” (top) grade, whereas without the scanner the share of A grade boards was 90,24%. Since “A” grade boards contribute to significant price premium, the reduction of false negatives observation due to human errors (where A grade boards are marked and sold as B grade boards) improves company profitability. This factor also determines the achievement of the client's financial goals that our scanner has allowed us to achieve.

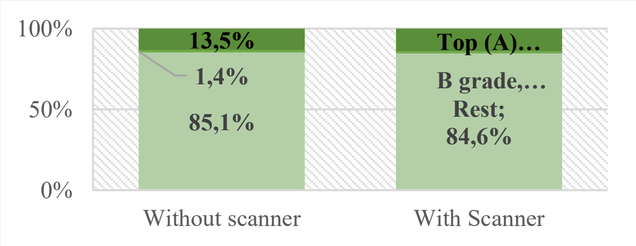

Fig. 5. Results of implementation of cross-cutting optimizing scanner in wood processing (*source: authors created based on SIA LV Timber data*).

Conclusions

The final result of the research project is a successfully developed prototype of an aspen and black alder cross-cutting optimizing scanner, able to ensure automated operation that meets the defined production tasks.

For small and medium companies and projects, using ML is usually costly, requires long period to adapt or issues with optimisation and defect recognition options. SME cannot provide Big Data to be analyzed or applied. Recognizing this, out prototype was elaborated to address these shortcomings and more quality classifications have been expanded to use 4 scanners with better resolution and board combinations. As a result, the state-of-the-art for modern wood processing companies is allowing to commercial contemporary technologies available on market, and also simplifying and speeding up learning process.

In this research, we have addressed the application of ML models for the prediction of wood defects for high value wood species. Our experience can become a good case to determine the scalability of ML systems and to apply them for specific manufacturing requirements based on production capacity and quality requirements. This brings new prospects for machine learning models to be applied in a wider range of manufacturing projects.

ML system for defect detection through CNN will contribute to technological innovation, industry, national development and other applications within European Union. According to our report, yield of quality aspen boards has gone up from 14,89% to 15,39% measured as a fraction of volume of raw materials (aspen logs). Another significant indicator is optimisation of material, whereby the new technology marks 92% of high-quality aspen boards as A (top) grade, while previously manual labour resulted in 90,24% recognition of A grade. Since A grade boards command significant price premium in comparison to B grade boards, the improved recognition of top-grade products has increased monetary value, with estimated benefits of 25 thousand EUR annually. Based on these facts, it can be concluded that our scanner has been able to find better solutions for optimizing each board and has achieved a reduction in material waste and bringing greater value for company. The recognition accuracy for greater quality can be obviously improved in future while CNN becoming more accurate due to learning process.

Therefore, we proved that commercial potential for scanners in wood processing developed for the wood industry is efficient and could be easily scaled up in size and in case of technology transfer will be basically using the similar technologies. This paper explored a scalable deep-learning approach for surface defect detection with a CNN from the point of view of specific industrial application. Our framework created from the project it is possible to increase management efficiency, reduce labour costs and increase sustainability results for the company and increased speed of production.

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References

[1] European Wood Policy Platform, “A wood-based circular bioeconomy for a sustainable Europe,” Brussels, 2024. [Online]. Available: https://europanels.org/wp-content/uploads/2024/11/CL053-24_WoodPoP-Policy-Paper_2024.pdf

[2] R. Garcia, I. Calvez, A. Koubaa, V. Landry, and A. Cloutier, “Sustainability, Circularity, and Innovation in Wood-based Panel Manufacturing in the 2020s: Opportunities and Challenges,” *Curr. For. Reports*, vol. 10, no. 6, pp. 420–441, Aug. 2024, doi: 10.1007/s40725-024-00229-1.

[3] M. Ramos-Maldonado and C. Aguilera-Carrasco, “Trends and Opportunities of Industry 4.0 in Wood Manufacturing Processes,” in *Engineered Wood Products for Construction*, IntechOpen, 2022. doi: 10.5772/intechopen.99581.

[4] E. Yildiz, C. Møller, and A. Bilberg, “Virtual Factory: Digital Twin Based Integrated Factory Simulations,” *Procedia CIRP*, vol. 93, pp. 216–221, 2020, doi: 10.1016/j.procir.2020.04.043.

[5] G. Rojas, A. Condal, R. Beauregard, D. Verret, and R. E. Hernández, “Identification of internal defect of sugar maple logs from CT images using supervised classification methods,” *Holz als Roh- und Werkst.*, vol. 64, no. 4, pp. 295–303, Aug. 2006, doi: 10.1007/s00107-006-0105-0.

[6] S. Seibold *et al.*, “Quantifying wood decomposition by insects and fungi using computed tomography scanning and machine learning,” *Sci. Rep.*, vol. 12, no. 1, p. 16150, Sep. 2022, doi: 10.1038/s41598-022-20377-3.

[7] L. Odstrčil, P. Valent, V. Kaputa, and M. Fabrika, “Digitization and Virtualization of Wood Products for Its Commercial Use,” *Forests*, vol. 15, no. 12, p. 2263, Dec. 2024, doi: 10.3390/f15122263.

[8] C. S. Utla, A. Dashora, L. Chandrasekhar Reddy, and A. V. Kulkarni, “Analysis of Ground Sampling Distance of Convergent Images for Keypoints Detection for Close-Range Photogrammetry,” *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch.*, vol. 43, no. B2-2022, pp. 93–98, 2022, doi: 10.5194/isprs-archives-XLIII-B2-2022-93-2022.

[9] M. Deval and P. Ruttico, “LokAlp: A Reconfigurable Massive Wood Construction System Based on Off-Cuts from the CLT and GLT Industry,” May 23, 2025. doi: 10.20944/preprints202505.1855.v1.

[10] J. Yang, Y. Zheng, and J. Wu, “Towards Sustainable Production: An Adaptive Intelligent Optimization Genetic Algorithm for Solid Wood Panel Manufacturing,” *Sustainability*, vol. 16, no. 9, p. 3785, Apr. 2024, doi: 10.3390/su16093785.

[11] Z. Yi, L. Luo, Q. Lu, M. Chen, W. Zhu, and Y. Zhang, “An efficient and accurate surface defect detection method for quality supervision of wood panels,” *Meas. Sci. Technol.*, vol. 35, no. 5, p. 055209, May 2024, doi: 10.1088/1361-6501/ad26c9.

[12] M. Pantscharowitsch, L. Moser, and B. Kromoser, “A study of the accuracy of industrial robots and laser-tracking for timber machining across the workspace,” *Wood Mater. Sci. Eng.*, vol. 20, no. 1, pp. 75–93, Jan. 2025, doi: 10.1080/17480272.2024.2324437.

[13] M. Haddouche and A. Ilinca, “Energy Efficiency and Industry 4.0 in Wood Industry: A Review and Comparison to Other Industries,” *Energies*, vol. 15, no. 7, p. 2384, Mar. 2022, doi: 10.3390/en15072384.

[14] V. Nasir and J. Cool, “A review on wood machining: characterization, optimization, and monitoring of the sawing process,” *Wood Mater. Sci. Eng.*, vol. 15, no. 1, pp. 1–16, Jan. 2020, doi: 10.1080/17480272.2018.1465465.

[15] G. Romanovskis, K. Bumanis, G. Kulikovskis, and P. Rivza, “Location and identification of oak wood defect by deep learning,” May 2021. doi: 10.22616/ERDev.2021.20.TF402.

[16] A. Diez-Olivan, J. Del Ser, D. Galar, and B. Sierra, “Data fusion and machine learning for industrial prognosis: Trends and perspectives towards Industry 4.0,” *Inf. Fusion*, vol. 50, pp. 92–111, Oct. 2019, doi: 10.1016/j.inffus.2018.10.005.

[17] M. Sydor, J. Majka, M. Rychlik, and W. Turbański, “Application of 3D Scanning Method to Assess Mounting Holes’ Shape Instability of Pinewood,” *Materials (Basel).*, vol. 16, no. 5, p. 2053, Mar. 2023, doi: 10.3390/ma16052053.

[18] J. Luo, B. Yu, Y. Jiang, A. Fingrut, and A. Holloway, “Upcycling of regular wood trunks and logs using wave function collapse (WFC), augmented reality (AR), and mixed reality (MR) technologies for circular design,” *Sci. Rep.*, vol. 15, no. 1, p. 36599, Oct. 2025, doi: 10.1038/s41598-025-20398-8.

[19] M. Moreno, C. De los Rios, Z. Rowe, and F. Charnley, “A conceptual framework for circular design,” *Sustain.*, vol. 8, no. 9, 2016, doi: 10.3390/su8090937.

[20] K. Morimoto, K. Tsuda, and D. Mizuno, “Literature Review on the Utilization of Rice Husks: Focus on Application of Materials for Digital Fabrication,” *Materials (Basel).*, vol. 16, no. 16, p. 5597, Aug. 2023, doi: 10.3390/ma16165597.