Digital Technologies for Reuse and Recycling of Construction Timber: the Re-sawmill

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Keywords: wood waste; digital manufacturing; reclaimed timber; urban sawmill; circular economy; Industry 4.0 (4IR)

Abstract A critical gap for wood reuse in construction is the absence of specialized focal firms that are capable of sorting and preparing wood waste for processing into fit-for-reuse and fit-for-recycling applications. We therefore initiated a feasibility study for the reverse sawmill, i.e. Re-sawmill – a facility that catalyzes the transformation from a linear timber construction value chain to a value cycle. This position paper elaborates on the various components of the Re-sawmill with an emphasis on digital infrastructure that can facilitate each step required for a circular timber economy. Based on previous and ongoing research, and observations of current timber processing facilities, we specify which digital technologies are used in the current value chain and identify those suitable for different Re-sawmill scenarios. The paper concludes with practical implications regarding the digital aspects of the Re-sawmill and illustrates the trade-offs and choices with the proposal of 3 types of process configurations.

1. Introduction

Responsible management of forests and efficient handling of wood, including a (re)valorisation of wood waste, are critical for sustainable environmental practices and the development of a circular timber economy. Today, large amounts of wood waste end up in energy recovery or low-value, short lifespan uses.

A significant barrier for timber reuse is the perceived lack of knowledge and technology [1, 2]. Digital technologies hold potential in advancing the circular built environment (CBE) [3], moving from demonstrations to scaling up the wider uptake of salvaged wood. Another requirement are focal firms that help to close the loop in timber use. Over the past decade, small-scale wood processing facilities or circular construction hubs have proliferated worldwide [4–8]. However, these ventures lack large-scale, industrial-level operations or only process the waste wood into low(er)-value uses.

The purpose of this study is to present and discuss digital technologies and information requirements for a so-called *Re-sawmill*, a facility that can catalyze the transformation from a linear timber construction value chain to a value cycle by automating the sourcing, processing and re-distribution of reclaimed wood to improve the quality of end-products and enhance the efficiency of their production. Some of the technology and knowledge required for a Re-sawmill such as those in data acquisition, analysis on features concerning quality, and storage may already be available, while their application in sorting, separation, and quality assurance of heterogeneous materials is under-explored in a Re-sawmill framework. The objectives of this study are therefore to:

1. Review the current technologies available for the various steps required in a Re-sawmill,
2. Evaluate whether the identified technologies are suitable for enabling the industrial-scale reuse of timber, and
3. Propose evaluation criteria for integration of these technologies in Re-sawmills.

Concludingly, we propose three scenarios with different levels of digital technology and resource requirements. While the aim of a Re-sawmill framework is to increase the likelihood of structural reuse, we also present a non-structural scenario to compare different technology constellations.

2. Methods

To achieve these objectives, this position paper weaves together ongoing research and innovation experiences and presents conjectures based on observation of similar facilities (e.g. sawmills, manufacturing companies, waste handling companies, circular construction hubs), and ongoing projects in Europe, the USA and Japan. We mapped existing and emerging procedures and technologies for timber assessment and processing, and data and expertise requirements for the Re-sawmill. Through a multi-level systems assessment and identification of tensions, opportunities and dependencies, we integrated knowledge on conceptual frameworks (e.g. [3]), digital workflows (e.g. [9–12]); data availability and requirements (e.g. [13, 14]), methods for retrieving information requirements in construction (e.g. [15]) and integration of industrial ecology logics in planning manufacturing (e.g. [16]).

Drawing on existing standards for quality assessment in sawmills and the architecture, engineering and construction (AEC) sector regarding timber construction, the study leveraged stakeholder engagement and action research within the SirkTRE consortium (e.g. [17]).

We curated a European panel of wood technology experts, architects, engineers, innovation managers and factory plant planners for a workshop in May 2023, aiming to address uncertainties via interactive sessions. This was followed up by online concept and intervention development workshops. These experts shared insights, provided feedback, and voted on hypotheses. In June-August, two other expert groups were consulted, 1) environmental engineers for life cycle impact simulation and 2) manufacturing robotic experts for a more bottom-up approach of operations research (multi-criteria assessment, simulation and bottleneck analysis) as prototype preparation.

3. Background: Re-Thinking Manufacturing processes

For an assessment of Re-sawmill, we take a multi-level co-design perspective [16]: 1) We relocalise and rethink so-called traditional facilities 2) integrate digital technologies and data requirements in one pipeline [18] and 3) implement iterative rounds of identifying, estimating and modeling from a circular economy (CE) level [16] to investigate the seamless integration of existing machines and technology providers, and identify the bottlenecks.

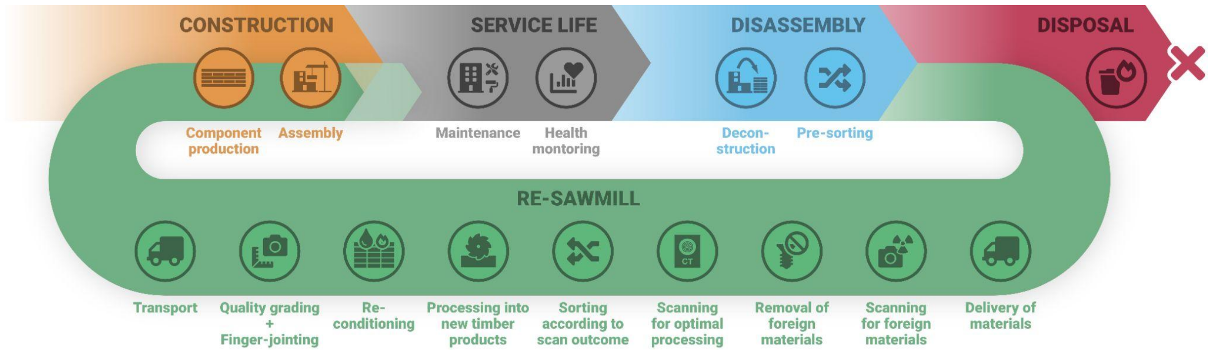
We examine the need for change in current timber industries that the introduction of reused timber in the value chain will entail (Table 1). The inherent differences between sawmills and the Re-sawmills and the varied information requirements will lead to differences in the technologies used. Re-sawmills handle geometrically more diverse and predominantly dry, sawn timber. The heterogeneity of the sourced materials, including a wide range of board dimensions and conditions and the expected presence of metal (screws, nails, coatings (e.g. varnish)) and surface modifications (e.g. brushed surfaces, impregnation) further complicates sorting in the Re-sawmill context. In contrast, sawmills receive a relatively homogeneous material stream, often pre-sorted during harvesting, differing mainly in log diameters and species. The Re-sawmill, conversely, faces a more unpredictable material stream, given the varied sources and lack of a centralized system for tracking planned demolitions or supply by urban miners or wood waste suppliers. This necessitates robust and flexible digital systems to manage these complexities. This analysis led to the re-thinking of the timber construction value chain into a value cycle, with the Re-sawmill as the focal firm closing the loop (Figure 1).

Table 1: Comparison of concerns (distilled from e.g. [1, 2]) and possible solutions/mitigation measures for linear and Re-sawmills, and new considerations required for Re-sawmills

		Sawmills	Re-sawmills
Material stream	Dimensions and state	Logs including bark ● Standard dimensions ● Wet state	Timber from construction, demolition, waste management and logistics, sawmill and manufacturing ● Different dimensions ● Dryer state ● Risk of contamination and metals
	Properties	Virgin wood grown in longer seasons in warming climates and with industrial fertilizers might have less quality and strength due to increased volume, and thus reduced density [19, 20].	**Timber from old buildings might have a better quality than fresh virgin wood.** In the past, forests were less managed and had more slow-growing trees. Forests in Central Europe experienced a decrease in density in the past century due to prolonged growing seasons and higher temperature, reducing the strength and stiffness of wood [19, 20]. **Impact of the lifecycle damages**: Cavalli et al. noted that the bending stiffness and strength are not affected by aging but by decay as a consequence of unfavorable storage conditions, load duration and deconstruction damages [21]. The current design codes for timber structures account for these aspects through safety factors and modification factors. This design system is built around statistical data covering the life expectancy of the building, and would require new data and additional codes to account for reclaimed timber [22]**.** **Impacts of swelling and shrinking over time**: Old timber can have poor quality because of more cracks and use defects. **Impact of cracks:** The mechanical performance of reclaimed timber can be affected by cracks. This often influences the structural resistance against shear and makes the internal structure more susceptible to moisture due to an increasing surface area.
Energy use	Drying	In a sawmill, the traditional process has a variety of regimes that remove liquid water from the lumen and bound water from the cell wall. Salin and Wamming have shown that the vast majority of energy is consumed during the initial drying below fiber saturation point [23].	If stored properly, most reclaimed timber from interior use has low moisture content (MC), therefore requires less energy for MC homogenization. For wet reclaimed timber, a method for reconditioning the heterogeneous material stream to the required MC in industrial scale in-line processing is needed. To analyze the stress development, distortion and fracture development in heterogeneous timber elements during drying, finite element models can be used [24, 25].
	Processing	Only cutting, offcuts are made into chips for energy use.	There is a need to remove nails, concrete, surface treatment and/or coating. Digital design and tools can help produce reclaimed timber components with lower emissions than other engineered timber products [26].
Quality assurances	Computed tomography (CT) scanning	Cutting pattern algorithms based on CT scanning of raw logs before sawing Feature detection in wet logs is difficult as the water in the sapwood diminishes the contrast in CT scans due to similar density to relevant features [27].	CT scanning will be easier in a Re-sawmill due to lower MC and can ensure more accurate and detailed stiffness and strength predictions of reclaimed timber (Section 4.3.2).

	Camera scanning	Using 3D scanning/camera imaging is more straightforward with fresh logs.	Detecting surface features can be hampered by dirty or coated wood surfaces and color changes due exposure to light or liquids.
	Strength grading	Properties are not checked in every sawmill.	**Quality assurance requires new grading and structural design standards**: Reclaimed timber has often been mechanically affected, e.g. by holes, notches, and wear and tear, and duration of loading (DOL). Checks and cracks caused by moisture variations can have a large effect on the capacity of timber. Long-term loading leads to increased deformations during service life due to creep and mechanosorption, which may negatively affect the shape of the timber and its strength properties. Fatigue properties may be affected, which may limit its suitability for load cycling applications.
	Treatment, pests	Despite the initial requirement for phytosanitary treatment prior to entry issued by most countries, new infections can arise in virgin timber too [28-30].	**The concern for wood rot as a result of fungal growth or damaging insects:** Although some countries require drying to prevent fungus and pests [30], new infections can arise during the lifespan of buildings. Reclaimed wood from demolition sites might need a process to stop fungal growth.
Design and products		**Generic, supply-driven products:** Sorted only according to dimensions	**Demand-driven products** Rethinking fabrication and starting from computational design reduces risks concerning quality of reclaimed timber, but would still require high-level scanning, computational tools to be used during planning and IT-capable architects (Section 4.4). **Matchmaking algorithms or configurations** (e.g. [31]): This needs to run on large data sets, ideally on log yard size. The question is when and if the inventory can be big enough that any design option could be achieved or resizing to standard dimensions is required.
Lifecycle of products		Often not concerned with next purpose	**Impacts of multiple use and processing**: Data models might be able to be used to predict how many times a piece of timber can be used and determine if there are fatigue effects from repeated drying or reconditioning processes.

Figure 1: Rethinking the timber construction value chain into a value cycle



4. Results

This chapter presents the assessment of different technologies that can be integrated into different Re-sawmill configurations. In the first four subsections, the digital technologies are listed according to the four phases outlined in Fig. 2. The fifth subsection envelopes Virtual Reality technologies for training and assisting the Human Resources as part of a human centered-digital transformation vision.

Figure 2: Operations, choices and supporting digital technologies in the Re-sawmill

OPERATIONS IN THE RESAWMILL	PHASE 1:SOURCING	PHASE 2: PREPARATION	PHASE 3: PRE-PRODUCTION	PHASE 4: PRODUCTION
CHOICE	Which purpose?	Hazardous substances? Processing required?	Which pre-treatment line does it need to enter?	What is the quality of the product or part of a product?
OPTIONS	Fit for reuse Fir for recycling Fit for recovery	Yes > Separate them No > Processing? Yes > Cutting line No > Direct to preparation	Reconditioning Direct to production	C24 or more C24 or less
INFORMATION NEEDS	Likelihood of presence of nails, screws, concrete, contaminants, quality	Dimensions, location of metals or other foreign materials, criteria, e.g., minimum dimensions	Threshold levels for certain criteria	Quality of product, or hyper grading parts of a product, threshold levels for quality
DIGITAL TECHNOLOGIES	Data acquisition & processing technologies, e.g., sensors, scanners & image processing	Data acquisition & processing technologies, robotics	Data acquisition & processing technologies, e.g., sensors, scanners & image processing	Data acquisition & processing technologies, robotics

4.1. Sourcing

The circular economy model for reclaimed timber ideally begins with pre-demolition data collection to inform the facility about the anticipated materials. Urban construction spaces present challenges due to the limited space for efficient waste segregation and handling [2]. Early-stage investigations, like 3D scanning of buildings, can provide insights into material types and quantities early in the sourcing process [32] and help plan logistics. Advanced sensing technologies (e.g. 3D imaging tools, ultra-wideband radars, spectral cameras) allow for detailed understanding of the material stock, and this knowledge aids in classification and determination of suitability for various end uses. Effective and flexible pre-sorting and automated warehouse systems with warning signals would be crucial to discard unusable items as early as possible, categorize the material stream and signal when there is enough material from one category based on criteria such as dimensions and species.

It is critical to presort timber as early as possible in the cycle on the basis of criteria such as severe damage/cracks, severe mold/decay, dimensions below a minimum threshold depending on the available automation technologies, and chemical compounds not allowed to be used in new buildings. Exclusion criteria disqualify a piece of timber (or part of it) from being processed further in the Re-sawmill. Incorporating machine-readable data formats and point cloud data from 3D scans can enhance this step by facilitating the development of self-supervised learning methodologies for automated diagnosis and analysis.

Digital technologies and effective data management underpin smart logistics in managing the heterogenous stream of wood waste. This phase also includes tagging and digital registry. Robust identification systems (e.g. RFID, barcodes, QR codes) facilitate material tracking in the facility [33]. One possible identifier is the distinct knot patterns in wood that essentially function as a finger-print as they are unique for each individual piece [34] that can be detected with X-ray scanners.

4.2. Preparation in the facility

Incoming materials, pre-sorted for reuse and recovery at this stage, often arrive as composites (e.g., pallets, timber frame, glued laminated timber (GLT)). This necessitates an initial visual sorting into various fractions, some of which require further disassembly.

A first step is separating pieces with hazardous chemical contamination from the material stream. To detect chemical contamination in reclaimed wood, near-infrared spectroscopy (NIR) [35], X-ray fluorescence (XRF) [36, 37] and laser-induced breakdown spectroscopy (LIBS) [38, 39] have been applied in scientific studies. However, industrial in-line application of the technologies and automated separation of timber pieces bigger than 50 mm has not been realized so far.

The second step includes detecting composite materials by utilizing visual recognition systems that are possibly data-trained. Relevant queries include the points in the process for data acquisition and transfer to pre-production and production stages, and the optimal stage for QR/barcode addition. While tagging can happen on-site (Phase 1), currently timber companies tag at the beginning of the production process [40].

Initial sorting and cleaning stages (Phase 2) at an industrial pace may be more complex than qualification tasks like non-destructive grading (Phase 3). Phase 3 would require scanning to record the dimensions and locations of metals that can damage the equipment. This data would need to be permanently linked to the scanned material, e.g. stored on the tag applied in Phase 1 and be updated after any processing on the material.

4.3. Pre-production in the facility

The variability of the incoming timber places significant pressure on the sorting and rinsing stage, slowing down the pace required for efficient industrial processes. Optical or X-ray computed tomography (CT) scanning could be used for the first material evaluation. Sawmills that process virgin wood and use CT scanning apply it exclusively at the log stage to optimize sawing. Two important discussion points are the minimum amount of data necessary for predictions and the influence of the scanning speed on the acquisition of meaningful data and information. For example, the regular production speed of CT scanners in current sawmills can reach more than 100 m/min [41], which may limit the reconstruction quality in the images and thus the level of detail for informed decision about the optimal use of the material. AI (Artificial Intelligence) could potentially improve the quality of noisy scans and compensate for the fast scanning speed. In addition, AI could enhance the obtainable information about the structural composition from fewer and less controlled X-ray measurements, such as discrete X-ray scans, which can be built into mobile containers and placed on site [42, 43].

Additionally, the scanning order—whether a thorough volumetric scan should be performed at the start followed by a surface scan at the end or vice versa—may significantly impact the workflow efficiency. An initial volumetric scan can identify necessary processes early on, while a final surface scan would capture the material's final dimensions for the database, ensuring a comprehensive data capture.

The role of humans and robots in the process also requires consideration. While automation can increase efficiency and handle potentially risky processes, such as pre-sorting toxic, lead-contaminated pieces or removing surface contaminants (e.g. concrete) in isolated areas, human involvement remains essential for oversight and addressing potential ambiguities that machines might struggle with (Section 4.5).

4.3.1. Removing concrete and nails

Reclaimed timber from old buildings frequently includes nails and those from newer buildings might be contaminated with concrete. If wood is to be processed, these elements can damage the equipment. Therefore, categorization into different impurities to sort into proper cleaning methods is needed. The operational information needs are the location and the quantity of contaminants, as well as the dimensions of the incoming wood elements.

Various methods exist for the removal of concrete and nails from reclaimed timber, each with its own advantages and potential limitations. Materials sorted according to consistent cross sections and design and fabrication methods that work around the presence of nails can help prevent the need for cutting and cleaning [26]. If cutting is necessary, approaches can involve using detection systems such as CT scanning to identify and cut around the nails with adaptive fabrication methods such as robotic milling. However, the scanned data will need to follow the timber piece across the pre-production and production process and maybe not all equipment are able to read such detailed information. Mechanical removal methods can effectively deal with a range of surface contaminants but might be destructive to the wood's surface. Therefore, an essential consideration in choosing a preparation method is the intended end-product.

4.3.2. In-facility quality assessment

After having been sorted, cleaned and tagged, the remaining pieces must be characterized with regard to mechanical strength, moisture content and the potential need for conditioning.

Conditioning and phytosanitary treatment

The moisture content of the reclaimed timber may vary greatly depending on its previous application (e.g. construction timber, engineered wood product, i.e. GLT or wood for interior application) and the storage conditions prior to entering the facility. In-line capacitive moisture meters are a means to roughly estimate the moisture content of sawn timber. Conditioning of timber to a common moisture content is considered applicable only for material with equal downstream utilization, e.g. lamellae for GLT, cross-laminated timber (CLT) or laminated veneer lumber (LVL). To analyze the stress development, distortion, and fracture development in boards during drying, finite element models are a popular tool [24, 25]. A more recent development is the use of AI to optimize kiln drying processes and prevent distortion and cracking. Machine learning (ML) is used to analyze the drying rate and average moisture content during kiln drying [44–48] and in combination with CT scanning, can aid in predicting whether conditioning is required for the reclaimed timber at a Re-sawmill.

Phytosanitary heat treatment (PHT), guaranteeing 56 ºC for at least 30 continuous minutes throughout the entire cross section of a piece of timber, is one possibility to fulfill ISPM15 [30] requirements for wooden packaging in international trade to avoid spreading of pests. PHT is very energy intensive and therefore, its necessity in a Re-sawmill should be carefully considered as most of the timber and wooden packaging entering the facility will have undergone sufficient heat treatment upstream- except air dried timber from older structures and wooden packaging for domestic trade.

Strength grading

For load-bearing applications in Europe, all timber has to be assigned a strength class based on non-destructive visual or machine grading as specified in EN 14081 [49]. Both visual grading rules and machine strength grading settings are specific for each species and for each growth area. Strength classes for machine grading are defined by strength, stiffness and density of the timber (EN 338 [50]). These *grade determining properties* are predicted, usually by regression models, from so-called *indicating properties* (IPs), which are elicited by non-destructive measurements of wood characteristics, e.g. density, modulus of elasticity, slope of grain [51]. In industrial applications, IPs can be based on evaluations of various features or a combination thereof; a) density, e.g. by load cells recording the mass and photocells or lasers recording the volume of the piece b) stiffness, e.g. by three-point bending, ultrasonic measurements or recording of the natural frequency [52], and c) evaluations of knot features and fiber orientations using surface scans, e.g. by optical Red-Green-Blue (RGB) and laser tracheid scanning [53, 54], or discrete X-ray scans to reveal internal structures [55]. Alternatively to regression, other statistical or ML models could potentially be used for prediction of the grade [56].

CT scanning is today used on wet logs only, however, the results in [27] and [57] indicate that the information contained in CT images of dried sawn timber is suitable for predicting stiffness and strength, e.g. by using finite element (FE) or continuum mechanical models of wood. FE-based prediction of properties may even enable a classification of the material at a higher-than-board resolution ("hypergrading") [58, 59] specifying areas along the board with their individual grades, which would drastically increase the material utilization efficiency. If full 3D CT reconstructions are not available, then AI algorithms based on sparse X-ray data as suggested by Adler and Öktem [60] and complemented with optical may be able to infer internal structures and consequently also enable the derivation of IPs for strength grading.

4.4. Integration into the digital timber value chain

Data from the non-destructive assessment of reclaimed timber can steer and streamline the processes within the Re-sawmill. However, this data can reach beyond this stage in the process and provide actors and processes in the further AEC timber value chain with valuable information for their design, engineering and production, reduce further waste and could create opportunities for demand-driven processes in the timber industry. Although data-driven processes in AEC are still under development [61], differ in level of implementation and quality, digital sustainability [62], collaboration as well as quality [63], they provide the framework for circular practices [64] and enable reuse in end-of-life scenarios through digital material and building passports, as well as in the integration of building design and construction.

In AEC, architects and engineers specify timber qualities for specific building elements and it is the producers' responsibility to achieve these. The quality of the elements, for instance as GLT or CLT, is heavily dependent on the raw material. In a future scenario, information on individual reused timber elements from the Re-sawmill can be integrated in producers' digital workflows, with matchmaking algorithms, (e.g. [31]) and increase productivity.

The integration of Re-sawmill data in AEC workflows allows for new digital design and simulation workflows, increasing efficiency of production processes and reducing waste. The current conservative grading of elements has safety factors included. Knowledge about the real strength of timber would stop the current practice of downgrading and enable the use of their actual capacity. The use of hypergrading concepts [12] in Re-sawmill products would enable new workflows by arranging the pieces in a way that their specific strength equals precisely the local demands determined in FEA. These concepts have been tested in research with virgin materials and could be transferred to reused timber. A predicament is, however, that the flow of material is accompanied by digital infrastructure that allows the tracking of the boards along different phases. While extended material passports would provide the necessary secure data models, traceability of the physical objects can be provided by computer vision, e.g. Microtec Connect [65], and help to quality assure the fabrication (e.g. the orientation of boards according to the data model).

The integration of this data in timber traders' platforms and systems would establish a digital market and library for reclaimed elements that, if provided via plugins or Industry Foundation Classes (IFC) format, could easily populate a Building Information Modeling (BIM) file, ensuring ease of use for design and BIM software to extract data from the database with the right resolution.

Such digital trading platforms might provide means for disruptive new business models that increase quality and value of timber and reduce waste and downgrading. While current business models are supply-driven, a regional, national or even European platform would enable a better fit of demand and supply, and a demand-driven approach, where specifications from clients and buildings are matched with hypergraded materials in stock or guide the salvaging process.

4.5. Training and Assisting Human Resources

Despite the advancements in digital technologies and automation in the construction industry, importance of human involvement is still evident in tasks such as pattern recognition, where humans exhibit superior performance in handling the extensive variety of incoming materials- a challenge often faced by automated systems. Conversely, robotic systems have the potential to carry out hazardous operations such as the removal of contaminants, and tasks requiring high levels of precision. Thus, finding a balance between human cognition and robotic precision is crucial in optimizing the overall process.

Extended Reality (XR) technology, which includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has the potential to offer a wide range of applications to optimize the Re-sawmill operations. While integrated XR applications including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are seldom explored, several VR and AR applications have been developed that can be relevant to the Re-sawmill [66–74]. XR technologies can enhance planning, production, productivity of workers and engineers, worker safety, training, product development, and maintenance processes [75, 76] (Table 2). These technologies can enable real-time sharing of vital information, augment the operator's understanding and perception of the process, and provide an intuitive and interactive medium to bridge the gap between human cognition and automated systems. Open questions remain regarding the transfer of generic setups to location-specific industrial layouts, and the inclusivity of instructions for varying levels of human sensory ability, suggesting the potential for incorporating haptic and auditory signals.

Table 2: Application of XR technologies in the Re-sawmill

Area	Process	Goals
Training and skill development	● replicate real-world scenarios in a digital twin (DT) of the Re-sawmill ● practice operating machinery and handling raw materials, understand safety protocols [75, 77] ● virtual safety training sessions, emergency simulations	● familiarize the employees with the environment through high repeatability and immediate application of the instructions in real-life settings ● experience and learn from potentially dangerous situations without any actual risks [78] ● identify potential hazards, reduce accidents, improve worker safety
Equipment operation and maintenance	● reflect operating instructions, maintenance guidelines, and troubleshooting procedures onto the actual machinery and equipment ● monitor their state and predict malfunctioning through real-time DTs of the equipment [76]	● help maintenance operators to perform tasks correctly, reduce downtime due to equipment malfunctions [76]

Remote assistance and collaboration	● remote guidance of the on-site workers using MR (e.g. smart glasses or headsets) by experts or supervisors ● provide real-time instructions, identify issues, and offer solutions	● improve efficiency and minimize delays [78] ● support supply chain collaboration in the wood industry (e.g. [79])
Quality control and inspections	● real-time quality control and inspections by overlaying virtual inspection data onto physical products	● identify defects, measure dimensions, and ensure adherence to quality standards [76]
Inventory management	● track, locate and count materials and products within the Re-sawmill using computer vision and AR	● streamline logistics and prevent inventory errors [76]
Design and layout planning	● visualize and optimize the layout of the Re-sawmill	● assess potential bottlenecks, improve workflow, and enhance overall efficiency before any physical changes [76, 79]
Environmental Impact Assessment	● simulate the environmental impact of Re-sawmill operations through VR	● identify potential areas for improvement and adopting more sustainable practices [79, 80]
Real-time Analytics	● real-time insights into production processes, machine performance, and worker productivity through XR integrated with data analytics	● make data-driven decisions and optimize operations [76]
Re-sawmill Process Visualization	● visualize complex processes (e.g. scanning, sawing, sorting): ● feed the scan data into AR devices to guide the worker through concrete and nail removal processes	● help operators to gain a better understanding of the operations and make real-time decisions [75, 79]

5. Discussion

To optimize sourcing and the configuration of processes in the Re-sawmill, trade-offs between data acquisition, transport logistics, processing needs, and end-use requirements need to be evaluated.

We identified three types of scenarios or constellations of operations that represent different choices or evaluation criteria (Fig. 3). Re-sawmills, when adapting to the challenges of reclaimed wood processing, can be broadly categorized based on three configurations considering capital investment, wood input heterogeneity, production volumes and consistency of quality assurance (Fig 3). Firstly, low-budget configurations may prioritize minimalistic digital technologies and cater to a more homogenous reclaimed wood input, potentially sacrificing high economic and CBE impact. On the opposite spectrum, high-budget operations, while being equipped with advanced scanners, may lean towards accuracy over speed, providing a wealth of data crucial for subsequent decision-making.

For example, after the material is acquired, there are three levels of assessment required: 1) scanning for geometric and feature analysis, 2) testing for contaminants, 3) testing for mechanical properties. The key question is the granularity, type and order of data needed for each piece, and appropriate tools. For 3D imaging, while CT scanning offers comprehensive results, it may not always be necessary or feasible. Alternative methods, including multi-angle X-ray, Lidar, or laser scanning could provide sufficient data for many applications and can be applied on-site at the deconstruction or sourcing location. On-site scanning can offer immediate data and allow for preliminary sorting. This upfront information can streamline downstream processes by enabling more efficient transport and storage of materials, as they are already sorted based on specific attributes. Conversely, while scanning within a dedicated facility might delay access to data, it can offer more controlled conditions and therefore yield more accurate and comprehensive results. Therefore, the choice between on-site and in-facility scanning hinges on the specific requirements of the project, the nature of the materials, and the available resources and infrastructure.

This precise scanning, though slower, can be mitigated by implementing multiple parallel lines, even though this amplifies investment and operational costs. Lastly, considering the integrity of the reclaimed wood, robotic disassembly emerges as a pivotal process, minimizing damage and maximizing the potential value derived from the timber. It becomes evident that the balance between speed, accuracy, and capital investment in the different resources or requirements (e.g. human skills, equipment, information, space) plays a significant role in the Re-sawmill's process configuration for reclaimed wood.

Fig. 3: Evaluation of 3 types of Re-sawmill process configurations, with focus on digital technologies and investment in digital technologies

SCENARIOS		LOW-TECH	HI-TECH	HI-PRODUCTIVITY
		Consistency of material supply Automation and digitalisation Variety of end-products Consistency of quality	Consistency of material supply Automation and digitalisation Variety of end-products Consistency of quality	Consistency of material supply Automation and digitalisation Variety of end-products Consistency of quality
FACILITY		Small-size mobile units. in collaboration with suppliers.	Large-size, high-tech centralized hubs.	Large-size, high-tech centralized hubs.
SOURCING	SITE	Any timber building and product, including composites and plate products.	Any timber building and product.	Any timber building and product.
	TECHNOLOGY	3D scanning of elements on site. Discrete X-ray scanners.	3D scanning of elements in facility. CT or discrete X-ray scanners with AI-augmentation.	Pre-demolition 3D scanning of buildings, pre-sorting on site.
	METHODS	Digital tracking (QR code).	Digital tracking. Classification algorithm to match with pre-determined uses.	Digital tracking.
MATERIAL STREAM		Small volume. Heterogeneous incl. plate products and composites.	Large volume. Heterogeneous, but only timber.	Large volume. Homogeneous, only timber.
DIGITAL TECHNOLOGIES AND HUMAN LABOUR	CONTAMINANTS	Visual and EDX-based investigation of timber to exclude timber with hazardous coating or preservative treatment	Spectroscopy measurement in facility	Spectroscopy measurement in facility.
	DRYING	Only dry timber intake.	AI-optimized kiln drying for timber> 12% MC.	Kiln drying in facility.
	CLEANING	Manual nail removal.	Robotic with human check.	Drying&re-conditioning. Fully automated robotic.
	TESTING	No non-destructive testing for mechanical properties.	Non-destructive testing and FEA-based hypergrading.	Non-destructive testing (ultrasound, laser).
	FABRICATION	Combination of manual and automated work.	Flexible, intelligent Robotic production line.	Automated, high-throughput robotic production line.
	ARTIFICIAL ASSISTANTS	Human operators might need artificial assistants to increase processing speed and handle errors, but low level. A 2D character that shows up providing more explanations to help humans better understand the task to perform it effectively without errors.	Human operators still required; artificial assistants required for complex operations. XR can be used to have 3D virtual assistants that provide real-time recommendations to humans to improve their performance.	Human operators work with artificial assistants. Objects that replace humans by performing tasks efficiently and effectively without any human intervention.
PRODUCTS		Low volume. Basic quality control. For non-structural applications.	High volume. Large variety of both non-structural & construction grade timber. Integrated quality control and documentation & certification.	High volume. Focus on a few specific construction timber products. Integrated quality control and documentation & certification.
LOGISTICS AND WAREHOUSING		Storage to maintain MC.	High volume storage space requirements including intelligent logistics.	Early warning systems for consistent material stock. Collaboration with traders who like secure supply.

6. Conclusion and future steps

The technology modules for a Re-sawmill are existing and their combination into an integrated process is feasible for implementation. The information required for a Re-sawmill should be generalizable, both human and machine-readable, and anticipate regulatory developments. By following an exploratory assessment, we identified technology and data requirements, their relationship with each other and the bigger ecosystem, and the criteria to evaluate the equipment needed for different Re-sawmill scenarios and products. In choosing scenarios and refining the operational models for potential Re-Sawmills, it is crucial to conduct a comprehensive evaluation that incorporates both technical and environmental metrics.

In the evolving landscape of timber construction, the CE paradigm presents multifaceted implications for practitioners. A holistic evaluation that considers not only the inherent risks associated with real-world implementation, but also an array of operational factors is imperative. These include the capital investments, volumes and types of materials, and the anticipated throughput. Furthermore, a comprehensive understanding of the supply chain dynamics, the technology readiness level of the state-of-the-art solutions, and the proficiency needed by users underpins the successful integration of CE principles.

While inventory, storage and warehouse management are crucial for the overall functioning of a Re-sawmill, they need to be addressed in separate studies. Future research should also explore intelligent logistic models and collaborative approaches with other facilities and digital and physical infrastructures (e.g. storage spaces, digital markets), integrating spatial parameters (e.g. [81]).

Furthermore, it is important to assess whether a decentralized approach, characterized by multiple, intelligently-connected hubs (scaling out), may offer greater sustainability and regenerative benefits compared to consolidating operations into a single, large-scale facility (scaling up).

The current processes and system design of a Re-sawmill represent a linear model of recycling. Breaking away from this, there is a consensus on the large potential of a circular model with reverse logistics. Few timber companies are exemplifying such a shift, with offerings that include taking back products they sell after their lifecycle [40, 82]. This take-back obligation for all components takes the concept of 'extended producer responsibility' to a new level, ensuring that the life of these materials does not end at the consumer's door. Moving forward, our challenge and opportunity lie in pushing boundaries and embracing more comprehensive circular approaches.

Lastly, facilities do not operate in isolation, but are part of bigger systems and assemblages of policies, power structures, and other socio-cultural factors ([83, 84]), which requires a contextualized approach to achieve a true holistic evaluation of CE practice.

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