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Kans, M., Eriksson, K., Lycke, L. et al (2026). Technology readiness in maintenance: an Industry 4.0 case study in the Swedish sawmill sector
with Industry 5.0 human-centric insights. International Journal of Advanced Manufacturing Technology, In Press. http://dx.doi.org/10.1007/s00170-026-19293-x

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The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-026-19293-x

ORIGINAL ARTICLE

Technology readiness in maintenance: an Industry 4.0 case study in the Swedish sawmill sector with Industry 5.0 human-centric insights

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Received: 8 May 2026 / Accepted: 4 October 2026
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Abstract
The sawmill industry presents unique opportunities for adopting emerging technologies due to its capital-intensive operations and dependence on high reliability. However, despite increasing digitalization, there remains limited understanding of how maintenance organizations can assess and develop technology readiness, particularly with respect to organizational and human factors. Understanding these factors is important not only for operational efficiency but also for supporting the human-centric, sustainable, and resilient ambitions of Industry 5.0. This paper investigates the technology readiness of maintenance operations in a Swedish sawmill. The study is based on a qualitative case study involving 21 in-depth interviews and three workshops with personnel from the maintenance organization (technicians, engineers, coordinators, and managers) and related functions (production, operations development, health and safety, and management). Findings reveal that while the organization demonstrates strengths in technology adoption and operational structure, challenges remain in areas such as strategic integration, workforce competence, and data utilization. The study highlights that advancing technology utilization and work processes alone is insufficient for successful development of maintenance. Thus, the study emphasizes human-centric perspectives such as leadership visibility, shared responsibility, cross-functional communication, and long-term planning, are critical for achieving technology readiness. The study concludes that technology readiness in maintenance depends on the combined development of technological, organizational, and human capabilities. Maintenance can serve as a strategic entry point for this transformation, enabling improved sustainability, resilience, and safer operations. Further research is recommended to combine methods and explore how human-centric factors influence the successful adoption of smart technologies.

Keywords Sawmill industry · Maintenance operations · Industry 4.0/Industry 5.0 · Operational resilience · Technology readiness

1 Introduction

The wood processing industry is an important base industry in the transition towards more sustainable and circular production systems. As a renewable resource, wood can reduce climate impacts compared with conventional construction materials. The industry's importance is reflected in its substantial global production and trade. In 2020, the largest exporters of wood-based materials were Russia, Canada, and Sweden, while the largest producers were the United States, Canada, Russia, and China [1].

The sawmill industry is characterized by capital intensive investment, and the current market situation has pushed the need to find new strategies to stay profitable. At the same time, it is a contradictory industry in terms of technological development [2]. Many process steps have a high degree of automation, but a relatively low adoption of I4.0 technologies, and sawmills remain largely based on mass production rather than being order driven. In contrast to the automotive industry, the raw material in the wood industry is far more unpredictable. The log size distribution and quality in a forest stand cannot be requested on demand

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Published online: 14 October 2026

[3]. Thus, the sawmill industry remains at an early stage of digital transformation. However, current equipment generates large amounts of data throughout the production process, with the same piece of wood being measured and assessed multiple times from the woodyard to the final product. One strategy to stay cost competitive is improved data utilization.

Maintenance and operational reliability are highly suitable for technology intensification [4]. Improved operational reliability contributes to reduced disruptions, more stable processes, resource efficiency, lower energy consumption, and extended equipment life [5]. In capital-intensive industries, maintenance has become a strategic enabler of production performance, asset longevity, sustainability, and resilience, where downtime can translate into substantial financial losses [6]. Its impact spans the entire asset life cycle, from design and engineering decisions to end-of-life strategies, through activities that restore, conserve, or extend asset functionality.

Industry 4.0 (I4.0) is a collective term for digital technologies and concepts, such as Artificial Intelligence (AI), Internet of Things (IoT) and Big Data (BD) analytics that integrate the entire value network from idea to recycling [7]. As I4.0 technologies have become more prevalent, the roles of people and organizations in successful technology adoption have gained increasing attention [8]. This is highlighted by Industry 5.0 (I5.0) with a focus on sustainable, resilient, and human-centered industry that effectively uses technology solutions [9]. Technologies such as IoT, AI, digital twins, and predictive analytics are revolutionizing how maintenance is planned, executed, and optimized. These tools enable real-time monitoring, data-driven decision-making, and predictive interventions that reduce unplanned downtime and extend asset life [10–12].

Although maintenance is increasingly recognized as a key enabler of digital transformation, limited research has examined technology readiness within maintenance functions in process industries such as sawmills. Existing Industry 4.0 readiness models primarily assess organizations at a general level and provide limited insight into the technological, organizational, and human factors influencing maintenance transformation. This study addresses this gap by assessing technology readiness in a Swedish sawmill maintenance organization and identifying priorities for future development. The aim is to study the evolvement of technology readiness of the maintenance operations toward I4.0/I5.0, with focus on how technology readiness supports human-centricity. To achieve this, the study investigates technology readiness of maintenance operations in a Swedish sawmill and propose suitable roadmap activities for strengthening maintenance as a strategic enabler of future industrial transformation.

2 Background and theoretical framework

2.1 Characteristics of the sawmill industry

The sawmill industry is heavily invested in machines and equipment with a high degree of automation, which requires high operational reliability. The production process is sensitive to disruptions; a stop in one section often leads to a halt in operations of the whole line [13]. In addition, sawmills are associated with dusty, heavy, and noisy work environments where moving machine parts and the constant flow of raw materials pose safety risks to people [14–16]. These conditions place demands on both technical systems and organizational practices. The traditional work environment and culture require change to meet the high demands that modern, safer work environments impose. To meet these demands, the sawmill industry requires development toward more advanced technologies and work methods, such as concepts and principles from I4.0 and I5.0, which have the potential to improve safety, reliability, and efficiency [3]. Such transformation goes beyond technological upgrades and involves deep changes in perspectives, attitudes, as well as working methods and technology use [17]. However, the forest industry has been shown to lack the innovative drive [2] required to make technological shifts comparable to those that the steel and automotive industries are undertaking.

2.2 Technology readiness and industrial transformation

The state of a system, organization, or process in terms of its preparedness to adopt, implement, or benefit from specific technologies. Technological readiness assesses the starting point before engaging in a development or maturing process, capturing the current capabilities, resources, and conditions necessary to successfully progress toward a desired future state [18]. To understand and guide technology transformations, several models assessing I4.0 readiness and maturity have been developed, some of which are illustrated in Table 1. Early frameworks like IMPULS [19] focus on strategic, operational, and technological dimensions [18, 20], while others, such as [21] and [22], emphasize digital capabilities and data governance. More recent models integrate both internal organizational dynamics and external ecosystem factors [20, 23]. Collectively, these frameworks emphasize that successful I4.0 transformation requires not only technological preparedness but also strategic alignment and a culture that supports change.

One of the more comprehensive models is the maturity framework proposed by Schumacher et al. [18]. The model includes nine categories that together assess an

Table 1 Comparison of selected Industry 4.0 readiness and maturity models (created by authors)

Aspect	IMPULS	Schumacher et al., [18]	Gökalp et al., [21]	Lucato et al., [22]	Sony and Naik, [20]	Nick et al., [23]
Internal						
Strategy	x	x	x		x	x
Leadership and organization	x	x			x	
Technology	x	x	x	x	x	x
Operations	x	x				
Products	x	x			x	x
Services	x				x	x
Employees		x			x	x
Culture		x				
Governance		x				
External						
Technology in the supply chain					x	x
Customers		x				
Ecosystem						x

organization's I4.0 maturity: Strategy, Leadership, Technology, Operations, Products, People, Culture, Governance, and Customers. These dimensions collectively capture the interplay between technological readiness, organizational capabilities, and human competences necessary to achieve successful digital transformation. *Strategy* evaluates the alignment of business goals with I4.0, including the presence of a roadmap, resource allocation, and business model adaptation, while *Leadership* focuses on managerial commitment and coordination. *Technology* examines the availability and use of modern Information and Communication Technology (ICT), mobile devices, and machine-to-machine communication. *Operations* address how processes are structured, decentralized, and supported by digital tools, as well as the degree of interdisciplinary and cross-functional collaboration. *People* assess digital competencies of employees, openness to change, and autonomy. *Culture* considers openness to innovation, knowledge sharing, and the perceived value of ICT, while *Governance* concerns the extent to which the organization has established clear, standardized, and integrated structures, procedures, and rules that guide daily work, risk management, coordination, and decision-making. A mature governance system ensures predictable workflows, transparent responsibilities, and consistent documentation practices that support continuous improvement and enable the organization to move beyond reactive work patterns. The final two categories, *Products* and *Customers*, evaluate the use of customer data, digitalization of services, and the degree of product customization and integration into digital ecosystems.

These nine categories also align well with the principles of a learning organization, e.g., Senge [24] or Garvin [25]. A learning organization can be explained as being accomplished at creating, obtaining, and transferring knowledge in parallel with being able to adapt its behavior to involve novel ideas and understanding [25]. Previous research identifies several success factors contributing to a learning organization, including collaboration within cross-functional teams, trustful and open communication, knowledge exchange, continuous improvement through learning loops [26], and leadership behaviors and organizational conditions that foster shared understanding, psychological safety, trust, and clarity of roles and competences supporting learning processes [27].

2.3 Maintenance transformation

As the sawmill industry undergoes broader technological and organizational change, maintenance plays a vital role in enabling this transformation. Modern maintenance is no longer limited to ensuring equipment uptime; it increasingly contributes to strategic development, operational resilience, and workplace safety. This shift requires both technological advances and changes in organizational culture, aligning well with the broader I4.0 transformation described in earlier sections. Current maintenance practices in sawmills are mainly based on planned maintenance interventions that are carried out under non-ergonomic and possibly risky working conditions [28, 29]. Introducing bold and transformative measures requires a culture that supports innovation and change readiness [29].

Several maintenance models can support such a shift, such as World-Class Maintenance, Maintenance 4.0, and Smart Maintenance. World-Class Maintenance emphasizes standardized practices, continuous improvement, and strategic alignment with production goals [30]. Maintenance 4.0 advances this by leveraging I4.0 technologies, such as sensors, condition monitoring, and automated data

collection, to improve decision-making and efficiency [10]. More recent research on Maintenance 5.0 emphasizes a human-centered and socio-technical perspective, arguing that advanced maintenance systems should integrate digital technologies with human expertise, promote human-in-the-loop decision-making, and support information-rich, system-integrated approaches that enhance reliability, resilience, and sustainability rather than replacing human judgment [31]. Smart maintenance consolidates technological innovation with organizational transformation by focusing on four pillars: data-driven decisions, internal and external integration, and human capital [4]. In this framework, maintenance becomes a domain where learning loops, cross-functional communication, and shared understanding are essential, areas that align closely with the principles of a learning organization [24, 25]. Employees are supported by predictive tools and real-time information, shifting their role from reactive problem-solving to proactive system optimization.

Further, dynamics in planning are achieved through predictive maintenance, which enhances the accuracy and timeliness of maintenance scheduling by using real-time condition data to anticipate failures before they occur [32]. Predictive maintenance increases the dynamic of planning, enabling organizations to move from scheduled interventions to condition-based and ultimately autonomous maintenance strategies. Such development requires not only technical tools but also a capability for dynamic business development [33], for example, by adopting new service models, rethinking roles and competences, and restructuring information flows. In this way, maintenance transformation is both a driver and an outcome of the digital and organizational shifts needed to support I4.0 and I5.0 ambitions, both generally and specifically within the sawmill industry.

In this study, Schumacher et al.'s [18] Industry 4.0 maturity model provides the primary analytical framework for assessing technology readiness within the maintenance function. The complementary perspectives of learning organizations, maintenance transformation, and Industry 5.0 are then used to interpret the results and guide the development of roadmap activities for future improvement.

3 Research methodology

3.1 Research design

Inspired by Design Research Methodology [34], the study followed a qualitative case study approach comprising four stages: preliminary observations and study design (Sects. 3.1–3.2), empirical data collection (Section 3.3), data analysis (Section 3.4), and validation and roadmap development (Section 3.5). Figure 1 provides an overview of the process.

The interest in studying the sawmill industry emerged through external monitoring and dialogue with stakeholders in wood manufacturing. It was evident that maintenance and operational reliability had received limited attention in innovation initiatives, making them relatively unexplored areas within the sector. A case study was therefore conducted, as this approach enables examination of a phenomenon in its natural environment [35].

The aim was to study and map the existing production system and its processes in relation to the current state of maintenance, with the objective of improving the overall maintenance system. The sawmill site identified for the case study was carefully selected as a unit where different new initiatives related to maintenance had been introduced during recent years. Initial informal observations were conducted to obtain an overview of the production processes and equipment in use. Insights from these observations informed the design of the research methodology, including the interview and workshop phases. The study was carried out by four researchers (the authors), who jointly planned the research and discussed the interpretation of findings throughout the study. Two researchers conducted the interviews, while all workshops were facilitated by the full research team.

The research group was transdisciplinary, comprising academic researchers and industrial specialists with expertise in maintenance, leadership, production systems, and wood sciences. The emphasis on a transdisciplinary research approach is important as it highlights the co-creation between academia and industry when approaching opportunities and challenges in today's manufacturing landscape [36, 37].

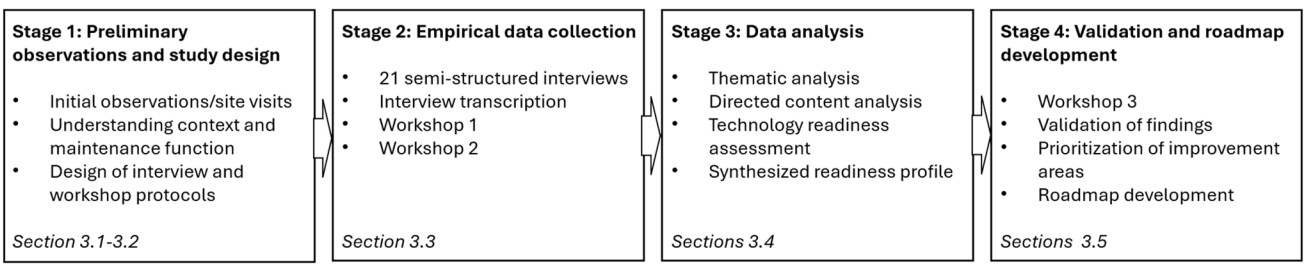


Fig. 1 Research methodology and study process (created by authors)

3.2 Case study description

The case study was conducted at Swedish forestry and wood manufacturing industry group. The company is an export-oriented organization with operations spanning the entire value chain, from forestry to international markets, and one of Europe's largest production capacities in both pulp and wood products. This study focuses on the maintenance function of one of the company's sawmills.

The broader sawmill industry is characterized by a contradictory relationship with technological development. Many individual process steps have a high degree of automation corresponding to Industry 3.0 (I3.0), yet the overall integration of I4.0 technologies remains limited. Production is largely based on mass production principles associated with Industry 2.0 (I2.0), with a primary focus on maximizing output volume rather than the value extracted from raw materials [33]. Furthermore, the industry is highly capital-intensive, relying on large-scale machinery that demands high levels of operational reliability [3], and is associated with harsh working environments characterized by dust, heavy workloads, and high noise levels. Current maintenance practices are predominantly based on planned maintenance activities carried out under physically demanding and ergonomically challenging conditions, while moving machine components and the continuous flow of raw material introduce significant safety risks for personnel. Thus, the study addresses the transformation of sawmills from I2.0/3.0 towards I5.0.

3.3 Empirical data collection

In-depth interviews were conducted to explore experiences related to organizational structure, technology use, and improvement potential. Purposive sampling was used to capture participants' perceptions and understanding of the phenomenon under study [38]. The interviews were carried out either online via Microsoft Teams or in person at the sawmill. A semi-structured interview format was employed [39], following the interview template provided in Appendix 1.

A total of 21 interviews were conducted between November 2024 and February 2025, see Table 2. Interviews lasted between 28 and 55 min (12 h 42 min in total) and were audio-recorded with informed consent. The interviewees represented 14 different roles spanning maintenance, production, engineering, and management functions. This ensured representation of both operational and strategic perspectives (Table 2).

Interviewees with strategic planning responsibilities participated in two additional workshops, while those with more operational planning responsibilities attended one workshop, see Fig. 1. Each workshop lasted 90 min, amounting to a total of 4.5 h. Workshops 1 and 2 were based on the interview findings and aimed to establish consensus and further elaborate identified themes. Various lines of reasoning were explored to foster collective learning within each workshop. Workshop 3 applied the collected data to propose how short- and long-term planning should be prioritized to develop and improve the maintenance function and propose suitable roadmap activities.

3.4 Interview analysis

The analysis assessed the current state of technology readiness and identified opportunities for future development. Interview data were analyzed in two phases: an abductive thematic analysis based on the interview guide [40], followed by a directed content analysis using selected dimensions from Schumacher et al.'s I4.0 maturity model

Table 2 Overview of interviewees and workshops (created by authors)

Interviewees (roles)	Category	Number of interviewees	Interview length (min)	Interviewees IDs	Workshop (WS) Participants		
					WS 1 Jan. 16 (90 min)	WS 2 Feb. 19 (90 min)	WS 3 Feb. 25 (90 min)
Lean Coordinator, Maintenance Developer, Operations Engineer, Health & Safety Engineer	Engineering and development	Four (4)	45, 30, 41, 40 ∑ 156	16, 18, 19, 21	16, 18, 19	19	16, 18
Maintenance Technician (Mechanical and Electrical)	Maintenance Technician	Seven (7)	37, 28, 28, 55, 37, 34, 28 ∑ 247	8, 9, 10, 11, 12, 13, 14			
Maintenance Planner (Mechanical and Electrical), Maintenance Engineer	Maintenance engineering and planning	Four (4)	31, 32, 35, 44 ∑ 142	3, 4, 5, 6		3, 4, 5, 6	
Maintenance Manager, Head of Production, Lean Manager, Site Manager, Production Supervisor	Managers	Six (6)	32, 35, 42, 43, 32, 33 ∑ 217	1, 2, 15, 17, 20, 22	1, 2, 15, 17, 20		1, 2, 15, 20
Total fourteen (14) roles	Total four categories	Total 21	Total 762 min (12 h 42 min)		Total 8	Total 5	Total 6

[18] as a predefined analytical framework [41]. Together, these phases enabled theory-informed interpretation while remaining grounded in participants' experiences.

All interviews were transcribed and subjected to a thematic analysis inspired by [40]. The interview guide included three overarching themes: organizational aspects, technology use, and improvement potential, which provided an initial analytical structure. Each transcript was reviewed and summarized within these themes, after which sub-themes were developed inductively. Patterns, recurring ideas, and noteworthy statements were identified, providing an overview of organizational, technological, and improvement-related issues across roles.

In the second phase, a directed content analysis was conducted using Schumacher et al.'s I4.0 maturity model [18] as the analytical framework. This enabled systematic coding according to constructs describing organizational readiness and maturity. The model, originally designed to analyze maturity levels based on questionnaire data using Likert-scale questionnaire items, was adapted for qualitative use by shifting from numeric maturity scoring to an interpretive assessment of how each maturity dimension was articulated in the data. Rather than calculating quantitative maturity scores, the analysis examined the presence, depth, and variety of meaningful statements within each dimension. Products and customers were excluded, as these dimensions primarily concern the business-unit or market interface and were not applicable to the internal focus on maintenance operations.

3.4.1 Operationalization of meaningful statements

Meaningful statements were operationalized using criteria aligned with the study aims. A statement was coded as meaningful when it:

- provided an explicit description of current practices, routines, challenges, or capabilities within the maintenance function;
- illustrated behaviors, actions, or examples that reflected conditions related to any of the maturity dimensions;
- conveyed assumptions, expectations, perceived challenges, or perceived enablers linked to digitalization or organizational readiness;
- referred to developments over time, such as changes experienced, lessons learned, or aspirations for future improvements.

General or abstract remarks without empirical grounding were not coded. The criteria guided inclusion in the deductive categorization process (Table 3).

Table 3 Coding framework and operational definitions for Industry 4.0 maturity dimensions (created by authors)

Dimension	Code definition	Indicators
Operations	Operational processes, integration, and collaboration capabilities supporting I4.0	• Decentralization of processes • Use of modelling and simulation in maintenance • Interdisciplinary and interdepartmental collaboration • Integration of processes • Standardization of procedures • Coordination of resources
Strategy	Statements about strategic planning, direction, or alignment related to Industry 4.0 and digital transformation. This includes roadmaps, resources, and strategic fit	• Mention of a digitalization roadmap • Allocation or lack of resources for digitalization • Business model adaptation due to digitalization • Alignment of digital initiatives with company vision or strategy • Communication/documentation of digitalization activities
Leadership	Refers to leadership commitment, capability and structures that support I4.0 development	• Leadership willingness to pursue digitalization • Management competences in digital technologies • Existence of a central coordinating body for digitalization • Leaders communicating digitalization priorities • Change leadership and sponsorship
People	Employees' competencies, readiness, openness, and autonomy related to digital transformation	• ICT competences of employees • Openness toward modern technology • Employee autonomy in digital environments • Learning capability, upskilling needs • Digital literacy gaps
Culture	Shared norms, values, and organizational mindset affecting I4.0 adoption	• Knowledge sharing culture • Openness to collaboration across company boundaries • Organization values the role of ICT • Innovation-friendly mindset • Risk-taking, experimentation, acceptance of failures
Technology	Technological infrastructure supporting I4.0, including ICT systems, connectivity, automation	• Existence and use of modern ICT infrastructure, such as • Mobile device use in operations • Sensorization and data collection capabilities • Digital/connected technologies and platforms • Robotics and automation
Governance	Formal rules, standards, legal structures, and policies enabling or constraining I4.0	• Labor regulations relevant for digitalization • Suitability of technology-related standards • Data governance (access, rights, compliance) • Cybersecurity policies

3.4.2 Coding procedure, validation, and bias mitigation

One researcher served as the primary coder and conducted the initial coding of all interview transcripts. Using a single primary coder reduced interpretive variation and ensured consistent application of the coding criteria. To strengthen the robustness of the analysis, three additional researchers reviewed coded excerpts, assessed code-segment alignment, and evaluated whether the coding criteria had been applied consistently. When uncertainties or differences in interpretation occurred, the research team returned to the original transcripts and jointly reassessed the material. This iterative review process was conducted across three cycles, resulting in a shared and well-grounded interpretation of the data.

The interviews were similar in duration (with only minor variations of a few minutes), so time-based or length-based normalization was not required. Some participants were more verbally expressive while others required more prompting from the interviewers, but these differences did not affect the substantive content of the interviews. Coding was therefore based on content richness, not frequency or verbosity.

Differences in topic depth across interviews were expected because participants held different roles and worked with various aspects of maintenance. These variations were treated as meaningful contextual variations rather than sources of bias. All participants' background knowledge and perspectives were considered equally relevant for the analysis. Reflexive discussions and repeated returns to the raw transcripts helped avoid over-interpretation and ensured that the coding remained closely anchored in the empirical material.

3.4.3 Aggregation into readiness dimensions

Coded statements were aggregated to form a qualitative proxy for technology readiness. Readiness levels were assessed based on the number and richness of relevant insights within each maturity dimension. A higher concentration of meaningful statements was interpreted as indicating more developed practices, while fewer insights suggested weaker or less established practices. All coded statements were treated as analytically equivalent, with no weighting applied between responses. Consequently, the assessment is relative and descriptive rather than directly comparable to standardized quantitative maturity assessments.

The coded material was then aggregated by maturity dimension to construct a qualitative readiness profile. Each dimension reflects the breadth and depth of relevant insights rather than the number of coded segments alone, providing a context-sensitive assessment aligned with the qualitative nature of the study. To support interpretation, the readiness profile was visualized using a radar diagram summarizing relative maturity across dimensions.

After coding was finalized, all statements were consolidated into the maturity dimensions included in the analytical framework (Operations, Strategy, Leadership, People, Culture, Technology, and Governance). Throughout the process, the researchers documented analytical reflections, creating an audit trail that supported transparency and traceability. The resulting readiness profile should therefore be interpreted as a context-sensitive indicator of strengths and areas for improvement rather than as a formally quantified maturity level.

3.5 Workshop analysis

In line with the design-oriented nature of the study, workshops were conducted to validate the assessment results and support roadmap development.

During Workshops 1 and 2, participants documented ideas using sticky notes and discussed them in small groups. All researchers participated as facilitators, supporting documentation and probing discussions when needed. Sticky notes and whiteboards were used as visual support, and workshop outputs were documented digitally during the sessions.

Outputs from Workshops 1 and 2 were organized and analyzed thematically with the guiding question: *What is needed to develop maintenance?* The aim was to identify key areas for maintenance development. Findings were cross-checked against interview data to ensure consistency across data sources. The synthesized results were subsequently brought forward to Workshop 3 for evaluation and prioritization.

Workshop 3 functioned as a validation and prioritization session. Interview and workshop findings were aggregated and discussed to build a shared understanding of short- and long-term goals for the maintenance function. A prioritization matrix was used to evaluate proposed activities according to importance and implementation difficulty. This enabled identification of activities suitable for immediate action and those requiring longer-term planning.

3.5.1 Bias mitigation in the workshops

To ensure the credibility and practical relevance of the proposed roadmap and readiness assessment, several measures were employed, including triangulation, participant validation, researcher reflection, and workshop-based evaluation. Participants generated and structured their own inputs through collaborative discussions, helping ensure that interpretations remained grounded in their perspectives rather than imposed by the researchers. The researchers acted as facilitators, supporting discussions and documentation rather than directing content. Multiple researchers participated in each workshop, and real-time documentation helped minimize retrospective interpretation and preserve the context of participants' contributions.

4 Findings

In this section, the main outcomes from the interviews and workshops are presented. The section begins with insights from the interviews describing the current use of technology within the maintenance function, followed by assessment of technology readiness using the I4.0 maturity dimensions. Finally, results from the workshops are reported, detailing the development of prioritized areas and associated actions for advancing maintenance practices.

4.1 Interviews: current use of technology

Maintenance technicians primarily use the computerized maintenance management system (CMMS) to manage work orders, fault reports, spare parts, and task prioritization. A new corporate-level system is currently being implemented, requiring parallel use of both systems. A production and downtime monitoring system supports the identification of recent disruptions and prioritization of maintenance activities. Other tools include control-system signal logging, vibration and temperature measurements for condition monitoring, remote troubleshooting tools, a separate safety application, and mobile phone cameras for documenting faults and maintenance actions.

Planners and schedulers primarily use the CMMS, production and downtime monitoring systems, and business intelligence (BI) tools, such as QlikView and Power BI. The CMMS supports planning and scheduling, inventory and material management, resource allocation, and time scheduling, while production and downtime data help identify bottlenecks and prioritize maintenance. BI tools support data analysis and visualization, while Excel is used for Gantt charts, lists, reports, and as a bridge between systems. Microsoft Teams and pulse meetings support daily and weekly coordination, as well as planned maintenance shutdowns.

Managers use production and downtime monitoring systems to track availability, short stops, technical availability, and overall equipment effectiveness (OEE), while BI tools support key performance indicators (KPIs) and trend analysis. The CMMS provides information on work orders, preventive maintenance (PM) backlogs, costs, and inventory. The company manual for investment supports project initiation, budgeting, and KPI follow-up. Managerial work involves substantial meeting activity, supported by Microsoft Teams, BI reports, and a digital pulse-meeting board to support the physical pulse meetings.

Engineers and specialists use measurement, process, quality, condition-monitoring, production, downtime, and BI systems to support root cause analysis, prioritization, improvement activities, preventive maintenance, and supplier requirements. Across all roles, telephones, email, and Microsoft Office applications support daily work and routine communication.

Taken together, the interview findings on current technology use reveal a maintenance function equipped with several digital tools, but facing challenges in achieving systematic and integrated utilization. To understand how these practices translate into organizational readiness for digital transformation, the next section presents the results of the technology-readiness assessment.

4.2 Interviews: technology readiness

The key results of the study with respect to technology readiness are outlined in Tables 4 and 5. The results are categorized according to the current situation and areas for improvement, with illustrative quotes provided in the tables.

The readiness profile reveals both established strengths and several maturity gaps that hinder progress toward more advanced digitalized maintenance practices. These gaps form the basis for the improvement areas described in the following section.

4.3 Interviews: areas for improvement

Table 5 summarizes the key improvement areas that interviewees identified as most important for strengthening maintenance-related technology readiness. The areas are organized according to the same maturity-model dimensions used in the directed content analysis to ensure analytical consistency.

From the analysis, three cross-cutting themes stand out:

1. Shifting from reactive to proactive maintenance: Several respondents emphasized the need to reduce emergency repairs, strengthen preventive and predictive practices, and improve the use of data to support decision-making.
2. Supporting people and leadership capabilities: Competence development, clearer roles, better onboarding, and more visible leadership were considered essential to sustaining digitalization efforts.
3. Establishing standardized and integrated ways of working: Challenges related to inconsistent methods, silo thinking, poor shift handovers, and underutilization of digital tools indicate the need for clearer governance and harmonized work processes.

These themes form a bridge to the more synthesized readiness profile presented in Section 4.4 and directly inform the development activities identified in the workshops (Sections 4.5 and 4.6).

Table 4 Results with respect to current situation in relation to technology readiness (created by authors)

Category	Current situation in relation to technology readiness	Illustrative quotes
Operations	• Established planning routines and meetings, supported by planning tools and coordination mechanisms • The maintenance organization collaborates extensively with internal and external actors • A substantial proportion of emergency maintenance work	"It's a lot of check ins, short check ins. We have small production meetings, pulse meetings, and we go over the past 24 h to see what we need to focus on." "And then we have a lot of external contractors coming in from time to time, and we're involved in that to varying degrees. We have internal coordination meetings every Friday where we look at what's coming up next week… and whether we see any conflicts or overlaps we need to sort out. " "A typical day is that you sit down… and then the phone rings. Something has broken, and then you head out to deal with it."
Strategy	• Clear effort exists for implementing modern technologies and improving operational efficiency • The technology strategy is not fully aligned with operations strategy • There is a strong emphasis on following project plans and manuals	"We buy things too fast, without proper studies." "[The central level] comes in with bureaucratic templates and wants us to do things that way, even though we want to do them this way…"
Leadership	• Lower and middle management are actively involved in day-to-day operations and decisions • A desire to improve communication and presence in the workplace • Recent reorganization	"I really want to prioritize being present, so I'm trying to pass by at least one department every day and actually talk with the staff." "There was simply a need to bring about a change, so it's a bit like changing the coach of a football team."
People	• The organization has skilled employees • Training in modern technologies is offered • Challenges in recruiting and retaining skilled staff	"It's nearly impossible to find competent electricians." "We have quite a lot of technology, but it's the human who is the limitation."
Culture	• Culture of strong problem-solving, with a focus on finding solutions when issues arise • Informal problem-solving and local workarounds • "Silo thinking" and fragmented communication across shifts and functions	"We're very good at solving problems and being clever about coming up with solutions to move forward. That's something we're extremely good at." "We don't even know what's been done during the last stop."
Technology	• Technicians primarily use the computerized maintenance management system and have basic digital maturity • Managers and engineers use technologies such as production monitoring and business intelligent systems for data analysis, and digital tools such as pulse boards	"We can access at least 90% of all the computers from the electrical workshop downstairs, you can connect remotely from there. And external suppliers can also log in and access the motors, so they can help with troubleshooting remotely." "We do have modern systems, like in the sawmill… we can monitor an awful lot."
Governance	• Established processes and systems to manage operations and maintenance • Weak process standardization and inconsistent working methods	"We can work in one and the same system for planning, execution, and inventory for managing all our parts." "There are no standardized ways of working, which means that when something happens, it's really hard to get solid facts… because everyone does things completely differently."

Table 5 Results with respect to proposed improvement areas (created by authors)

Category	Areas for improvement	Illustrative quotes
Operations	• Reduce the focus on emergency repairs and strengthen preventive and predictive maintenance planning • Enhance data utilization for decision-making and optimize the use of digital tools • Improve shift handovers and internal communication • Increased collaboration and a holistic approach to maintenance operations • There is a need to improve standardized working methods and reduce lead times	"We're great at solving problems, but not at preventing them." "We're bad at shift handovers. Things fall between the cracks." "There are no standardized ways of working, which means that when something happens, it's really hard to get solid facts… because everyone does things completely differently."
Strategy	• The strategy can be more long-term and detailed, especially when it comes to technology adoption and integration • Strengthen long-term maintenance and technology strategy through clearer prioritization and more structured, fact-based investment decision-making	"We have a lot of technology out there that isn't being used… I think we've paid a lot of money for it, and it's not being used." "The biggest obstacle is… well… knowing what we should prioritize, I'd say. We work with a maintenance-priority list that we go through every day."
Leadership	• More visible and proactive leadership, leading to active decisions, is needed • Improve communication between different levels and functions of the organization	"Something that's becoming more and more obvious to me is how little time managers and leaders actually spend out in the operations…//… They really need to be out there, seeing what's going on…//… Seeing what's happening in the workplace, what it looks like, whether things are in order that kind of stuff. I think that's super important." "How do you create a good [working] climate, involvement? …//… We need to make first-line managers more like actual managers."
People	• Need to improve skills transfer and training • Strengthen structured competence development and onboarding across roles • Improve organizational understanding of processes and workflows	"It takes two to three years to build basic competence, and not everyone is suited for the job." "The facility itself can be as safe as possible, but in the end it's still a human being who has to take care of it, and if that person doesn't have the knowledge and competence, then things go wrong in the end."
Culture	• Greater focus on continuous improvement and better communication across different levels of the organization • Foster a culture of collaboration and shared responsibility • Clarify the value of maintenance	"What clearly needs improvement is the storage or spare parts management. Everything is spread out in several places, it's hard to find things, and not everything is entered into the system, so you cannot actually search for it." "You're driving around in a forklift that costs as much as a Ferrari, but I don't think the people driving the forklift would look like that [driving irresponsible] in the cab if they were driving a Ferrari instead."
Technology	• Better use of existing technologies and integration of modern technologies such as AI for predictive maintenance • Need for more flexible data solutions and better summarization of production data • Improve integration of digital tools into operational workflows	"We have a lot of technology …//… and no one even asks why it isn't being used, which I also find strange. Is there something wrong with it?" "Production data collection that will give us better access to real-time data…//… something we really should have done 20 years ago…"
Governance	• Improve governance structures to better support adoption and integration of modern technologies • Strengthen risk governance and documentation compliance	"…that we become better at following the project handbook [company manual for investment]… all changes that are to be made to a machine should really be verified by the machine suppliers."

4.4 Interviews: synthesized technology-readiness profile

This section synthesizes the maturity assessment across all I4.0 dimensions, integrating the detailed findings from the previous sections into an overall readiness profile. In line with Schumacher et al's Industry 4.0 maturity model, the qualitatively derived relative maturity levels reflect the extent to which organizational practices, structures, and capabilities associated with each dimension are currently realized. Figure 2 presents a radar diagram that visualizes the relative maturity levels derived from the qualitative analysis in Tables 4 and 5. The radar diagram provides a qualitative assessment of readiness across the identified dimensions, rather than representing quantitative maturity scores. Each dimension reflects the relative breadth and depth of meaningful statements identified during the directed content analysis, rather than numerical scores or frequency counts. A higher relative level in the diagram indicates that practices associated with a given dimension



Fig. 2 Synthesized readiness profile across I4.0 maturity dimensions (created by authors)

were described as more established, integrated, and consistently articulated across roles, while lower levels indicate more fragmented or reactive practices. The radar diagram therefore serves as an interpretive aid for comparing relative maturity across dimensions and should be understood as a qualitative proxy for technology readiness, not as a quantified maturity assessment.

In this context, higher maturity reflects practices that are consistently established, formally supported, and effectively integrated into daily maintenance workflows, while lower maturity indicates fragmented, reactive, or inconsistently applied practices that constrain the organization's ability to advance toward predictive and data-driven maintenance. The narrative below elaborates on the strengths and weaknesses reflected in the diagram.

The radar diagram shows that the organization demonstrates its highest maturity in the Technology, Operations, and Leadership dimensions. *Technology* maturity is strengthened by the availability of modern digital systems, remote troubleshooting capabilities, and the use of production and downtime monitoring together with BI tools. However, readiness varies across roles and tasks, and some tools are underutilized due to limited training, integration challenges, and low trust in digital solutions. The primarily challenge is therefore not technological availability, but the integration of systems into daily decision-making and maintenance practices. To improve technological readiness, there is a clear need to increase adoption, enhance data utilization for decision-making, and actively explore predictive maintenance and AI-based approaches.

Maintenance *operations* are relatively mature, with structured planning, planned shutdowns, cross-functional collaboration, and digital support. However, frequent short stops and reactive maintenance limit the capacity for preventive and predictive practices, as planning is often redirected toward acute issues. Respondents identified further needs for improved data and digital-system use, internal communication, and a more collaborative and holistic approach to maintenance.

Leadership is visible and engaged in daily operations, but respondents identify challenges regarding decision transparency, involvement, and consistency across levels. Following the reorganization, greater emphasis has been placed on feedback and role clarity. However, more inclusive leadership is needed to support I4.0 initiatives and continuous improvement.

The People and Culture dimensions show low-to-moderate maturity. Regarding *people*, there is strong awareness of competence development and commitment to upskilling. However, recruitment, onboarding, knowledge transfer, and high staff turnover challenge the development and retention of operational competence, limiting readiness for scaling digital initiatives.

Cultural readiness is moderate. A strong problem-solving and innovation culture is counterbalanced by silo thinking, fragmented communication, and reliance on informal workarounds. While collaboration and a more proactive, learning-oriented culture are developing, challenges remain in cross-shift communication, resistance to change, and inconsistent practices. The strategic importance of maintenance is also not yet consistently recognized in the organization.

The lowest maturity levels appear in Strategy and Governance. *Strategic* readiness is underdeveloped. Although initiatives and investment discussions exist, there is no unified long-term I4.0 roadmap. Strategic tools are applied inconsistently, and communication gaps hinder alignment and decision-making. Investments are often driven by immediate operational needs rather than long-term priorities, resulting in insufficient preparation and integration.

Governance structures are emerging but not yet robust. Formal procedures for work processes, documentation, safety, compliance, and risk management exist but are inconsistently standardized and applied. Gaps in documentation, integrated information systems, and consistent data structures further limit coordination and technology integration. These findings reflect a governance maturity level where formal structures exist but are not yet robust, harmonized, or consistently applied.

In summary, the interviews indicate a solid technological and operational foundation for I4.0, supported by digital tools, structured workflows, pulse meetings, effective shift handovers, and planned maintenance. However, cultural and human dimensions remain less mature, with challenges in shared responsibility, cross-shift collaboration, skills, recruitment, and retention. Progress toward I4.0/I5.0 requires stronger strategic planning and governance, clearer roles, structured training and onboarding, improved data and system integration, and greater use of AI for predictive maintenance. Strengthening collaboration across shifts and departments is also essential for a more cohesive, learning-oriented culture.

4.5 Workshops 1 and 2: concretization of areas for improvement

Workshops 1 and 2 were designed to recognize areas of practice to develop the maintenance function. Five principal areas of practice were identified for development: *Maintenance development*, *Organizational development*, *Learning*, *Work processes*, and *Planning and prioritization.*

Regarding *maintenance development*, workshop participants emphasized greater awareness of maintenance activities and their impact on overall process performance. They highlighted continuous operator-driven maintenance through daily routines, as well as asset management to support effective maintenance, long-term performance, and a lifecycle perspective.

Workshop participants highlighted *organizational development* as important for the maintenance function, emphasizing culture, attitudes, and improved communication across roles. A more holistic understanding of organizational processes and business knowledge was seen as essential for strengthening collaboration and communication.

When it came to *learning*, workshop participants identified this as a key area requiring further development and the need for long-term competence development through education, training, upskilling, and reskilling were emphasized. Clear roles and responsibilities were also considered essential for sustained competence assurance and supporting employees through ongoing technological development.

Work processes were identified as requiring further development, particularly through standardized ways of working and improved efficiency. Participants highlighted on-the-job training and better use of existing and emerging technologies to support and enable effective maintenance processes.

Planning and prioritization were identified as key development areas. Participants emphasized systematic follow-up, clear prioritization, and improved planning routines that balance short- and long-term perspectives to support structured decision-making and implementation.

4.6 Workshop 3: creation of roadmap

Workshop 3 applied the collected data to propose how short- and long-term planning should be prioritized to propose suitable roadmap activities. During the workshop it became evident that most identified areas of practice for development were perceived as important. Prioritization primarily differentiated areas based on implementation effort (easy versus difficult), thereby implying actions suitable for the short term and the long term, respectively.

Short-term priorities (important and easy to implement) included organizational culture and individual attitudes, training in business-related knowledge, active leadership involvement and visibility, formulation of a maintenance strategy, long-term planning, adopting an asset life-cycle perspective, and analysis of the external environment. For the long-term horizon (important but difficult to implement), the following areas were identified: external (industry-wide) culture and attitudes, development of business knowledge, competence assurance, implementation of operator-driven maintenance, short-term planning, and technology development to support decision-making, system integration, and data visualization.

Based on the prioritization results, actionable activities were identified to inform the development of a technology roadmap, see Fig. 3. The actions were categorized using the

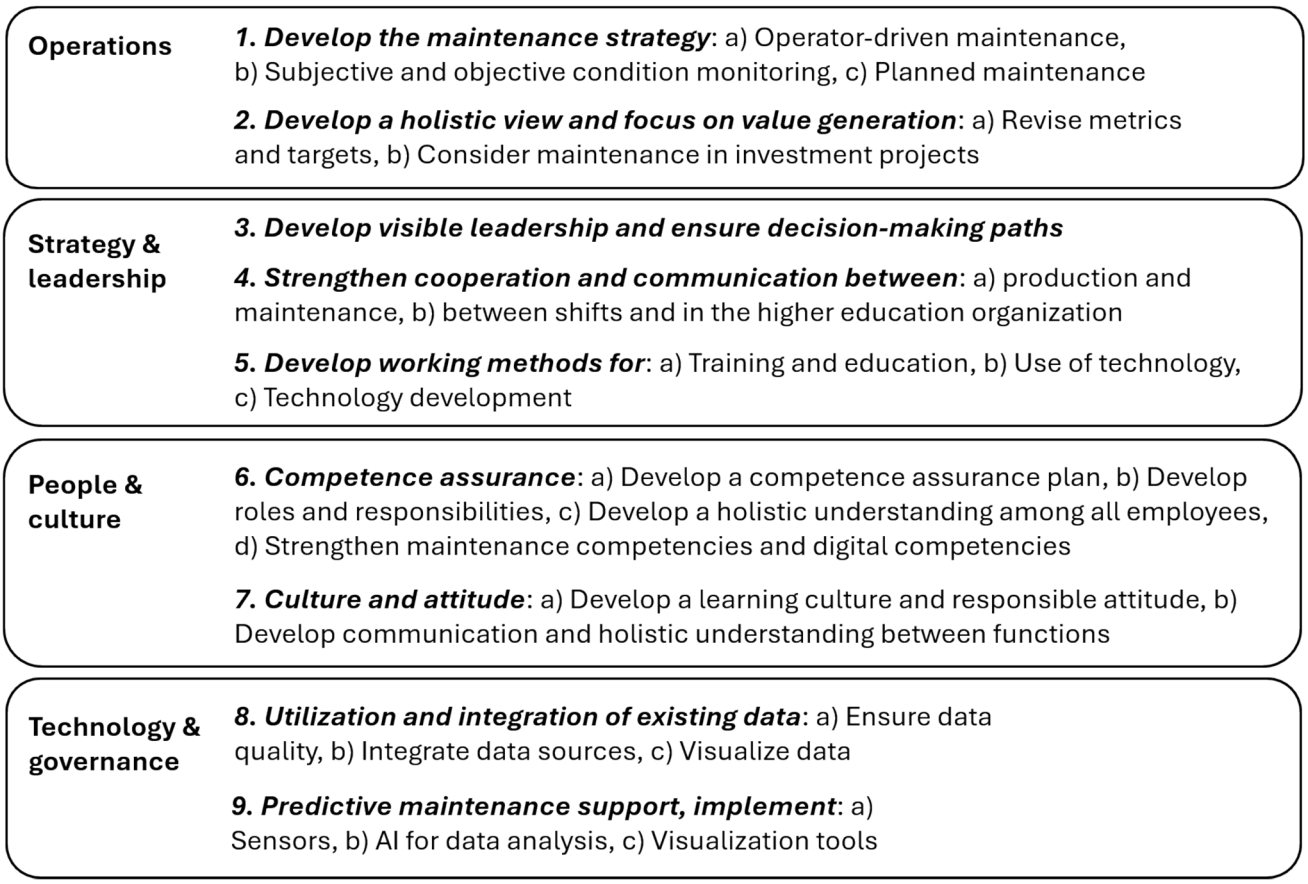


Fig. 3 Prioritized development areas supporting technology readiness in maintenance (created by authors)

I4.0 maturity model proposed by Schumacher et al. [18], by clustering strategy and leadership, culture and people, and technology and governance into three distinct categories. From this set of actions, the most urgent activities were selected for immediate implementation, while others were scheduled for implementation over a longer-term horizon.

5 Discussion

The results from this study show some areas of special attention for enhancement of the maintenance function especially in relation to the eras of I4.0 and I5.0. Findings highlight that advancing technology utilization and work processes alone is insufficient for successful development of maintenance as the study brings forth the importance of the I5.0 perspectives of human-centric, sustainability and resilience. The human-centric perspective emphasizes the necessity of organizational prerequisites, e.g., competence development, and cultural development and innovation for maintenance development. Up-skilling and re-skilling are aspects explicitly brought out in I5.0 [26], i.e., a need for the human-centric perspective within manufacturing to fully garner the benefits of digital transformation in the era of I4.0. To leverage advanced technologies effectively, companies must invest in up-skilling and re-skilling of the end users. Otherwise, investments in novel solutions risk underperformance, as technological potential cannot be realized in isolation [29]. The culture should focus on continuous improvement and shift in employee mindset with shared responsibility for assets. To achieve this, organizational conditions must be initiated, e.g., time for dialogue and cross-functional communication, reflection and learning between organizational levels and teams. Therefore, top management should adopt a strategy of a learning organization based on trust, competence and responsibility among all employees including governance structures to support modern technologies [25, 27]. Focusing on a shared vision of building competence and knowledge to adapt and integrate modern technologies could be the starting point for initiating change. Leaders at all levels, from top management to team leaders, need to be visible and present to constantly evaluate and re-evaluate initiatives and results together with employees. This learning loop built on communication and mutual trust, is essential for building a learning organization, as confirmed by Garvin's definition [25].

Though not explicitly brought forward in this study it needs to be highlighted that in addition to the human-centric perspective of I5.0, the perspectives of sustainability and resilience are important for maintenance and operational reliability. Effective maintenance reduces resource use, energy consumption, and equipment wear, supporting more sustainable operations [5]. At the same time, a focus on reliability and dynamic maintenance enhances the ability to prevent, withstand, and recover from disruptions, which strengthens system resilience, particularly in interconnected value chains [6, 9]. Thus, making maintenance a key enabler of resilient operations.

The findings support the progress towards the concept of Maintenance 4.0, where digital solutions enhance predictive, preventive, and operational practices [4, 12, 32]. Thus, not only does the maintenance function benefit from technological advancement, but such initiatives can also serve as a visible starting point for broader organizational learning, cultivating an adaptive organization capable of continuous improvement. For the organization to reach a higher level of analytical capability a transition towards data- and knowledge-driven decision making in relation to the maintenance operations is necessary. The sawmill processes generate large volumes of data, though, much of this data remains underutilized primarily due to lack of, or low, analytics competence. Further, novel technologies create opportunities for safer working environments, improved skills development, and career pathways that empower workers rather than replace them.

A roadmap to technological readiness in the sawmill context emerges from this study. Technology should act as both a catalyst and a reference point, meaning that advanced systems in place allow the organization to identify opportunities, experiment with the technology, and adapt to new ways of working. For example, pilot studies and incremental testing are useful tactics, but success ultimately depends on human-centric design and engagement, emphasizing social sustainability and participatory approaches consistent with I5.0 principles. Maintenance emerged from the study as a strategic entry point for technological readiness and transformation. The I4.0 maturity model proposed by Schumacher et al. [18] is highly applicable as analytical model for studying technology readiness in the sawmill context. Its structured and multidimensional framework enables a comprehensive assessment of both technology and organization, helping to identify strategic, cultural, and workforce-related gaps that are critical for advancing toward I5.0.

Maintenance holds significant untapped potential as a strategic lever for achieving technology readiness with the capacity to drive sustainability, resilience, and innovation across industrial operations [7, 11]. To realize this potential, organizations must move beyond technical implementation and adopt a holistic strategy that integrates digital capabilities with organizational culture, human resource development, and long-term value creation [12].

Broadening the perspective, this study offers insights that extend beyond the sawmill industry. Other industries seeking to reach technological readiness can learn from the emphasis on aligning technology investments with organizational development. Beginning with maintenance as an entry point, building human competencies, piloting technologies, and integrating systems provides a generalizable approach to navigating technological challenges. Moreover, the study illustrates the value of transdisciplinary collaboration, combining interdisciplinary perspectives with boundary crossing between academia and industry can support innovation in manufacturing industry [12, 35].

6 Conclusions

The transition towards I5.0 calls for organizations to balance technological innovation with human and environmental priorities. Maintenance in the sawmill industry can develop under I5.0, where technology readiness supports human-centricity, sustainability, and resilience. Predictive and knowledge-driven tools within maintenance 4.0 can facilitate the reduction of waste and extend asset life. With such a view, maintenance becomes not only an operational necessity, but also an enabler of sustainability and resilience in the sawmill industry.

Practical implications for the sawmill industry emphasize the importance of effective communication across all departments, not only within maintenance function. Maintenance should be regarded as a prerequisite for resilient and robust production processes, enabling a more reliable system that also enhances human safety. The study highlights the need for strengthening maintenance practices, continuously involve operators and promoting a cultural shift in mindset towards shared responsibility for company assets. To accomplish this transformation journey, the suggestion is to use maintenance as a foundational arena for transformation. Positioning maintenance as an operational testbed enables structured experimentation with digital tools, data-driven methods, and new collaborative routines. Concurrently, building human competencies becomes essential; organizations should invest in continuous skill development, hands-on training, and learning environments that allow personnel to integrate digital technologies into daily work practices.

The study underscores that technological readiness in industrial settings is as much about people, learning, and organization as it is about technology. Advanced systems may yield limited success unless accompanied by competence development and cultural understanding. Maintenance functions offer a practical and strategic starting point,

supporting both operational improvements and broader organizational readiness for technological advancements. By integrating technology and human capability companies can pursue a more sustainable, human-centric development that aligns with both I4.0 and I5.0 principles.

One limitation of this study concerns the adaptation of a quantitative maturity model to a qualitative research context. The model applied is originally based on survey data with weighted assessment points. In this study, the number of relevant interview statements was used as a proxy for technology readiness, which constitutes methodological alteration and application. For future studies, a combination of qualitative interviews and quantitative surveys may provide a more robust assessment. An additional limitation is that this is a preliminary study involving only one organization. On the other hand, a substantial amount of data has been collected through 21 interviews with fourteen distinct roles, resulting in rich and nuanced data. The interview findings have been further developed and validated through three workshops and compared with research results from other industries through literature review. The results can therefore be considered to have a certain degree of generalizability.

Additionally, future research should explore the development of digital capabilities and the human-centric transformation required for sustainable I4.0 adoption, for instance by investigating how organizational culture, employee engagement, and leadership influence the integration of smart technologies. Understanding the interaction between human factors and technology development is essential for enabling human-centric and resilient production systems. Furthermore, future research addressing the I5.0 perspectives of sustainable and resilient maintenance operations are ongoing focusing on concrete examples and implications for KPIs such as safety, downtime resilience, energy impacts, and competence metrics. This research focuses on bringing forth crucial organizational changes, within wood manufacturing value chain collaboration, for effective maintenance and operational reliability that contributes to sustainability and resilient industries in conjunction with the human-centric perspective.

Appendix 1. Interview template

Background information

Gender
- Function/role
- Number of years at the workplace
- Number of years in the function/role
- Work experience (At the company and previous positions)

Theme 1 – Organizational aspects

Describe a typical workday. What are your tasks?

Who do you collaborate with? (Internal and external cooperation between different functions).

What works well in the organization, and what would you like to see improved?

Theme 2 – Use of technology: understanding interaction

What technologies (machines, IT systems, etc.) do you encounter during a typical workday?

What works well with technology, and what would you like to see improved?

Theme 3 – Improvement potential

Spontaneously, what would you say is the biggest obstacle in your daily work?

What would you like to change?

What are the biggest obstacles for maintenance operations?

Where do you experience the most stoppages and problems in production?

Do you have any concrete ideas for changes (organization + technology)?

What prevents production from being efficient (economic), safe (social), and environmentally friendly (ecological)?

Acknowledgements The study was carried out within the research project READY2, Sustainable, robust, and resource-efficient wood manufacturing industry with dynamic maintenance, funded by the Swedish Governmental Agency for Innovation Systems (Vinnova) [Grant number 2025-01202].

Author contributions All authors contributed to the study conception and design. Material preparations were performed by Mirka Kans, Kristina M. Eriksson, Liselott Lycke and Tinh Sjökvist. The interviews were conducted by Mirka Kans and Liselott Lycke, while workshops were conducted by Mirka Kans, Kristina M. Eriksson, Liselott Lycke and Tinh Sjökvist. The main part of the analysis was performed by Mirka Kans and Liselott Lycke then discussed and iterated with all authors. The first draft of the manuscript was written by Mirka Kans. All authors contributed to writing sections, constructed tables, drew figures and commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the Swedish Governmental Agency for Innovation Systems (Vinnova) [Grant number 2025–01202].

Declarations

Competing interests No competing interests.

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References

1. Skogsindustrierna (2025) Koll på svensk skogsindustri. https://www.skogsindustrierna.se/siteassets/bilder-och-dokument/rapporter/koll-pa-svensk-skogsindustri/koll-pa-svensk-skogsindustri_2025.pdf. Accessed 14 January 2026
2. Weiss G, Ludvig A, Živojinović I (2020) Four decades of innovation research in forestry and the forest-based industries–a systematic literature review. For Policy Econ 120:102288. https://doi.org/10.1016/j.forpol.2020.102288
3. Dumetz L, Gaudreault J, Bril El-Haouzi H, Thomas A, Lehoux N, Marier P (2019) Simulation and evaluation of coordination mechanisms for a decentralized lumber production system with coproduction. For. Prod. J. 69(4):260–271. https://doi.org/10.13073/FPJ-D-19-00002
4. Bokrantz J, Skoogh A (2023) Adoption patterns and performance implications of smart maintenance. Int J Prod Econ 256:108746. https://doi.org/10.1016/j.ijpe.2022.108746
5. Vargas B, Miño G, Vega P, Mariño J (2019) Application of resource efficient and cleaner production through best management practice in a pallet manufacturer sawmill located in the city of Puyo-Ecuador. Maderas-Cienc Tecnol 21(3):367–380. https://doi.org/10.4067/S0718-221X2019005000309
6. Holgado M, Macchi M, Evans S (2020) Exploring the impacts and contributions of maintenance function for sustainable manufacturing. Int J Prod Res 58(23):7292–7310. https://doi.org/10.1080/00207543.2020.1808257
7. Sousa-Zomer TT, Neely A, Martinez V (2020) Digital transforming capability and performance: a microfoundational perspective. Int J Oper Prod Manag 40(7/8):1095–1128. https://doi.org/10.1108/IJOPM-06-2019-0444
8. da Silva LBP, Soltovski R, Pontes J, Treinta FT, Leitão P, Mosconi E, de Resende LMM, Yoshino RT (2022) Human resources management 4.0: literature review and trends. Comput. Ind. Eng. 168:108111. https://doi.org/10.1016/j.cie.2022.108111
9. Breque M, De Nul L, Petridis A (2021) Industry 5.0: towards a sustainable, human-centric and resilient European industry. LU: European commission, directorate-general for research and innovation. https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/industry-50-towards-sustainable-human-centric-and-resilient-european-industry_en. Accessed 29 Jan 2026
10. Bokrantz J, Skoogh A, Berlin C, Wuest T, Stahre J (2020) Smart maintenance: a research agenda for industrial maintenance management. Int J Prod Econ 224:107547. https://doi.org/10.1016/j.ijpe.2019.107547
11. Saihi A, Ben-Daya M, As'ad R (2023) Underpinning success factors of maintenance digital transformation: A hybrid reactive Delphi approach. Int. J. Prod. Econ. 255:108701. https://doi.org/10.1016/j.ijpe.2022.108701
12. Kans M, Campos J (2024) Digital capabilities driving industry 4.0 and 5.0 transformation: insights from an interview study in the maintenance domain. J J Open Innov Technol Mark Complex 10(4):100384. https://doi.org/10.1016/j.joitmc.2024.100384
13. Fore S, Mudavanhu T (2011) Application of RCM for a chipping and sawing mill. J Eng Des Technol 9(2):204–226. https://doi.org/10.1108/17260531111151078
14. Yamanaka MW, Guidotti TL, Koehncke N, Taylor FM, Taylor C, Harman L (2009) Wood dust levels in Alberta sawmills. Arch Environ Occup Health 64(4):270–277. https://doi.org/10.1080/19338240903338247
15. Poisson P, Chinniah Y (2016) Managing risks linked to machinery in sawmills by controlling hazardous energies: theory and practice in eight sawmills. Saf Sci 84:117–130. https://doi.org/10.1016/j.ssci.2015.12.010
16. Ajayeoba AO, Olanipekun AA, Raheem WA, Ojo OO, Soji-Adekunle AR (2021) Assessment of noise exposure of sawmill workers in Southwest, Nigeria. J Sound Vib. https://doi.org/10.32604/sv.2021.011639
17. Eriksson KM, Carlsson L, Olsson AK (2022) To digitalize or not? Navigating and merging human-and technology perspectives in production planning and control. Int J Adv Manuf Technol 122(11):4365–4373. https://doi.org/10.1007/s00170-022-09874-x
18. Schumacher A, Erol S, Sihn W (2016) A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises. Proc CIRP 52:161–166. https://doi.org/10.1016/j.procir.2016.07.040
19. IMPULS-Stiftung des VDMA (n.d.) Industry 4.0 readiness online self-check. https://www.industrie40-readiness.de/?lang=en. Accessed 29 Jan 2026
20. Sony M, Naik S (2020) Key ingredients for evaluating industry 4.0 readiness for organizations: a literature review. Benchmarking 27(7):2213–2232. https://doi.org/10.1108/BIJ-09-2018-0284
21. Gökalp E, Şener U, Eren PE (2017) Development of an assessment model for industry 4.0: industry 4.0-MM. Software process improvement and capability determination. SPICE 2017. Commun Comput Inf Sci 770:128–142. https://doi.org/10.1007/978-3-319-67383-7_10
22. Lucato WC, Pacchini APT, Facchini F, Mummolo G (2019) Model to evaluate the industry 4.0 readiness degree in industrial companies. IFAC-PapersOnLine 52(13):1808–1813. https://doi.org/10.1016/j.ifacol.2019.11.464
23. Nick G, Kovács T, Kő A, Kádár B (2021) Industry 4.0 readiness in manufacturing: company compass 2.0, a renewed framework and solution for Industry 4.0 maturity assessment. Procedia Manuf 54:39–44. https://doi.org/10.1016/j.promfg.2021.07.007
24. Senge PM (1990) The fifth discipline. Currency Doubleday, New York
25. Garvin DA (1993) Building a learning organization. Harv Bus Rev 71(4):78–91
26. Eriksson KM, Lycke L (2025) May the force of lifelong learning be with you – sustainable organizational learning in HEIs meeting competence needs in industry. Learn Organ 32(1):126–145. https://doi.org/10.1108/TLO-12-2022-0158
27. Alshaibani E, Bakir A, Al-Atwi A (2025) The impact of leadership behaviors on organizational innovative performance and learning in AI-driven industry 5.0 environments. Learn Organ 39(3):18–21. https://doi.org/10.1108/DLO-06-2024-0159
28. Ajayeoba AO (2019) Risk, postural and physical strain assessment of sawmill workers in Nigeria. Int J Eng Res Afr 45:74–88. https://doi.org/10.4028/www.scientific.net/JERA.45.74
29. Appio FP, Frattini F, Petruzzelli AM, Neirotti P (2021) Digital transformation and innovation management: a synthesis of existing research and an agenda for future studies. J Prod Innov Manag 38(1):4–20. https://doi.org/10.1111/jpim.12562

30. McKone KE, Schroeder RG, Cua KO (2001) The impact of total productive maintenance practices on manufacturing performance. J Oper Manag 19(1):39–58. https://doi.org/10.1016/S0272-6963(00)00030-9
31. Psarommatis F, May G, Azamfirei V (2023) Envisioning maintenance 5.0: insights from a systematic literature review of Industry 4.0 and a proposed framework. J Manuf Syst 68:376–399. https://doi.org/10.1016/j.jmsy.2023.04.009
32. Jardine AKS, Lin D, Banjevic D (2006) A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech Syst Signal Process 20(7):1483–1510. https://doi.org/10.1016/j.ymssp.2005.09.012
33. Vergara FP, Palma CD, Nelson J (2018) Modeling lean and agile approaches: a western Canadian forest company case study. Forests 9(9):529. https://doi.org/10.3390/f9090529
34. Blessing LTM, Chakrabarti A (2009) DRM, a design research methodology. Springer, London. https://doi.org/10.1007/978-1-84882-587-1
35. Säfsten K, Gustavsson M (2024) Research methodology 2.0 – for engineers and other problem-solvers. Studentlitteratur, Lund
36. Scholz RW (2020) Transdisciplinarity: science for and with society in light of the university's roles and functions. Sustain Sci 15:1033–1049. https://doi.org/10.1007/s11625-020-00794-x
37. Gooding H, Lattanzio S, Parry G, Newnes L, Alpay E (2023) Characterising the transdisciplinary research approach. Prod Manag Dev 20(2):1–11. https://doi.org/10.4322/pmd.2022.024
38. Bell E, Bryman A, Harley B (2019) Business research methods, 5th edn. Oxford University Press, Oxford, United Kingdom
39. Denzin NK, Lincoln YS (2018) The SAGE handbook of qualitative research, 5th ed. Sage Publications, USA
40. Braun V, Clarke V (2012) Thematic analysis. In: Cooper H, Camic PM, Long DL, Panter AT, Rindskopf D, Sher KJ (eds) Handbook of research methods in psychology vol 2. American Psychological Association, Washington, pp 57–71
41. Elo S, Kyngäs H (2008) The qualitative content analysis process. J Adv Nurs 62(1):107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x

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