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INNOVATIVE APPROACHES TO OPTIMISATION AND SUSTAINABILITY IN TIMBER CONSTRUCTION: INSIGHTS FROM THE AUSTRIAN RESEARCH PROJECT SYS.WOOD

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ABSTRACT: The research project Sys.Wood addresses the entire life cycle of timber buildings aiming to develop new interfaces, methods, and principles for system optimisation in Austrian timber construction. The aim of Sys.Wood is to transform the value chain by optimising processes and methods at every stage, including design, manufacture, use, maintenance, reuse, and disposal. Main objectives are sustainability, digitalisation, and quality management. A particular focus is on enabling small and medium-sized enterprises to participate competitively in larger projects by integrating manufacturing expertise early in the planning process. This paper outlines the strategy and objectives of the project and presents findings from the ongoing three-year project, setting the stage for further research in the timber construction industry.

KEYWORDS: Planning process, resilient construction, repair, reuse, lean management

1 – INTRODUCTION

The ongoing research project "System Optimisation in Austrian Timber Construction" (Sys.Wood) focuses on the comprehensive investigation of planning, prefabrication, construction, and the durability, maintenance and repair of timber buildings to identify potentials and generate new interfaces, methods, and principles for system optimisation. Given that the sector is predominantly comprised of small and medium-sized enterprises (SMEs)in Austria, with 84% being micro-enterprises, 15.1% being small enterprises, and 0.7% being medium-sized enterprises [1], the project has formed a consortium consisting of eight corporate partners and five scientific institutions. The project is structured around four key work packages (WPs): WP2 Planning Methods for Timber Construction; WP3 Resilient Timber Construction; WP4 Timber

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Construction's Lifecycle and WP5 Quality Management (QM) in Timber Construction. All WPs, are supervised by scientific entities which collaborate closely with at least two corporate partners, ensuring interdisciplinary collaboration.

2 – WP2 PLANNING METHODS FOR TIMBER CONSTRUCTION

In Austria there were 2522 timber construction companies listed in the year 2024 engaging an average of 4.79 employees each [1]. Given the considerable number of SMEs, a high level of communication among companies is necessary to enhance collaboration and, consequently, the productivity of the entire timber construction sector, particularly in the context of larger projects. For this reason, the objective of WP2 is to identify and develop examples of best practice and to formulate guidelines for action and standardisation addressing digital and human interfaces.

Four distinct methodologies were employed to collect data, analyse process structures, stakeholder roles and interfaces. These methodologies were implemented in close collaboration with the corporate partner companies: 1) System limits: prior to the data collection and problem analysis, the system limits must be defined. Based on existing project phases, the limits were discussed amongst the corporate partners and research institutions to set the margins according to the project [2], [3]. 2) A two-phase online survey was developed to collect data on digital and human interfaces, as well as collaboration issues. The initial phase of the survey involved the distribution of a self-developed qualitative form among the eight corporate partners. This form contained 44 free-text questions designed to elicit a wide variety of responses. The survey's duration was adjusted to allow for a response from all eight companies. The responses were subsequently transformed into multiple-choice items for a secondary quantitative form, which was disseminated extensively within the industry via various channels. This secondary form was made available online for a period of nine months, from February to October 2024, and comprised 41 multiple-choice questions, which were subdivided into the following topics: legacy data, employees, software, processes, data types, human interfaces, and project development. 3) The gathering and analysis of process chains sought to create a process chain diagram, with the objective of identifying common process steps and milestones that facilitate the collaboration of SMEs. To that end, the process chains of four manufacturing corporate partners were recorded, analysed, and discussed on site. During post-processing, the process chains were structured, sorted, and cross-checked in collaboration with WP5. The final step involved abstracting the process chains to the desired level of detail, which entailed the retention of items that were similar across all four companies. These items were then combined into a single, generalised version, enabling subsequent handling and facilitating the drawing of conclusions. 4) The objective of the building information modelling (BIM) collaboration study is to conduct a thorough analysis of the digital interface between an architectural and a specialist planning corporate partner using BIM. First, a selection of 19 mock-ups was defined based on their frequency of occurrence comprising various building elements such as interior and exterior walls in various timber construction methods, shapes and intersections; columns and beams; variously shaped breakthroughs including doors and windows; ceilings and floorings; various roof geometries including dormers, skylights and attics; and a staircase. Three different software interfaces were assessed as they are the preferred software of the involved architecture and specialist planner partner companies: Archicad [4] to Revit [5] Archicad to AutoCAD [6] and Revit to Archicad. The evaluation criteria encompassed the adoption of the element's correct entity, labelling, family/style, geometry, scale, coordinate position, building physics characteristics, building material properties, editability and position of the reference line when exporting and importing the objects from one software to another using the widely used ifc2x3 file format.

The main findings are: 1) System limits: the system's limits were delineated in accordance with the project lifecycle, which comprises the following stages: project development, project execution and the utilisation phase, which ensues project handover [2], [3]. In Figure 1, the limits are shown for material-independent construction with a high degree of prefabrication. Following the discussions, the standard process chain for conventional construction was adapted, with emphasis placed on early collaboration and contributions from detailed planners, such as the definition of efficiently producible key details and manufacturing companies, such as more transparent communication of specifications and available services. In this context, both human and digital interfaces are subjected to analysis.
2) Two-phase online survey: the initial survey revealed the quantity and complexity of employed software, file formats, and human interfaces given by the open response configuration of the form. The second part achieved 63 entries, of which only 20 were completed and evaluated, offering clear numbers including the following especially noteworthy insights sorted by topic. Legacy data and employees: the participants in the survey consisted of 55% micro-enterprises, 25% small enterprises and 10% medium enterprises with building companies making up a share of 59% and engineering companies 18%, a distribution that matches the target group of this study and therefore allows a representative conclusion to be drawn. Software: the most prevalent computer-aided design (CAD) and BIM software was, SEMA [7], followed by AutoCAD, BIMx Desktop Viewer [8], Allplan [9], Dietrich´s [10] and ArchiCAD. The most preferred CAD/BIM software was SEMA, followed by Dietrich´s, AutoCAD and ArchiCAD. A discrepancy exists between usage and preference, with the greatest disparity being evident in Archicad. The structural analysis software most frequently utilised are

RFEM [11] Wallner Mild [12] and RuckZuck [13], while SEMA is the predominantly employed computer aided

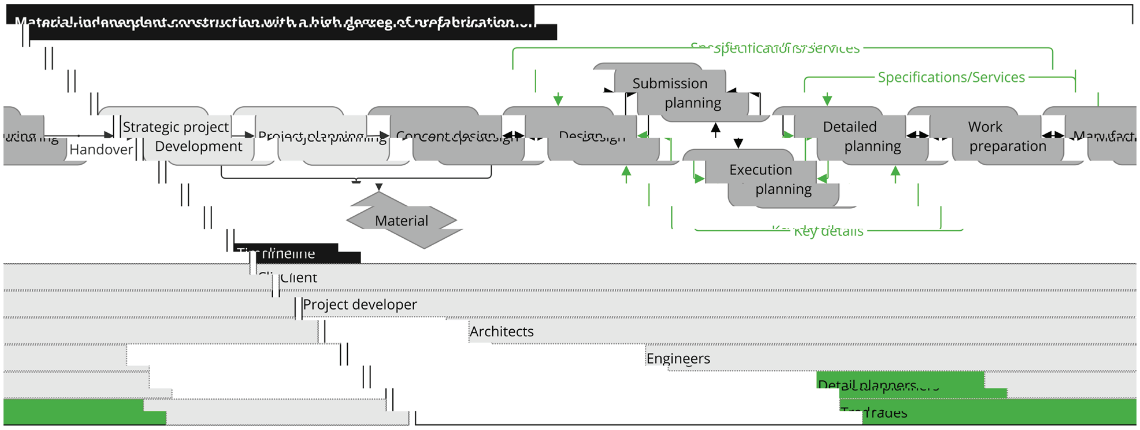

Figure 1: System boundaries of the analyzed manufacturing processes and interfaces for general prefabricated construction methods. Differences from conventional construction are highlighted in green.

manufacturing (CAM) software. Processes and data types: A significant proportion of the companies, 65%, assert that effective collaboration is contingent on the utilisation of specific software interfaces, owing to data compatibility constraints. This necessitates adaptation of processes including software changes by 74% of the respondents, and the adaptation of data formats by 80%. Of the surveyed companies 58% reported a decline in productivity as a result of the adaptations made. Consequently, 40% of the companies report that existing guidelines are insufficient and 85% express a need for examples of best practice to facilitate cooperation with SMEs. The most prevalent building plan type is paper (75%), followed by 3D (60%) and 2D (45%) CAD formats. Furthermore, 50% of respondents claim to participate in BIM projects (predominantly architectural LOD 200 and static analysis models LOD 350), and the most frequently used file formats are .dwg, .ifcx4, and .dxf. A timber construction specific .ifc file format with defined attributes is reported as advantageous or very advantageous by 75%, while 10% claim it to be disadvantageous. In 65% of the companies interviewed, problems are identified in human interfaces. This phenomenon may stem from the absence of clearly delineated protocols for communication within project frameworks, as indicated by 65% of the surveyed companies. The communication rules are particularly insufficient regarding general project information and structure as well as the definition of completion and processing levels for the transfer of the required data and file formats. The companies claim that missing time (35%), budget (17.5%) or overly complex specifications (17.5%) are the reasons for non-compliance with communication rules. Regarding the factors of punctuality and quality, among all stakeholders project developers were rated with the lowest levels of performance, while structural analysts were rated highest. In the context of project development, the survey respondents from all companies expressed a consensus on the value of engaging detailed planning and manufacturing companies in the design phase of the planning process, as also indicated in Figure 1. This approach is aligned to early contractor involvement which has already proven to be significantly beneficial [14].

3) Process chain analysis: a generalised process chain diagram of four manufacturing companies was created, and the reported process steps can be structured into the following phases: offer, work preparation, production, assembly and utilisation. The items comprise processes of internal and external parties, decisions, milestones, advance payments and include associated employee profiles. The results are the foundation for future work, such as the identification of opportunities for improved cooperation between SMEs. Furthermore, lean management will be applied for additional quality enhancement, as further described in WP5.

4) BIM-collaboration study: the analysis of the mock-ups revealed that errors occurred during the transfer of all construction elements. It is therefore evident that a high level of attention and subsequent review and post-processing is required in order to successfully transfer a project from one software environment to another. It is important to note that the analysis is still ongoing and therefore more detailed results will be provided in future publications. A central part of the ongoing investigations will be the model information handover to the manufacturer to complete the process from BIM to CAM.

3 – WP3 RESILIENT TIMBER CONSTRUCTIONS

WP3 concentrates on enhancing the resilience of timber construction methodologies. The initial phase of this work package involved research of existing construction solutions, with a particular focus on evaluating their resilience. Criteria catalogues [15] were used as reference and appropriate assessment methods, in particular the

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Failure Modes and Effects Analysis (FMEA) was applied. In collaboration with the corporate partners',

Figure 2: The matrix representation of the results (e.g., showing the highest rated base detail 06 and the lowest rated base detail 04) reveals clear differences through the heatmap visualisation.

relevant construction details for a further qualitative analysis were selected and embodied in a newly developed online assessment tool to facilitate evaluation. These generated findings significantly improved the evaluation process for resilient timber constructions. In this context, resilience is defined as the capacity to produce reliable solutions that are less sensitive to building errors and unexpected situations. Modified criteria catalogues, based on a previous research project [15] and the online assessment tool provide valuable resources for skilled practitioners in the field.

Based on the FMEA-tool of the previous project, which was originally developed to assess the resilience of structures regarding various types of damage in timber buildings, the applied online assessment tool was developed. The evaluation method favours a subjective evaluation of timber construction details, based on experience by leading timber experts among the corporate partners. The results are summarised in an evaluation matrix and presented quantitatively as seen in￼￼. With the aim of creating a more accessible evaluation process, the further development of the tool included the reduction of its complexity as well as the adaption for implementation as an online questionnaire as part of the Sys.Wood research project.

Subsequently, the various factors influencing the components were grouped into three categories, which allowed a more precise questionnaire with nine questions to be created for the FMEA assessment. For the timber construction sector, potential damage is examined according to three FMEA categories:

- Occurrence Probability
- Risk Severity
- Detection Probability

Each of these categories is assessed subjectively in relation to the following three areas of influence:

- Building Physics Influences
- Environmental Influences
- Usage-Related Influences

In addition to the FMEA, a series of supplementary questions were posed with the objective of obtaining information regarding the potential degree of prefabrication and the reuse potential of the specific design solution. In addition to the subjective, experience-based evaluations of the respondents, information about their expertise, background knowledge, and duration of work experience in the respective fields is also collected. For the evaluation using the online assessment tool, an adapted survey catalogue was created, including 26 details to be examined. The details were selected in collaboration with project partners from following sources: LongLifeWood [15], dataholz.eu [16], BigWood [17] and the revised Leitdetailkatalog by the Institute of Building and Industrial Construction (TU Graz) [18] and natuREbuilt [19]. The detail categories focus mainly on building components classified as "particularly stressed" due to their relatively high occurrence of damages. Most damages were found in ground-contacting components (25%) such as base connection details as well as roofs and balconies (24.5%) such as roof connection details [20]. The survey includes selected variations representing the two main building methods in timber construction: mass timber and timber frame. Additionally, it examines two facade cladding systems: the External Thermal Insulation Composite System (ETICS) with wood fibre insulation boards and the ventilated timber cladding system.

The focus of the assessment is directed toward specific aspects of the detail, depending on the questions and the provided criteria catalogues. This highlights the strength of the FMEA in the practical application, as it leads to more objective results of the qualitative assessment.

In a follow-up workshop for example, a particular detail - considered by the experts to be intricate and costly to prefabricate - was nevertheless rated the highest in the online assessment tool because it performed better in certain sub-aspects. In retrospect, when partial aspects were discussed objectively by the expert team, this result was considered plausible and demonstrates the tool's ability to assess highly specific technical issues.

Based on the feedback from the surveyed parties and the decreasing number of responses for the details to be evaluated chronologically later, it can be assumed that an FMEA with this quantity of evaluation content is time-consuming for routine application in everyday practice.

4 – WP4 TIMBER CONSTRUCTION'S LIFECYCLE

The investigation includes a life cycle assessment (LCA) based on on-site monitoring of prefabrication processes at partner companies, aiming to promote sustainability and resource efficiency. Data on material volumes and

As part of the scientific investigation, centrally connected wall elements made from cross-laminated timber (CLT) are being examined, alongside the application of prestressed and thus separable systems. Comparative calculations were conducted to assess the reuse potential of vertically prestressed CLT elements.

The findings of the work package are in ecological assessments, the share of prefabrication is neither explicitly included in EPDs nor in relevant databases. The emissions from the prefabrication of timber frame components range between 2.5 and 7.1 kg CO_2 equivalents per m², depending on production conditions. Emissions from prefabrication account for approximately 2% to 7% of the total CO_2 Equivalent of phases A1 to A3, depending on the specific element buildup. These emission shares are offset by significant technical, economic, and ecological advantages compared to on-site construction methods.

Based on normative requirements, service life catalogues and existing literature on maintenance in building construction, a "Maintenance Manual for Building

energy flows were collected through on-site measurements and production monitoring to assess the impact of prefabrication processes. The analysis focused on key manufacturing steps, such as cutting, assembly, and connections, as these aspects are not covered in Environmental Product Declarations (EPDs). Strategies for repair and reuse were discussed and investigated in collaboration with industry partners. While repair strategies analyse existing constructions and maintenance practices, reuse potential is seen in connection systems designed for centric vertical load transfer across multiple stories, facilitating design for disassembly. To evaluate prefabrication components in production of timber building elements (Module A3 according to EN 15978) [21], comprehensive surveys were conducted with partner companies to document material flows and energy expenditures according to EN 15804 [22] . The collected data were compared with values from scientific literature and simplified approaches derived from annual balances of energy consumption and production output.

For repair, encompassing maintenance and refurbishment, literature reviews and interviews with a partner company and a non-profit housing developer were conducted. To analyse the reusability of timber constructions, best-practice examples of buildings that have been disassembled or specifically designed for disassembly were examined. This includes parameters such as construction method and materials, connections designed for disassembly, utilisation and building class. The case studies provide insights into current strategies for designing reusable construction systems. Challenges and obstacles of legal framework conditions were examined based on a related project. Disassembly-friendly connection techniques were discussed with experienced planning offices and executing companies.

Construction and Timber Construction" is being developed. This manual addresses the perspectives of both operators and users while providing supplementary guidance for construction professionals. The "Maintenance Manual for Building Construction and Timber Construction" is designed to preserve the value of existing structures and to extend the duration for which sequestered carbon in timber remains stored. The manual addresses issues of particular importance to timber construction, such as correct ventilation and moisture management. An important recommendation is the implementation of regular maintenance intervals that exceed the requirements currently specified in standards. When analysing functional layers in buildings across their life cycles, a key consideration is the ability to separate components with shorter life spans from those with longer ones [23]. Evaluation schemes for circularity, incorporating disassembly hierarchies, are applied for this purpose [24], [25], [26].

In context of reuse of components and building elements, disassembly of connections, the circularity of the elements and the legal framework conditions are of

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central importance. Regarding sustainable construction and circular economy, the legal basis for reuse covers a clearly defined area. As soon as the potentially reusable components must be post-processed after a building has been dismantled, it is no longer a matter of reusing certified products, but of recycling waste. To avoid the declaration of waste and close the product cycle in the construction industry, component connections must be designed to be separable without destruction, allowing for easy disassembly and reuse at the end of a buildings life cycle.

The study compares various analysis models, emphasizing the potential of push-over analysis in accordance with Eurocode 8 - Design of structures for earthquake resistance. The investigation also explores the potential of vertical prestressing with crenelated interlocking of wall elements. It concludes with a practical use case demonstrating the application of these modelling techniques at different complexity levels, highlighting critical findings and proposing directions for future research to develop robust, reliable, and efficient design tools for CLT buildings. Prestressing elements located within wall components demonstrate high fire resistance, are favourable for sound insulation, enable controlled friction for horizontal load transfer and allow dismountable structures. Additionally, prestressed systems show excellent load-bearing behaviour under seismic conditions, as confirmed by verifications using push-over analyses in accordance with the second-generation of Eurocodes.

5 – WP5 QUALITY MANAGEMENT IN TIMBER CONSTRUCTION

QM standards are to be evaluated, adopting Lean Management principles (LMP) to improve existing QM-processes among timber construction SMEs. Therefore, a comprehensive training program based on [27] is developed that uses a digital interactive learning platform to make Lean quality management techniques accessible in a scalable way. With this knowledge transferring tool employees of SMEs are able to acquire knowledge independently and as required. Additionally, core processes were analysed to implement LMP tools as well as derive success and barrier factors for sustainable application to improve QM in SMEs.

Three distinct methodologies were employed to transfer LMP knowledge, analyse process structures and identify specific success and barrier factors for sustainable LMP application. These methodologies were implemented in close collaboration with the corporate partners:

1) The digital interactive learning platform is divided into five sections, which are distinguished by different colours, as seen in Figure 3: Introduction, Basics, Checkpoint, QM Section and Tools. After a general introduction to LMP, the basics provide an overview of the different application areas of Lean in QM. The Checkpoint serves as a self-check for the user. The QM section provides in-depth content on LMP with a focus on quality. In addition, the developed tools show possible applications and implementations for woodworking SMEs. The individual areas are structured in related modules. Each module again consists of several sections, which contain both theoretical and interactive content. After completion of a section, the content can be reinforced by iterating through the most crucial terms again. The learning path was distributed to the participants via an online platform and underwent continuous improvement in two different test phases. The first phase took place from October to November 2023 and the second test phase took place between May 2024 and July 2024. A questionnaire was developed to obtain feedback on the functionality and effectiveness of the learning path, which included 28 questions. These ranged from multiple choice to open-ended questions as well as ratings. Figure 3 shows the structure and design of the digital scalable knowledge transfer tool for LMP.

2) In order to fill the 22 modules of the digital interactive learning platform with wood construction-specific examples, the process chains of various planning and executing corporate partners were first recorded and analysed. In cooperation with WP2, an abstracted process chain for timber construction SMEs was developed. LMP with a focus on quality improvement was presented to three corporate partners in their facilities and the application within the abstracted core process steps was discussed together. 3) In addition to the knowledge transfer via learning platform and the implementation of individual Lean tools for quality improvement, specific success and barrier factors for the successful implementation of LMP solutions for the timber construction industry are gathered and analysed. The data is collected through interviews with employees who work directly with the lean solutions in the processes. The questionnaire consists of 10 questions which are divided into three main categories. First, general questions about QM are asked, followed by questions about success factors and barriers related to the learning journey. The interviews conclude with specific questions on success and barrier factors in the application of LMP tools and methods in timber construction. The interviews will be analysed using qualitative content analysis.

The findings of the study indicate the following: 1) The first testing phase of the learning platform included a total of 10 subjects from two companies. The second phase included 25 test persons from nine different companies and scientific organisations. A total of 10 questionnaires were filled out and sent back to be evaluated. The results indicate that all respondents have a better understanding of the various areas and tools of Lean Construction after completing the learning platform. 2) Specific tools were presented with which the LMP can be successfully implemented. [27]

These include 5S [28], Poka Yoke [29], meeting standards [30] and the Last Planner System (LPS) [31]. In cooperation with the corporate partners, the two tools meeting standards and Poka Yoke were selected for the

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LMP implementation. The development of practical examples for meeting standards and Poka Yoke was structured according to the individual modules of the

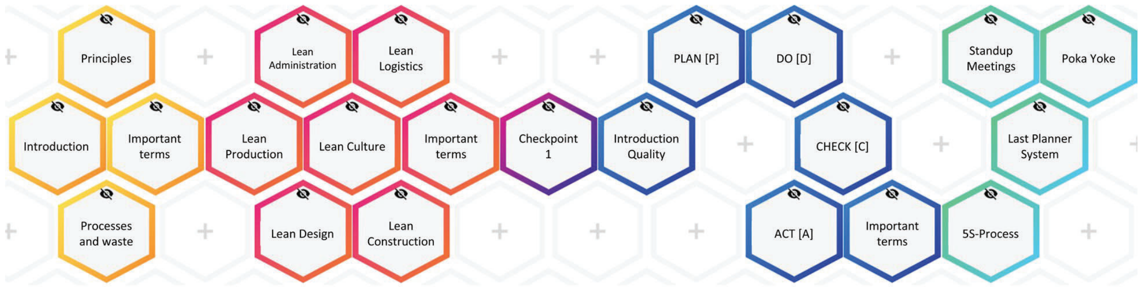

Figure 3: Structure and design of the digital scalable knowledge transfer tool for LMP

Plan-Do-Check-Act (PDCA) cycle [32]. These were first planned (Plan), then tested in implementation (DO), subjected to a quality check (Check), and then further improved and developed into a new standard (Act). For the meeting standards, the already existing standard of a timber construction SME was used as a basis. The further improved version was tested in several meetings. In a reflection meeting with the corporate partner, the effect on quality improvement was evaluated. As a result, the tool was optimised and developed into the current standard for the planning department. In cooperation with another corporate partner, specific Poka Yoke solutions and questions for systematic error avoidance and prevention along the production process were developed together with the production staff. These were made available in digital form at the workstations and tested. The impact on quality improvement is measured in cooperation with the corporate partner. Based on the results, a standard for the production department will be developed. 3) The collection of success and barrier factors is currently ongoing. Further results will be disseminated in future publications. First evaluations indicate different success and barrier factors for the learning path as well as for the application of LMP tools and methods in the QM structures of the corporate partners. In order to be able to effectively use the learning platform as a tool for the independent transfer of knowledge, examples from the practice of wood construction are essential. The integration of LMP tools and methods into the QM structures of the corporate partners must above all be practical and understandable. The added value to be achieved must be quickly recognisable. These developed LMP tools and methods can be implemented along the abstracted process chain for timber construction SMEs. The specific success and barrier factors were investigated through expert interviews conducted with corporate partners. Gathered data will be analysed with qualitative content analysis in the beginning of year three. Extracted results will be incorporated in guidelines for QM improvement in timber construction SMEs.

6 – CONCLUSIONS AND OUTLOOK

This paper presents a comprehensive analysis of the objectives and initial findings of the ongoing research project “Sys.Wood”. The research results achieved so far by the interrelated work packages can be summarised as follows: 85% of respondents reported a productivity impairment due to adapted processes. Paper-based building plans are the most preferred format, but 50% of respondents participating in BIM projects. Issues with human interfaces stem from undefined communication rules. 40% of companies find existing guidelines insufficient, while 85% seek best practice examples to improve SME collaboration.

To this end, a generalised process chain diagram was developed to identify opportunities for enhanced cooperation and Lean management in future research. The examination of BIM collaboration identified significant challenges that will be examined in subsequent research. As a result, a guideline for incorporating SMEs to large-scale projects including best-practice examples will be developed.

The supplementary information obtained from the individual responses in the FMEA is utilised to formulate design guidelines and a component catalogue. Best practice exemplars are then developed based on these guidelines. The evaluated specifics are subsequently consolidated with the corresponding constructions in a detail catalogue. The supplementary data collected from participants via the online questionnaire, grounded in the FMEA framework, is currently undergoing further comparative analysis. Preliminary findings suggest divergent tendencies contingent on participants' background knowledge, experience, and professional domain. For instance, architects have been found to underestimate the severity of potential damage, while contractors have been observed to assign it a higher level of seriousness.

The findings of the LCA for prefabrication demonstrate substantial congruence with existing literature [33]. However, there is a need for further research in the collection of data for prefabrication.

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The "Maintenance Manual for Building Construction and Timber Construction" offers a compendium of recommendations for extending the lifespan of timber construction components. From the consortium's perspective, these innovations encompass not only technical advancements but also novel business models in Austrian timber construction that can be adopted by micro, small, and medium-sized enterprises.

The analysis of best practice examples for reuse and disassembly indicates that the use of different load-bearing systems depends on the building typology. The research will entail a comparison of various evaluation systems for circular construction, with a focus on disassembly methodologies. A systematic classification of fasteners for reuse in timber construction will be developed based on identified current reusable constructions. The arrangement of plasticising pin-shaped metallic connectors according to Eurocode 8 [34] is partly in contradiction to circular design and requires further investigation and the development of new ductile elements (e.g., prestressed constructions). Further investigation is necessary to substantiate this hypothesis.

A digital scalable prototype for knowledge transfers specific to LMP in timber construction SMEs was developed. Selected LMP tools and methods targeting the improvement of the QM structures could be integrated into the existing structure of corporate partners. Numerous success and barrier factors could be identified, which were separated into factors indicating the effectiveness of the prototype learning platform as well as the integration of specific LMP tools into existing planning and production processes of timber construction SMEs.

These factors will be systematically evaluated to serve as a basis for the guideline, which is the objective in the final third research year. The guideline for the successful application of LMP in timber industry consists of different components, including the digital scalable learning course, which serves as the knowledge transfer instrument. The abstracted process chain offers an overview of and possibilities for the application of LMP in timber construction SMEs. Specific success and barrier factors for knowledge transfer via the learning path and successful implementation of Lean tools make the topic of Lean construction management practical and accessible for the timber construction industry. Finally, the structure and content of the guidebook will be determined by an interdisciplinary consortium using focus group interviews.

The optimising interfaces and digitalising processes to boost collaboration, the development of an advanced catalogue for reliable construction details as well as proof of sustainability of prefabricated timber constructions based on LCA compared to traditional constructions are achieved.

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