Summary report InFutUReWood –

Innovative Design for the Future – Use and Reuse of Wood (Building) Components

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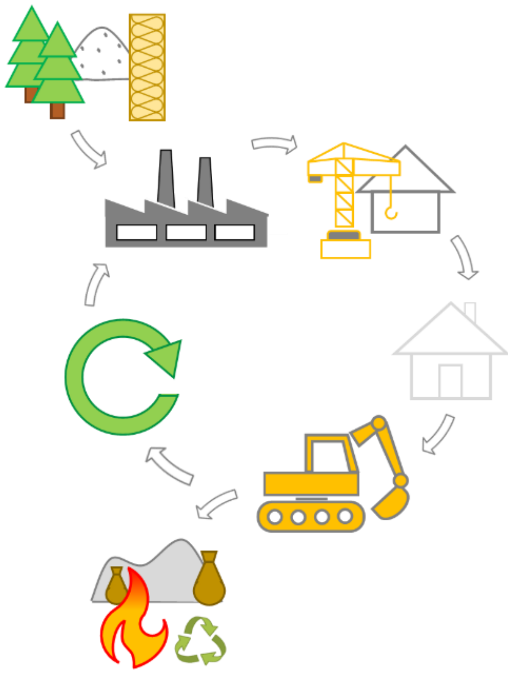

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InFutUReWood

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Abstract

The InFutUReWood project aimed to answer the question: "How should we build today to be able to circulate tomorrow?" It started in March 2019 and ended March 2022, covering both the design of new buildings, and the reuse of timber from buildings already at the end of their life. At that time, the subject was a rather novel research area for timber buildings, but this period of three years saw many changes. Increasing concern for climate change could have been expected, but shortages of building materials caused by the Covid-19 pandemic and political events encouraged many to take an interest in the reuse and circularity of wood products.

InFutUReWood was a European project within ERA-Net cofounded with ForestValue and funding agencies from each of the seven participating countries Finland, Germany, Great Britain, Ireland, Slovenia, Spain and Sweden. This summary report compiles the work and results from the project divided into work packages. The compilation of the main results in this report was made by the WP-leaders and the project leads from each country.

- Three methods to adapt a design for deconstruction and reuse were developed.
- Five case studies were carried out to illustrate design solutions adapted for reuse.
- Different ways to structure guidelines for deconstruction and reuse (Deconstruction Plans) were explored.
- Design for deconstruction and reuse DfDR can contribute to reduce the environmental impacts of timber frame constructions for residential buildings.
- Mass timber products (cross laminated timber) from recovered timber were developed.
- Environmental benefits can be achieved from the use of recovered solid timber in high-quality CLT panels.
- Methods of assessment and assignment of design values for in-situ timber were researched.
- Potential material traceability methods were identified.
- Key factors in the demolition of building affecting the material recovery potential were identified.
- Quality criteria were developed against which recovered wood can be assessed. A stock- and flow model was developed, enabling future volumes of recovered wood to be predicted.
- Database of properties of recovered wood products including embedment strength was created.
- Technical and normative barriers to the strength grading of secondary timber were explored.
- A new framework for strength grading was developed, to complement the current ones.
- Demolition machines are 91-95% the main influence on the environmental impacts of the building demolition stage

Results from the project can be found on the website https://www.infuturewood.info/ and videos on the https://www.youtube.com/channel/UCdpJNt6h3eBD6NFmZQXuErw

Key words: circularity, design, disassembly, reuse, sorting, timber buildings, remanufacturing, waste management

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Preface

This report is a summary of the results from the InFutUReWood project - Innovative Design for the Future – Use and Reuse of Wood (Building) Components.
A big thank you to all who have supported the project and contributed to the results. This includes the academic and industry project partners, numerous people who worked on connected projects, and everyone who helped share their knowledge with us through discussions, site visits and surveys. We have, through good cooperation and shared values, reached a new level of understanding and awareness.

It was 22 partners from seven countries Finland, Germany, Great Britain, Ireland, Slovenia, Spain and Sweden in the project. The research and academia project partners are RISE (Sweden), Edinburgh Napier University (Great Britain), National University of Ireland Galway (Ireland), University College Dublin (Ireland), Universidad Politécnica de Madrid (Spain), University of Ljubljana (Slovenia), Aalto University Helsinki (Finland), and Technical University Munich (Germany).

The industry partners are Kiruna Municipality Technical Service, Swedish Wood, Derome, Isotimber, Offsite Solutions Scotland, Hegarty Demolition, SIP Energy, Connaught Timber, Stora Enso Spain, Klimark + Nova domus Hábitat, The Federation of the Finnish Woodworking Industries, Jelovica HISE, The Swedish Federation of Wood and Furniture Industry and Balcas Timber. Brenner planungsgesellschaft mbh participated as partner to TUM.

The compilation of the main results in this report was made by the WP-leaders as editors and the project leads from each country, in alphabetic order.

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Thanks to students whose thesis work has contributed to the project, see appendix Students work.

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Karin Sandberg, Project coordinator, October 2022

1. Introduction

1.1. Aims and objectives

InFutUReWood - Innovative Design for the Future – Use and Reuse of Wood (Building) Components aimed to answer the question: “How should we build today to be able to circulate tomorrow?”

It is a complex task, that requires being attentive to the different building cultures across Europe, various potential scenarios for deconstruction, reuse, or recycling, coupled with developing evidence for the properties and potential of recovered timber.

The objectives of the project were:

- To develop a method for ensuring the future possibility of circulation of timber products with true consideration of whole life cycle, and practical industry issues at design, construction and deconstruction phases.
- To plan primary design to facilitate deconstruction rather than demolition, and to pay attention to the use of chemical treatments, adhesives, and other synthetic materials including to decide whether their use is technically necessary and avoid over-specification.
- To optimize the primary design to enhance resource efficiency as well as reduce environmental impacts along the life cycle (build and deconstruction).
- To allow grading for quality of recovered wood, and similarly variable new wood from more diverse sources, in a way that is compatible and equivalent to grading of new timber from the main commercial species (including the basis in European standardization).
- To identify potential new construction products using recovered timber.
- To examine the economic and environmental factors over a building’s life cycle to inform what is to be optimized, encouraged, and avoided in design (to be described by a "rebuilding factor").
- To inform current engineers, architects and wood-based construction product manufacturers through professional development, industry bodies, codes, and standards.

The concept of InFutUReWood was innovative: to design while considering the future deconstruction, recovery, and reuse of timber in other (new) buildings and building products and doing so with the objective of incorporating the kind of reclaimed wood that is currently available. The concept was to close both the material loop and the knowledge loop.

1.2. Implementation and workplan

The work in InFutUReWood has been accomplished in seven work packages (Figure 1.1).

The scope of the project was the reuse of structural timber from current buildings and how current and past experience of demolition helps the design of timber buildings (1-3 storey) to facilitate future deconstruction and new products out of recovered wood. The primary focus for new products was sawn and laminated structural timber.

WP 2 provided models and frameworks for how to design today with virgin timber to be able to reuse timber in the future. Activities include studying current design methods and practices; improving primary designs and connections; and creating data documentation for deconstruction.

WP 3 explored the scope for new products from recovered wood, and virgin fibre from less usual species. Laboratory scale fabrication and testing and a desk study covered wood property requirements, methods for recovering and reprocessing wood, and potential traceability methods.

WP 4 provided information about quality and amount of material available via an inventory of structural timber in current construction. It evaluated demolition and deconstruction practices to increase the amount of future recovered structural timber that can be used for construction. It developed criteria for initial usability grading for material segregation.

In **WP 5** the properties of recovered spruce and oak wood were explored through laboratory scale non-destructive and destructive testing. This explored the practical and sampling issues when working with recovered timber, as well as contributing data into the extensive existing datasets of project partners for use in evaluating the performance of alternative strength grading approaches. A potential alternative grading framework was identified.

WP 6 provided the environmental and economic performance of the reuse of structural timber or structural timber components in new construction using LCA and LCC methods. A special focus was set on the building demolition phase. Furthermore, a comparison of the environmental performance of CLT panels made from recovered timber with panels made from virgin wood was performed. Recommendations for the building documentation along the life cycle are developed.

WP 7 transferred the results to users, stakeholders, students etc by reports, videos, seminars and learning materials. Much of this can be found on the project website https://www.infuturewood.info/. A great deal of the work is in the form of video on-demand.

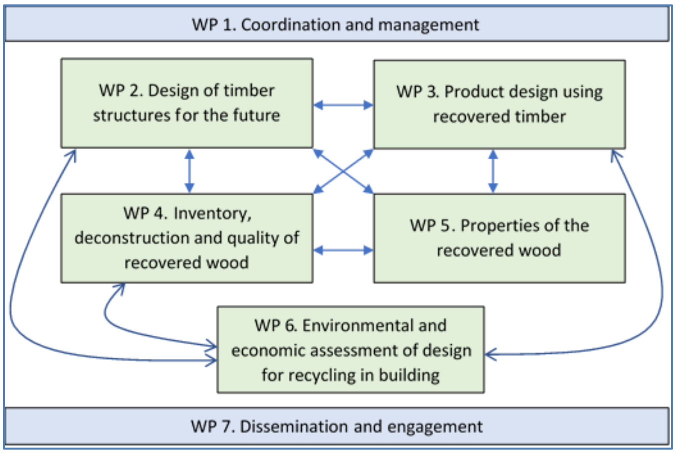


Figure 1.1 Work packages overview

2. WP 2 Design of timber structures for the future

2.1. Background

Wood has been used in construction across Europe for hundreds of years, though the extent and manner of its use – as primary structure, internal or external finish, or building types - varies substantially by region. Differences in conditions for construction - as primary materials available historically - gave rise to regional building traditions. Current construction methods, particularly factory-assembled panels, in tandem with global trade in raw materials, has encouraged more similar patterns of use between European regions. As timber-based structural solutions have become more common as a route to sustainable construction, a need has arisen to reconsider how these construction systems can be optimised to enhance both resource efficiency and ultimately deconstruction and reuse of the primary building material in the future.

Considerable high-level research has identified the principles of designing for deconstruction (Morgan and Stevenson (2005), Guy and Ciarimboli (n.d.), Crowther (2005), Thormark (2001) and Hradil et al. (2017)), however much of this knowledge has failed to be operationalised in the design professions that could have the greatest impact on the ultimate recovery of timber.

Currently there is no commonly accepted comprehensive framework with methods and tools for the systematic and transparent assessment of the potential for a second life of timber building components and systems. Rating systems (such as BREEAM and LEED) are in the process of integrating DfDR (Design for Deconstruction and Reuse) credits, yet specific DfDR strategies for timber are limited.

The literature gives occasional references (Durmisevic 2006; Halliday 2007) to the form of documentation that would be useful for future facility managers and contractors about to carry out disassembly processes. The research field rarely explores how deconstruction plans should be developed, structured, or stored for future use, but two early DfD (Design for Disassembly) manuals (Morgan and Stevenson 2005; Guy & Ciarimboli (n.d.)) and ISO 20887:2020 *Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements, and guidance* identify both the need for and potential structure of such plans.

There is a need for studies in the design phase (as opposed to the operation and management of timber buildings), to identify means to improve timber recovery and reuse at the building's deconstruction phase (Figure 2.1) and a need for guidance on the topic of deconstruction plans.

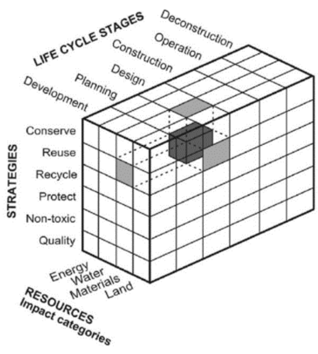


Figure 2.1. Crowther's (2005) representation of a design for deconstruction model for sustainable construction based on Kibert (1994). There is a need for studies in the field marked in the figure – focusing on design, reuse, and material use.

2.2. Aim and research questions

The aim of WP2 was to identify more effective design procedures and construction details to facilitate deconstruction and reuse of primary structural timber from housing stock in the future. We sought to answer the following research questions:

- Q1: What methods can be adopted to optimise a primary design for deconstruction and reuse?
- Q2: What new designs can be suggested?
- Q3: What can be said about timber connections in relation to deconstruction and reuse?
- Q4: How can guidelines for deconstruction and reuse be formulated?

The study has focused on residential buildings. One to three-storey houses with a timber structure were studied, focused on structural members. This typology has potentially the greatest benefit even from a social and environmental standpoint since construction of residential projects outstrips other sectors across all European regions (UN 2019).

2.3. Highlights

2.3.1. State-of-the-art review

WP2 first undertook a review of relevant research and guidance documents to answer the research questions, resulting in *Design for deconstruction and reuse of timber structures – state of the art review* (Cristescu et al., 2020) and in the *Glossary for Circular Timber Construction* with references. The review study highlighted that considerable research in the last 25 years has identified key DfDR principles and specific strategies, with some practical applications in built projects. However, much of the work remains at the level of hypothesis rather than actively applied in practice. Though the principles outlined in the published research were found to be useful reference points and offer some high-level strategic guidance, for this knowledge to be operationalised in the design and construction sectors a more directed decision-making tool, developed according to phases of design and construction work was required.

Kibert's (1994) early definition of stages (Development: Planning: Design: Construction: Operation: Deconstruction) is a useful starting point, but a finer grain linking principles, strategies, and specific tactics appropriate to each stage is required to properly direct decision making in designing DfDR buildings. It was equally clear, from the discussion of regional building types, that while general principles may be useful, strategies and specific tactics should be informed by regional variations in construction, supply chains, and culture. Thus, while Hradil's Hierarchy of building components (Hradil 2014) may suggest that a modular, volumetric solution may be the most effective construction system to ensure effective disassembly and reuse, the lack of modular production in some regions, and specificity of local building traditions, could influence the viability of this as the optimum solution.

2.3.2. Methodology - method development and case studies

To generate more specific answers to our research questions, a method to optimise a primary design by calculating a "ReBuilding Index" was suggested, as well as a series of case studies from industry partners in Sweden, UK, Ireland, and Spain.

A workshop was held with stakeholders, to discuss a first draft for a tool to calculate the ReBuilding Index (Sandin & Sandberg 2021). The workshop led to the conclusion that due to different stake holder needs, three different methods were needed to optimise a primary design, as researchers needed a case study method, industry appreciated the idea of an indicator system, while designers found a design decision tool more appropriate (Figure 2.2).

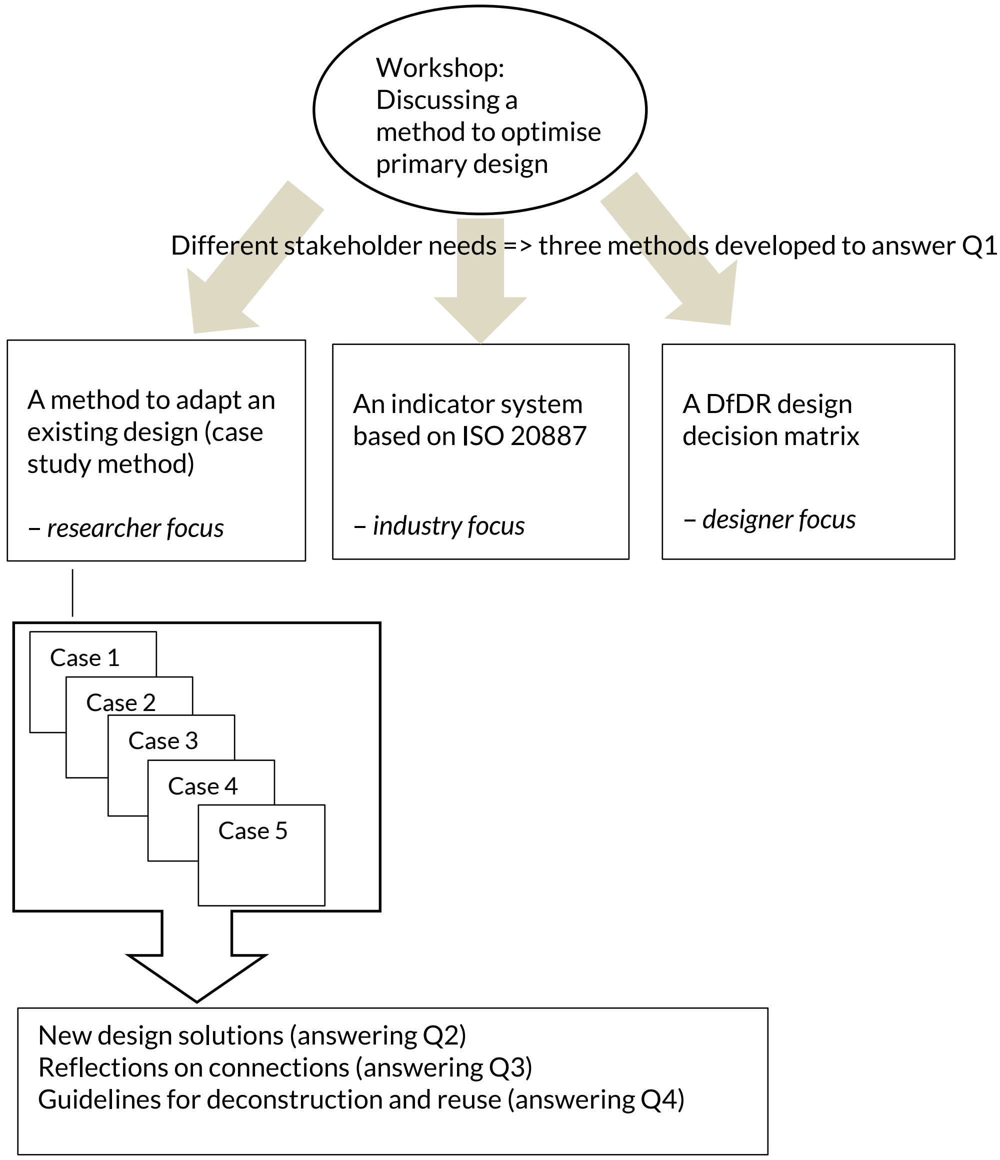


Figure 2.2. Overview of work in WP 2 following the initial state-of-the-art report.

Therefore, WP 2 developed three different methods to answer Q1 and carried out five case studies to answer Q2-Q4. Based in part on this work, guidelines for a material passport for the building elements based on BIM was further developed by WP 3 and WP 6. General methods used were literature studies, interviews, workshops, studies of drawings, field studies and design work.

The work was summarised in *Design of Timber Buildings for Deconstruction and Reuse: Three methods and five case studies* (Sandin et al., 2022a, Sandin et al., 2021).

This work informed the work of T3.3 in WP3 as well as WP6.

2.3.3. Methods to optimise a primary design

Indicator system

An *indicator system* was developed based on needs of manufacturers to evaluate and express the suitability of their design concepts for future deconstruction and reuse. The tool is based on a set of indicators, that highlight strengths and weaknesses of a concept and help to optimize designs with respect to deconstruction and reuse. The recently published ISO 20887:2020 *Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements, and guidance* was used as a framework.

The ReBuilding Index, created in Excel, measures the suitability of a load bearing structure for adaptability, design, deconstruction, reuse and documentation to support these goals (Sandin & Sandberg 2021, Zabala Mejia 2021). The resulting grade indicates how well the demands for adaptability, deconstruction, and reuse have been achieved, visualised on a spider chart (Figure 2.3).

DfD/A Category	DfD/A Principle	Principle Score	Principle mean value score	Total Score	Weight Factor
1.0 Adaptability	1.1 Versatility (ISO20887 - Sec. 5.2.2)	1.0	0.5	54	0.2
	1.2 Convertibility (ISO20887 - Sec. 5.2.3)	2.0	0.7		
	1.3 Expandability (ISO20887 - Sec. 5.2.4)	1.0	0.4		
2.0 Construction Design	2.1 Simplicity (ISO20887 - Sec. 5.3.6)	1.0	0.5	62	0.2
	2.2 Standardization (ISO20887 - Sec. 5.3.7)	2.5	0.7		
	2.3 Accessibility (ISO20887 - Sec. 5.3.2)	2.5	0.9		
	2.4 Independence (ISO20887 - Sec. 5.3.3)	1.0	0.5		
	2.5 Durability (ISO20887 - Sec. 4.3.2)	0.5	0.5		
3.0 Disassembly Design	3.1 Safety (ISO20887 - Sec. 5.3.7)	1.5	0.8	73	0.2
	3.2 Deconstruction process (Sec. 5.3.7)	1.5	0.5		
	3.3 Finishes (ISO20887 - Sec. 5.3.4)	1.0	1.0		
	3.4 Connections (ISO20887 - Sec. 5.3.2/5.3.3)	4.0	0.6		
4.0 Circularity	4.1 Reusability (ISO20887 - Sec. 5.3.5)	0.5	0.5	42	0.2
	4.2 Refurbishability (ISO20887 - Sec. 5.3.5)	0.5	0.5		
	4.3 Remanufacturability (ISO20887 - Sec. 5.3.5)	0.5	0.5		
	4.4 Recyclability (ISO20887 - Sec. 5.3.5)	1.0	1.0		
	4.5 Reclaimed material (ISO20887 - Sec. 5.3.5)	0.0	0.0		
	4.6 CE Market (ISO20887 - Sec. 5.3.5)	0.0	0.0		
5.0 Documentation	5.1 General design documentation (ISO20887 - Sec. 6.1)	4.0	1.0	58	0.2
	5.2 Construction documentation (ISO20887 - Sec. 6.1)	2.0	1.0		
	5.3 Disassembly documentation (ISO20887 - Sec. 6.2)	0.0	0.0		
	5.4 Material and manufacturers information (ISO20887 - Sec. 6.3)	1.0	0.4		
	5.5 Documentation handling and transference (ISO20887 - Sec. 6.5 & 6.6)	1.0	0.5		

2.0 Construction Design	62	100
3.0 Disassembly Design	73	100
4.0 Circularity	42	100
5.0 Documentation	58	100
1.0 Adaptability	54	100

ReBuilding Index	58

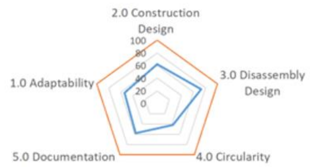


Figure 2.3. Example of result from using the indicator system developed in WP2: a ReBuilding Index with results from categories shown in a spider chart (Zabala Meja 2021).

Design Decision Matrix

To achieve a tailored approach that could provide relevant guidance to architects and engineers, a *Decision Matrix* was developed, also based on the ISO 20887:2020 and linked to the RIBA Work Stages (RIBA 2021), for buildings where timber is the primary structural material (Figure 2.4).

The intention was to provide clearer guidance for implementation of DfDR principles in practice at each stage of the design process. Thus, the matrix incorporates a different range of strategies and tactics, gleaned from research, that are appropriate to consider in each respective RIBA work stage (horizontal tabs). These are linked to DfDR principles (vertical tabs) from the ISO 20887, with specific design strategies and tactics combined with complimentary design tasks. Each expansion offers an increased level of detail on the potential design decisions at each stage of the process.

	Stage 1- Preparation & Briefing	Stage 2 - Conceptual Design	Stage 3-Spatial Coordination		Stage 4-Technical Design	
	STRATEGY	STRATEGY	STRATEGY	TACTIC	STRATEGY	TACTIC
RIBA Typical Workstage's						
Design For Disassembly & Reuse Matrix						
Design & Project Team						
Allow for safe deconstruction						
Supporting re-use (Circular Economy Business Models)						
Standardisation						
Ease of Access to components & Services						
Simplicity						
		Refer to existing construction onsite and local vernacular construction.	Aim to simplify material pallet at planning stage where appropriate.	- Many different types of materials will result in quantities of material that are uneconomical to salvage and potentially make the disassembled building less appealing for reuse. These changes may be difficult to undertake following planning approval.	Minimise the different number of materials used (3,6,7)	- Selecting timber which can be used both externally and internally such as Douglas fir. - Large ranges of timber may result in difficulties in sourcing replacements meaning less chance of reuse.
					Minimise the number of different components and connectors. (2,3,4,5,6,7)	- avoiding complexity which makes it difficult for a contractor to plan for demolition. - Increasing the speed of deconstruction will decrease the likelihood of demolition and waste.
			Consider traditional methods of construction which may utilise simpler methods of construction.	- Liaise with local craftsmen to understand what methods have been used locally. This will increase the potential adaptability of the structure as specialists need not be required.	Use low technology solutions and standard tools and practices. (2,3,4,5,6,7)	- Avoid specialist tools which may not be available when disassembly is underway. - Complex construction techniques will limit ability of user to make changes.
					Avoid use of adhesives (2,3,4,5,6,7)	- Utilise bolt connects or friction fit.
			Design for maximum flexibility to preserve the building as a whole (2,3,5)	-Utilise layers which can be indepently diassembled i.e. inner layer, strucure, outer or infill & structure. - Limiting the diverse materials so that they can be easily replaced. -Use standardised or locally sourced materials. - Construction methods which are not too complex as this may result in demolition. - Utilise connections which can be removed a number of times.		
Independence / Reversible connections						

Figure 2.4. Example of a DfDR Decision Matrix with RIBA stages organised horizontally and the ISO principles vertically, populated by strategies and tactics identified in existing research.

Case study method

Studies on existing timber building designs were carried out and to that end a *case study method* was developed which included: defining the scenario; analysis of existing design; development of improved design; comparison of material recovery rates between existing and improved designs; and development of guidelines for deconstruction and reuse (deconstruction plans), Figure 2.5. One of the cases was different in character, as it concerned a new design based on traditional post-and-beam structures. For this study the method had to be adapted.

Step 0. Defining a scenario to design for

Step 1. Analysis of existing design

1.1 Description of the building and how it is assembled

1.2 Simulation of deconstruction and reassembly as well as identification of strengths and weaknesses

1.3 Identification of areas to improve

1.4 Selection of areas to improve

1.5 Calculation of the amount of wood that can be reused with today's design

Step 2. Modified design

Step 3. Comparison existing - modified design

Step 4. Guidelines for deconstruction and reuse

Figure 2.5. Case study method.

2.3.4. New designs and studies on connections

The five case study buildings were Villa Anneberg (off-site, light-timber, Sweden), Everett Grand (off-site, light-timber, UK), Villa Forshälla Sund (off-site, massive wood, Sweden), Cygnum Reflect 140 House (off-site/on-site, light timber, Ireland) and Cuenca Village, (off-site, post-and-beam, Spain), further described in Sandin et. al (2022a).

On three case studies (Villa Anneberg, Villa Forshälla Sund and Everett Grand), a future scenario assumed the building is deconstructed into its original prefabricated light-timber wall/floor panels after 50 years and reassembled in a region with similar environmental conditions. A broader scenario in two case studies (Cygnum Reflect 140 and Cuenca Village) envisioned the buildings to be deconstructed to discrete material components after 50 years, with material reused in new construction. This latter scenario was important to study, as any building would ultimately have to be deconstructed into its separate elements, which has implications for a different series of connections than those studied in the prefabricated cases. These two cases, as well as Everett Grand, also considered aspects of adaptability. In most cases studied the manufacturers were actively participating as partners in the analysis, with additional input from demolition contractors. Results were often influenced by local building traditions, markets, and regulations. For instance, I-joists were considered unusable after 50 years in the Irish study (Cygnum Reflect 140) while in one of the Swedish (Villa Forshälla Sund) and the UK (Everett Grand) cases they were judged to be reusable as part of the floor modules.

The prefabricated assemblies showed good promise for deconstruction based on reusing the panels in an identical manner. Obstacles identified were the complexity and number of panel types; irreversible, hidden, or unplanned connections; inaccessible services; and interconnected layers. Recovery rates (Table 2.1) were improved through limited changes to panel-to-panel connections, which removed adhesives; reorganised vapour barriers to reduce damage by screws; provided better identification and access to the connections; and replaced nails with screws.

Table 2.1. Proportion of wood/wood-based material judged reusable arranged by reuse scenario.

Reuse scenario	Case Study	Proportion of wood judged reusable - original design	Proportion of wood judged reusable - modified design
After 50 years, deconstructed, transported, and reassembled into identical building in region with same snow and wind loads	Villa Anneberg	83 %	86 %
	Everett Grand	94 %	98 %
	Villa Forshälla Sund	97 %	100 %
After 50 years, disassembled into its discrete materials	Cygnum Reflect 140 (for solid timber)	41 %	67 %
	Cuenca Village for post-and-beam structure / for wall, floor, and roof panels	67 %	94 %

In the scenario where individual timber members were recovered there was a greater loss of timber material in both the existing and modified designs as compared to the direct reuse of panel assemblies, because board products, I-joists and smaller timber sections with extensive connector damage were not considered reusable. There was nevertheless a significant improvement in recovery rates with modifications that included the use of timber joints and bolted connections (Cuenca Village) and a combination of wood nails in stud/joist ends to reduce damage, and screws to replace nails (Cygnum Reflect 140). The standardisation of panel types (Cuenca Village, Everett Grand) and timber sizes (Cygnum Reflect 140) through rationalisation of the building and structure layout also increased recovery and reuse potential as well as facilitating partial deconstruction or expansion to extend the building's service life. Other issues identified were the number of deconstruction steps, deconstruction damage, complexity, unknown or short service life, recertification of assemblies to building regulations, value of recovered elements and size of recovered elements. Some of the new solutions developed (Villa Anneberg, Everett Grand) were considered so valuable to the manufacturers that they will be used in production this year.

The Villa Forshälla Sund, as a massive wood panel construction (Figure 2.6), excelled in the simplicity and reduction of the number of steps required with maximum recovery due to the simplicity of its uniform wall composition of CLT and IsoTimber.

Figure 2.6. Prefabricated wall elements of IsoTimber panels and CLT. The number of IsoTimber panels depend on desired U-value.

2.3.5. Guidelines for deconstruction and reuse

The case studies also examined forms of documentation that would be useful for a Deconstruction Plan in Sandin et. al (2022a). Based on a guidance found in literature (Morgan and Stevenson (2005), Guy and Ciarimboli (n.d.)), these included: a deconstruction and reuse strategy statement; a list of building elements including warranties, service life and reuse potential; disassembly instructions including plans, equipment required and removal techniques; and a clear proposal for document storage. The case studies expanded this guidance, most notably to reflect prefabricated assemblies, which had not been addressed previously despite being an increasingly common form of construction. In the prefabricated case studies, panel information (number, weight, size, assembly, u-value, fire rating) rather than material data was supplied in tandem with pre- and post-disassembly audits, as advocated by Zero Waste Scotland (n.d.). There was also a recommendation that the manufacturer retain the building information and disassembly plan, extended in the Everett Grand case to suggest the manufacturer also retain ownership of the assembly, which could strengthen the outlook for successful circularity. All case studies also had some form of recommended targets for recovery, though they varied substantially in form from a stated target (%, Villa Anneberg); an anticipated value of recovery of elements either explicitly (Everett Grand) or implicitly (Cygnum Reflect 140) stated; to a spreadsheet to calculate actual recovery rates (Cuenca Village). Taken as a group of studies, there are advantageous additions proposed to earlier guidance documents: strategy statement for flexibility and adaptability; information on panel assemblies intended for reuse; targets for reuse and a method to calculate actual recovery rates; pre- and post-disassembly audits; and key details / junctions illustrated.

Equally significant, but understudied in the field, is the impact of future technological changes on viable documentation formats. Given the magnitude of change that has occurred in the last 50 years in design and construction practices, the question of how elaborate or simple a system of documentation to rely on is key. It is telling that the case studies with the closest involvement of the manufacturer (Villa Anneberg, Villa Forshälla Sund and Everett Grand) did not address this question, as the documentation would remain in-house and presumably evolve with changes to digital platforms. The remaining case studies proposed low-tech solutions such as marking the timber (Cuenca Village) or providing hard-copy documents (Cygnum Reflect 140) to avoid obsolescence.

2.4. Conclusions and discussion

2.4.1. Our contribution beyond state-of-the-art

The contribution from WP2 beyond state-of-the-art in the field of design for deconstruction and reuse is concluded by answering our research questions.

What methods can be adopted to optimise a primary design for deconstruction and reuse?

WP2 has developed two tools that could be used by manufacturers and design professionals to optimise a primary design for deconstruction and reuse: an indicator system, producing a ReBuilding Index, and a Decision Matrix. Also, a case study method was developed, that provides a simple and efficient means to improve an existing design for deconstruction and reuse. However, adding these results to the existing guidance in the field of DfDR and DfA is not enough; a more concerted effort is required to disseminate the knowledge to design professionals, contractors, prefabrication manufacturers, and building authorities. Results could be valuable in third-level education, professional development courses, professional bodies, and building certification schemes such as LEED and BREEAM.

What new designs can be suggested and what can be said on timber connections in relation to deconstruction and reuse?

The case study analyses made clear that prefabricated assemblies are well positioned to be deconstructed to facilitate the reuse of the panel assemblies, with minor alterations in strategic design details to improve identification and access, provide independence, and replacement of nailed connections with screws. Consideration of connection details within the framed assembly, which has implications for the ultimate recovery of timber elements, can be enhanced through the use of timber joints, wood nails to reduce the damage in stud and joist ends, and the use of screwed or bolted connections. Modular and prefabricated construction, consistent with the Standardization principle of ISO 20887:2020, reduces construction waste, improves quality due to factory controls, reduces time on site for assembly, and results in fewer unplanned connections that can undermine the deconstruction process. This can be enhanced for adaptability by limiting the number and complexity of the panels to improve reuse/replacement potential; rationalising spatial and structural layouts to allow for flexibility, adaptability, and expandability; and centralising the service runs for maintenance. The use of durable, long-lived materials also facilitates reuse cycles, through the use of mass timber or heavy timber or replacing engineered joists using OSB (oriented strand board) with solid timber. The reuse of composite panel assemblies is also improved through the use of components with similar life spans within assemblies, and suggests that developing components, such as vapour barriers, insulation, and board products, with a longer guaranteed life span of 100 years is critical.

How can guidelines for deconstruction and reuse be formulated?

Existing guidance provided a structure for Deconstruction Plans that was used in all case studies. Taken as a group of studies, there are advantageous additions proposed to earlier guidance documents. Despite being based on the same source, the plans suggested by different case study teams varied substantially. There was a noteworthy difference between manufacturers in-house plans to those proposed by architects, which speaks to the uncertainty regarding the appropriate structure and format. Also unaddressed is the scale of the building, which could influence the complexity required.

2.4.2. Future work

The methods developed still need to be improved. The indicator system has been updated to be used by a third-party assessor, an important prerequisite as the indicators is based on subjective measures which could otherwise be manipulated by someone too closely associated with the project. The updated tool will be based on data collected in studies on real-life deconstruction and reuse processes. Work has started on four cases where timber buildings are presently, or have recently been, deconstructed and reassembled. One example is shown in Figure 2. and another is reported on in (Sandin et al. 2022b). The Design Matrix will be further tested on prototypical designs developed using DfDR principles and tactics as outlined in the matrix, using various structural systems. Further research with stakeholders is required to identify a coherent standard for Deconstruction Plans, which is likely to become legally required in the future.

Three issues require further clarification: 1) where should such a document be stored, 2) the structure of the document and 3) the document format, that is whether it is digital or hard copy.

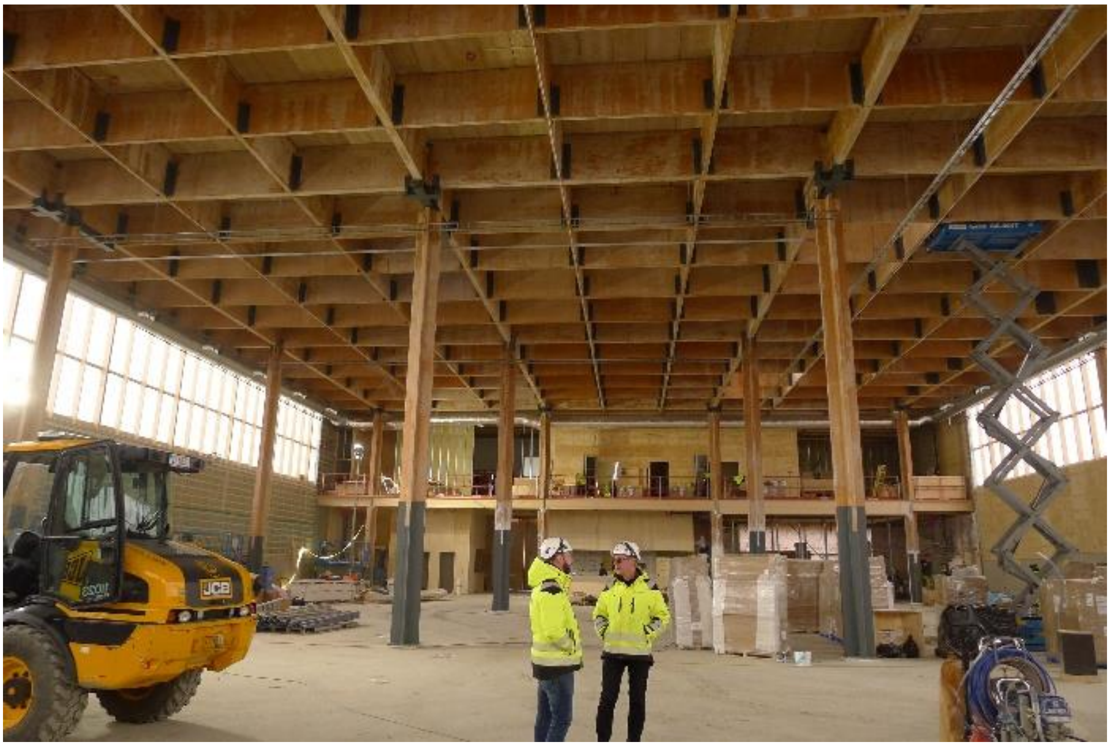


Figure 2.7. A market hall in Stockholm, Sweden that was deconstructed and moved is presently being reconstructed in Mölnlycke as a sport centre (a paddle tennis hall). Photo: Ylva Sandin.

2.5. Moving a city and timber houses

Part of the city of Kiruna, Sweden will be moved due to the mine that is developing under the city centre causing cracks on the surface. Due to that some of the old cultural heritage timber buildings have been moved to new locations and renovated Figure 2.8 and Figure 2.9.

Figure 2.8. Kiruna is under transition moving to the new city centre, photo Kiruna Municipality.

Figure 2.9 Moving houses from the beginning of 1900. On the top a house with 16 rooms built for the workers. Below to the left "The engineer's villa" weight 280 ton being moved, photo Kiruna Municipality and *https://www.youtube.com/watch?v=0EHSfgZFzxM* . To the right the house on the new location, photo Karin Sandberg.

3. Product design using recovered timber

3.1. Background

A key objective of the EU is the reduction of construction and demolition waste, which is currently not only a significant environmental hazard but also fails to capitalise on valuable natural resources. With the demand for renewable, low-carbon construction materials such as timber and engineering wood products growing rapidly across the globe, there is an urgent need to recover and reuse timber components from buildings at the end of their life to supplement the new material coming from our forests. The focus of this WP is the investigation of the use of timber recovered from demolition in the manufacture of mass timber products.

3.2. Aims and objectives

The primary aim of WP3 was to develop new ways to reuse and recycle timber and engineered wood products from demolition, especially into construction products. To achieve this aim, work was carried out in four tasks.

The objectives of the first Task 3.1 “Specification of timber property requirements for products” were to identify the typical range of timber products that are available from building demolition, to establish the scope of the reuse and recycling of salvaged material currently, to examine potential wood-salvage yield for reuse and recycling, and to explore the practical limitations of each application. This work was carried out using a combination of site visits to demolition sites and recycling facilities and by means of an industry survey carried out in conjunction with WP4.

The objectives of Task 3.2 “Recycling timber in new mass timber products’” were to investigate the processing of recovered softwood and hardwood timber into cross-laminated timber (CLT) panels and glued laminated timber (GLT) beams and compare their structural performance with equivalent products from new timber, to characterise the performance of adhesive bonds in CLT and GLT manufactured from recovered timber, to undertake a study of the embedment behaviour of recovered timber through experimental testing and finally to quantify the environmental impact of CLT produced from recovered timber.

The aim of Task 3.3 “Design of new products optimised for improved deconstruction potential at the end of life“ was to develop construction products from new wood that are suitable for deconstruction at the end of first use. More precisely, the aim is to improve the design and assembly approach used currently by timber product manufacturers and builders such that the reuse viability of the product is increased. Two types of timber construction systems, namely, light timber frame and mass-timber panellised systems were investigated using case study examples from WP2.

The aim of Task 3.4 “Develop traceability protocols for new products” was to address the lack of information available for used timber regarding its species, origin, grade, and chemical or heat treatment. The main objective of the study is to improve the traceability of building timber and engineered timber products so that designers can have confidence in the origin and work history of reclaimed wooden materials from demolition.

3.3. Highlights

The work of T3.1 is summarised in the D3.1 report *Recovered timber in Europe: sources, classification, existing and potential reuse and recycling* (Harte et al., 2020). The report highlights the fact that most timber extracted from building demolition is broken to minimise the cost of removal and is subsequently reduced to woodchip for biomass energy production, as in Figure 3.1, for the manufacture of pallet blocks or for particle board production and agricultural use where it is appropriately uncontaminated.

Figure 3.1 Woodchip for biomass energy production.

The reuse of whole structural timber elements is mainly found in the case of the demolition of older buildings, such as in Spain where timber elements can have significant cultural value, or for larger mass timber elements, such as in Sweden where 90% of glulam beams are recovered for reuse. (Llana *et al.,* 2020, Arana-Fernández *et al.,* 2020). The amount going to landfill across the partner countries is low. The potential for timber from demolition that is currently chipped for bioenergy and other uses to be redirected to higher cascade uses, such as in mass timber construction products, was highlighted.

The work of T3.2 is detailed in the D3.2 report *Recycling timber in new mass timber products* (Uí Chúláin *et al.,* 2021). This report presents the findings of an extensive experimental campaign carried out across several partner countries and provides scientific data to support the potential reuse of recovered timber in the production of mass timber products.

In the first set of studies focussed on the production of mass timber products from recovered timber, experimental programmes were carried out in Ireland, Spain, and Sweden. In the Irish study, three-layer cross-laminated timber (CLT) panels were manufactured from spruce timber recovered from the demolition of a roof truss in Dublin, Figure 3.2.

Figure 3.2 Utilize material from existing buildings in new wood products, photos Copyright NUIG.

Similar panels were made with new Douglas fir, which is a minor conifer species in Ireland. As it is often difficult to recover long lengths of timber, hybrid panels were also manufactured using new timber for the longitudinal layers and recovered timber for the shorter cross layers. The study found no difference in the mean bending modulus of elasticity (MOE) between the three designs, which ranged between 10340 N/mm^2 and 10870 N/mm^2, Figure 3.3. The mean bending strength ranged between 42 N/mm^2 and 50 N/mm^2. Values for recovered and new panels were the same with the hybrid panels slightly lower. Overall, the study has shown no difference in the performance of CLT manufactured from recovered and new softwood timber.

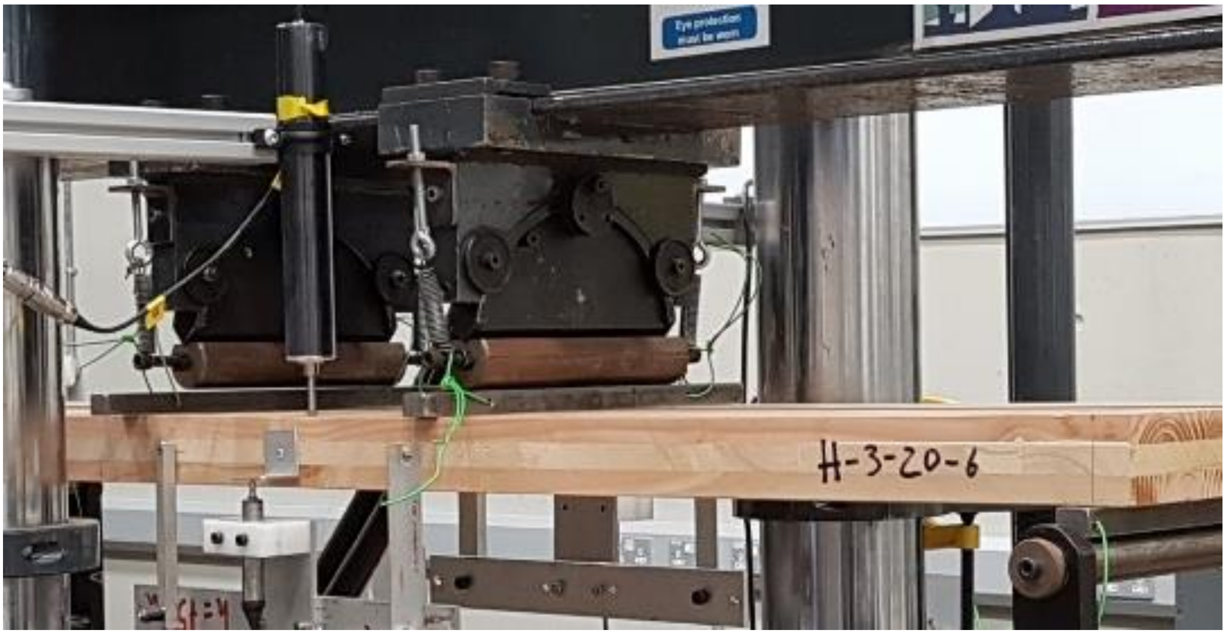


Figure 3.3 Test of CLT from reused timber.

In the Spanish study, CLT panels and glued laminated timber (GLT) beams were manufactured from recovered and new oak specimens (Llana *et al.*, 2022). The recovered oak was about 150-200 years old and had large cross-sections, which were cut into several smaller pieces to manufacture the mass timber products. Three-layer CLT panels were manufactured with recovered timber, new timber, hybrid with new outer layers and recovered timber core and hybrid with recovered timber outer layers and new timber core.

Results show that the MOE remains unchanged when testing CLT panels manufactured from new or recovered timber. However, in the case of bending strength, while lower values were obtained in recovered timber longitudinal-layer panels, these values are high enough for structural applications (Llana *et al.*, 2022). Similar findings were obtained in the GLT study. For five-layer GLT beams made from recovered oak and from new oak, the MOE remains the same, while the bending strength was lower for beams manufactured from recovered oak. The values were high enough for structural applications.

It can be concluded from these two studies that the mechanical performance of mass timber products from recovered softwood and hardwoods is comparable to those of similar products made with new timber and both are suitable for structural applications.

Regarding the yield from the recovered timber, in the case of the Irish mass timber products the recovered timber cross-section was significantly larger than the board dimensions required for panel manufacture resulting in a yield of about 28% when length reductions are included. The yield would be greatly increased if recovered timber dimensions closer to the final board dimension were available. In the case of Spanish mass timber products, the yield was only 15% as much wood waste was generated in sawing the large cross-section to final boards. In terms of yield, mass timber products are a good option for recycling medium cross-section recovered timber (e.g. joist and roof rafters). However, for large cross-sections, direct reuse for rehabilitation works will be a more efficient use of the material.

In the Swedish study, an IsoTimber wall panel was manufactured with reclaimed timber as material for the uprights and tested (Cristescu *et al.*, 2021). This panel and similar panels of new timber had load capacities exceeding the test limit of 400 kN. However, the recycled panel showed a stiffness reduction above 270 kN compared with panels with new timber. As only one panel was manufactured from recovered wood, it is not possible to draw firm conclusions, but lessons were learnt that will be useful for the company, which intends to use recovered wood in its manufacturing process and to undertake further comparative studies of new and reclaimed wood used as components of a structural elements.

Following on from the bending tests, a number of studies were carried out in Ireland, Spain, and the UK to investigate the integrity of the adhesive bonding between the lamina in mass timber products manufactured from recovered and from new timber timer (Uí Chúláin *et al.,* 2021). In the Irish study, specimens were extracted from undamaged parts of the CLT panels, which had been tested in bending. The bond strength of the glue lines was determined using the delamination test and shear test in accordance with EN 16351:2015. The specimens from the CLT panels manufactured with recovered timber and the hybrid CLT panels satisfied all the requirements of EN 16351:2015 with respect to delamination and shear strength. Of the specimens manufactured with new timber, three failed the delamination test. However, all displayed high values of shear strength well in excess of the minimum requirements. The results of the test series show that designers can be as confident in the use of recovered timber as with new timber with respect to the bond strength of CLT panels.

In the Spanish study, specimens for glue line testing were similarly extracted from the CLT panels and GLT beams tested in bending, Figure 3.4.

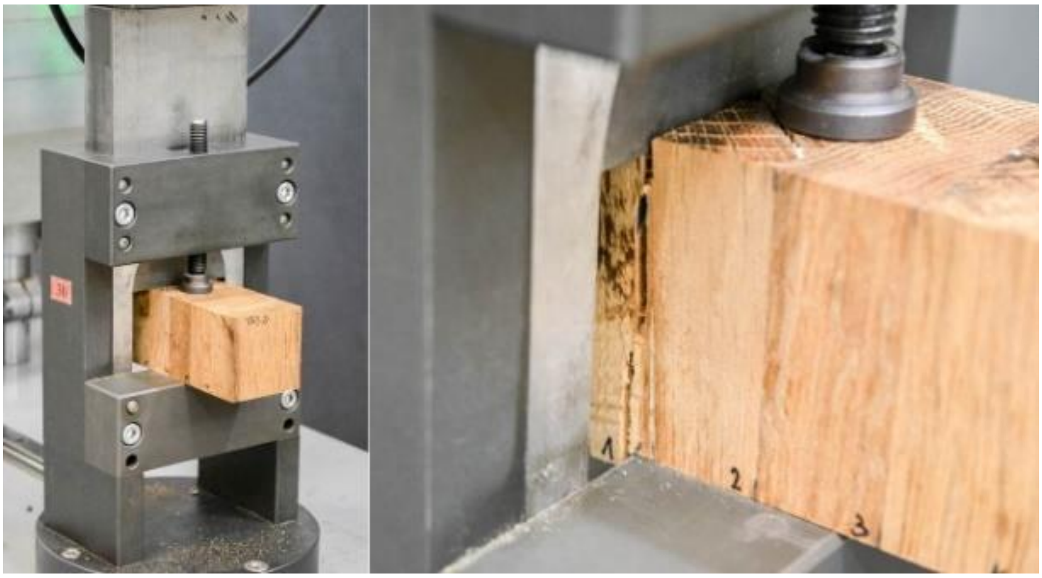


Figure 3.4 Glue line testing.

The delamination tests on the CLT specimens showed a pass rate of 75% for bond lines between recovered timber, 50% for bond lines between recovered and new timber and only 16% for bond lines between new timber. Even though the surface preparation was identical for new and recovered timber, the recovered timber had a rougher surface after planing, which may explain the difference in performance. For the specimens extracted from GLT beams, all glue lines failed the delamination test. This may be due to the test method used, the adhesive selection, surface treatment, or manufacturing parameters or a combination of these and will require further investigation. Shear tests carried out on specimens taken from the GLT beams gave a pass rate of 90% based on wood failure percentage for the recovered oak specimens compared to 42% for those from new oak. Nevertheless, the shear strength achieved well in excess of the requirement in EN 14080:2013.

In the UK, shear tests were carried out on specimens extracted from GLT beams manufactured with recovered wood as part of another project (CIRCuIT, Horizon 2020 Framework Programme Grant Agreement no. 821201). For these tests, 95% of specimens satisfied the requirements of EN 14080:2013 with respect to shear strength. It can be concluded that the recovered wood glulam does, indeed, have a level of performance we expect to see in equivalent glulam from new timber.

Having demonstrated that recovered timber can be successfully utilised in the manufacture of mass timber construction products, the next step was to consider connections between recovered timber elements. As dowel type connections are the most widely used in modern timber structures, it was decided to focus on the timber property governing the behaviour of these connections: the embedment strength. For this study, recovered timber was sourced from three demolition projects: spruce from roof structures in Dublin and Ljubljana and oak from a 90-year-old bridge over the River Sava in Slovenia. Embedment tests according to EN 383:2007 were carried out on specimens extracted from these sources using three different dowel diameters loaded parallel to the grain and also loaded perpendicular to the grain. The test results were generally in line with the current Eurocode 5 (2014) empirical predictions and were comparable with mean values for new timber reported in the literature.

The LCA comparison carried out in WP 6 indicates that the use of recovered wood in CLT manufacturing is a feasible environmental option, when compared to the use of primary wood. In most categories, the use of recovered wood results in lower or similar environmental impacts. Only the incineration of the contaminated fractions of the recovered wood results in higher environmental impacts in some categories. A reduced utilization of wood preservatives would thus lower the impacts during recycling processes as well as during the end-of-life treatment. The impact savings from the reduced drying effort for the recovered wood motivate to keep the material dry during disassembly and the recovery process. The use of recovered wood as a resource results in the saving of primary resources, of land area, which would be available for further wood production, given the renewability of wood resources.

The work of T3.3 is detailed in the D3.3 report *Design concepts for building products optimized for deconstruction* (Uí Chúláin *et al*, 2022a). For three light timber frame and two mass timber house designs, the current building practices that complicate disassembly and reuse were identified and alternative systems were developed to enhance the reuse potential. For the light timber-frame designs, the main complicating factors were the use of additional fixings during construction, which were not specified, detailing of air-tightness membrane at connections between panels, and gluing of connection between floor cassettes. Revised designs with improved connection details were provided and a recommendation that specific temporary supports be provided on site to obviate the need for unprescribed connectors. For mass timber construction some of these problems were avoided and in general, deconstruction was straightforward. Airtightness is achieved by taping of the junction, so membranes are not needed. Temporary supports and propping of panels are included in mass timber assembly schedules so use of undocumented temporary fixings should be reduced.

The work of T3.4 is detailed in the D3.4 report *Traceability protocols for materials and products* (Uí Chúláin *et al*, 2022b). This report considers how the necessary information relating to materials and building products can be stored and updated over their lifespan and also what information needs to be stored for retrieval at the reuse/recycling phase of the lifespan.

Building Information Modelling (BIM) is a virtual database that is used to digitally document and manage information throughout a building project and can be updated by building stakeholders over time. The report identifies three main caveats to bear in mind when endorsing BIM in the context of material traceability protocols. They are: (i) the reliability of the information obtained from a BIM is determined completely by the detail and accuracy of the model created and whether it is updated to reflect on-site amendments to the design, renovations, and maintenance. (ii) the availability of the data stored on a BIM relies on the continued availability of the software used to build the model and its compatibility with future technology, and (iii) the trustworthiness of the BIM depends on the secure management of the files. With the move towards the digitisation of the construction industry, BIM technology is becoming the norm and this should increase reliability. The issue of software obsolescence is always a concern when data is required to be stored and accessed over extended time periods. With the significant investment in BIM by the construction industry, one can be relatively confident that this issue will be resolved. Regardless of how documentation is stored, the confidence in the verification of certification of a building, including its design, products, and materials, is based on the reliable accreditation of the certifier. Distributed Ledger Technology (DLT) is emerging as the most trusted method to permanently log accreditation and documentation in the digital world. The most secure branch of DLT is Blockchain (Komdeur & Ingenbleek, 2021). A recent report commissioned by the BRE Trust (Cooper & Ghumra, 2018) observed that blockchain technology could combine certification and verification of elements with regard to physical and chemical characteristics.

A key part of the traceability chain is the digital to physical link between the BIM model and building element. Electronic Identification technology is widely established and provides a potential solution. It is commonly used in outdoor working environments. The data can be accessed without direct or very near proximity to the tag making is relatively easy to scan elements in situ. The information is transferred and stored electronically in a way that can be accessed and updated repeatedly.

The information that should remain with the building component during first and subsequent uses to facilitating safe design of new structures using these components includes physical, mechanical, acoustic, thermal and fire properties as required for design using new materials. In addition to the as-built properties, it is essential that a record of any damage to the building element over its service life is recorded together with any interventions which may occur. Additional data required to enable the safe deconstruction of the element should also be included such as a deconstruction manual, location of connections, lifting points, and element mass. Examples are provided in the report.

3.4. Conclusions and discussion

The studies carried out in this WP have shown that the mechanical performance of mass timber products from recovered softwood and hardwoods is comparable to those of similar products made with new timber and both are suitable for structural applications.

The LCA comparison indicates that the use of recovered timber in CLT manufacturing is a feasible environmental option, when compared to the use of new timber and can contribute to the implementation of wood cascading as part of a bio-based economy

3.4.1. Our contribution beyond state-of-the-art

Within WP3, new mass timber construction products have been successfully designed, manufactured, and tested using recovered timber. These CLT panels and GLT beams have been shown to have load carrying capacities equivalent to similar products from new timber. The materials considered include recovered oak and spruce and new oak, Douglas fir and pine from a range of partner countries. The possibility of mixing different species and also mixing new and recovered timber was studied using similar hybrid panels with equally successful results.

Bonding performance of new and recovered timber from CLT and GLT specimens has been characterised in a series of studies. Bonding of CLT elements using softwoods or hardwoods was shown to satisfy the code requirements for new timber products. For the GLT specimens, high shear strength values were achieved but further work is required in relation to delamination.

The embedment behaviour of recovered spruce and oak, which is a required property for the design of timber connections, has been characterised. To our knowledge this is the first study to investigate this essential property of recovered timber.

3.4.2. Future work

While the outcomes of this work have been very promising in terms of developing high-performance mass timber products from recovered timber, the scale of the test programmes was limited by the budget available. Further testing is required to increase confidence in the results and to work toward the requirements of technical approval under the ETA and EAD system.

This programme of testing should include the following:

- Bending and shear tests on 3- and 5-layer CLT panels from recovered timber considering a range of species and age groups
- Optimisation of the bonding performance of GLT beams from recovered timber considering different adhesives, surface treatments and pressing parameter
- Further investigation of the use of mixed species, both old and new, in hybrid mass timber products
- Further studies on the embedment behaviour of recovered timber by increasing the number of tests and range of species and ages.
- Characterisation study on the rolling shear behaviour of recovered timber.
- Development of dowel-laminated timber products from recovered timber.

4. WP 4 Inventory, deconstruction, and quality of recovered wood

4.1. Background

Wood used in construction ranges from ancient hewn timbers to CE marked strength-graded construction timber, as well as various forms of engineered wood product like glue laminated timber (glulam), laminated veneer lumber (LVL) and wood-based panels such as plywood, oriented strand board (OSB) and particleboard. Frequently, different wood products are combined to form sub-systems within a building (e.g., shear panels), or are attached to one another to perform a certain structural function (e.g., roof trusses), making their separation, and the subsequent recovery of the wood products themselves more difficult, and can lead to a reduction in both quality and dimensions during demolition. Added to this, different buildings utilize wood in different ways and to different extents, largely depending upon type and function, geographical location, local building traditions, as well as when the building was built. The result is that it is often difficult to know what wood products are used in a building and how they are used. This then has a direct bearing upon how easy it is to recover wood products for reuse, as well the condition and useable dimensions of the recovered wood. This in turn impacts upon the cascading potential of the recovered material (Sakaguchi et al 2017).

The total amount of wood incorporated in buildings can be estimated using statistical approaches (e.g., Kalcher et al 2017; Nasiri et al 2021). Whilst this approach is useful in determining the "order of magnitude" of waste wood that is potentially available for recovery, reuse, and recycling, it provides little information about the dimensions and quality of waste wood that is necessary when considering how to implement cascading in practice (Sakaguchi et al 2016). In WP4, we investigated the types of wood products and their dimensions used in buildings and their relative proportions to add "granularity" to data on the total volumes of wood incorporated in buildings. Much of the intrinsic "quality" and dimensions of wood products that is not lost during installation and use, is lost during the deconstruction/demolition process. Identifying key factors in the demolition process that can affect the quality and dimensions of the wood material is essential to pinpoint actions that could be taken to retain quality and dimensions as well as suggest possible design strategies that can enable rapid deconstruction. The quality of recovered wood is presently not well understood and currently there are no criteria to describe waste wood quality. We developed a set of criteria, that could be used to assess and measure the quality of waste wood in practice, and we tested these criteria against waste wood obtained from a commercial waste management enterprise. Further, we developed a materials flow analysis model to predict the future availability of waste wood, its quality, and dimensions.

4.2. Aims and objectives

The overall aim of WP 4 was to understand the volumes, dimensions and quality of material that could currently be recovered and reused, and which might be recoverable in the future following the implementation of design for deconstruction principles. In this WP, we conducted an inventory of wood materials used in the construction of the current building stock as well surveying the demolition methods most frequently used nowadays. Our goal was to establish the wood products most frequently used in buildings (T4.1) and to understand how the demolition methods employed affect the "quality" and dimensions of wood that could be recovered (T4.2). Recovered wood is essentially a "new" material resource and, whilst there have been limited studies conducted about the properties of recovered wood, there are no established criteria by which to assess the quality. One of our aims was, therefore, to establish new criteria for recovered wood quality (T4.3). Being able to predict the future volumes, dimensions, and quality of wood from demolitions is important to establish a cascading system. For this, a materials stock and flow model, that combines both the volumetric flow of waste wood exiting the building stock, as well as information about its dimensions and quality, is needed. In task 4.4 our aim was to develop a bottom-up stock and flow model, incorporating information about the (wood) product type, dimensions, and quality.

4.3. Highlights

The objectives of task 4.1 were to identify the building types with the highest content of timber, identify the characteristics of the timber products used in their construction, and quantify the timber contained in the selected building types. Typical building typologies in Finland, Ireland, and Spain were identified and, for selected building types, the wood products used in their construction, their types, typical *in situ* dimensions, location within the building and function, as well as whether they had undergone any treatment etc. was assessed (Figure 4.1). This was achieved by studying design drawings, consulting literature and where possible, conducting on-site assessments.

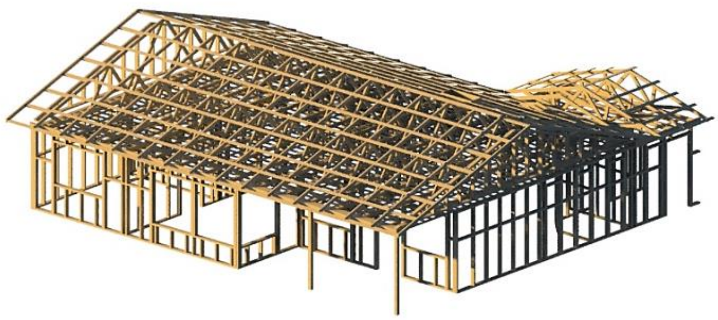


Figure 4.1 Inventory data created through Revit.

The building types identified as having the greatest amount of wood products in them were detached and attached houses in Finland, detached houses, semi-detached houses and terraced houses in Ireland, and corridor and traditional block type construction in Spain. In Finland, detached and attached houses are constructed predominantly from timber and comprise, on average, 82.5% of the completed gross floor area (contrasting with a mere 2.5% of completed gross floor area (GFA) of blocks of flats built from wood). Because the main structures of Finnish detached and attached houses are of wood, the amount of wood products used in their construction is consequently greater than in either Ireland or Spain, were masonry or a combination of masonry and timber framing are commonplace. For houses built around 1950 in Finland, the buildings incorporate approximately 0.17 cubic meters of wood per square meter (m^3/m^2) of GFA (the "timber intensity"). This contrasts with a timber intensity of around 0.35-0.38 m^3/m^2 for buildings completed earlier; the difference being accounted for by the earlier houses being constructed of logs, whilst the later houses were built using the balloon framing method. Interestingly, an analysis of CLT construction in Spain yielded a timber intensity of 0.2-0.3 m^3/m^2, commensurate with log building – another form of "massive" timber construction. In Ireland, the comparative timber intensity was found to be an average of 0.031 m^3/m^2, a figure over five times lower than that of Finland: the reason for this difference being due to the predominant masonry construction of houses in Ireland, with timber use being restricted to roof structures, flooring and internal partition walls, rather than the main load-bearing structure. In Spain, the timber intensity of the post and beam construction of the corridor and traditional block type construction was found to be on average 0.085 m^3/m^2 (Batista, 2020), which is intermediate between the masonry construction of Ireland and the wood construction of Finland, albeit the building type in Spain differs from the domestic houses of Finland and Ireland. These results clearly show not only country-to-country variation, reflecting the available timber resources, but also differences arising from the different construction methods used. What is evident is that even 'masonry' construction has useful quantities of timber that could be reused or repurposed, so not only "timber constructions" should be targeted, but any construction where wood is used can be seen as a potential resource. Another factor worth considering is that since timber intensity varies with construction type, if carbon storage is the goal, then "massive wood" construction can provide an excellent opportunity for carbon storage, though naturally, more (wood) resources are used in the first place.

Regarding the mix of wood products found in the buildings, these were almost exclusively solid (sawn) timber products, due to the age of the buildings studied (Figure 4.2). The majority of wood products embodied in each house in terms of volume comprise the following cross-sections: 22 mm × 100 mm, 20 mm × 100 mm, 22 mm × 125 mm and 40 mm × 125 mm, with the 20 mm × 100 mm cross section constituting by far the highest volume in all case studies. Similar analyses were carried out in Ireland and Spain. In Ireland, for example, the most common section size used is 37.5mm x 112.5mm, accounting for approximately 60% of all linear meterage, which in total amounts to an estimated 475 million linear meters in the current national housing stock.

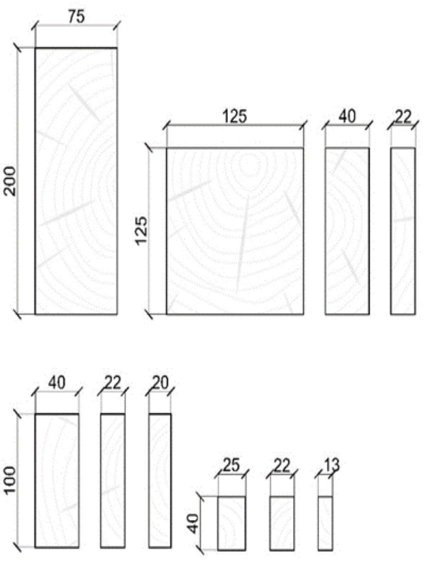


Figure 4.2 Cross-sections used in analysed balloon framing houses in Finland.

Even though different approaches had to be adopted in each of the three countries when quantifying the amount of timber in buildings, the timber intensity coefficients determined are logical when the different construction types are considered. Since each country has different statistical data and information available upon which to calculate the timber intensity coefficient, it is encouraging to see that there is no need for a "one-size-fits-all" approach to quantifying timber intensity reliably though, naturally, the investment in time and effort will vary depending on the method adopted.

The aim of task 4.2 was to investigate current demolition practices to identify problem areas where, potentially reusable, material is lost and to determine what improvements could be made to recover more re-usable material. Data were collected by visiting demolition sites (Figure 4.3) and through the responses received from a survey questionnaire that was developed in collaboration with WP 3. The demolition site surveys investigated several different building types, ranging from a large concrete-built multistorey public building from the 1970s to a domestic dwelling house built in the 1930s. There were commonalities in all the demolitions studied.

Figure 4.3 Heavy demolition phase of a wooden building located in Espoo, Finland.

Generally, the demolitions had three major steps: first, the interiors were demolished, this was followed by heavy demolition of the main structure (Figure 4.4), and third demolition of underground structures (e.g., foundation). Even the concrete public building contained around 120 m^3/ 55 tones clean wood, which had formed the interior fittings of the building. This amount of wood was of the same order of magnitude as the domestic dwelling, however, as with the other demolition case studies investigated, the wood material was damaged significantly during the demolition of the interior and the heavy demolition steps. One of the main findings was that useful quantities of wood could be recovered from all building types.

Figure 4.4 Heavy demolition phase of a residential house located in Jyväskylä, Finland.

Currently, practices prioritize speed of demolition, using heavy demolition equipment, over the recovery of material, resulting in a loss in wood quality and dimensions. In Finland, recovered wood, is however, separated on site into “contaminated” (i.e., containing preservatives) and “clean” wood. Among the reasons cited for not prioritizing material recovery were the design of the building, motivation of the demolition contractor and demolition method, which prioritized time and money over material recovery. In general, the recovery of wood in good condition has not been profitable for the contractor as there has not been a market for it (Husgafvel et al, 2018).

An estimated 132 m^3 of clean wood was recovered from a 1930s domestic dwelling, however, much of the wood recovered from the building was rotten as it had been poorly maintained. Nevertheless, trusses and floor beams were built of untreated wood which made it favourable for cascading. However, microbial degradation was suspected. Damage due to microbial degradation was often cited as a reason for the demolition of wooden buildings, suggesting that initial design, and maintenance, are crucial to material recovery. Moreover, the wooden elements within the building were connected using metal fasteners which is a barrier to reuse and recycling.

Manual deconstruction can be used to recover wood for reuse or recycling, though naturally it takes more time, but the method does retain the wood quality, thus might be a viable alternative if it can be established that there is material of sufficient quality to warrant recovery. A pre-demolition audit may reveal the underlying quality of the material and if it is deemed valuable from a materials persecutive, alternative demolition or dismantling methods could be used, that preserve material quality.

The aim of task 4.3 was to develop criteria to assess the quality of recovered wood (Figure 4.5). Based on the concepts of assessing the quality of recovered wood previously developed by Sakaguchi et al (2016, 2017), criteria to assess the quality of wood recovered from deconstruction in terms of: damage, contaminants, metal fasteners, recoverable length/dimension etc. were developed in conjunction with WPs 3 and 5 (Figure 4.6). These criteria could be used to assess the quality of recovered wood from demolition projects to ensure, as far as possible, comparability of data obtained from multiple demolition projects, undertaken by different contractors, in different European countries/geographical location and different building types. Data about the quality of recovered wood can later be combined with material flow analysis models to predict the quantity of recoverable wood from demolition.

Figure 4.5 Recovered wood selected for assessment.

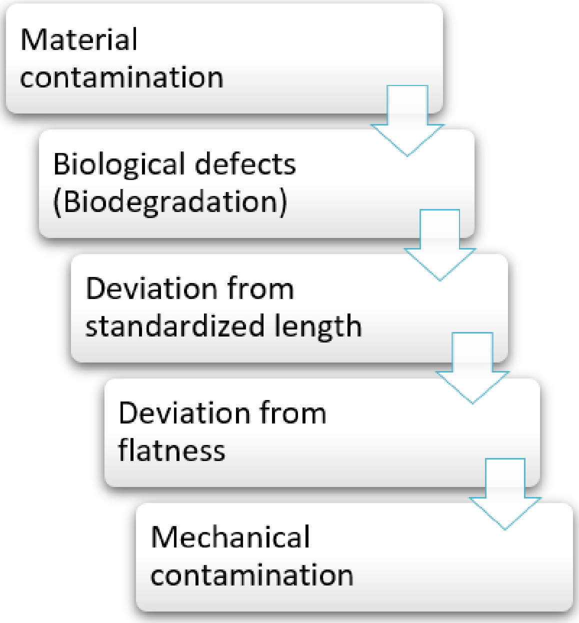


Figure 4.6 Criteria influencing visual quality of recovered timber.

The aim of task 4.4 was to create a model to predict the volumes and quality of recoverable wood (Figure 4.7). To calculate the flow of materials, the dynamic-stock-model package of Python was used and adopted to Finnish data. The historic inflow of new constructions built between 1966-2020 by volume were used as input to extrapolate future scenarios of the outflow of wood until 2060. The outflow of wood was developed according to the two decay functions most often used in similar studies, the normal distribution, and Weibull distribution, to see how they affected the results. The results showed wide variation, with significant effects on the forecast of waste production. In general, the longer the lifespan of a building is, the longer wood stays in the building, and the longer it stores carbon. Additionally, our results emphasize the importance of lifetime data and the choice of a suitable decay function and its variables (Miatto et al., 2017).

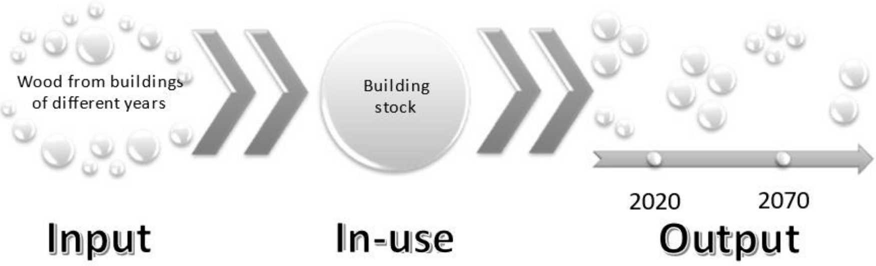


Figure 4.7 Material flow model developed for predicting the volume and quality of recoverable wood.

The results of the study show that the Weibull distribution with beta equal to 2 works best on Finnish buildings, which is in line with the conclusion that demolition is not only affected by the building life. There is, however, the need to conduct further research on Finnish building lifetime trends, including whether demolitions are affected by the building type and the year of construction. Further analysis in this area is required, especially in Finland, as such analyses will help policymakers understand the quantity, quality, location, and the time when the material becomes available, enabling them to introduce policies that prioritize reuse, recycling, DFD(R), and adaptation over energy recovery and demolition.

4.4. Conclusions and discussion

All buildings, irrespective of type, potentially contain useful quantities of wood products that could either be reused or recycled, rather than burned for energy. However, in practice the demolition methods used, which in turn are dictated by inter alia the economics of the demolition process and the lack of a market for recovered wood, result in the wood being significantly damaged and the dimensions reduced. This in turn, naturally affects the market potential. In other words, we have a vicious circle to contend with. In addition, the initial design, as well as maintenance, affects the condition of the wood contained in buildings. Design and poor maintenance often lead to fungal decay, making reuse impracticable.

To quantity the amount of wood embodied in buildings, we can use different approaches, based on the available statistical sources and computed material intensity coefficients. Nevertheless, even where access to statistical data is good, there are often gaps in the data, or simply the data is missing, making it difficult to create accurate models, especially when information and statistics about demolitions is lacking. It might be fruitful in the future to explore alternative methods and approaches to modelling the outflow of wood, such as those based on GIS (Global Imaging System).

Having material of suitable quality for reuse or recycling is imperative, and to determine what is of good enough quality requires criteria against which to assess it. We created a set of criteria as part of WP4, which has been tested against recovered wood obtained from a waste management company. Further validation should now take place to assess the validity of the criteria and determine if any further amendments are necessary.

We developed a materials flow model, based on an input calculated from statistical data and output based on mathematical functions representing building survival probability. Whist the model is functional, it requires development to improve accuracy and to predict the volumes and quality of individual wood products.

4.4.1. Our contribution beyond state-of-the-art

In WP4 we have developed new material stock (and flow) models to predict the volumes (and mass) of timber in three countries: Finland, Ireland, and Spain. Moreover, we have also determined materials intensity coefficients for each country.

We have identified some of the key pitfalls relating to the demolition of buildings and the recovery of wood materials for reuse, finding that beyond economic considerations, initial design and maintenance have a significant effect on the quality of recovered wood. Metals fixings etc, compromise the ability to deconstruct building and the added complexity that comes with modern building systems inhibits the recovery of materials for recirculation. In this respect traditional forms of construction – such a log construction – can often be a "guiding light" in terms of design thinking.

We have developed a prototype predictive tool to provide information about the volumes of wood material that will become available in the future in Finland.

4.4.2. Future work

Stock and flow models, based on statistical data, though useful, have their limitations due to the availability of data. Other approaches, such as the GIS approach noted above may prove useful, so would be worth exploring as an alternative, and perhaps, complementary approach.

To improve the accuracy of the model, a better understanding of the survival of buildings is required. Now, the reasons for demolition and the general survivability of buildings are not well understood. In terms of a circular economy hierarchy, extending the lifetime of existing buildings is the best way to reduce impact, increase carbon storage and avoiding harvesting of primary material. So, understanding what steps might be taken to extend building lifetimes and incentivizing these, might be a very effective way to reduce the climate impact of buildings. A project application to address exactly these issues was submitted to the Finnish Ministry of the Environment and has been approved and began in May 2022.

The "quality" of recovered wood requires further investigation. In the frame of InFutUReWood, it was not possible to directly use the quality criteria developed, so these should be tested against wood of known provenance recovered from demolitions. Moreover, the mechanisms of wood ageing (beyond straightforward decay and mechanical damage) should be investigated as this will invariably have a big impact on its refuse potential.

5. WP 5 Properties of the recovered wood

5.1. Background

In order to use recovered timber again, in structural applications, it will be necessary to know what values of properties to use in the design calculations. This knowledge is a combination of estimates of values (average and variation), and uncertainty of those estimates – but for the designing engineer these are reduced to simple numerical "design values" for simplicity. For new sawn timber this is done by a process called "strength grading" under the harmonised standard EN 14081-1:2019 (Ridley-Ellis et al. 2016). This standard is also required to be followed for the production standards for glulam and cross-laminated timber (and other commonly used standards), but it is incompatible with recovered wood for three main reasons:

- It requires that the species and growth area are known (very difficult to know for recovered wood). Grading rules are not transferable to other species or other growth areas and may also not hold true for timber grown many years ago due to the changing character of the resource.
- It requires knowledge of any prior grading and any other sorting process that affects grading (practically impossible to know for recovered wood in most cases).
- Establishing grading under this system requires extensive destructive testing (which is far too expensive for recovered wood, even if there was sufficient of each kind of resource to test).

It is very expensive to establish grading rules under this system for new species and sources, so an alternative route is also required for new timber from minor species and forests not managed primarily for timber. In key respects this is a similar grading situation to recovered wood. However, lower certainty of the properties (compared to comprehensively tested mainstream species) can be balanced by more conservative design values, which may still be adequate for many types of timber construction.

Under the current system, timber is sorted into "grades" (sets of pieces), which are assigned design values (most usually by reference to "strength classes"). These design properties (via "characteristic values" – means and 5th percentiles) relate to sets of pieces rather than individual pieces. The current way of doing this (whether by machine grading or visual grading) assumes a certain invariant initial population of timber, and a certain reliable relationship to the criteria used in the grading – for convenience the criteria are referred to here as "indicating properties". If this population of timber changes in some way (by the properties changing, or part of the population being removed) or the relationship between the important (grade determining) properties and indicating property changes, then the timber being sorted into a grade will have different characteristic values (means and 5th percentiles) meaning different design values would be required. This is why this approach to grading is impractical to apply to recovered wood (Figure 5.1) as there are numerous ways in which the timber can be changed by actions before, during and after service in the building which are, in general, unknowable.

For assembles (e.g. trusses, walls, floor cassettes, glulam and cross-laminated timber) it is a reasonable approach to assume (provided there is no evidence of degradation or a substantial change in the standards), that the item has the same design properties as when it went into the building. However, for sawn timber such an approach requires much more caution. It may be possible to use the grade stamp on the timber (assuming it is still readable and understandable), but while this can reveal useful information (grading, species, and origin) it must be remembered that the grade describes a set of boards, not individual boards. Therefore, in addition to the question as to whether the timber properties have degraded in any way, there is also the question about whether there was any process that removed some of the timber, in such that what remains no longer matches the grade (i.e, in simple terms, has the better timber been removed?).

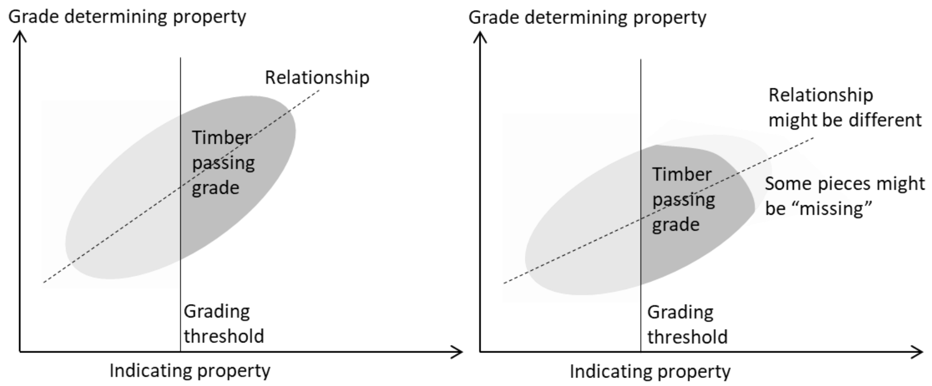


Figure 5.1 The basic model for timber strength grading in Europe (left) and how it does not fit with recovered timber, because the distribution of the properties of the graded timber could be changed.

5.2. Aims and objectives

In summary, WP5 aimed to develop:

- An approach that is equivalent to the current system in safety, that can work without knowing species, origin, prior grading etc
- To list other grade quality criteria, appropriate for recovered wood (extra to the 'visual override' criteria for new wood)
- Propose revisions to standards to make them more suitable for the circular economy, and systems that can be adopted now for one-off buildings (i.e. outside CPR)
- Develop and demonstrate some methods for in-situ assessment to allow timber to serve longer in existing structures

5.3. Highlights

Grading does not currently work on predicted properties of individual boards, but modern technology used in grading can get very useful estimates for individual boards. It is therefore possible, without new technology, to move from a grading framework that has a probabilistic approach across all graded timber, to one that has a probabilistic approach on a piece-by-piece basis. This allows the statistically based design values (the characteristic values based on means and 5th percentiles) to be applied to specific sets of timber, such as a pack of timber placed on the market or a set of timber to be used in a certain building. Since evaluation of stiffness (from acoustic methods or non-destructive direct bending) and density (from mass or x-ray attenuation) is very similar (with some exceptions) across many species and growth areas it is possibly to determine design values for these with a high degree of certainty. Estimation of strength is much more difficult, being impossible to measure non-destructively, and more varied across species and growth areas. Estimated strength must therefore be more conservative as a result, but it could be verified with destructive testing, or proof loading, with adequate certainty for safe building design, albeit with lower design values.

The proposed framework for grading (Figure 5.) is flexible in terms of how the probabilistic estimates are done, and with more research could employ methods such as quantile regression (Bather, 2022) to improve performance. However, even simplistic grading methods with high uncertainty could still be useful for applications that do not demand high design values for the timber.

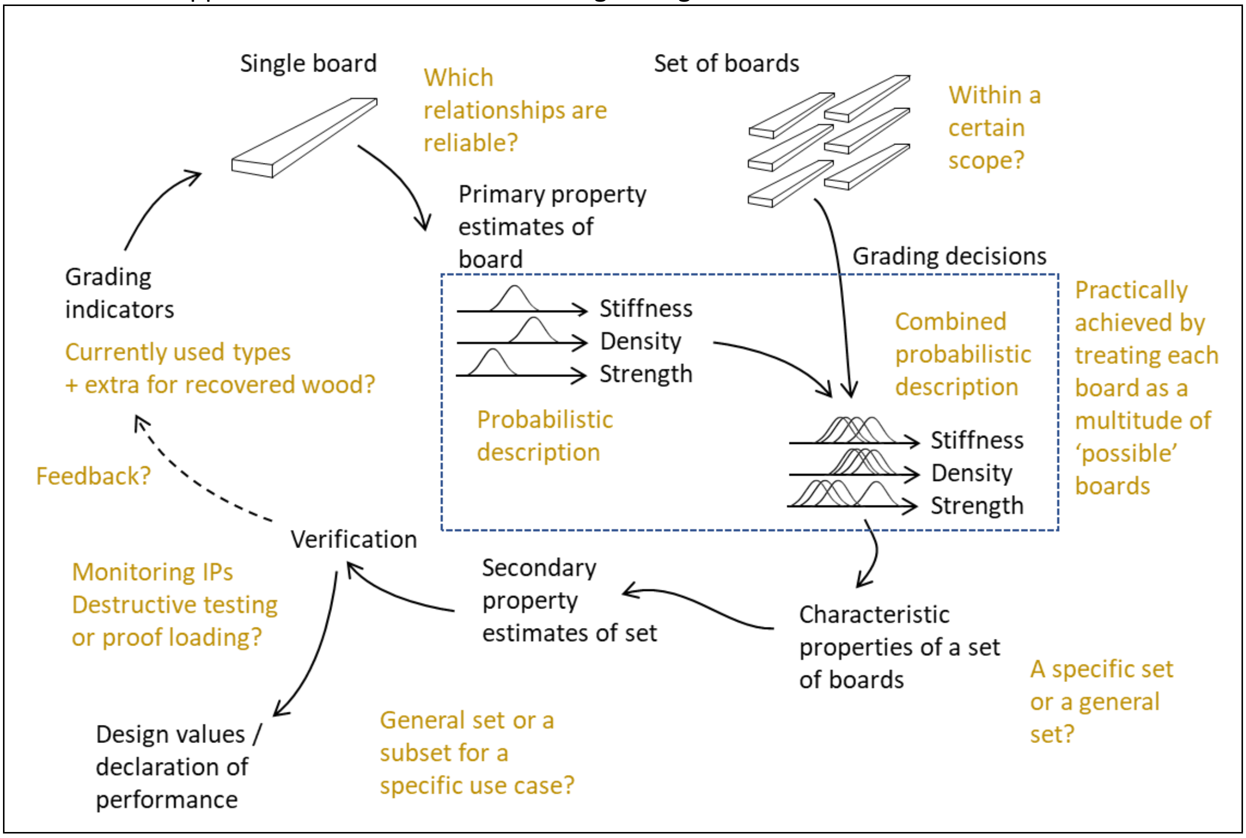
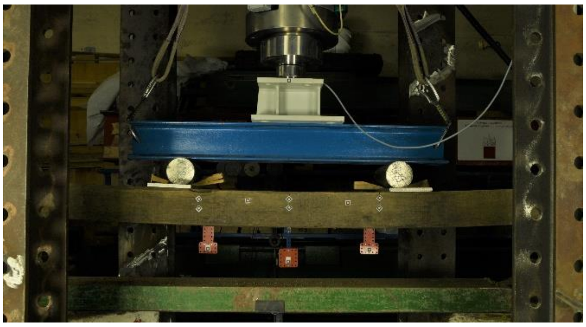


Figure 5.2 Outline of the alternative grading approach

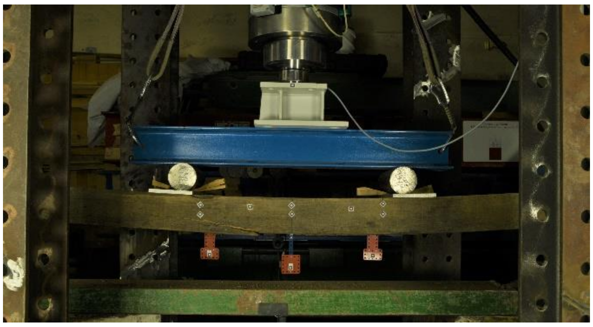
Together with WP4 a set of additional grading criteria was drawn up, which covers the same purpose as the visual override criteria in EN 14081-1, adding in additional factors specific to recovered wood, such as cut holes and notches, in-service decay, mechanical damage, and treatments.

The various actions that can affect wood properties were considered. The biggest issue identified is the possibility of mechanical damage (in-service or during demolition) which is not apparent from visual inspection or grading measurement because the fracture has closed up when the load is removed. Where this possibility is a particular risk, it may be necessary to take special steps to detect it through methods like proof loading of all pieces or combined flexural and longitudinal resonance.

Destructive testing work on recovered wood was also carried out, giving both insight into the degree to which the timber varies from new timber, and the numerous additional practical issues for grading, reprocessing, and testing, Figure 5.3.



a



b

Figure 5.3 Bending test of oak a) start position b) finished.

This testing covered spruce from Slovenia and oak from Slovenia and Spain, and results will be published separately as a paper about NDT grading of recovered timber (in preparation).

In the case of Slovenia, recovered timber from two sites (oak bridge over Sava River and spruce from a timber roof structure in Ljubljana) has been tested in the laboratory of the University of Ljubljana, Faculty of Civil and Geodetic Engineering Figure 5.4 and a number of non-destructive tests were performed. The bending strength of the beams was determined using the standard four point bending tests.

a

b

c

d

Figure 5.4 a) old oak b) investigation of properties c)-d) Recovered wood with brittle failure

There was rotten part that was removed before the test, Figure 5.5.

Figure 5.5 Damaged oak

In the case of Spain, a batch of 30 recovered oak timber beams from a 150-year-old house (Figure 5.6) has been tested by the Timber Construction Research group of the Universidad Politécnica de Madrid. Visual Strength Grading (VSG) and non-destructive testing were performed, followed by four-point bending test according to EN 408 (Figure 5.7).

Figure 5.6 Collection of recovered oak Madrid.

a

b

c

d

Figure 5.7 a) Spanish recovered oak b) non-destructive testing c) moisture content estimation d) four-point bending test.

The testing revealed additional questions, such as the reliability of standard equations for secondary design properties when applied to recovered wood, which were investigated by some additional exploratory testing under WP3.

This work also tested some approaches that can be used for in-situ assessment, and an allied PhD study concluded that the currently employed visual assessment methods are less reliable than assumed by the people who use them (Bather, 2022). In addition, knowledge gaps and barriers imposed by the standards to the use of recovered wood were mapped.

5.4. Conclusions and discussion

The current grading system has become a detriment to the circular economy. Standardisation and optimisation of value chains has focussed on a decreasing number of species and grades. At the same time, habitual overspecification (in part due to lack of knowledge by the trade and building professionals), has led to a drift towards higher strength classes, and an increased need for expensive testing work to ensure the properties of these high strength classes – which in many applications are not actually needed. The system needs to be rebalanced, so that there is a less demanding route for strength graded timber, for building types and structural timber elements that do not require high strength.

For recovered timber, it will not be possible to rely only on grade marks or other records of the initial grading. However, it is possible to assess density and stiffness very well with existing grading technology. Assessment of strength is more challenging, but more conservative design values may not be a problem, so long as the properties are not declared in a way that also (unnecessarily) brings down the design values for stiffness and density.

It is neither possible nor appropriate to try to replace the current grading approach in Europe, but many issues overlap with gaps in standards for new timber – especially with the need to grade a wider range of species and sources, possible shifts in resource quality over time and possible changes in grading relationships resulting from tree improvement, forest practice and climate change. A full solution will require extensive testing, which will take many years, but with substantial new investment in production facilities for CLT, producers should be preparing now to be able to adapt in future.

It remains a question as to how best to do the verification of properties. The level of verification needs to be balanced with the risks in the application, and at present the most commercially viable uses for recovered timber are not yet known. However, it can already be observed that many uses of timber for which strength graded timber is used but has much better design values than needed – meaning a higher level of uncertainty could be managed by safety factors without much altering the design.

5.4.1. Our contribution beyond state-of-the-art

The researchers involved in this project are also experts involved in strength grading new timber and shaping current standards. The project has already synergised with work making progress with user defined grades and exploring the limits of species combinations and minor species. This project has added to the knowledge and expertise of the standards committees. Crucially, for the first major exploration of this topic, it has uncovered many more research questions that were not appreciated before the project began.

5.4.2. Future work

The next steps, following on from this work, are to develop and publish a protocol for determining design values for a given package of recovered timber, and to begin work adapting the current standards framework where there have been issues identified that affect grading of lesser used species (notably secondary properties, adjustment factors and a more flexible strength class system).

The new protocol for determining design values for a package of recovered timber will be useable in practice but will necessarily have limited scope due to the still unresolved questions about how to deal with less common species and the effects of things like cut holes and notches. The protocol will also include an alternative set of strength classes to reflect the necessarily more conservative strength value, without unnecessarily reducing the potential for applications where design is more limited by stiffness and density (or other factors).

Much more testing is required, and since it is both expensive and difficult for anyone research project to sample the wide range of recovered timber coming from buildings in Europe, it is recommended a common, open, database of materials property data is created. This would also require the development of a schema for storing such data.

Since it was not possible to address all the open questions within this project – and indeed more questions were revealed during the work – there remain a list of items that require more research. These include:

- If a piece of recovered timber has a grade stamp, or some other traceability, to what extent can we say this is still the grade? If we do, who is responsible for the correctness of the declaration? To what extent do wood treatments (other than preservatives) change wood properties?
- What is the effect of actions on the wood in service on its properties? Does it affect behaviours like creep, splitting and brittleness?
- Does recovered wood have the same relationship between primary and secondary properties?
- When grading recovered timber, how best to verify that the grading has been done correctly?
- Since preservative treatment changes density, how does it affect grading?
- How best to grade wood that is not rectangular in cross-section?
- What are the other aspects of usability that should be covered by the strength grading?
- Are the various adjustments used for things like size and moisture content also valid for recovered timber?

There are also several open research questions that apply to strength grading generally, especially as grading is being applied to a wider range of species and sources. These include:

- How stable is the relationship between grading indicators and grade properties?
- How long should grading settings and assignments last? How can they be re-confirmed? How can producers know that the resource is not changed in such a way that the grading is also changed?
- What are the limits for how much a batch of graded wood can differ from the declared properties?
- What are the possibilities and problems for mixed species grading?
- What are the actual distributions of strength, stiffness, and density in ungraded wood? Normal, lognormal (as assumed) or something else?

6. WP 6 Environmental and economic assessment of design for recycling in building

6.1. Background

With a share of 39%, the construction sector is the main contributor to the global carbon dioxide emissions. Thereby, 11% of the impacts are attributable to the provision of raw materials used during the construction and assembling stage (IEA and UNEP, 2019). Thus, an efficient and responsible use of resources is essential. One way to achieve this goal is to implement the circular economy in the construction sector. For an efficient recovery of waste wood after its first utilization, the primary design should enable a secondary material utilization. The principles of design for deconstruction and reuse (DfDR) provide an opportunity for the construction sector to reduce environmental impacts. The purpose of WP 6 was to determine whether the DfDR concept offers environmental advantages over the conventional way of construction using life cycle assessment (LCA).

Despite its renewability, the availability of virgin wood is limited. With the implementation of the bioeconomy, the demand for renewable resources, especially wood, will likely increase. To meet the demand in the future without disregarding the sustainability principle in forestry, wood cascading can increase efficiency of wood cascading. Wood cascading is defined as the sequential use of material in multiple material applications before it is incinerated for energy recovery (Risse et al., 2019). One possible high-value cascade step is the production of CLT from recovered wood. So far, the environmental impacts of the CLT manufacturing made from recovered wood have not been determined. Therefore, in WP 6 LCA is used to compare the environmental effects of CLT from recovered timber with CLT from virgin wood.

Due to the German energy act for buildings (GEG, 2020) and financial support for energy saving strategies during the use stage (KFW), the trend is moving towards zero emission buildings. Thus, the life cycle stages besides the use stage become more relevant from environmental perspective. An integrated LCA of a building should therefore include all stages of the building's life cycle according to EN 15978:2011 and EN 15804:2021. Previous building LCA studies focused on the construction and operation stage (Adalberth, 1997; Kellenberger & Althaus, 2009; Vilches et al., 2016). Other studies included the End-of-Life (EoL) stage but the sub-stages (demolition, transport to waste management, waste management) were considered as one step (Petrović et al., 2019; Teshnizi et al., 2018). Although the demolition stage was considered separately in the studies by Dodoo & Gustavsson (2013) and Martínez et al. (2013), no detailed inventory data is provided. WP 6 aims to fill this gap by collecting LC inventory data for the deconstruction and demolition of buildings.
A building's life cycle covers several decades and multiple stakeholders and is subject to modifications. To not loose information of the materials and construction methods used in a building, in particular when it is constructed for disassembly, a long-term documentation of building data is mandatory for a successful implementation of DfDR.

6.2. Aims and objectives

The aim of this work package was to investigate whether the new design strategies and the recovered wood products developed in the project offer benefits from an environmental and economic point of view. Furthermore, a documentation matrix was developed as a recommendation for documenting the building construction and material use to support the implementation of DfDR.

6.2.1. Environmental assessment of wood panel construction – case study Villa Anneberg

This task examined whether the design for deconstruction and reuse (DfDR) concept developed in the project are beneficial from an environmental and economic perspective. The life cycle assessment (LCA) methodology according to standard EN-ISO14040:2020 and EN-ISO 14044:2020 was used to estimate the environmental impacts of the conventional wood panel construction of Villa Anneberg from Derome company, compared to a design according to DfDR principles as developed in WP 2. The LCA was performed by modelling the manufacturing, assembling and end-of-life (EoL) stage of two building cycles. It is assumed that the use stage is identical for both systems and therefore excluded from the study. The schematic system boundaries of both systems are represented in Figure 6.1. For the status-quo building (SQ), both manufacturing stages are realized with virgin material. For the initial DfDR building, virgin materials were used. In contrast to the SQ system, the recovery of the wall and floor elements and their reuse for the second building was modelled. The EoL scenario of the second building of the DfDR system is identical with the SQ system.

a) b)

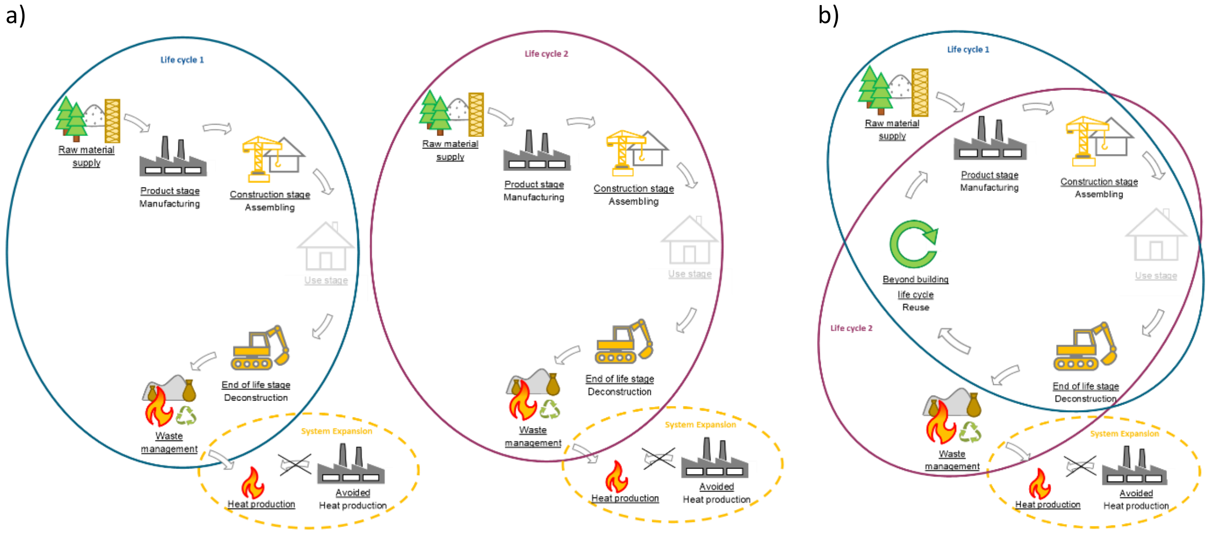


Figure 6.1 Schematic representation of the system boundaries; petrol loop represents the first life cycle, purple loop the second life cycle a) reference system (SQ) b) DfDR system.

6.2.2. Analysis of building demolition stage

The aim of this task was to determine the factors influencing the building demolition process and to develop a life cycle inventory (LCI) database for use in building LCAs. For the LCI assessment of the building demolition stage, the scientific observation methodology according to Döring & Botz (2016) was used with a combination of qualitative and quantitative approach. Thus, the demolition process of five case study buildings in Germany was observed. On the basis of the collected inventory data, an LCA based on EN-ISO 14040:2020 and EN-ISO 14044:2020 for the building demolition stage with a hotspot analysis was conducted (Figure 6.2). The demolition process is part of the EoL stage according to the standard EN 15978:2011 and includes all materials and energies required for demolition.

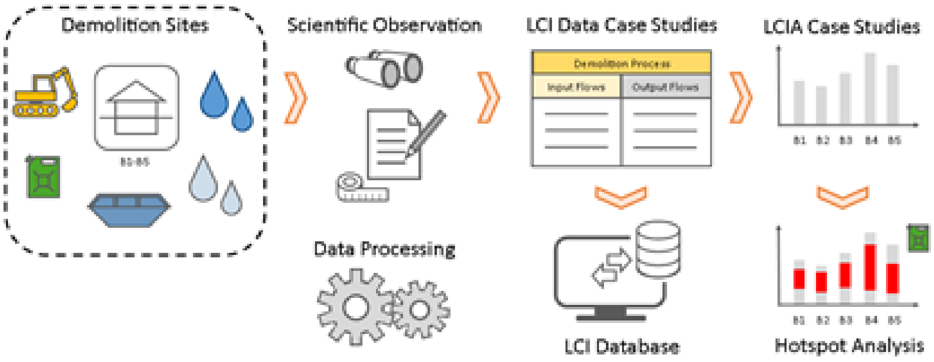


Figure 6.2 Schematic representation of the inventory data collection, LCI database, life cycle impact assessment, and hotspot analysis (Ivanica et al., 2022).

6.2.3. CLT production from recovered wood

The objective of this task is to determine the environmental performance of CLT from recovered wood in comparison to CLT from virgin wood using LCA methodology. The functional unit is defined as 1 m² of CLT wall along with 342 MJ of electricity and 1026 MJ of heat. To achieve functional equivalence between both systems, system expansion was applied. Therefore, the CLT production from virgin wood is expanded considering energy from a) grid and b) virgin wood incineration. The system boundary of both systems is represented in Figure 6.3.

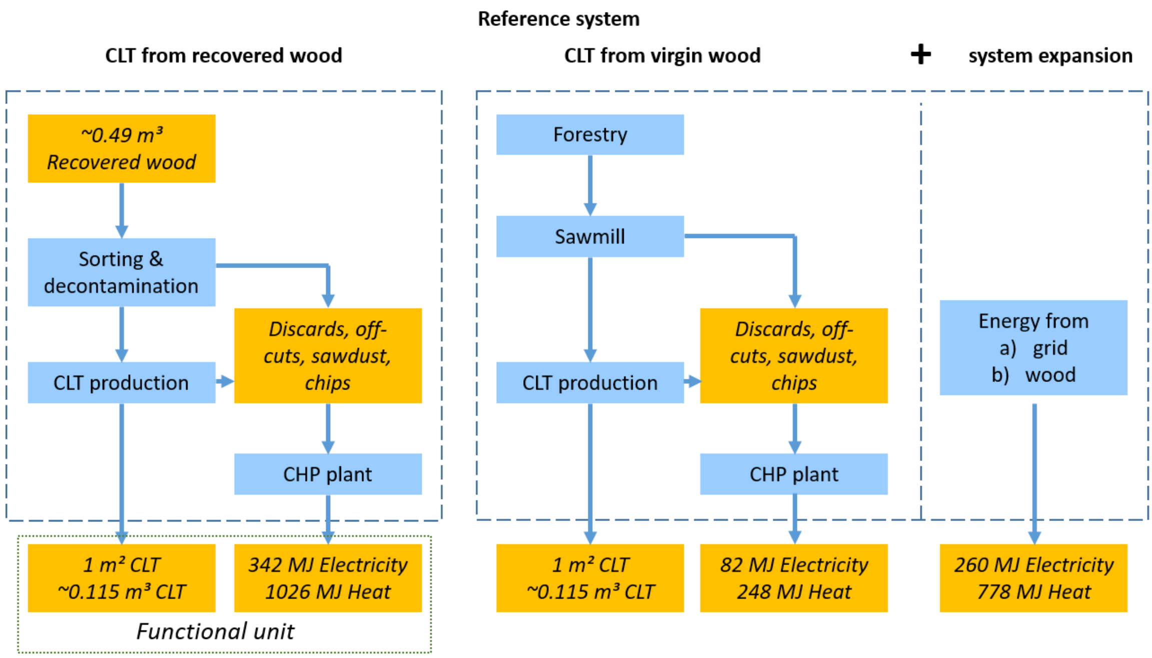


Figure 6.3 System boundary for the comparison between the environmental impacts of CLT from recovered and virgin wood.

6.3. Highlights

6.3.1. Environmental assessment of wood panel constructions – case study Villa Anneberg

The results show that the implementation of the DfDR concept can considerably reduce the environmental impacts (Figure 6.4). The stacked bars represent the impacts from the manufacture of the elements to transportation, assembly, and the EoL of the buildings. Information module D represents the loads and benefits from internal heat generation (incineration of wood residues) leaving the system boundary (open loop). The marker for the difference represents the sum between the impacts and the loads and benefits (module D).

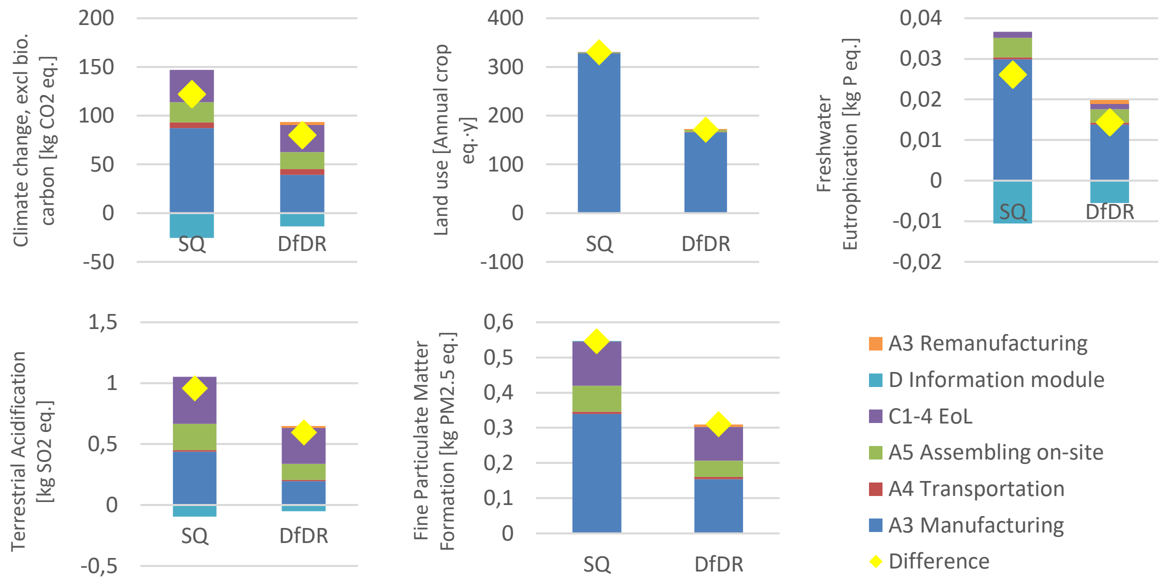


Figure 6.4 Environmental impacts of the status quo (SQ) and DfDR building system of Villa Anneberg.

The highest reduction of the environmental impacts with 48% compared to the SQ system can be achieved in the impact category land use, the lowest with 38% in the category terrestrial acidification. The main contributor to all impact categories is the manufacturing processes of exterior walls and intermediate floor elements (A3). These can primarily be attributed to the raw material supply. Other hotspots in the impact categories climate change potential, freshwater eutrophication, terrestrial acidification, and fine particulate matter formation are the assembling on-site (A5) (due to the materials and energy required for assembling) and the EoL stage (C1-4) (due to demolition/deconstruction and waste management). The remanufacturing processes of the DfDR concept contribute only marginally to environmental impacts. Module D shows a negative contribution to the categories climate change potential, freshwater eutrophication and terrestrial acidification. This effect can be explained by the avoided energy (due to internal heat generation) from Sweden's current grid mix, which would have higher environmental impacts than the heat leaving the system (open loop). Even though the benefits from the module D of the SQ system are higher compared to the DfDR system, they cannot compensate for the higher emissions during the life cycles of the buildings.

6.3.2. Analysis of the building demolition stage

From the scientific observation of the building demolition sites, five influencing parameters can be identified: The demolition excavator, including both its initial manufacture and operation during the demolition process; freshwater to reduce the dust from demolition; the resulting wastewater; the container for C&D waste collection and transportation. The resulting inventory data were transferred into an LCI database. Further information is available in Ivanica et al. (2022).

The hotspot analysis of the environmental impacts is based on the LCA of the five demolition processes (B1-B5) and is represented in Figure 6.5. The results show that 91-95% of the environmental impacts of category climate change, fossil depletion and terrestrial acidification are assigned to the diesel used during the excavator operation. In the impact category freshwater consumption, the freshwater consumption can be identified as hotspot with a share of 36% up to 68%. The excavator operation (49% to 59%) and the container manufacturing (31% to 38%) represent the hotspots of the impact category freshwater eutrophication.

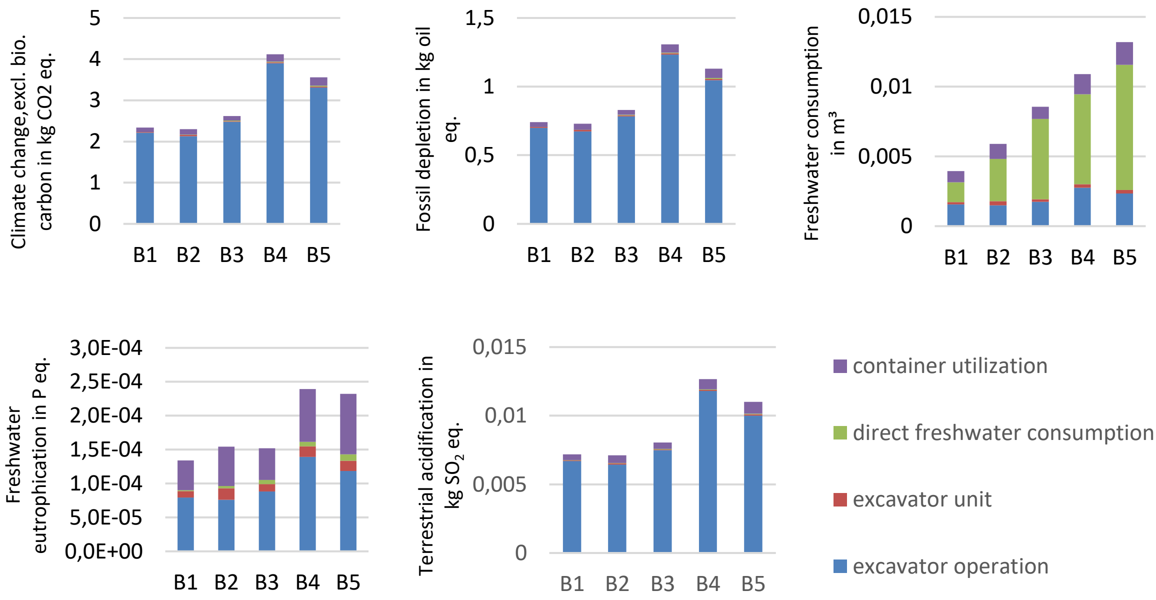


Figure 6.5 Case study specific LCIA result differentiated by input flows; (Ivanica et al., 2022).

6.3.3. CLT production from recovered wood

The overall results show that CLT produced from recovered wood represents an ecological alternative compared to the considered reference systems (Figure 6.6). The savings can be assigned to the decreasing drying effort for the recovered wood (RW) system from 22% to 13% (VW: 70% To 13%) and to the system expansion which is added to the CLT production from virgin wood (VW). Through the utilization of waste wood, virgin wood can be substituted which has a particular influence on the impact category land use. One of the main contributors to the impacts of the RW system is the incineration of the large quantities of potentially contaminated wood residues of the production process. In both VW systems, lower environmental impacts are assigned to the incineration, which can be attributed to the higher yield compared to recovered wood processing. In the VW+SEw system, the system expansion includes the impacts of energy generation from virgin wood. The environmental impacts associated with the production of the CLT panels are similar for both systems, due to minor differences in the use of recovered wood for CLT manufacturing.

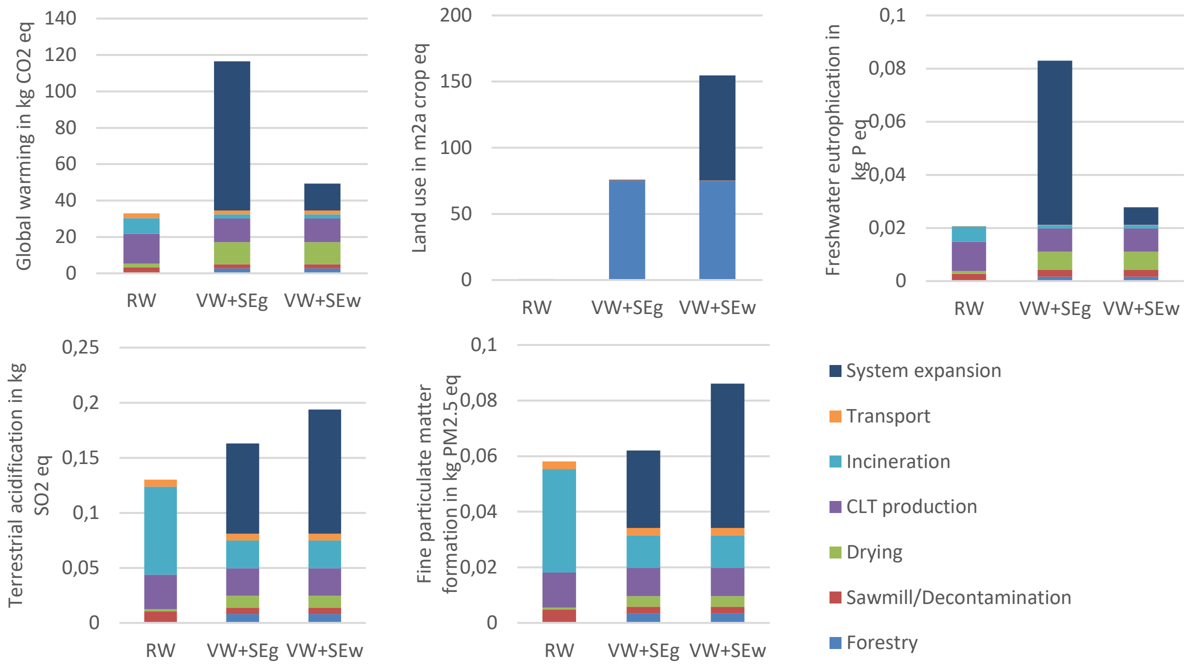


Figure 6.6 Environmental impacts of 1 m² of interior wall made from CLT from recovered wood (RW) and virgin wood (VW) with system expansion (SP) from grid (g) or virgin wood (w).

6.3.4. Development of a documentation matrix for building data

Figure 6.7 shows an ideal documentation matrix for building data, such as construction details and materials. The matrix combines the material and product flows with the stakeholders and arranges them along the entire life cycle of a building, from the material extraction, via the building planning and erection to the deconstruction and disposal. The matrix is a simplified illustration of a complex process and provides an idealized approach for the documentation. The documentation can vary between buildings, products and stakeholders, but the overall framework and responsibilities are identical. The matrix illustrates, how important defined and standardized processes are for a successful documentation and usability of the data, considering the timeframe, the number of stakeholders and the complexity of the data, among others. Further information on the matrix is under preparation.

Building information modelling (BIM) is considered as ideal starting concept for the documentation of building data, but requires further standardization, databases and distribution across stakeholders, to enable a better cooperation between them and along all life cycle stages. Furthermore, the data required from materials and products need to be identified, collected, stored and shared to be available for the building documentation. For example, material information is fundamental for the future utilization of the documentation model, such as for the recycling at EoL or the calculation of the environmental impacts of the building during the planning phase, among others. Therefore, the documentation process already starts with the information on the raw materials used for the production of building products, which then need to be organized, combined and distributed over several stakeholders until the information are used in the final building model. Combining and collecting such a complex variety of data requires fundamental standardization. To enable the use of the documented data from the model during the use phase for maintenance, or for the final disassembly and planning of the disposal strategies, an as-built digital twin of the building that contains all the information on materials, products and connections, needs to be created at the end of the planning and erection phase and be safely stored and updated for the time of the use phase.

In general, documentation is likely to contribute to an efficient circular economy. It, however, requires long-term life-cycle thinking, common standards and cooperation between several stakeholders and institutions.

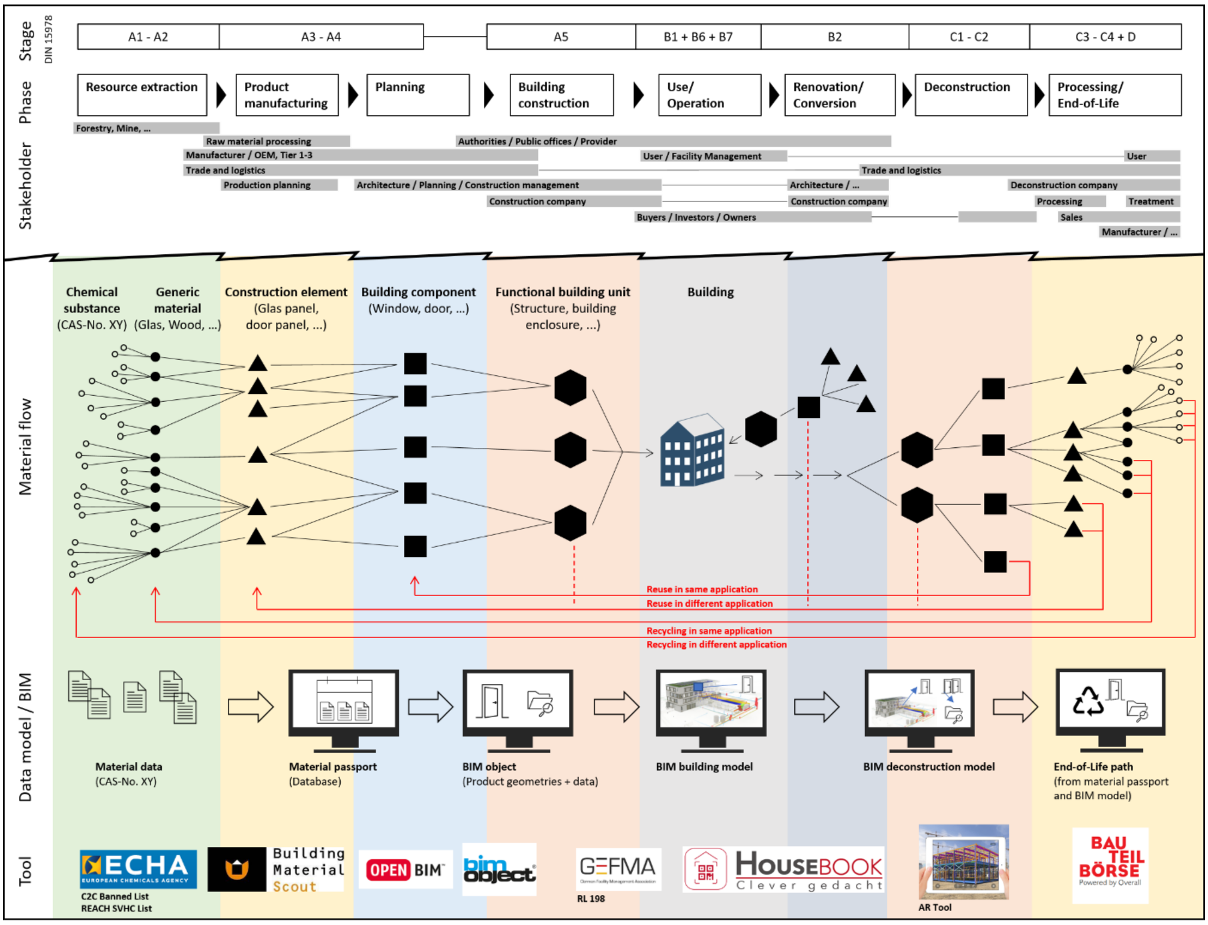


Figure 6.7 Schematic illustration of an ideal documentation process for building data.

6.4. Conclusions and discussion

6.4.1. Our contribution beyond state-of-the-art

Overall, it can be concluded that the concept of DfDR and cascade use of wood and wood products leads to a reduction of environmental impacts. The substitution of virgin wood with recovered wood and the reuse of finished elements offers the greatest potential for the reduction especially in the manufacturing and production stages of new products. Although the CLT panels made of recovered timber require a higher use of e.g. glue and metal, the environmental benefits outweigh them. The use of recovered wood results in the saving of primary resources which would be available for further wood production, given the renewability of wood resources. By implementing the system of DfDR, the amount of required virgin materials can be decreased by 47%. In addition, the energy consumption during the assembling and disassembling stages can be reduced by 4%. Moreover, selective deconstruction can increase the yield of recoverable waste wood and reduce the amount of C&D waste and energy allocated to waste management. The investigations on the building

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demolition phase have shown that as the number of different material layers of wall construction increases, both total demolition times and manual sorting efforts increase. With the introduction of the DfDR concept and the high-value wood cascading, a possibility is created to integrate the circular economy into timber construction.

6.4.2. Future work

The findings from WP 6 lead to the conclusion that the current methods of construction should be reconsidered, especially in wood panel construction. The complex structure of layers and the combination of different materials complicates the disassembly and sorting and thus the high-quality reuse and recycling of wood and wood components. Therefore, it is recommended to focus on a circular design of timber constructions, in particular focusing on the joining techniques and fasteners to enable an easier and quality maintaining disassembly.

Proper storage of the reclaimed wood or wood elements is necessary to prevent further damage or additional drying processes.

The lack of documentation of the masses, dimensions, location and material properties (e.g. origin, treatment, etc.) makes reuse or cascading of wood more difficult. Hence, future building projects should include a holistic building documentation from the design to the EoL stage of a building's life cycle, which includes a deconstruction and recycling strategy. This will require an industry-wide standardization process, to enable the management and sharing of the data across the great number of stakeholders, the long timeframe and all life cycle stages. In addition, the methodology of LCA should be integrated in the early design stage of buildings to estimate the resulting environmental impacts. Therefore, the developed LCI database for the building's demolition stage should be expanded to include additional case studies and building types.

For the transition towards a circular economy, policies should support a circular design and recovery strategies, for example through financial incentives and the harmonization and novelization of regulations and guidelines. For example, a new waste wood ordinance should encourage the use of recovered wood in more applications under certain conditions, ideally on European level. Only with the implementation of cascade use and circular economy, the increasing demand for renewable raw materials and the limited supply can be kept in balance.

7. Dissemination and engagement

This chapter contains an overview of the activities and a compilation of the main results from the project.

- Five questions from each country, Q&A
- Exchange information with other projects and standardisations groups
- Interviews with industry & stakeholders
- Site visits both physical and digital
- Internal seminars and partners presentation sharing information
- Workshop with stakeholders
- Five case studies and a house design for reuse in the new city of Kiruna (Sweden).
- Thesis works
- Reporting and academic papers

Academic teaching

The results of the research studies had been implemented in academic courses.

In Ireland, at University College Dublin where Elizabeth Shotton used to teach a 12 weeks Masters of Architecture course called "Irish Timber and Sustainability", DfDR was used as a theme during 2021. There was a strong cooperation with NUI Galway and Napier University, Annette Harte and Dan Ridley-Ellis contributed to the course. St John Walsh, Master student at UCD, also member of the project, was active in the teaching process as well.

During the spring of 2022 Elizabeth Shotton taught a course in concrete structure where DfDR was again used as theme and research question. The knowledge acquired during the project does not limit only to timber. There are several materials used in a building and applying DfDR principles to concrete benefits timber also.

In Finland, at Aalto University, "DfD and cascading" have been an important part in the following of courses: "An Introduction to Wood and Wood Products"- a course aimed primarily at architects and "Materials for a World in Transition"- course is for engineers, designers and business students as part of Aalto's Creative Sustainability program.

Mark Hughes and Bahareh Nasari also created a "one off" (hopefully to be repeated) project-based course called "Re-imagining Wood Waste" that was held autumn 2021.

Dissemination via films on Youtube and via project's website

Because of the Corona-19 pandemic, some conferences and physical meetings were cancelled during 2020 and 2021, therefore InFutUReWood transferred some of the results digitally and arranged a Webinar on 20 October 2020. The webinar had a broad audience with participants from, Europe, Australia, New Zeeland and presentations from USA. The presentations and discussions based on questions from public took three hours and 14 videos were published. They can be accessed on the project's website (www.infuturewood.info/on-demand/).

Marlene Cramer, Daniel Ridley-Ellis and the team at Napier University have been active in publishing films on a variety of subjects related to our project. The channel's name is InFutUReWood and some of the titles are "A look at demolition in the UK" and "Timber grading explained". Another video is about visual grading of reclaimed timber by Mitja Plos, Tamara Suligoj, and Goran Turk, Slovenia. Other subjects are "DfDR Design Tool" by St John Walsh and Elisabeth Shotton, Ireland, "Environmental and economic assessment" by Michael Risse and Raphaela Ivanica, Germany, "Inventory, deconstruction of recovered wood" by Mark Hughes and Bahareh Nasiri, Finland.

The website infuturewood.info was launched by RISE who also engaged in publishing posts and to maintain it. It was meant to be a dissemination platform for work within the project but also it presented inspiring work and events from outside, connected to the project. It also contains researchers' publications, from scientific articles to scientific reports, conference papers and posters.

Sharing knowledge and results to society, municipalities, industry

How should we build today to be able to circulate in the future? Workshop with Swedish and timber building companies to test an assessment tool, by Sandin & Sandberg (2021), 3rd September 2020. The project has been presented at several conferences and seminaries, one of them in Figure 7.1.

Figure 7.1. Presentation of the results at seminars and conferences, here Trä&Teknik in Gothenburg Sweden 1st September 2022. WP 2 leader Ylva Sandin (right) interview the industry partners Anders Carlsson, Derome and Janina Östling, Isotimber how they will use the findings from the project, photo Lars Blomqvist.

An interview with three of the industry partners is published 2021 https://forestvalue.org/wp-content/uploads/2021/12/InFutUReWood-article-Nov18-2021.pdf, photos of the participants, Figure 7.2 .

Nicola Jackson – Technical Manager at Robertson Timber Engineering and Chair of Offsite Solutions Scotland

Anders Carlsson, R&D Manager, Derome, Sweden

Janina Östling, sustainability manager, Isotimber

Figure 7.2. Industry partners that participated in the case studies and worked on new design solutions.

An interview in "Plan", a magazine edited by Swedish Association of Sustainable Planning was published in the edition Climate Neutral 2045 (#3-4, 2021, pp 50-53). The title was "Dags att å-trä-bruka" (Time to re-wood-use) and the interview was about the InFutURe project, with Karin Sandberg and Carmen Cristescu.

Increased recycling in construction, what do municipalities need? was a workshop with 20 municipalities, architects and industry partners organized by Carmen Cristescu, RISE, in, November 2021. Activities, publications and results of the project were disseminated to Swedish society.

Communication with other projects

At ZAG (the Slovenian National Building and Civil Engineering Institute) Ljubljana, in September 2019 we met the team of another Forest Value project: InnoCrossLam – Innovative Solutions for Cross Laminated Timber Structures. We shared ideas and discussed with the project's leader about planning for demountable CLT structures.The picture below presents almost all the InFutURe Wood project team, Figure 7.3.

Figure 7.3. From left to right: Boris Azinović (ZAG, InnoCrossLam project), Goran Turk (Ljubljana Univ), Karin Sandberg (RISE Skellefteå), Tamara Šuligoj (Ljubljana Univ), Guillermo Íñiguez-González (UP Madrid), Michael Risse (TU Munich), Mark Hughes (Aalto Helsinki), Daniel Llana (Univ. Galway, UP Madrid), Annette Harte (Univ. Galway), Mitja Plos (Ljubljana Univ), Björn Källander (Swedish Wood), Carmen Cristescu (RISE Skellefteå), Raphaela Ivanica (TU Munich), Anna Pousette (RISE Skellefteå), St John Walsh (UC Dublin), Bahareh Nasiri (Aalto Helsinki), Daniel Ridley-Ellis (Napier Edinburgh), Katja Ceglar (ForestValue Slovenia), Elisabeth Shotton (UC Dublin), during a project meeting organized by Ljubljana University, in September 2019.

Other projects transfer of information took place:

- CE Wood Circular Economy – A Game Changer for the Wood Building Industry

- Circuit: a close cooperation keeps on developing with via Daniel Ridely-Ellis and Marlene Cramer from Napier University

ForestValue Conference 21-22 June 2022

The conference that took place in Skellefteå presented results from the Forest Value financed projects. It was initiated and organized by Karin Sandberg, the InFutUReWood project leader together with Mika Kallio from Forest Value and with the Swedish founders Vinnova – Sweden´s Innovation Agency, Formas – Swedish Research Council for Sustainable Development, Swedish Energy Agency, in a hybrid format. The 80 minutes long presentation from the conference is accessible at RISE YouTube.

The presentations had a dialogue format with two of the industrial partners: IsoTimber and Robertson Timber Engineering.

Figure 7.4 From left to right: Raphaela Ivanica (TU München), Daniel Ridley-Ellis (Napier Edinburgh), Marlene Cramer (Napier Edinburgh), Bahareh Nasiri (Aalto Helsinki), Annette Harte (Univ. Galway), Karin Sandberg (RISE Wood Building Technology Skellefteå), Janina Östling (IsoTimber Östersund), St John Walsh (UC Dublin), Elisabeth Shotton (UC Dublin), Ylva Sandin (RISE Wood Building Technology Gothenburg) during a the Forest Value conference at Skellefteå, June 2022.

Published results of the project

Title, embedded link of document (or film), short description	Publication
Estimating the material stock in wooden residential houses in Finland Quantification of the amount of timber in residential buildings. Material stock analysis, the mass of wood and gross floor area of buildings in each building type.	Nasiri, B., Piccardo, C., & Hughes, M. (2021). Estimating the material stock in wooden residential houses in Finland. *Waste Management, 135, 318-326.*
Demolition in the UK, Marlene Cramer (WSE 2021) A presentation on a demolition case study in the UK for the Annual Meeting of the Northern European Network for Wood Science and Engineering.	Cramer, M. (2021) https://www.youtube.com/watch?v=qkYha-4_wvk
Cascading potential for recovered wood from heavy timber frame typologies in pre-modern dwelling buildings in Madrid An overview of traditional typologies and timber constructive systems in residential buildings in Spain and a quantification of amount of recoverable timber.	Arana-Fernández, M. de, Llana, D.F., Nasiri, B., Íñiguez-González, G. (2020). Cascading potential for recovered wood from heavy timber frame typologies in pre-modern dwelling buildings in Madrid. *In Proceedings of the 63rd International Convention of Society of Wood Science and Technology (SWST)*, July 13-15. Online due to Covid-19. Pp. 16-27.
Recovered timber in Europe: sources, classification, existing and potential reuse and recycling The motivation for deconstruction in each country depends mainly on the building location and site value. An overview of international and national classification systems for timber waste from construction and demolition is presented.	Harte, A.M., Uí Chúláin, C., Nasiri, B., Hughes, M., Llana, D.F., Íñiguez-González, G., de Arana-Fernández, M., Shotton, E., Walsh, S.J., Ridley-Ellis, D., Cramer, M., Risse, M., Ivanica, R., Cristescu, C., Sandberg, K., Sandin, Y., Turk, G., Plos, M., Šuligoj, T., Hogan, P. (2020). Recovered timber in Europe: sources, classification, existing and potential reuse and recycling. *Report No.: NUIG-TERG-2020-0 Galway, Ireland*
Awkward questions about timber density A discussion about some open questions on how we measure and predict wood density in timber grading. **U**sing data collected on spruce from the British Isles.	Ridley-Ellis, D., & Cramer, M. (2020). Some awkward questions about density. Timber 2020 Conference.
Grading of recovered timber An overview of reasons why recovered timber is different from new timber and reasons why we cannot grade it with existing grading approaches.	Cramer, M. (2020) https://www.youtube.com/watch?v=G7Y7HCSgGwo https://www.youtube.com/watch?v=oNdnVVftGQg
Timber Grading explained An explanation of timber grading with help of plums.	Cramer, M. (2021) https://www.youtube.com/watch?v=gDXAj8VIqg4
Visual grading of reclaimed timber	Plos, M., Suligoj, T., Turk, G. (2021)

An overview of visual inspection and basic visual grading measurements for recovered timber, from Slovenia.	https://www.youtube.com/watch?v=f6bhhPnQ29A
The assessment of the mechanical and physical properties of recovered timber An approach for assigning design properties for a batch of timber, when the situation is out-of-scope of EN 14081.	Bather, M. (2022). The assessment of the mechanical and physical properties of in situ timber , *Doctoral dissertation, Edinburgh Napier University.*
Mass timber Secondary timber products Proof of concept that high properties products (such as cross laminated timber (CLT), glulam (GLT) and IsoTimber) can be achieved from recovered timber. Demonstrates the potential for CLT and GLT production from recovered softwoods and hardwood. Bending, bonding and embedment performance characterised experimentally.	Uí Chúláin, C., Gil-Moreno, D., Llana, D.F., González-Alegre, V., Íniguez-González, G., Plos, M., Turk, G., Risse, M., Stemmer, M., Ivanica, R., Richter, K., Cramer, M., Ridley-Ellis, D., Cristescu, C., Sandberg, K., Hogan, P., Harte, A.M. (2021). *Recycling timber in new mass timber construction products*. Galway, Ireland
Reuse of solid timber- Case study IsoTimber IsoTimber building elements made with a core made from recovered wood shown similar result to IsoTimber building elements made from new wood.	Cristescu C. Sandberg K. Häggström U. (2021), Reuse of Solid timber – Case Study IsoTimber Frame system, In: Proceeding of the 17th annual *meeting of the Northern European Network for Wood Science and Engineering WES 14-15 October 2021; Ed Laureckienė G. Kaunas University of Technology, 2021, e-ISBN978-609-02-1762-7, PP 149-150*
Cross Laminated Timber (CLT) manufactured with European oak recovered from demolition: structural properties and non-destructive evaluation It covers the grading methodology of cross laminated timber panels by non-destructive testing.	Llana, D. F., González-Alegre, V., Portela, M., & Íñiguez-González, G. (2022). Cross Laminated Timber (CLT) manufactured with European oak recovered from demolition: *Structural properties and non-destructive evaluation. Construction and Building Materials*, 339, 127635
Design concepts for building products optimised for deconstruction The report gathers and presents design examples of low-rise residential timber construction in Sweden, the UK and Ireland. Two different timber construction approaches for residential buildings are reported here, namely, light timber-frame construction and mass-timber construction. Both building systems are manufactured offsite in panel format and are assembled and finished onsite.	Uí Chúláin, C., Sandin, Y., Walsh, S.J., Shotton, E., Cramer, M., Ridley-Ellis, D., Carlsson, A., Jackson, N., Harte, A.M. (2022a). Design concepts for building products optimised for deconstruction. *Report No.: NUIG-TERG-2022-02*
Design for deconstruction and reuse of timber structures– state-of-the-art-review It discusses technical premises for a potential circular use of timber in building construction in low-rise timber buildings, up to 3 storeys, in seven countries	Cristescu, C., Honfi, D., Sandberg, K., Sandin, Y., Shotton, E., Walsh, S. J., ... & Krofl, Ž. (2020). Design for deconstruction and reuse of timber structures–state of the art review, *Report no: RISE 2020:05*
A tool for assessing the reuse potential of timber buildings An indicator system to assess if a building is designed for disassembly in accordance with ISO 20887	Sandin Y, Sandberg, K, (2021). A tool for assessing the reuse potential of timber buildings, *Report No: RISE 2021:50*

Design for deconstruction of timber buildings: case study This practical case study, carried out in close collaboration with industry, shows how an existing building design can be adjusted to improve its for reuse potential	Sandin Y., Carlsson A., Uí Chúláin C Sandberg K. (2021). Design for Deconstruction and Reuse: Case study Villa Anneberg, Report No: RISE 2021:96
Adding value to timber components through consideration of demolition and disassembly Design matrix; practical implementation of Design for Disassembly and Reuse principles	Walsh, S. J., & Shotton, E. (2021, August). Adding value to timber components through consideration of demolition and disassembly. In *World Conference on Timber Engineering, WCTE, 9-12 August 2021, Santiago, Chile*.
Design of Timber Buildings for Deconstruction and Reuse: Three methods and five case studies Methods developed for working with design for deconstruction and reuse, as well as examples of design solutions based on cases studies in four European countries	Sandin, Y., Shotton, E., Cramer, M., Sandberg, K.,Walsh, S., Östling, J., Cristescu. C., González-Alegre, V., Íñiguez-González, G., Llana, D., Carlsson A., Uí Chúláin, C., Jackson, N., García Barbero, M., Zabala Mejia, A., (2022). Design of Timber Buildings for Deconstruction and Reuse — Three methods and five case studies. Report No: RISE 2022:52
Traceability protocols for materials and products Methods to improve the traceability of building timber and engineered timber products over whole life-cycle.	Uí Chúláin, C., McGetrick, P., Harte, A.M. (2022b). Traceability protocols for timber construction materials and products. *Report No.: NUIG-TERG-2022-03*
Development of a life cycle inventory database and life cycle impact assessment of the building demolition stage: a case study in Germany Project-specific inventory data for the calculation of life cycle assessments for the building's demolition stage.	Ivanica, R., Risse, M., Weber-Blaschke, G., & Richter, K. (2022). Development of a life cycle inventory database and life cycle impact assessment of the building demolition stage: A case study in Germany. *Journal of Cleaner Production, 338, 130631*.
Glossary of definitions A list of the most used scientific terms in the project, and their definition from different literature sources.	Cristescu, C., Honfi, D., Sandberg, K., Sandin, Y., Shotton, E., Walsh, S. J., ... & Krofl, Ž. (2020). Design for deconstruction and reuse of timber structures–state of the art review. *Annex 1 in Report No: 2020:05, p.86-92.*

Research Institutes of Sweden

Edinburgh Napier University

National University of Ireland Galway

University College Dublin

Polytechnical University of Madrid

University of Ljubljana

Aalto University

Technical University of Munich

Kiruna Municipality's Technical Service

Swedish Wood

Derome

Isotimber

Offsite Solutions Scotland

Hegarty Demolition

SIP Energy

Connaught Timber

Federation of the Finnish Woodworking Industries

Jelovica

Swedish Federation of Wood and Furniture Industry

Balcas

Stora Enso

Nova domus hábitat

Brenner Planungsgesellschaft mbH

8. Conclusions

"How should we build today to be able to circulate tomorrow?"

It generally takes longer time to disassembly buildings than to demolish, therefore they are almost always demolished at end-of-life and go to incineration.

But there are promising results from the project:

- Design for deconstruction and reuse (DfDR) can be implemented with small changes and existing technologies.

- DfDR can contribute to reduce the environmental impacts of timber frame constructions for residential buildings.

- Products from recovered timber tested structurally show similar properties to equivalent new products.

- Environmental benefits can be achieved from the use of recovered solid timber in high-quality CLT panels.

- Recovered spruce and oak shows promising results of stiffness and density compared to new timber. A new framework for strength grading was developed.

- There is a huge amount of wood in existing buildings with potential for reuse.

The project has developed three methods to plan and optimize a primary design for deconstruction and reuse, rather than demolition: one qualitative method to assess and improve an existing design, one assessment tool producing a ReBuilding Index adopted to industry needs, and one Decision Matrix to be used by designers. Cases studies carried out with manufacturers show that timbr building designs exist that are relatively well adapted for deconstruction and reuse already today. Simple changes in design are sometimes enough to augment the reuse potential of a building. There are many possible ways to structure guidelines for deconstruction and reuse of a building (Deconstruction Plans) and no standard is yet established. Deconstruction Plans are likely to become legally required in the future and finding a coherent standard is considered as an important area for future research.

8.1. Recommendations

In the InFutUReWood project, we focused on investigating how wood from current buildings can be reused especially as structural material. Here are the recommendations based on our research results:

For new buildings, deconstruction plans made by designers should be demanded by the local or the building authority as part of permission to build, to enable disassembly and reuse in the future.

- Evidence from our project shows that small changes in the design of timber buildings can have a big impact in improving building details for deconstruction and reuse. The deconstruction plan can be combined with the tracing of materials used in building components and documenting their environmental impact. For new buildings, deconstruction plans required at building permission stage should be combined with material passports and recycling information to enable the circular use of the materials in the future.

Financial incentives in form of tax advantages and subsidies should encourage the reuse of timber coming from buildings for several life cycles, to avoid its premature conversion to biomass energy. Since biomass energy having incentives is what prevents a lot currently

- The cascading use of timber needs to be encouraged by financial incentives so that renovation and reuse is favoured over the new construction that use of virgin materials. Assessment methods should be used to show that cascading contributes to both sustainability (social, economic, environmental) and circularity.
- Industry can only innovate towards more sustainable building practices if standards for construction products and European Assessment Documents are harmonized, and this normative work can keep pace with technical developments and societal need. This should be addressed by the revision of the Construction Products Regulation.
- Integrated policy frameworks are needed for the building construction process and recycling industries/recycling processes so that up-front costs are considered as an investment into a global resource deposit.

Incentives for reuse, material traceability after first use, recycling information, and addressing the issues with harmonized standards are part of the European Commission’s review of the Construction Product Regulation, but timber will need specific approaches due to its special nature compared to abiotic construction products. If general solutions cannot be found, there should be streamlined processes (or assistance) for lower risk circular economy products and applications.

Building safety is vitally important, but measures to ensure it should be proportional to the risk and take a wider view – not just of individual buildings, but of buildings as part of a wider system. Buildings are one of the main contributors to climate change, and the effects of this, in turn, bring increased risks to buildings through mechanisms including storms, flooding, landscape-scale fires.

8.2. Future work

While some outputs of this project can be implemented now, more research is needed in all aspects covered by this project. Cross-laminated timber, in particular, has been identified as a construction product with high potential for reuse in the future also make use of reclaimed timber.

Gathering the required data for wood characterisation and product certification is a very large task. For this reason, projects working in this subject should cooperate to share data so that a sufficient shared body of knowledge can be accumulated over time.

For research point of view no one project can collect enough data about wood quality and properties since they are so variable – therefor multiple projects sharing their data are needed.

Besides data, a guide to Good practice should be compiled with different solutions to circular design, combining research projects and industry solutions and integrated in adapted to regulations in different countries.

Knowledge transfer to society as well as education of building professionals are key issues because moving away from the current state have many challenges and obstacles such as new building regulations, adaption to harmonized standards.

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Appendix. Student works

Thesis worker and Bachelor Thesis and Students work

Micheal Bather, PhD Thesis, WP 5, GB

Andres Oswaldo Zabala Meja, Master's Thesis WP 2, SE

Ida Lundgren, Master's Thesis WP 2, SE

Sara Bergås, Master's Thesis WP 2, SE

Sara Khanalizadehtaromi, Master's Thesis WP 2, SE

St John Walsh, Master's Thesis WP 2, IE

Viktor Henriksson, Bachelor's Thesis WP 3, SE

Pablo Batista Martín, Bachelor`s Thesis, WP 4, ES

Inés Kásner Tourné, Master's Thesis, WP 2, ES

Nora Siebels – Master's Thesis, WP 6, DE

Michael Stemmer – Master's Thesis, WP 6, DE

Sonja Braun – Bachelor's Thesis, WP 6, DE

UCD MArch, Irish Timber & Sustainability, 2021

Sara Kerttu Siivola, Bachelor's Thesis WP4, Finland

Onni Poikkeus, Bachelor's Thesis WP4, Finland

Alice Bowler, student work WP2

Nadine Buckley, student work WP2

David Byrne, student work WP2

Thomas Delahunt, student work WP2

Jenna Ely, student work WP2

Lars Hervik Helgesen, student work WP2

Xinran Liao, student work WP2

Leoni Lichtblau, student work WP2

Brian Mc Donnell, student work WP2

Laoise Mc Grath, student work WP2

Kate Monahan, student work WP2

Siren Fjærvoll, student work WP2

Maureen Sotak, student work WP2

Shannon Walker, student work WP2

Maral Alae, student work WP4, Finland

Thara Warfen, student work WP4, Finland

Majid Raza, student work WP4, Finland

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