Design for deconstruction and reuse of timber structures – state of the art review

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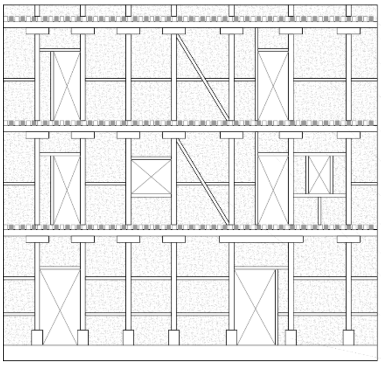




InFutUReWood Report:1

RISE Report 2020:05

ISBN: 978-91-89167-67-4

DOI: 10.23699/bh1w-zn97

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December 2020

Innovative Design for the **Fu**ture – **U**se and **Re**use of **Wood** Building Components – Report:1

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Foreword

This report represents the first publication of the InFutURe Wood project - Innovative Design for the Future – Use and Reuse of Wood (Building) Components.

InFutUReWood is supported under the umbrella of ERA-NET and financed by funding agencies from each of the participating countries. The industry partners participate mostly with in-kind.

The research and academia project partners are RISE (Sweden), Edinburgh Napier University (UK), National University of Ireland Galway (Ireland), University College Dublin (Ireland), Polytechnic University of 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, The Federation of the Finnish Woodworking Industries, Jelovica, The Swedish Federation of Wood and Furniture Industry, Balcas Timber, Stora Enso, Klimark + Nova domus Hábitat, and Brenner Planungsgesellschaft.

ForestValue

InFutUReWood is supported under the umbrella of ERA-NET Cofund ForestValue by Vinnova – Sweden's Innovation Agency, Formas, Swedish Energy Agency, the Forestry Commissioners for the UK, the Department of Agriculture, Food and the Marine for Ireland, the Ministry of the Environment for Finland, the Federal Ministry of Food and Agriculture through the Agency for Renewable Resources for Germany, the Ministry of Science, Innovation and Universities for Spain, the Ministry of Education, Science and Sport for Slovenia. This is supported under the umbrella of ERA-NET Cofund ForestValue, and ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773324

Summary

This report is a state-of-the-art on timber construction in selected european countries and discusses technical premises for a potential circular use of timber in building construction, focusing on Design for Deconstruction and Reuse (DfDR) in low-rise timber buildings, up to 3 storeys. It describes the historic and contemporary building techniques of timber buildings in all project countries (Sweden, Finland, Ireland, UK, Spain, Germany, Slovenia) and finds, that all of these countries have a long history of building with timber, but in most regions other materials dominated the housing output from the beginning of the 20th century. Only in the second half of the 20th century timber started gaining importance as a building material in Europe again, with light timber frame construction becoming an important construction system. From the beginning of the 21st century, innovations in the sector started transforming the construction industry. Mass timber products like CLT opened the market for high-rise timber buildings and in some countries office blocks, schools and hotels are built using timber, although the majority of timber construction remains residential. An even more important development might be the uptake of offsite construction, that makes timber construction more accurate, material efficient, fast and it reduces waste These modern methods of construction are gaining importance in the construction sector of all partner countries and are likely to dominate the European housing output in the future. There will be some regional differences in the level of prefabrication, material choices and designs, so that any design guidelines for DfDR need to be adapted to the regional context. However, modern timber construction is not currently aligned with circular economy principles and is seldomly taking buildings end-of-life-into account.

Therefore, the report continues to summarise novel design concepts for deconstruction and reuse, that could be used in modern timber buildings. It outlines that the feasibility as well as the reuse potential depends on the scale of reclaimed components, where larger components and assemblies are often considered beneficial in terms of time, greenhouse gas emissions and waste production. If volumetric or planar units could be salvaged in the future, they also need to be adaptable for altered regulations or standards or alternative functions. It is further necessary that assemblies can be altered within buildings, since different building components have different life expectancies. Various examples for DfDR in buildings with the accompanying design strategies are presented. The buildings in the examples are often designed to be in one place for a limited timeframe and can be deconstructed and re-erected elsewhere without replacement of components. Key-features often include modularity of components, reversible connections, adaptability of the floor-plan and circular procurement. Even though it is evidently possible, the structural reuse of timber is not a wide-spread approach to date. Barriers to the use of reclaimed structural components are mainly a lack in demand for salvaged materials, but also prohibitive building regulations and the lack of design standards. Demolition practices play a crucial role as well and need to be considered in the design of buildings, to avoid damage to the components.

Finally, the report summarises principles and guidelines for DfDR by different authors. As a generic approach an indicator system for deconstructability and reusability could be introduced. Time, Separability, Risk and Safety, Simplicity and Interchangeability are identified

as the main indicators for DfDR, that remain somewhat abstract. As opposed to using a generic indicator system, a more practical approach of assessing DfDR on an individual basis could be taken. This way specific shortcomings of the design can be addressed. But if DfDR found a wider application in the future, this approach may be too time consuming and there is a need for a more directed decision-making tool that can be used during the design phase of buildings to enhance DfDR. As the InFutUReWood project proceeds, it will examine a more granular approach to DfDR, relating it to the actual construction stages used in practice, developing a general template to be appropriated and adjusted to account for regional variations in construction. A strategic matrix is in development which will provide designers with a methodology based on relating principles, strategies and specific tactics to the typical design stages, to aid design decisions that promote DfDR.

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1. Introduction

1.1. Background

This delivery is part of the InFutUReWood - Innovative Design for the Future – Use and Reuse of Wood (Building) Components – project which aims to answer two main questions:

1. How easy is it to reuse wood from current buildings, especially as structural material?
2. How can the past experience help the future?

To address these questions the project's objective is to identify the key opportunities and challenges, and to propose technical and methodological solutions. This knowledge will be transferred to industry to avoid inadvertent and unnecessary problems for future generations.

Within the project Work Package (WP) 2 *Design of timber structures for the future* aims to develop building concepts that optimize the design of wooden buildings to enhance resource efficiency and deconstruction. This deliverable is the result of the work carried out within Task 2.1 *Study new ways to design structures and details to facilitate recovery of materials, meeting building regulations and standards of different countries, and investigate need for future changes* of WP2.

1.2. Aim & Objectives

The aim of this report is to provide an overview about the state of the art regarding timber construction and reuse of timber structural elements in particular. To achieve this several objectives are set out:

- Identify timber construction types for developing promising concepts for reuse;
- Identify obstacles and potential for reuse of structural timber;
- Identify (and possibly adapt) existing methods for the evaluation of reusability of wooden structural members.

1.3. Method

The report gathers together information studied and selected by the authors from different sources: scientific articles, books, websites of manufacturers, of research institutes, website focused on architecture, but also interviews with key-actors in the project, industry partners and branch organisation representatives. The study is mainly qualitative with a collection of quantitative data about the actual trends in timber buildings across the seven countries.

1.4. Limitations

The report is focused on timber buildings; thus, it may not be possible to directly generalise findings for other construction materials. Similarly, results and solutions regarding other buildings materials may not be directly transferred to wood buildings, though principles and strategies will be examined with both general and specific construction in mind.

The focus of the Work Package 2 is on the design phase as opposed to the operation and management of timber buildings. Many principles regarding design for deconstruction emphasize the importance of engaging with clients and the design team at an early stage, best described as conceptual planning in the pre-design phase, which will be discussed in this report but will not form part of later design studies in WP2. The study has focused on housing stock, as being the building type in which the greatest quantity of timber per square meter is found. Equally important, from a social and environmental standpoint, focussing on this typology is potentially of greatest benefit, as construction of residential projects outstrips other such sectors significantly. More precisely, later stages of the study will focus on: the primary design of 1-4 storey wooden houses for flexibility, adaptability and to facilitate deconstruction; and to use materials in a resource efficient manner and make it possible to separate materials for more efficient material recovery in the future. Designing the structures in this way will then influence deconstruction, waste management and designing with reused materials in the future.

1.5. Short glossary of terms

A full glossary of terms can be found in Annex I.

The most used terms in the report are defined as follows:

Design for Deconstruction and Reuse (DfDR) is the design of the building so that the parts are easily dismantled and separated from each other for reuse or recycling (Moffatt and Russel 2001). The main focus is on component preservation (reuse, repurposing) before material preservation (recycling).

Recycling is any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. (EC 2008).

Reuse is any operation by which products or components that are not waste are used again for the same purpose for which they were conceived, with minimal pre-processing, i.e. checking, cleaning and repairing. (Adapted from EC 2008).

Timber is used here to refer to any wood-based building material, whether structural or non-structural. Depending on the context, the word is used to refer to sawn wood in a prepared state for use in building (or wood intended for that purpose), but it can also be used in a general sense to include laminated elements and other engineered wood products. Wood based panel products are not, themselves, referred to as timber, but they do fall under the general heading of timber construction. In some countries, timber refers to specific end-uses and/or cross-section sizes, but that distinction is not made here (Adapted from ISO 6707-1 (2020).

2. Reuse in circular timber construction

2.1. Circularity in the building sector

Circular Economy (CE) is described by Geissdoerfer et al. 2017 as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling".

In "A Critical Literature Review of Concepts" (Beaulieu et al. 2015) the authors discuss the different meanings of the definitions found in the literature: some of them claim CE to be based on effectiveness ("doing the right thing") but many definitions from various organizations seem to focus on efficiency ("doing things right"), while some concepts such as Functional Economy aim to reconcile both ("doing the right thing the right way"). This can be paraphrased by adding "in the right moment", a concept best illustrated by the model for sustainable construction (Figure 2.1) by Kibert (1994), which will be discussed in more detail in Section 3. By this the authors emphasize the importance of the design stage, of planning for circularity from the very beginning of a construction project.

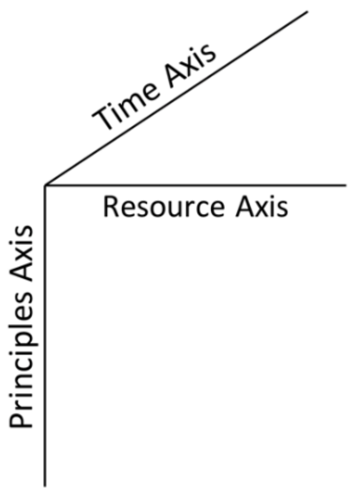


Figure 2.1 Conceptual model of sustainable construction (Kibert 1994)

An appendix with preliminary glossary of definitions most often used in the context of building process as part of CE can be found in Annex 1.

For all industries, not only in building industry, materials flow and management is the common denominator across all value chains. The European Union through its strategy (CEAP 2020) that has led to the launch of national initiatives (such as in Sweden, Swedish Government 2020) supporting the idea that business must adapt itself to circularity by changing its models in order to gain the most value from circulating in loops.

There are five important technical (and value creating) loops in CE, where the most immediate loop, product maintenance (the 'inner circle' or 'Waste prevention'), yields the highest value and the loop furthest downstream (reprocessing material) yields the least value:

1. Product maintenance
2. Product reuse/redistribution
3. Product refurbishment/remanufacture
4. Product recycling
5. Reprocessing of technical nutrients. (Beaulieu et al. 2015)

The loops of CE described above are strongly connected to the waste hierarchy concept. In the Netherlands, following a parliamentary proposal in 1979, a "waste hierarchy" was developed with a preference order for waste management: from prevention, reuse of products, recycling of materials, energy generation through incineration to functional landfilling (Figure 2.2).

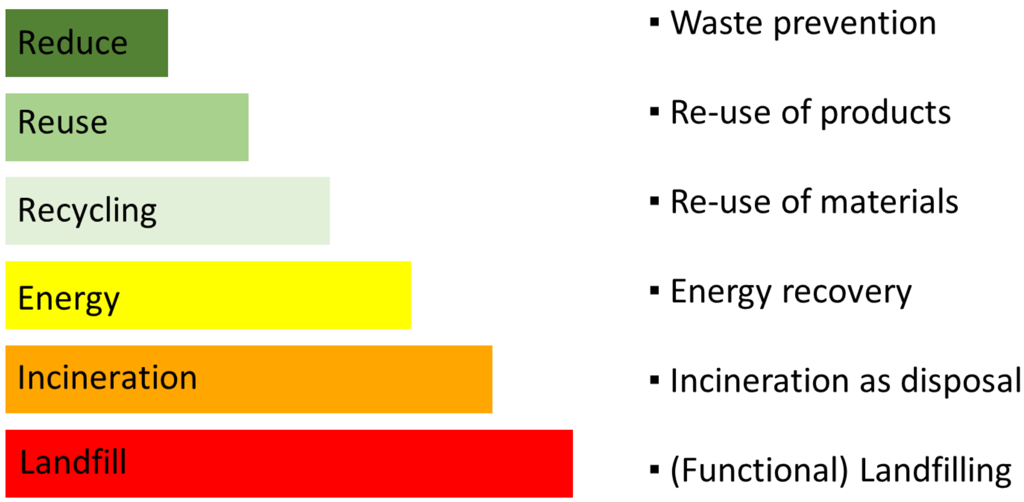


Figure 2.2 Lansink's waste hierarchy with explanations to the right (Lansink 2017)

The majority of wood from the construction and demolition (C&D) sector, depending on each countries' legal regulations, regional and technological situation, is mostly incinerated for energy recovery or landfilled (with great differences across European countries, Vis et al. 2016). Only about one third of C&D wood waste in Europe is currently recycled into material for board products (Risse et al. 2017). There is debate (Seltenrich, 2013) on the term wood recycling, as waste management companies are using this term to describe the incineration for energy recovery but, according to Lansink (2017) and the EU, recycling refers to materials being transformed into new products.

Wood has a special place in the circular scheme, as shown by McArthur (2020), see Figure 2.3 It is a biodegradable material that belongs to "renewables" and it should therefore strive to follow such a scheme and, further, to be considered as carbon store. Nevertheless, wood is also a structural building material, with a technical application. The finite materials scheme has been adapted to construction and the finite materials used within it to inspire the reuse of concrete or steel but has been very rarely applied to wood.

In Figure 2.3 the study and the aim of this project could be positioned in “cascades” on the left side of the graph (Renewables) but actually the aim of transforming the wood building industry from a linear to a circular type can be fulfilled by considering the loops on the right side of the graph as well, presented as suitable for finite materials. They are the same loops as described by Beaulieu et al. 2015 and we argue that the way renewable materials are used should receive the same consideration as finite materials before being considered “biomass”.

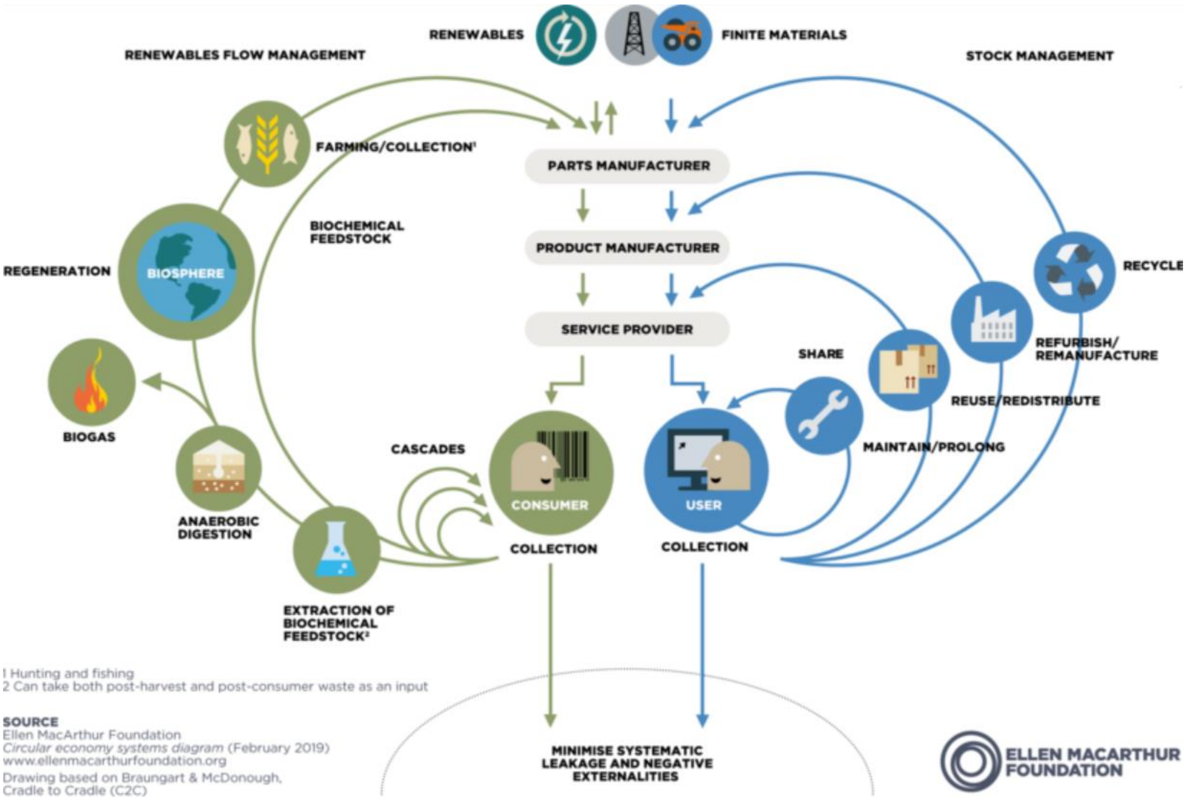


Figure 2.3 Circular economy systems diagram (2019) Source: MacArthur 2020

The concept of “cascading” was developed in the Netherlands with the aim of better resource efficiency by Sirkin and ten Houten (1994) and referred to all types of materials. In “The cascade chain: A theory and tool for achieving resource sustainability with applications for product design” the authors discuss among others: “What possibilities lie in the application of the cascade concept for the appropriate exploitation of the intrinsic and extrinsic properties of resources, substances, materials and products?” The concept was later applied to wood by Fraanje (1998), as seen in Figure 2.4.

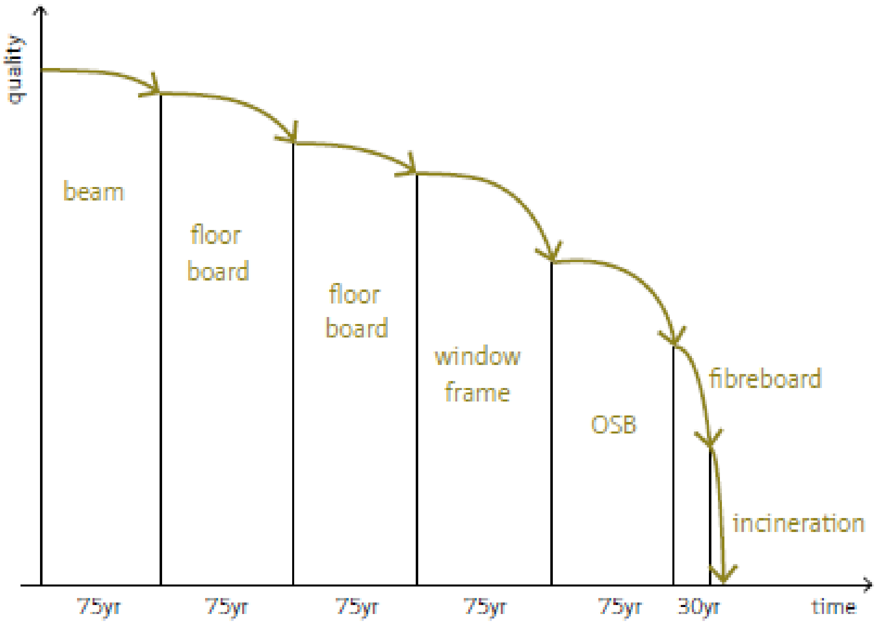


Figure 2.4 Potential cascading of pine wood. Fraanje (1998), adapted by Icibaci (2019)

Given the development towards a more climate friendly and resource efficient bio-based economy, the demand for wood will increase in the next years and likely exceed the supply that is currently available from a sustainable forest management (Mantau et al. 2010). Developing and applying the concept of cascading can contribute to satisfying this increasing demand.

The term cascading was coined by the biomass sector (see Figure 2-3) but the principle is the same for all materials, briefly: material use first, energy use last (Arnold et al. 2009). In 2017 it was considered that a consistent definition of the term “cascading use” was lacking across all sectors including science, economics and politics (Fehrenback et al. 2017). Moreover, the integration of a cascade approach into existing legislature has differed widely among individual countries, as well as the associated effects. It is noticeable that the term “cascading use” has been included in both German and European strategy and position papers since about 2010, most frequently in explicit reference to biomass use.

The ability of the forest to absorb the carbon dioxide emitted by the incineration of timber (Figure 2.5.) as it grows has been something of an impediment to the successful implementation of wood cascading in European countries. The general perception has been that the carbon cycle and the fibre reuse cycle already assure the circularity of wood (Figure 2.5). The importance of reusing a wooden product without downcycling it, without reducing it to a source of material for another product, without milling it, has been neglected especially in countries with significant forest cover. Instead there was more focus on biochemical and thermochemical conversion of wood, which is also important in terms of circular economy, but focuses more on virgin wood rather than recovered wood as a resource.

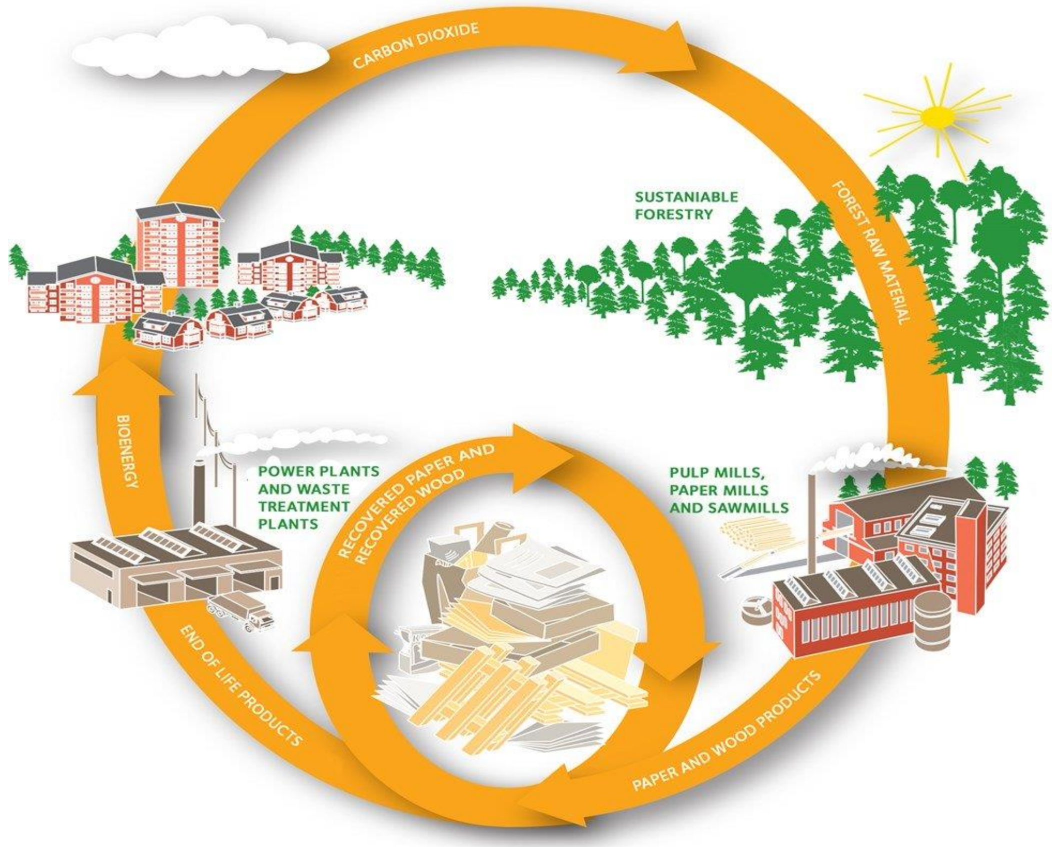


Figure 2.5 Illustration of wood circularity with its carbon cycle (Bergkvist and Fröbel, 2013)

Prolonging and diversifying the use of the same resource, via cascading, is the most useful strategy for reducing waste (Figure 2.3). As defined by Risse (2019), cascading refers to the sequential use of one unit of a resource in multiple material applications and, in the case of wood, ends with its use for energy generation through incineration. As Risse explains “It follows a holistic perspective on the material’s value chain and can include various reuse and recycling processes as well as end-of-life treatments” (2019). The cascade use of recovered material also reduces the environmental impacts associated with product manufacturing. Furthermore, cascading can increase the time of carbon storage and postpone carbon emissions, with potential benefits for climate change mitigation (Maguire, 2018).

To further enhance wood cascading in practise, new recycling technologies and product applications are required and were under research in recent years. Some research activities revealed that the use of recovered wood is technically possible (e.g. Irle et al. (2015); Lesar et al. (2016); He et al. (2019)). However, due to the heterogenic and often low quality of the recovered wood, only small yields are obtained for high value recycling processes (Privat 2019). Thus, cascading not only required new technologies, but also a different demolition and waste treatment in order to increase material quality. Ideally, products and buildings should be designed in a way that preserves the material’s quality and enables easy and efficient recycling.

Here, wood buildings may receive greatest attention for several reasons. Currently, most of wood from building demolition is mostly incinerated for energy recovery (especially heat in power plants) and a very small amount is still landfilled, tending to each, see Table 1, (data for 2016 partially collected from Bioreg, 2017).

Table 1 Share of waste wood sent to landfill in 2016 and 2018 in selected countries

Country	Finland	Ireland	Germany	Slovenia	Spain	Sweden	UK
Year	**2018**	**2016**	**2020**	**2016**	**2016**	**2020**	**2018**
Wood to landfill (% of total wood waste)	0,06	3,39	0	0,01	1,65	0	< 1

In the countries participating in the project wood waste is usually used as energy source. Large quantities of high valuable wood products and assemblies of products, including structural frame components, are lost for a potential wood cascading scenario. Developing and implementing a design for reuse and recycling concept in the wood building sector is likely to offer great potential to the reuse of timber structure and to create the prerequisites for wood cascading in practise.

Circular buildings - the concept

Durmisevic (2006) notes that demolition practices are largely responsible for the negative impact of construction on the production of waste in construction, and that design for disassembly if implemented could reduce this impact significantly. It is proposed that it is necessary to change how we perceive the performance of a building as well as the manner of its composition across all levels of a building. Durmisevic suggests that green buildings should be designed in a way that allows for transformability. The research provides a design framework and guidelines for design of transformable systems and buildings as well as a means of evaluating this design with a transformation capacity index (Durmisevic 2006)

Buildings seen as temporary depositories of valuable materials at specific sites is a concept developed and studied in BAMB (2020). The subject was recently researched by Van den Berg (2019) who notes: “The metaphor of ‘buildings as material banks’ (Debacker and Manshoven, 2016) captures this view well, since it emphasizes that materials can be brought to, stored in and collected from man-made structures. In circular building projects, those materials are reduced, reused and/or recycled to the maximum extent possible” (Van den Berg, 2019). The author intended to break with the ingrained viewpoint that a building lifecycle starts with a design stage and is then followed by construction and operation only to end with demolition. Instead, given the large existing building stocks (particularly in developed countries) he proposes that a building lifecycle starts with demolition (of salvaged buildings) and is then followed with design, construction and operation stages in a continuous cycle. Van den Berg

(2019) argues that the main strategy to close material loops for buildings at the end of their useful life is reuse.

In Europe the international projects focused mainly on structural materials that had showen to affect the environment and that are non-renewable, such as concrete in RE4 (Attanasio and Largo, 2017) or steel in PROGRESS (Hradil et al. 2017). The transition to a bio-based economy that takes place in many European countries puts pressure of the availability of wood, it will be used resource material for numerous products and applications. Lundmark (2020) showed that a fossil-free Sweden in 2045 would mean an increase in the need of quantities of wood. The requested amount will not be available by that time, taking also into account that the forest should keep its biological diversity and provide the absorption of carbon dioxide. That is why it is highly important to reconsider how wood structures are seen by society, they should also be part of the "material bank", and be reused as structures and components.

Such an effort requires a transition from linear to a circular construction model (Figure 2.6) even for timber buildings. In a linear model, buildings are made of materials extracted from natural resources, then processed into materials, manufactured into components, assembled into buildings, used and then after the end of their lifetime *demolished* followed by being sent to landfill or incineration, depending on material and country.

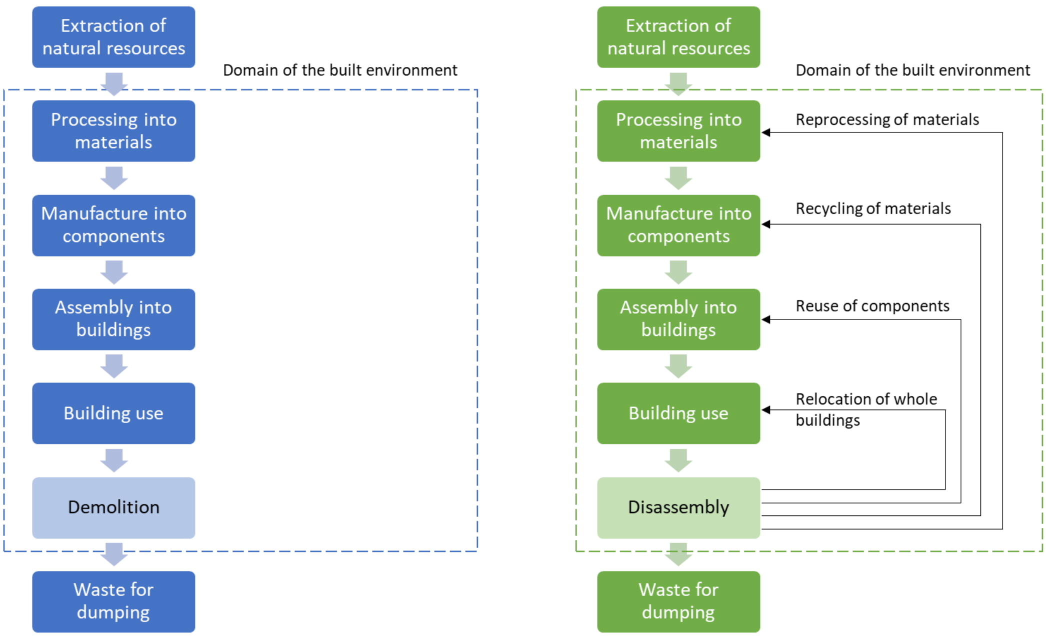


Figure 2.6 Changing the life cycle in the domain of built environment from linear to cyclic model through disassembly of buildings (Crowther, 2005)

In a circular model, waste is prevented and reduced through various processes after disassembly including: complete or partial relocation of the building, reuse of components or subassemblies, recycling of building materials into new components, or reprocessing into new materials. The "smaller" the cycle the larger the expected environmental benefit, i.e. typically relocation and reuse, are the preferred options, though maintenance, adaption or flexibility (reuse on site) prior to relocation is optimum

This then suggests a hierarchy of waste management as proposed by Kibert et al. (2000) and shown in Figure 2.7.

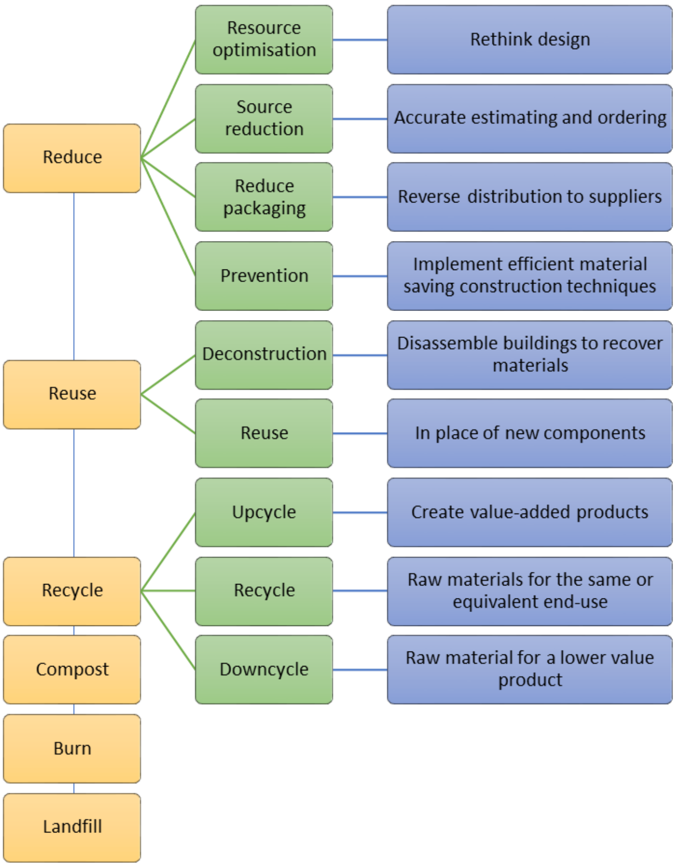


Figure 2.7 Waste management hierarchy for demolition and construction operations, adapted from Kibert et al. (2000)

Disassembly that aims at the reuse or relocation of building components or assemblies within a new or existing building is often termed as deconstruction (Long, 2014). During deconstruction consideration is given to 1) dismantling without causing damage and repairing damaged components; and 2) utilizing the remaining lifetime of the dismantled components either for original purpose or for other purposes (Moffatt and Russel, 2001). The primary goal of deconstruction is to reuse the dismantled components; however, recycling can also be considered as a secondary objective. The term disassembly is often used in a wider context and typically enables the possibility of recycling of recovered building materials into new components or reprocessing into new materials. Thus, disassembly is typically less environmentally friendly than deconstruction as it preserves less embodied energy and requires additional energy for reproduction.

3. Timber building design: potentials and obstacles for future reuse

3.1. Building systems and processes

3.1.1. Timber construction systems

Various ways exist to construct buildings made of timber and wood-based products as load-bearing components with different levels of prefabrication. These buildings range from single family houses to high rise wooden buildings, office buildings, schools and pre-school buildings, sport halls and multi-storey car parks. Wood, with its advantage of being lightweight compared to its strength, has increased the capacity of building larger components, as well as quick and easy assembly on site.

Different types of wooden building systems can be categorized based on several aspects, such as: structural system, use of material, type of building elements, level of prefabrication, etc. Table 3.1 Classification of timber construction systems shows how these aspects could be arranged in different classes. The systems in use are thus a combination of these classes. A brief summary of common modern construction systems is presented after Table 3.1.

Table 3.1 Classification of timber construction systems

Aspect	***Type***
Structural system and material use	Light-frame construction (stud frame, I-joints)
	Post and beam
	Massive timber construction (Log construction, Post and plank, CLT)
Prefabrication and automation level	On-site building (stick building)
	Prefabricated (beams, columns, plane elements)
	Industrialized construction (volumes)

Light frame timber on site construction

The light-frame technique can be categorised to two techniques: first, the balloon framing technique (maximum of two-stories) and second, the platform framing technique (more than two-stories). The balloon frame technique consists of full-height wall framing elements which usually use light sawn timbers, assembled with nails (Allen et al. 2017). In the platform technique the load-bearing elements are mainly exterior walls which are built on top of the floors, storey-by-storey. This method enables the use of smaller pieces of timber in the load-bearing elements to create a “platform” of wood flooring, stable enough to place the supports for the upper floor on top of it. Similar to balloon framing technique, the platform framing technique usually uses basic sawn wood grades. Nowadays, the load-bearing structures in wood-frame multi-storey constructions increasingly rely on engineered wood products. (Hurmekoski et al. 2015)

Light frame building on site method is suitable for houses built without advanced lifting equipment, typical for single family houses but also for multi-storey buildings. Most of the work is done on site carried out by carpenters. The common construction material is either ready-cut timber or timber cut on site. Walls are assembled horizontally on foundation slabs and floor with vertical studs placed between the top and the bottom plates, and the nailed frame raised into position (Figure 3.1). After the structural frame is built, typically without sheeting material and insulation, a protective roof is installed. When the weathertight roof is in place, installation of moisture-sensitive materials (e.g. insulation and plasterboards) begins. For taller buildings bracing boards are often required to ensure stabilization during the construction process. On-site construction tends to take a longer time than prefabricated construction (Kuzman and Sandberg 2016).

Figure 3.1 Example of onsite light frame family house (photo: D. Honfi)

Light-frame construction using I-joists

I-joist is a general term used for a light-weight engineered structural elements with a section in the shape of I, made out of two flanges in e.g. solid wood that are connected by a web material such as OSB or other type of wooden board (see Figure 3.2). They are used not only as joists for floors but also as rafters in roofs and as stud elements (the latest are used in prefabricated walls together with insulation). The benefit of the I-shape is an effective load transfer through the cross-section, giving a lightweight product with a high ratio between strength properties and the material consumed (Masonite 2018).

Figure 3.2I-joist structural elements on metal joist hangers (photo: Steico 2020)

According to Persson and Wikner (2020) it possible to build high-rise wooden buildings up to 12 storeys using systems based on I-joists, also to produce floor structures with spans of up to 8 metres, with thicknesses from 413 mm. The walls can be produced in lengths up to 9 metres and thicknesses between 300 and 600 mm.

As solutions for connecting it is mainly metal web joist hangers, such as the ones produced by Simpson Strongtie (2020) or that are chosen in Figure 3.2 as well as variable pitch connectors, choices based according to the loads and size of the I-joist elements.

I-joists are very popular in the UK, especially in timber frame houses, and increasingly replacing solid timber in masonry construction too. It is quite rare to find solid wood joists in floors as i-joists are much more normal. They are successfully used studs and roof trusses also.

Post and beam

Post and beam system are made of largely prefabricated units that are joined together on site. They also require a weatherproof roof and often some kind of protective cover even during transportation of the structural elements.

Post-and-beam techniques are constructed of a skeletal framework of massive columns and beams (Figure 3.3) that the intermediate and upper floor planes, as well as the exterior walls, are installed on top of it (CWC 2014). This technique enables large openings in façades, making it ideal for the construction of modern architectural design (Puuinfo, 2020). The span of posts and beams are derived by engineering calculations based on the strength and size of the timber members, the span of the beams and infill floor joists, in tandem with anticipated loading based on anticipated use, with the normal distance being 1200 mm or more (CWC, 2014). The beams provide flexibility in the interior, even after completion of the buildings since the walls and dividers are non-load-bearing elements (Puuinfo, 2020).

Figure 3.3 Post and beam frame (photo: D. Honfi)

Massive Timber Construction

Log construction

An early form of solid construction was log construction, a system with horizontal logs stacked directly on top of each other. The load-bearing walls acts doubly as structure and enclosure, leaving joints exposed and expressive of the construction (Mayo, 2015). The trunks can be squared off, as in Figure 3.4, but round logs are also used in the “blockwork” type of construction (Mayo, 2015). Log construction is still occasionally used for building summer houses, in most cases totally handcrafted in Sweden. Industrial manufacturing, laminated logs and finger jointing enable production of lengthy logs in Finland, allowing the construction of large size buildings and modern architecture designs (Laukkanen, 2018).

Figure 3.4 Traditional log construction from year 1830,"Bonnstan", Skellefteå, Sweden (Photo: Karin Sandberg)

Post and plank construction

According to Rybníček (2018) world's oldest dendrochronologically dated archaeological wood construction, year 5481 BC, was a post and plank type, in oak, discovered near Ostrov (Czech Republic). This confirms Mayo's (2015) statement that using vertical logs to create a skeletal load-bearing structure is one of the oldest forms of building and developed in parallel with blockwork construction.

Unlike the blockwork construction, skeletal frame timber buildings do not rely on stacking and massive exterior walls to crate stability. Rather than relying on gravity, these structures rely on sometimes exceedingly complex wood joinery for stabilization (Mayo, 2015).

An example of a post and plank construction is presented in Figure 3.5.

Figure 3.5 Traditional construction in Norway, a combination of post-and-plank in the front area, and log construction in the back area (Photo: E. Shotton)

CLT construction

Cross laminated timber, crosslam, CLT, X-Lam, BSP, mass timber and multiply are common names for sheets, panels, posts and beams made of glued boards or planks layered alternately at right-angles (Gustafsson, 2019). CLT panels are made up of boards or planks with a thickness of 20 – 60 mm. This surface timber product is typically fabricated by laminating three to nine layers of timber boards with each layer typically placed at 90 degrees to the next (as in plywood), although studies exist on 45 degrees layering (Buck et al. 2016).

In relation to their own weight, CLT panels have a higher load-bearing capacity than most other construction materials, which is why large structures can be built to withstand high loads (Gustafsson, 2019). Panel dimensions vary, with the common largest proportions of length, width and thickness between 18m, 5m and 0.5m (Harte, 2017). The length can sometimes reach 30 m (Gustafsson 2019).

CLT panels are used for the primary above ground structure of walls, floors and roofs and assembled with the use of cranes (Figure 3.6). The external walls have a load-bearing and stabilizing function, and have to be insulated to give the building a high level of energy efficiency in colder cliamtes. Internal walls for stabilization are made of CLT, while sound-insulating walls between rooms sometimes are of traditional timber-frame structure (Kuzman and Sandberg).

Figure 3.6 CLT Wall panels craned into position on construction site (Strongtie 2019)

Buildings of up to 18 storeys in height have been constructed (Brock Common's Student Residence, Canada), with studies suggesting that very tall structures using CLT are feasible (Harte, 2017). An example of a "pure" tall solid wood building that has concrete only as a platform is Origine, built in 2017 in Quebec, Canada. It is 40,9 m high and 13 storeys out of each 12 storeys are build entirely in solid wood, predominantly in CLT with help of glued-laminated timber (posts and columns), supported by a concrete podium (Nordic 2017).

According to Gustafsson (2019) there are many different types of fixings that can be used in designing joints between CLT walls and floor slabs or joints between other materials and CLT. Long self-drilling wood screws are commonly used in joints between CLT panels (Wilded, 2020) but other traditional fixings such as nails, inset plates and nail plates are also widely used.

There are also several more innovative solutions such as glued-in rods, advanced package solutions that cover all corner solutions, including assembly fixings and systems for invisible load-transferring joints. The new systems often rely on a high degree of prefabrication of CLT panels and the fact that CNC machines are used to design fixings (Gustafsson 2019).

In central Europe, wooden dowels are becoming more and more popular as connectors, such as the products by Knapp (2020).

Prefabrication and automation:

To reduce the construction time on site, parts of the structural frame can be modularized into planar structural elements, such as floor units and walls (Figure 3.5), or volumes.

Planar structural elements

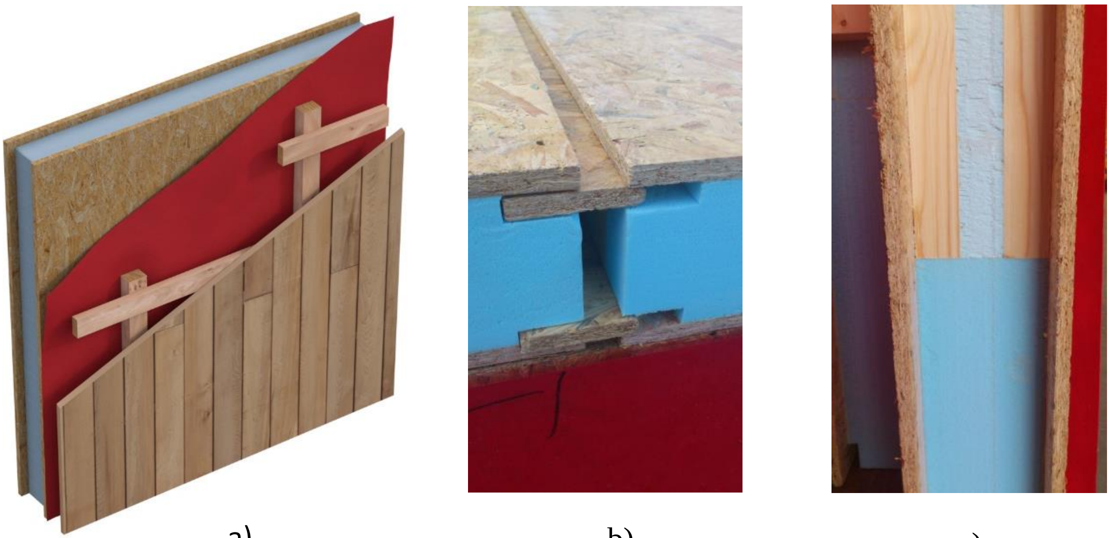
Planar structural elements are generally of two types: small and large. Sizes of a small planar elements are produced up to 1.2m wide and are lightweight and compact to enable a crew of two workers to set up a house without the need of a crane. The large planar element are an up-scaled version of the small unit system in which the sizes of are assembled up to 22 metres long (Siikanen, 2008). Due to the size and weight of the large prefabricated units, a crane is essential in the construction process (Figure 3.7).

Figure 3.7 Lifting of large prefabricated wall element in Sweden (Courtesy of Derome AB)

The technique for manufacturing planar elements and the connections between materials differ between construction systems and countries. The most common system in Sweden, Finland, Slovenia, and the UK are panels where the insulation material is inserted between studs and joists in a light-frame type construction, but structural insulated panels (SIP) are also used in the UK and Ireland.

SIP

SIP is a sandwich system composed of an insulating layer of rigid core (a type of foam) glued on each side to two structural boards (also called skins), which most commonly consist of Oriented Strand Board (OSB) (Figure 3.8a). Two of the most widely used panel joint connections are the surface spline and the block spline (Simon 2020, Figure 3.8b, Figure 3.8c). In Ireland SIP Energy is the sole manufacturer of wood-based SIP panels which mainly have a domestic use.



a) b) c)

Figure 3.8 Example of a Structural Insulated Panel (SIP) used in e.g.Ireland (Courtesy of SIP Energy) a) positioning in the wall; b),c) panel joint connections

In the UK, SIP had around 5% of the offsite construction market share in in 2012 (Research and Markets, 2012).

Isotimber

It is a unique type of load-bearing and insulating exterior wall. A building blocks consist of studs, placed next to each other, supported by vertical thin (6 mm) plywood board glued on each side, see Figure 3.9 . The air ducts that are milled in the studs provide insulating properties. A planar element (wall) contains at least two layers of building blocks. They are available in three thicknesses 60mm, 100 mm and 150 mm (IsoTimber, 2020)

Width and length of the wall element are of maximum 3.1 m x 8 m, to fit transport requirements. The dimensions are adapted based on the individual project's design and technical requirements. They are assembled together with wrap joints and wood screws on the construction site, all joints are taped to get a building with good air tightness.

Figure 3.9 IsoTimber block composition: studs with air ducts placed next to each other, vertical plywood boards glued on each of the large sides (IsoTimber 2018)

The building engineers calculate frame dimensions and provide assembly drawings for the contractor as well as manufacturing drawings for the own factory, located in in Östersund, Sweden. This small-size company is project partner and further studies about possibilities for reuse of the blocks and of entire walls will be presented in following reports.

Volumes (volumetric units)

Volumes are boxes with openings containing one or several rooms often including electric and plumbing installations pre-installed at the factory before onsite construction (Hurmekoski et al. 2015); only levelling the ground, laying the foundations, and making connections to the sewer system are carried out on-site.

An assembly of a building made of volume elements is shown in Figure 3.10. This form of construction offers benefits in allowing for construction higher than six floors, reducing waste in the factory and on-site, allowing for quick and simple on-site construction, and can be disassembled and reassembled (Hurmekoski et al. 2015). Its limitations include an increase in transportation costs and a loss of customization (Hurmekoski et al. 2015).

Figure 3.10 Assembly of multi-storey building made of volumes (Courtesy of Derome AB)

Future adaptability is limited, as walls along the perimeter of the volumes will be structural so cannot be easily altered, including window and door openings, and as plumbing comes pre-installed and stacks vertically through the building, bathrooms and kitchens cannot be moved from their original locations (Carlsson, 2020). Finishes, whether internal or external, which have a shorter service life, are easily replaced. As with planar elements, their successful reuse will be dependent on any changes to building regulations and a means of guaranteeing their performance.

3.1.2. Timber construction in selected countries

Timber construction in Sweden

Until last century in Sweden timber was the most used building material, due to the abundance of forest land and therefor the knowledge built about timber construction. The selection of timber for building purposes used to be made with special attention, usually only heartwood was used for the load-bearing parts (Björk et al. 2013). Handcrafted timber was used for log construction until 1920. A strong sawing industry started to develop after 1870 and sawn timber became the dominant building material. From 1920 standard houses started to be developed in cooperation with sawmills. Sweden's effort to find prefabrication methods can be traced back to the 1780s (Waern) and were continuously developed further on (Schauerte 2010), which contributed to the actual situation where 80% of the single-family houses are built off-site. Compared with other countries, Sweden was not affected in the same way by the Second World War during the mid-20th century. This influenced to some extent the evolution of building industry and also of the type of building technology that was used. The traditional timber frame building technology continued to be used for one family houses but for multi-storey residential buildings and for non-residential buildings, concrete became the most used material.

Nowadays 95% of the single-family houses are built in wood and the light-frame system (based on timber studs) continues to be the most used (Figure 3.11).

Figure 3.11 Single-family house "Villa Anneberg", year 2018, one of the case-studies chosen in the project (Photo: Husfoto, via Derome)

Walls consist of plane elements made of vertical studs with insulation material inserted between the studs and usually faced inside with gypsum or wood-based panel materials, and outside with a type of façade covering. The façade covering can be brick, plaster or timber. The level of completion in the factory varies depending on the choice of façade covering, because only timber façades can normally be prefabricated and mounted in the factory. The floor structure is prefabricated in the same way as the walls (Kuzman and Sandberg 2016). A share of 80% of single-family wooden houses is built off-site and the strategy is either manufacturing plane elements in the plant and transporting them to the site for final assembly or, in most of the cases, assembling in the factory in complete volumes and then shipping volumes to the building site. With prefabricated wood modules, the total cost is up to 20-25% lower than to building on-site. This is partly due to a time saving of up to 80% on-site; on-site assembly of the building until the roof is constructed takes 1-2 days. (Kuzman and Sandberg 2016).

Concerning multi-storey houses, three-story houses were the most common type of house, most of them built after 1945. Nowadays the off-site manufacture with light-framing that dominates single-family house construction is also becoming more and more common for multi-storey housing but the CLT construction type is used, see Figure 3.12.

Figure 3.12 Inner harbour in Sundsvall, Sweden, year 2004. Five apartment blocks, from right to left: three blocks with a structural frame made from CLT, and two blocks with a light-frame building system. The wooden façade is of glulam cladding. Photographer: Per Bergkvist (Swedish Wood 2020)

Generally during the 20th century it was not allowed to build multi-storey buildings in timber (as a result of previous fire incidents in the 19th century), but when the country joined the European Union in the beginning of the 1990s, building regulations were changed allowing for significant development of multi-storey timber buildings together with relevant standardisation and regulatory processes, which led to various types of buildings systems. The techniques for building multi-storey timber buildings was also influenced by the research work with mass timber constructions that started in the 90's on cross laminated timber (CLT). The CLT systems developed in Central Europe were used in some cases in combination with glulam structures (Gustafsson, 2019)

After 2015 the development has further accelerated due to environmental considerations and the increased need for affordable new housing. Currently, the use of timber as a construction material in multi-storey buildings has increased from 13% in 2018 to approximately 20% at the end of 2019 (TMF, 2020).

The architectural and engineering construction industry is now planning more higher timber buildings in Sweden (Landel, 2018).

In the northern part of Sweden, the municipality of Skellefteå builds a 19-storey cultural centre with hotel in wood that will be completed by 2021 (Figure 3.13). It is a rare example of modular off-site building using CLT and glulam for the hotel rooms (SVT, 2020).

Figure 3.13 " Sara" Cultural Centre and Hotel in Skellefteå, Sweden will be 80 meters high and have 20 storeys. The total volume of the structure will be 10.000 m^3 CLT and 2200 m^3 glulam delivered by Martinsons. Photo: Jonas Westling (Sara, 2020)

Timber construction in Finland

Until the mid-19th century log houses were the most common residential structures in Finland, when the old wooden towns were present (Figure 3.14). The buildings in these old towns were mostly single storey log huts; two-storey buildings only became common in towns after the middle of the 18th century (Karjalainen & Koiso-Kanttila, 2005). There still are well preserved wooden buildings, for example in Porvoo, Rauma, Kaskinen, and Kristiinankaupunki (Siikanen, 1998).

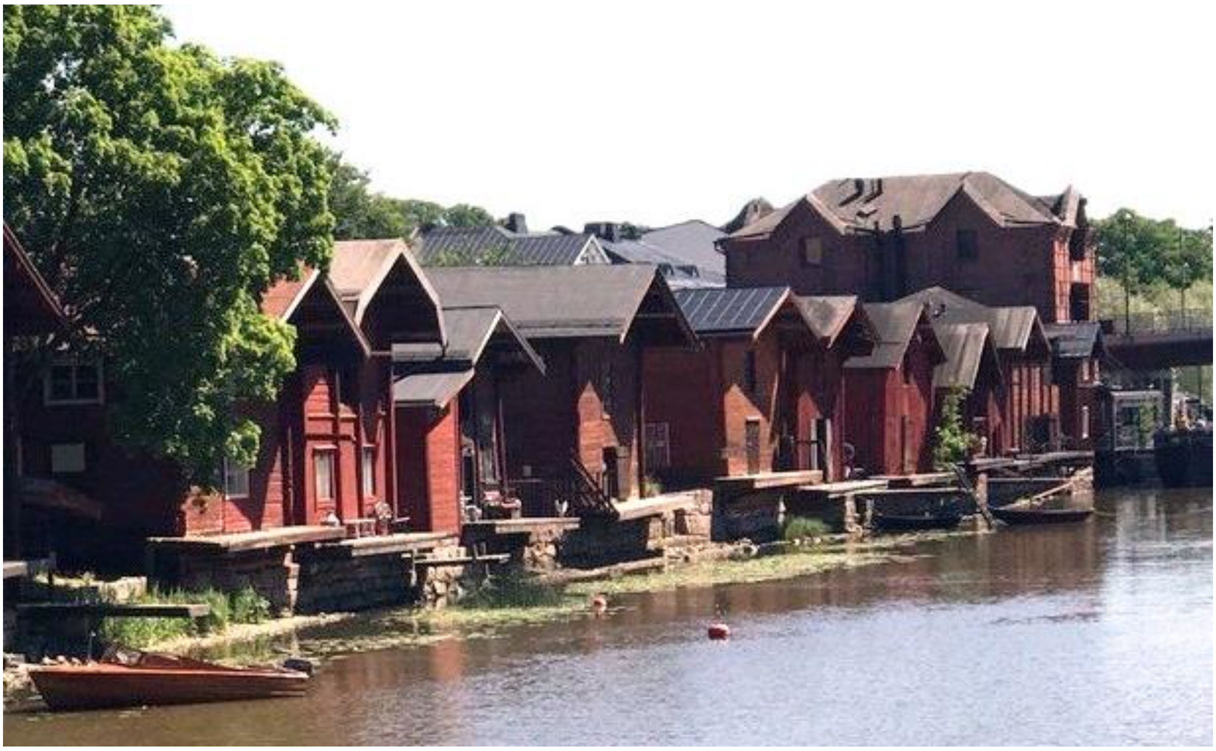


Figure 3.14 The old town of Porvoo, Finland, with well-preserved 18th century wooden buildings. (Photo: Bahareh Nasiri).

Alongside the development of the forest industry in the 19th century, a variety of commercial timber products became available. Simultaneously, there was an increasing demand for accommodation, thus the cost of wood increased. These factors make log houses unaffordable for public as they use large amount of wood for construction (Norri, 1996). Thus, timber building methods moved towards balloon framing techniques, which required less timber, at the beginning of the 20th century (Norri, 1996).

After the Second World War, standardized houses were developed in Finland, with manuals and standardized drawings of wooden single-family houses made available to the public, Figure 3.15. Most of these designs used balloon framing techniques with gable roof framing. They had 1.5 storey height with external board cladding. The main advantage of building standardized light-framed houses compared to on-site balloon framing was that precut components became available as an assembly set and thus the construction became easier and less time intensive.

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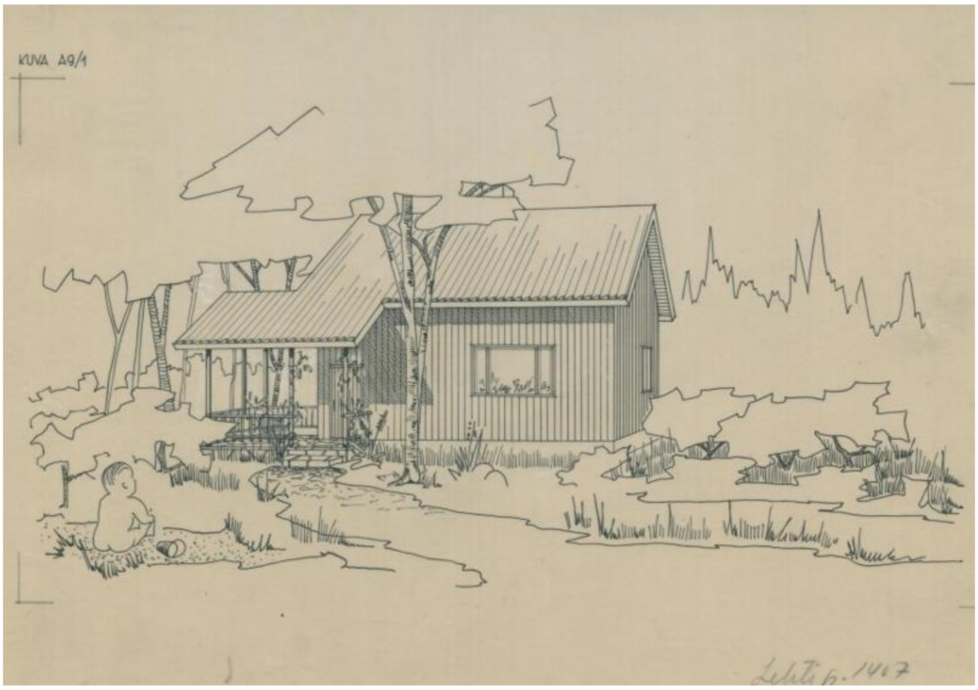


Figure 3.15. Perspective view of a standardized balloon framed timber house in Finland. Type A9, designed in 1952. (Source: Metsätalousministeriö, 2020)

Later on, prefabricated unit techniques were the dominant construction system for 1-2 storey buildings in Finland. Like in the other Nordic countries, prefabrication technique developed from processed component to prefabricated unit and volumes (Schauerte, 2010). The constructors of detached houses started to use prefabricated roof trusses in 1960s. In general prefabricated techniques and light-frame systems have been the most popular way of constructing detached houses but during the last decade that the sale rate of new log houses is a more than twofold of all new prefabricated detached houses (Lakkala, 2020).

Regarding timber multi-story residential buildings (Figure 3.16), the use of wood only began in Finland in the mid-1990s, when Finland's fire code (RakMK E1) was revised in 1997. This fire code allows residential and office buildings to be built in timber up to four storeys. Residential buildings up to eight storeys were allowed when launching a new fire code in 15.4.2011 (Karjalainen, 2018).

Figure 3.16 Residential building in Kuninkaantammi, Helsinki, year 2018. Developer: A-Kruunu OyArchitectural design by ARK-house arkkitehdit Oy, Wood Structural design by Sweco (Photo by Jari Härkönen)

The fire code once again revised in 1.1.2018 (Ministry of the Environment statute 848/2017 concerning building fire safety), permitted the construction of residential buildings, offices, lodging and institutional buildings up to eight storeys. Currently, timber buildings with over eight stories are also possible to be built, but only if the analysis of functional fire design is met. Currently, platform framing is the most popular method in construction of multi-storey wooden residential buildings (with more than three floors) in Finland. Platform framing accounted for 62% of multi-storey timber building in Finland in 2018 (Karjalainen, 2018). The building system usually uses pre-cut and prefabricated planar unit systems. The other type of construction systems such as CLT construction (developed by StoraEnso in Finland), prefabricated volumes technique, and post and beam are less common methods of multy-storey timber construction in Finland.

Timber Construction in the UK and Ireland

Timber is a historic building material in the UK, but the majority of houses have always been built in masonry or brick. The housing stock of pre-1850 buildings contains around 10% timber framed houses, but houses built in the early 20th century rarely use this method (Communities and Local Government, 2008). In the 1960s and 70s, in a time when the aftermath of the war and the clearance of slums led to an explosive demand for housing, pre-cast concrete systems increased in use. Since house building was an industry under high demand at the time, new construction firms emerged, and 500 new building systems were registered between 1919 and 1976 (Hashemi 2013). But not all of these companies held enough expertise and not all these systems were ripe for the market so that many houses built during that period lacked in quality and prefabricated materials lost their appeal in the 1970s. Since the demise of pre-cast concrete, timber frame and traditional masonry construction are the main construction methods again.

Currently timber platform frame construction is the most common structural timber use in the UK. In Scotland 81% of new houses use timber frame construction while in England, Wales and Northern Ireland the majority of houses is still constructed using masonry. Overall, around 25% of new domestic houses are built in timber frame. Prefabricated panels (Figure 3.17) and volumetric elements are gaining popularity in the UK construction sector, but to date only 11% of new single-family homes are manufactured off-site (de Laubier et al. 2019). In comparison to mainland Europe, the degree of prefabrication of off-site elements is usually small, since mostly open 2D panels are used and volumetric elements are still regarded a novelty in the UK (Duncheva and Weir, 2019).

Figure 3.17 Modern timber house construction in Scotland, year 2005, light-frame and prefabricated panels (Photo: D. Ridley-Ellis)

Commonly used materials in these panels are softwood timber studs and OSB or chipboard sheathing. A large share of the timber used in construction is imported from Europe (85%), while 50% of particleboard is imported with the remainder produced locally (Egan, 2016). CLT on the other hand is not currently manufactured in the UK, and this could be one factor that has contributed to a relatively slow uptake of mass timber systems in the UK from the mid-2000s. In the recent years the market growth of CLT is more rapid. The government encourages the use of modern methods of construction, since the productivity of the UK construction sector needs to improve in order to meet the housing target of 300k new homes per year (Farmer, 2016, Department for Communities and Local Government, 2017). Only 214k homes have been built in 2017 (NHBC, 2018) and the aforementioned reports suggest that the only way to reach the target is the enhanced use of off-site construction. On the other hand, timber is not specifically targeted as a building material and increasingly sharp fire regulations inhibit the use of combustible materials in buildings with six or more storeys, which especially slows down the uptake of CLT in high rise buildings (Ministry of Housing, Communities and Local Government, 2018).

As with the UK, the principle residential construction in Ireland has been load-bearing masonry or brick, with timber use restricted to spanning elements in the flooring and roofing (Figure 3.18 and Figure 3.19). In the 20th century, the predominant construction method in Ireland involved external masonry load-bearing walls on concrete foundations. The ground floor was constructed as either a concrete ground bearing slab or suspended timber joist floor while intermediate floors and ceilings generally made use of solid timber joists and timber cut trussed roof structures.

Figure 3.18 Conventional one-storey Irish Bungalow (Photo: SJ Walsh)

Figure 3.19 Conventional mid-20th century load-bearing masonry house in Ireland (Photo: SJ Walsh)

Prior to 1990, less than 1% of annual residential construction was undertaken using timber frame. However, by 2002, timber frame housing accounted for approximately 15% of the annual Irish housing output (TFHC, 2002). This increased to almost 25% by 2004. In 2019, 5500 houses were built using timber frames (ITFMA, 2020a), which represented 27% of new houses in Ireland that year (CSO, 2020).

Domestic modern timber construction is predominantly undertaken using platform frame prefabricated panel construction with the systems available categorised as open panel, pre-insulated, hybrid or closed panel (ITFMA, 2020b). Historically, floor framing has commonly been in solid timber joists but increasingly engineered timber components such as I-joists and metal web joists are used, with an expected increase of these engineered products in timber frame construction in the future (Robinson, 2007).

While CLT has become more common in the UK, where 600 buildings had been built by 2017 (Harte, 2017), this form of construction in Ireland is rare. Some use has been made in bespoke single-family housing, as well as two recently completed commercial buildings in Dublin, with further plans for a 7-storey hotel in the near future (Harte, 2017). The use of CLT in construction may increase as with the construction industry adapts to this new technology, but for the moment most developments use concrete frame.

Timber construction in Spain

Timber was one of the most used construction materials until the first half of the 20th century in Spain. After this, other materials gained prominence and were widely used in new constructions such as brick, concrete and steel. Currently timber is regaining its former importance due to society's growing consciousness around the environment, the need to consume less resources, and timber's potential to be reused.

In Spain, until the 20th century, almost every dwelling building had at least part of its structure made of timber; mainly the horizontal structures. The vertical structure was usually either bricked or timber-laced with masonry, rubble or adobe filling. In the aftermath of the Spanish Civil War (1936-1939), the materials used were brick, concrete and steel; timber was not used in the cities. In the countryside it was still used, but not to the degree it had been used before.

In Spain, the main timber constructive system is heavy timber frame and the most used wood product is large-section timber (either massive or timber-based – glulam or CLT). Although there is demand for timber-derived structural products, such as glulam and CLT, large-section timber is and was the most used product. The typologies may have evolved, but the product is approximately the same, and that is why in Spain, it is quite easy to imagine a market for reused timber from existing buildings. In the recent years, the market of timber-based products such as CLT has grown, developing new constructive systems and adapting to situations typically solved with more traditional solutions.

In contrast to other countries, housing construction in Spain are mainly collective, especially in the cities. Midrise constructions (3+ storeys) are the most common in the centre of the cities but are also present in almost any urban area alongside the country, so significant quantities of timber may be recovered or reused from those buildings.

In some traditional typologies, like the one that is proposed for this project, recycled or reused timber is already in place. Those 200-year-old buildings already used recycled material such as masonry debris or even reused timber because they were originally cheap housing (cheap houses because of the small apartments, shared facilities and low-quality materials) of quick construction.

Spanish laws do not yet encourage the use of timber over other construction materials even though it is very present in Spanish heritage and in pre-modern constructions. Although in recent years, timber has been gaining presence in the Spanish paradigm, presenting itself as a less polluting material, and interesting solutions have emerged.

Heavy timber frame systems, as the ones mostly used in Spain, consist of timber-made vertical and horizontal structures. In the vertical structure, the rigidity is obtained by filling the in-between spaces of the timber columns (structural components of the supporting walls) with either masonry, adobe or wattle-and-daub; that makes the walls work as shear walls (Figure 3.20).

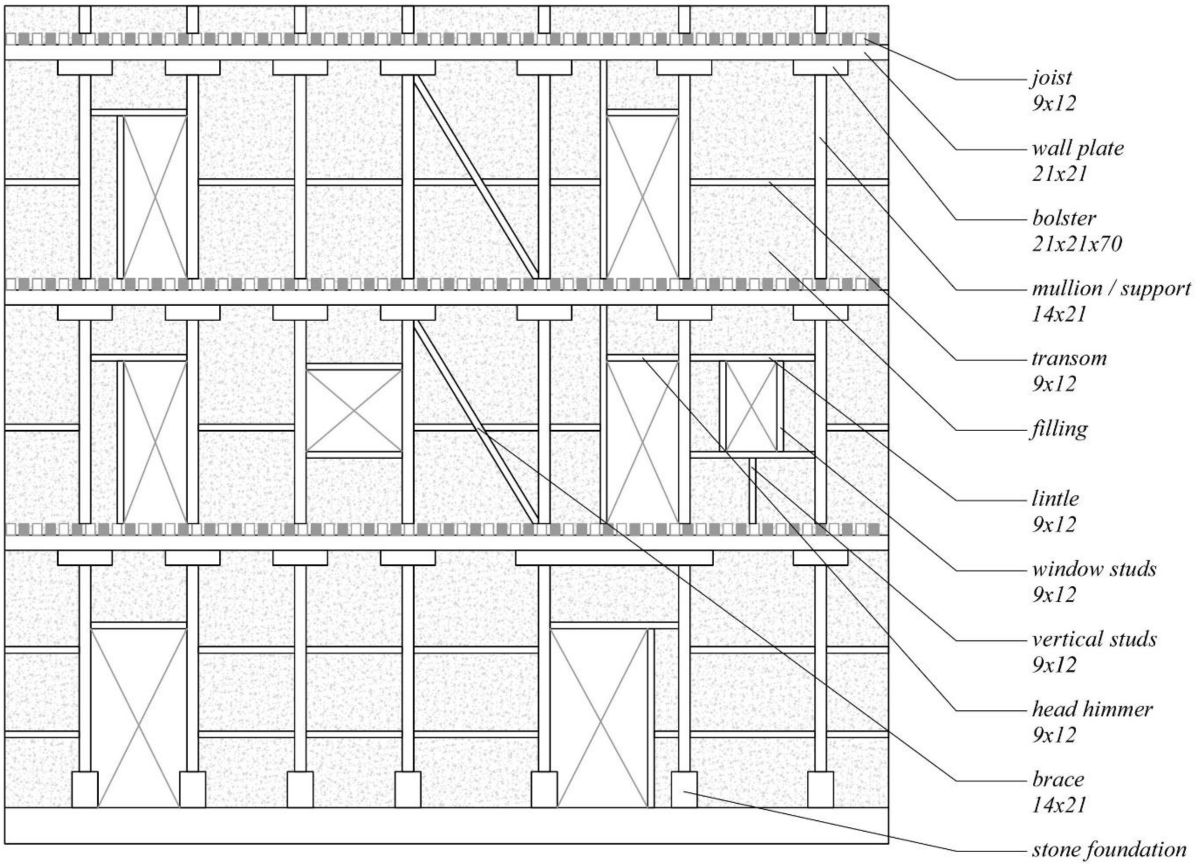


Figure 3.20 Wall construction of a typical Corrala house type (Drawing: M. de Arana Fernández)

As It has been mentioned, in premodern constructions (until the first decades of the 20th century) the most used constructive system was heavy timber-frame with large-section of sawn timber as main material. It is interesting to point out that in the pre-modern era (considered before the appearance of steel and concrete as construction materials), the joints were solved with mortise and tenon joinery, in contrast with the present constructive system with joinery usually solved by steel connectors.

The horizontal rigidity of the structure is generally obtained using the traditional wooden planking or using a massive masonry filling intertwined with the beams. The usage of timber wooden planking is not present in the traditional Spanish architecture as a structural component.

From the point of view of resource utilisation and optimisation, the traditional system is as easy to be built as it is to be demolished or deconstructed. It is only one step away from allowing an easy, fast and cheap assembly/disassembly methodology.

Ideally, timber construction in Spain should follow this path and promote easy-to- deconstruct systems. Using two-dimensional and pre-fabricated rigid elements, like walls or floor slabs, combined with the main linear structural timber elements (beams and columns), allow the elimination of complex knots and joinery. The use of two-dimensional rigid elements, like floor slabs and walls, that will be used as architectural divisions, is the most efficient way to solve timber structures.

These rigid elements (walls and slabs) combined, create three-dimensional structures adaptable to almost any building. These elements would consist of large-format timber-derived products like CLT, LVL, Wooden Sandwich Panels (WSP), or timber-framed panels.

Timber construction in Germany

For a long time, wood was the most important building material in Germany. At the beginning, log and stilt houses were common construction types in Germany. While log houses were common in areas with a large wood supply, stilt houses were typical for areas with a smaller availability of wood, as they require less material (Krötsch, 2020).

Wood building construction reached its height in Germany throughout the 16th and 17th centuries with half-timber houses, as in Figure 3.21.

Figure 3.21 Half-timber house in Eichstätt, south Germany (photo: R Ivanica)

Their characteristic wood frame structure and the frames filled with plastered masonry or wood mesh can be considered as the first wood frame construction with a high extent of prefabrication (Dederich, 2013). The carpenter work was done in advance in the workshop: detailed planning and designing the building, cutting the pieces and joints. The final assembly was conducted on site but required less qualified workers as the major and complex work had already been done. Some of these buildings still exist today. But more importantly, during this time, a fundamental knowledge of wood construction and structural wood protection developed, which is still applied in today's modern wood construction.

With the beginning of the industrialization in the 19th century, wood was replaced with masonry, especially in urban areas. However, as wood was the only material available that comes in long dimensions, it remained relevant for the construction of roofs and floors with larger spans. This ended with the development of reinforced concrete, which finally replaced wood as a structural material in buildings. Until the middle of the 20th century, brick, masonry and concrete have been the most important materials for building construction in Germany, despite the development of new wood building products like glulam around 1900. Nevertheless, a rising environmental awareness in consequence of the oil crisis meant that wood received new attention in the building sector as a renewable, resource and energy efficient material (Krötsch, 2020).

Since the middle of the 20th century, new wood-based building products were developed or introduced to Germany, such as Oriented Strand Board (OSB), as well as new construction, fastening and connecting technologies. During this time, traditional timber frame construction was further optimized and combined with the possibilities of a prefabrication (wood panel construction). The possibilities of the prefabrication, along with the renewability and energy efficiency of wood buildings, were the main drivers of the increasing use of wood in building construction, in particular in detached houses. The development of long-span glulam beams facilitated wood utilization in non-residential buildings like sports halls, event rooms or production facilities (Krötsch, 2020). As a result, about 18,7 % of the new residential buildings in Germany are made from wood today (2019), with the highest proportion among the one- and two-family houses, as well as small multi-residential projects (Figure 3.22). A similar share is reported for non-residential buildings (17.8 %) (Holzbau Deutschland, 2020), one such example is presented in Figure 3.22.

Since the introduction of mass-timber products like CLT in the 1990s, new opportunities in the construction of multi-residential apartment buildings in dense urban areas evolved. Thus, across Germany, several of such buildings were erected in the last 20 years reaching up to 12 stories (Krötsch, 2020).

Figure 3.22 Modern timber frame building (2019) in the newly developed residential area "Prinz-Eugen-Park" in Munich (Photo: Ralf Rosin, TUM)

Despite the construction of much higher wood buildings globally, German legislation stills limits the construction of higher CLT buildings. For this reason, hybrid buildings from wood and concrete are quite common. The combination of the strengths of each material allows a functional, structural and economic optimization of modern buildings, which still meet the required regulations. With the increasing urbanization in Germany, timber frame constructions are highly relevant for building additions and roof extensions, due to the combination of lightweight and high mechanical properties (Cheret and Seidel, 2013). Driven by the ongoing change towards hardwood species in forest management to adapt to climate change, building products like CLT and glulam from hardwoods are under further investigation. Due to the challenges of hardwood processing and gluing, only a few hardwood products are commercially available for building construction, such as laminated veneer lumber from beech.

Timber construction in Slovenia

Slovenia has always been very forest rich country. Currently, the forests cover an area of 1.2 million hectares or almost 60 % of the entire country and rising (Kuzman, 2010). Due to availability of timber, building with wood has a long tradition in Slovenia. (Figure 3.23).

Figure 3.23 Old traditional wooden hut with shingles made of larch, in Kranjska Gora (Photo: Žiga Krofl)

Most of the residential buildings up to the modern times were constructed with masonry walls using wooden flooring and roofing. With the advent of concrete, the wooden flooring was replaced by concrete slabs.

In the 1960's the wood industry started producing prefabricated modules, at first smaller wall panels, used for building single family housing, schools and kindergartens. A considerable amount of production was exported.

Today, the majority of the residential buildings in Slovenia are single family dwellings, most of them built in reinforced masonry and concrete, but a steadily increasing percentage of the new buildings are constructed out of wood, an example in Figure 3.24 – currently 10 % (Kuzman, 2012; Obućina et al. 2017; Štravs, 2020;). Roof load bearing structures on the other hand are traditionally almost entirely made out of massive timber and are usually replaced every 30 – 50 years. Rough estimation gives 30.000 m^3 of timber per year from roof replacement alone. A lot of halls in Slovenia (sports, indoor swimming pools and warehouses) have large span roofs made out of laminated timber.

Figure 3.24 Solid timber house for a family of five, year 2017, in Savinjska. Photo: Lesoteka hiše d.o.o.

The wooden housing stock is largely prefabricated, but a non-negligible part is made by small contractors, as they are contracted for higher added value architecture with wood as a green building material (Kuzman, 2012). According to a recent study, almost 40 % of respondents in Slovenia would choose wood as the construction material (Kuzman, 2012). Slovenian government is also using Green public procurement to increase the use of eco-friendly materials and procedures. On the use of wood in buildings, it is generally required that 30 % of in-built material (by volume) must be timber or timber-based (50% can be substituted by products with EcoLabels I or III). Furthermore, an award criterion gives additional credit if the 30 % minimum threshold for in-built material is exceeded. (Obućina et al. 2017)

An overview over the latest trends regarding buildings systems used in timber construction in the countries participating in this project is presented in Table 3.2:

Table 3.2 Trends in timber construction and building systems in selected countries.

Country	Building systems
Finland	It is planned that 31% of public buildings should be built in timber by 2022 and the number will increase to 45% in 2025 (Ymparisto, 2020). The proportion of prefabricated timber buildings has slightly increased in the past years, reaching up to 45% off all timber buildings (Heino 2020). On average, timber represents 35% of vertical supporting structures of buildings which are built in the current decade (OSF, 2017).
Ireland	There are currently about 5,500 light timber-frame units constructed annually, mostly single family detached or semi-detached two-storey houses, manufactured off-site. The number of post and beam and mass timber buildings is very small.

Germany	The share of residential timber buildings increased reaching up to 18,7% of all buildings in 2019. The share of non-residential buildings was situated at around 19,5% in 2019. Most of the constructions are built offsite. (Holzbau Deutschland, 2020)
Slovenia	Masonry and concrete dominate generally but steadily increasing percentage of the new buildings are constructed out of wood – currently at 10 %. Roof load bearing structures on the other hand are traditionally almost entirely made out of massive timber and are usually replaced every 30 – 50 years. Rough estimation gives 30.000 m³ of timber per year from roof replacement alone. The wooden housing stock is largely prefabricated (2d panels), but a non-negligible part is made by small contractors.
Spain	Timber is not often used as structure material of multi-story apartment blocks (which is the main type of construction). It is estimated that 300 family houses per year (light timber-frame and CLT), and 400 multi-story buildings per year (from 2 to 6 stories, in CLT) are build, paid and owned by the public sector.
Sweden	Approximately 10 000 single family houses are built every year and 95 % of those are built in wood: 80 % of is prefabricated (off-site) in 2D cassettes or 3D volumes while 15 % of the total is built on-site out of precut timber. Approximately 45 000 apartments in multi-storey houses are built every year and 5 000 of these are built in wood. These are mostly prefabricated in 3D volumes (framing system) but there is an increasing number of houses built with CLT and glulam (post and beam system). Buildings made from 3D modules for pre-schools, schools are sometimes leased for 5 to 10 years and then modules are rearranged according to the needs or moved to another site.
United Kingdom	Timber frame construction makes about 25% of newbuilt dwellings (NHBC 2016), with 83% in Scotland and only 23% in England (Structural Timber Association 2016), where most houses are built. The popularity of timber frame tends to grow (NHBC 2016). Offsite construction is also gaining popularity, reaching a 26% growth between 2014 and 2017 (Pbctoday 2018). It can be estimated that 7-12% of all new dwellings are constructed offsite (Future Focus) and that is mostly light timber frame, but also light steel and precast concrete (Research and Markets 2012). Out of the platform-frame built houses 78% are using 2D open panels, 14% 2D closed panels and 8% volumetric units (Timber Offsite Construction Exhibition 2019-2020). Since 2013 the industry has seen steady growth, mostly due to the recovery in the housebuilding, commercial and education sectors. While timber frame is the most widely used type of offsite system in both the social and private housebuilding sectors, over the next few years, it is expected to face stiff competition from cross laminated timber. (AMA, 2020)

3.2. Novel design concepts with respect to deconstruction and reuse

3.2.1. Design for Deconstruction and Reuse

Sustainability in construction became a serious concern during the 1990s. A conceptual model for sustainable construction was suggested by Kibert (1994) based on the triplet of so-called *principles*, *resources* and *time*. These could be seen as representing the axes of a 3-dimensional space in which a specific combination of a principle, resource and time (i.e. a point in the space, see Figure 3.25) forms the basis for decisions regarding sustainability, i.e. minimizing resource consumption and preventing environmental damage.

The principles of sustainable construction include the following strategies, based on Kibert (1994), later modified by Crowther (2005):

1) Minimize resource consumption (Conserve)
2) Maximize resource reuse (Reuse)
3) Use renewable or recyclable resources (Renew/Recycle)
4) Protect the natural environment (Protect Nature)
5) Create a healthy, non-toxic environment (Non-Toxics)
6) Pursue quality in creating the built environment (Quality)

In the above context, resources relate to those finite resources typical for the construction industry:

1) Energy consumption
2) Water use
3) Materials
4) Land use

There are obviously other resources that are important, but these ones seem to be most important when considering the protection of resources for future generations.

To represent the time aspects in construction one could think of different phases of a construction project and the lifetime of a building. Thus, the labels on the time axis, according to Kibert, could be:

1) Development
2) Planning
3) Design
4) Construction
5) Operation
6) Deconstruction

An important aspect of sustainability in the construction industry, in addition to reducing the consumption of resources, is to reuse resources that have already been extracted and used for construction or in other industries. In contrast to recycling, reuse typically refers to repeated using of practically intact items with minimal reprocessing whereas recycled items are reprocessed in completely new products.

In order to facilitate an increased reuse of construction products, the design of buildings needs to be carried out with this objective in mind. This design philosophy is often termed as design for deconstruction or disassembly and abbreviated as DfD. In this report we will use the term **Design for Deconstruction and Reuse (DfDR**). According to Moffatt and Russel (2001) DfDR refers to the design of the building so that the parts are easily dismantled and separated from each other for reuse or recycling. This includes: how building parts can be repaired or dismantled without breaking them; and how the remaining lifetime of the dismantled parts can be utilized in new applications. The primary goal is to reuse the dismantled components: either reusing for the original purpose or for other purposes; whereas the secondary goal is to recycle. DfDR is an integral aspect of cascading, it's the 'doing things right' at each level which prolongs the value and use of the resource.

Some authors, e.g. Long (2014), make a distinction between Design for Deconstruction and Design for Disassembly: with the former including the direct reuse or relocation of building recycling of existing building materials into new materials or components. Long views Design for Disassembly the lesser environmentally friendly approach as, with allowing for recycling, it preserves a lesser amount of embodied energy and requires additional energy to produce new materials.

Using the aforementioned sustainability model by Kibert (1994), Crowther (2005) illustrates the place of DfDR (Figure 3.25) and suggests that the model may help designers in understanding of how they can design better for disassembly via highlighting potential relationships with other environmental issues and strategies. This quite abstract model, however, does not answer practical questions concerning DfDR. Therefore, the author derives a number of design principles by studying historic examples of buildings that have been dismantled. More details on these principles is to be found in Section 4.

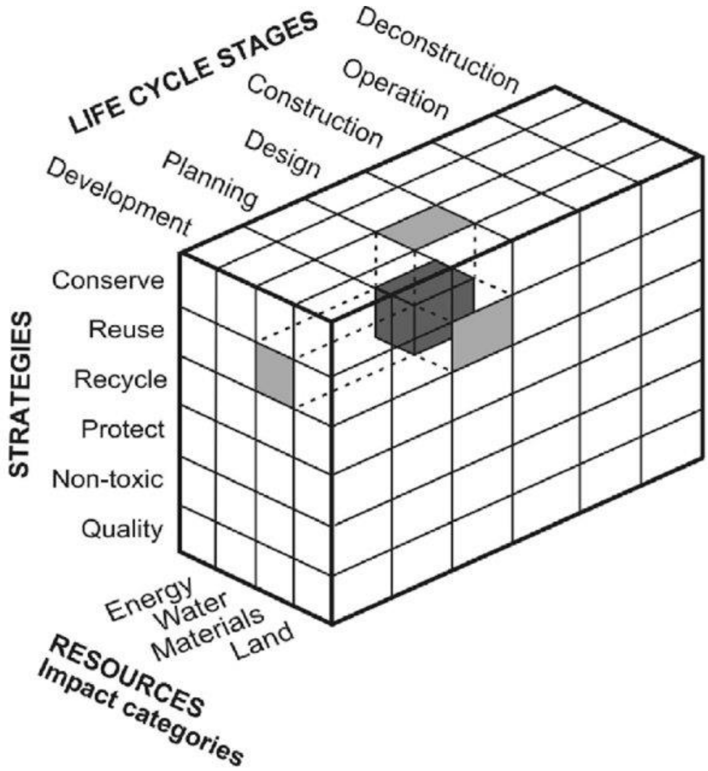


Figure 3.25 Areas of concern to DfDR Crowther (2005) a modified representation of a model for sustainable construction based on Kibert (1994)

Although not easy to represent in a drawing, the model could be extended to add additional aspects to it. For example, it could be interesting to know which actors have influence on the decisions at each stage of the process. When thinking about DfDR, they are likely the architect and the structural engineer, but they need to interact with other stakeholders, so could extend to contractors, developers, building authorities and clients.

3.2.2. Scale in design for deconstruction and reuse

In general, the more of a building that could be reused, the higher is the environmental gain, i.e. less waste will be produced, and less energy will be consumed.

In the Finnish project ReUSE (2015), Hradil (2014) looked at different building materials, including timber (focus on the mass timber construction type). Hradil notes that there is a large variety of building elements that are part of load-carrying structure and can be re-used. Some of them are successfully salvaged from the construction and demolition waste, some are even re-used without becoming a waste. They can be divided according to their size and complexity into the following five categories:

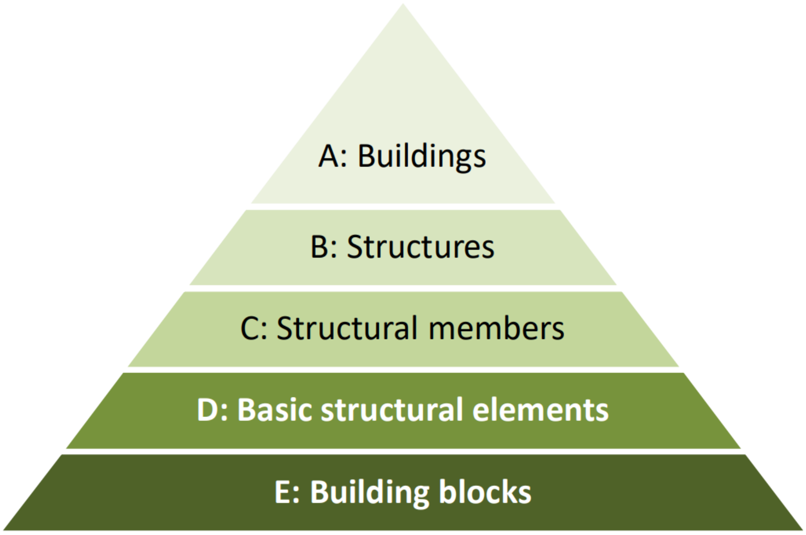


Figure 3.26 Hierarchy of building components considering reuse (Hradil 2014)

He summarizes the definition of building element in Table 3.3 which provides the indication about the most important criteria in the decision about the element category.

In the case of mass timber, the building components are (Hradil et al. 2014a):
A: modular houses, sports halls, bridges, towers
B: glulam frames, roof trusses
C: sandwich panels, curved glulam beams, ceiling joists
D: straight solid or glulam beams, wood-based panels
E: boards

Table 3.3 Re-usable structural element categories (Hradil 2014)

Elements in the category …	A	B	C	D	E
… resist all structural loads and transfer them to the foundations.	x				
… have a single defined purpose.	x	x			
… have a defined size (usually including connection points).	x	x	x		
… resist some loads (excluding small loads e.g. on cladding).	x	x	x	x	
… are part of a larger system.		x	x	x	x
… can be used for more than one purpose.			x	x	x
… allow for the easy (on-site) modification of their size.				x	x
… need to be joined together to form a load-bearing part.					x

"Building elements of higher category can be often separated into several elements of lower category. Even though the higher category elements have typically higher value than their parts together, the separation would make sense, because it may be more difficult to find a suitable application of higher category elements. The re-using complexity depends on many factors. Handling of heavy parts may be difficult; architects may require modification of the element; structural part has to be cleaned or separated from the other materials or it has to be disassembled and assembled again; the structural design has to be provided again; the element may be used in other application than in the previous building; the quality and geometry has to be re-evaluated because of the missing documentation (especially for smaller elements reclaimed from waste).” (Hradil 2014)

Hradil’s study confirms that time is a key parameter in the entire process of designing, building, deconstruction and reusing constructions because time is often translated in effort labour costs as well as environmental. Time is determinant in the decision process of changing from a linear to a circular flow in the building industry chain. A successful DfDR contributes to saving the time needed for the decision making, for selections (including assessing in which of the different categories an structural elements can belong, such as the ones in Table 3.3) , but also to the time invested in the work of disassembly, followed by finding the most appropriate reuse and finally accomplishing the reconstruction, the reuse.

The obstacles and possibilities that will occur in design for deconstruction and reuse (DfDR) will depend on what we can refer to here as “scale” of the element. It will depend on which building system that is used and of the aim of the process, i.e. how large units are considered for reuse (Figure 3.27). For example, there will be different issues to address if one is to design a volume system for *deconstruction and reuse of its entire volumes* or *deconstruction and reuse of its planar subcomponents*. Furthermore, there will be different problems to solve depending on whether the planar units are built up by studs and chipboards or by CLT elements. The issues will also be different for a building system with an onsite stick frame structure where the aim is to retrieve and reuse the separate studs. Joint types, equipment needed for deconstruction, transportation possibilities, labour costs and so on all depend on the scale/type of building and aim of deconstruction, perceived quality and resale value of the salvaged elements, whether planar, modular, or elements, will influence the motivation for disassembly, as it has been noted that due to their inherent quality and ease of disassembly slates and bricks are commonly reused.

It can be concluded that DfDR needs not only to be adapted to timber as a building material, but also to different types of constructions (as presented in Table 3.1).

Figure 3.27 presents the different levels of how a building can be assembled and disassembled. Level 3 shows a building with a structure built up by volume components. This can be designed for deconstruction and reuse of its separate volumes or for deconstruction and reuse of wall and floor elements and so on. Level 2 represents a building with a structure built up by planar components and the various options in that regard. Level 1 follows the same principles as the ones for traditional light-frame stick building. For post and beam systems the variations are more limited, often involving engineered timber elements, occasionally of a special shape such as portal frames used in halls for sport, industrial or commercial purposes.

There are reasons for aiming at retrieving larger components. Each deconstruction step - as it involves more time, labour and equipment - necessarily adds to the costs and emission of global warming gases so that one has an interest in maintaining jointed parts. Chisholm (2012) makes the argument that, as reclaimed materials lack structural guarantees or warranty they are rarely reused, then "…in the contemporary world, DfDR emphasis must be attuned to modular, component deconstruction – i.e. of wall, floor and roof cassettes – as opposed to individual member construction" as these modular components may find more favour in reuse. In Figure 3.23, arrows mark deconstruction steps to focus on if such an approach is adopted.

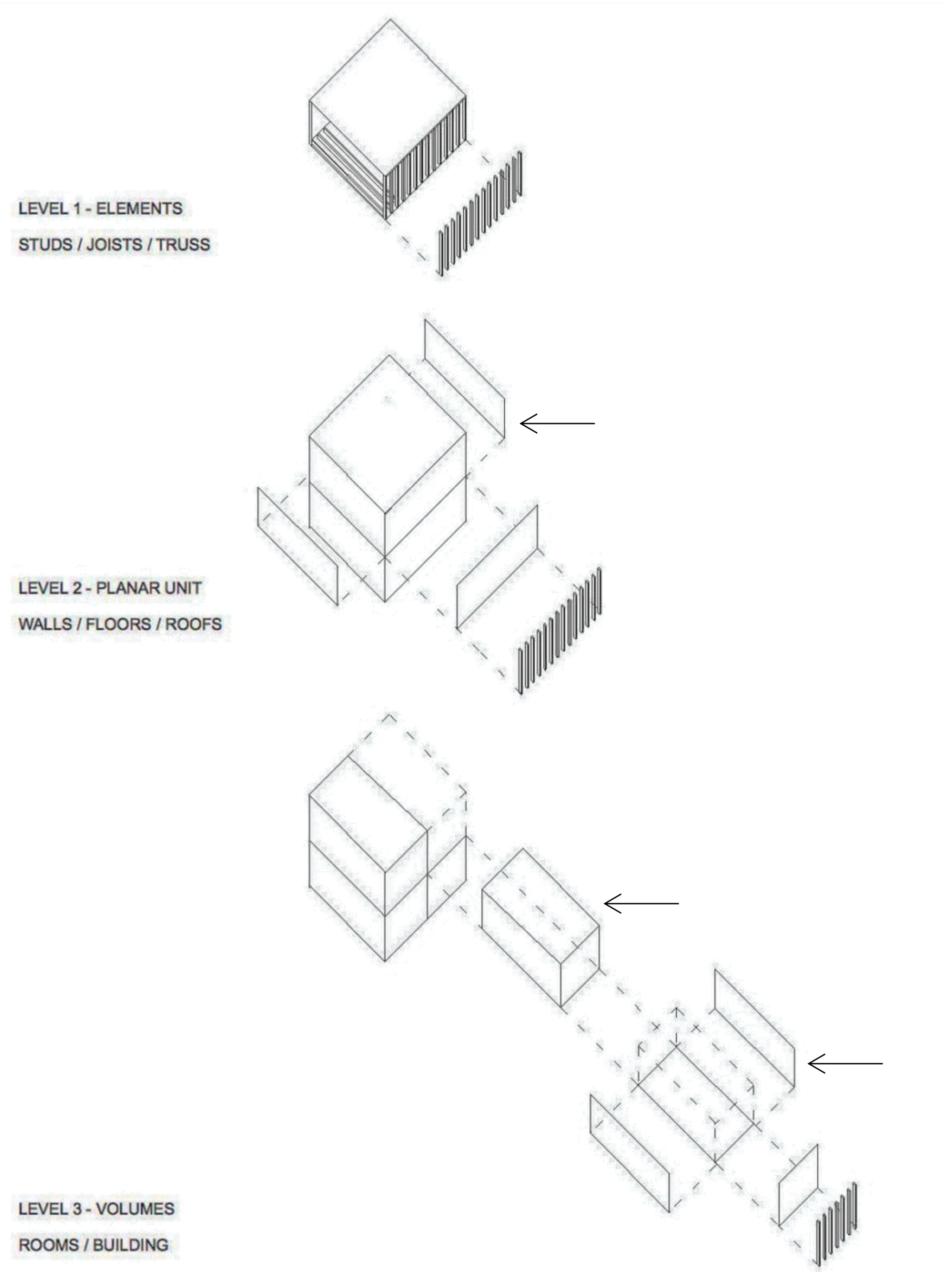


Figure 3.27 Design for deconstruction and reuse issues will depend on scale. The scale is affected both by the type of building system used (vertical) and by the type of components that are to be deconstructed and reused (horizontal). (Drawing: SJ Walsh after an idea by Y Sandin).

However, as noted in an interview with the Derome Group, planar and volume elements will also require a system of certification for reuse, and their successful reuse in the future is dependent on whether the assemblies still meet future building regulations (Carlsson, 2020). Nevertheless, there is a perception by manufacturers that planar and volume elements may have more significant economic value than their separate parts, which deserves more study.

As planar elements are constructed using light-timber framing, future alterations such as adding or changing window openings is easily achieved (Carlsson, 2020). In terms of deconstruction, Carlsson noted that the units are secured in place with screws, which can be difficult to locate, so they could generally be marked with colours to make them more visually apparent. The reuse of salvaged planar elements will face two issues in the future: whether they still comply with regulations that may have changed in the intervening years and, similar to salvaged timber, there will be a need to test or otherwise guarantee the performance of salvaged panels (Carlsson, 2020).

3.2.3. Changes in buildings. The role of structure

The InFutURe Wood project would focus on structural use of wood: reusing today reclaimed structural components in structural purposes and designing structures that can be used in the same purpose. A way to visualise the differences between structure and the other components is by looking at a building as several layers.

In his book "How buildings learn: What happens after they're built" (Brand, 1995) Brand discusses the fact that different parts of buildings change at different rates. The author quotes architect Frank Duffy who summarized his view on buildings as a set of components that evolve in different timescales: "Our basic argument is that there isn't any such thing as a building. A building properly conceived is several layers of longevity of built components. The unity of analysis for us isn't the building, it's the use of the building through time. Time is the essence of the real design problem".

Brand expanded Duffy's building layer distinction (that was referring to office buildings) into a general purpose one, slightly revised, as shown in Table 3.4:

Table 3.4 Shearing layers of change (Brand, 1995)

Part/level	***Time frame***	***Description***
Site	Fixed	This is the geographical setting, location, and the legally defined lot, whose boundaries and context outlast generations of ephemeral buildings.
Structure	30-300 years	The foundation and load-bearing elements are perilous and expensive to change, so people don't. These *are* the building. Structural life ranges from 30 to 300 years (but few buildings make it past 60, for other reasons).

Skin	20-30 years	Exterior surfaces now change every 20 years or so, to keep up with fashion, technology, or for wholesale repair. Recent focus on energy costs has led to reengineered Skins that are air-tight and better insulated.
Services	20-30 years	These are the working guts of a building: communications wiring, electrical wiring, plumbing, sprinkler system, HVAC (heating ventilating, and air conditioning). Buildings are demolished early if their outdated systems are too embedded to replace easily.
Space plan	3-30 years	The interior layout – where walls, ceilings, floors, and doors go. Turbulent commercial spaces can change every 3 years or so; exceptionally quiet homes might wait 20-30 years.
Stuff	Continual	Chairs, desks, phones, pictures; kitchen appliances, lamps, hairbrushes; all the things that twitch around daily to monthly. Furniture is called *mobilia* in Italian for good reason.

Brand looks at how layering defines how building relates to people: "Organizational levels of responsibility match the pace levels. The building interacts within individuals at level of **Stuff**; with the tenant organization or family at the **Space** Plan level; with the Landlord via the **Services** (and slower levels) which must be maintained; with the public via the **Skin** and entry; and with the whole community through city or county decisions about the footprint and volume of the **Structure** and restrictions on the **Site**"

This idea was further developed by Rodden and Badford (2003) who looked at the stakeholders and representations involved in building changes as well as the time to make change. They considered that for Structure this would take from weeks up to months (Table 3.5).

Table 3.5 Time to make building changes (Rodden and Badford 2003)

Part/level	***Time to make change***
Site	Months to years
Structure	Weeks to Months
Skin	Weeks to Months
Services	Days
Space plan	Hours
Stuff	Minutes to Hours

In 1995 (Table 3.4) it was considered that "structures do not change" but in 2020 the perception changed significantly; designing buildings with structures to be changed, to be reused will probably affect the time needed to make changes, it will shorten it compared to 2003 (Table 3.5).

3.2.4. Examples of wooden buildings with DfDR design philosophy

There has been an increased interest in buildings that were planned to be reused. Some examples include:

Techbuilt House 1950
Architect – Albert Carl Koch

Intended as a 1 to 1.5 storey house, the Techbuilt prefabricated housing system (Figure 3.28) was developed in the US in mid 1950s (Johnson et. al, 2020). A modular house system, using standardised 1.2m wide panels of varying lengths to allow for user adaption but typically forming a rectangular floor plan.

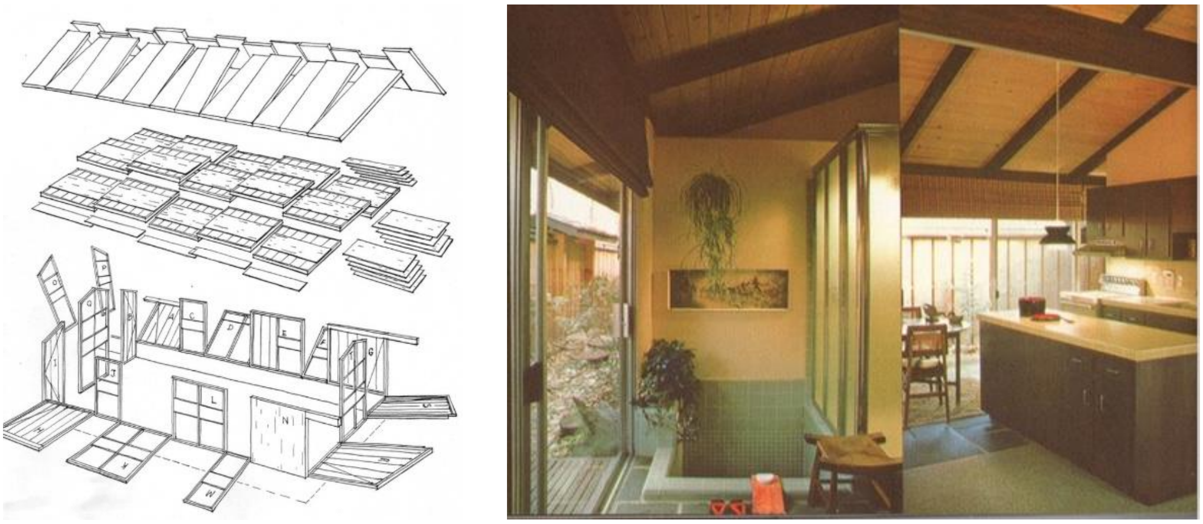


Figure 3.28 Techbuilt diagram (1954) and interior photos of custom Shikoku Techbuilt house, Johnson et.al, 2020 (Shikoku images are from a Techbuilt catalogue, circa 1973, from the collection of Jeff Adkisson, see https://thetechbuilthouse.com/)

The system specifically allowed for dismantling and reassembly on a different site. According to Johnson 2020 the Techbuilt system was marketed as a contemporary solution to housing, carefully designed to limit material use, construction time, labour and cost.

Brummen Town Hall (The Netherlands, 2011-2013)
Architects – RAU; Construction company BAM; Circularity advisor: Turntoo

It is an extension in the form of a temporary office building that was built to last for a period of at least 20 years (Figure 3.29). It is a design for disassembly, flexibility, reassembly and reuse. A flexible system for the interior walls makes it possible to modify the floorplan during the usage period. In the end, more than 90 percent of the design was delivered dismountable according to Rau (2019). The wooden components (supporting structure, façade and floors) were prefabricated.

To improve reuse the following action were taken:

- Materials were not glued together, but instead mechanical joints were used so that parts could be taken apart without demolishing the building. "Wood is a perfect material for this, concrete would have been more difficult." (Salonen and Vangsbo 2019)
- Wooden beams were made thicker than necessary, which gave the supplier more flexibility for the next use-cycle and according to the company 20% higher residual value

Figure 3.29 Brummen Town Hall, the Netherlands. Wooden structure planned for reuse (courtesy of Petra Applhof)

The Dutch company Turntoo had an alternative business model based on retaining its products throughout the life-cycle rather than selling them to consumers. The Turntoo model fits into the broader trend of extended producer responsibility, which integrate services into a product offering. With the launch of the new town hall in Brummen, Turntoo delivered a building conceived as a raw materials 'depot'. The building is a temporary arrangement of construction materials, of which all details are known including their destination in a subsequent second use phase or ‘second life’(material pass). In its request for proposals, Brummen municipality only asked for “a temporary office for a period of 20 years”. A Turntoo building turned out to be the answer: a design made for disassembly, consistent use of reusable and renewable high-quality construction materials, and a contractual approach that guarantees circularity at the end of the intended use period. (Geet et al. 2015)

Bullit Center (Seattle, USA, 2011-2013)

In 2011 Seattle set a citywide goal of recycling 70 percent of its waste by 2025. A high value was set on salvaging building materials during construction and demolition of the existing structure, working with the municipality to enable use of existing materials in a proposed structure (Seattle, 2012). The building was planned according to principles of design for deconstruction (Figure 3.30), with the key features being:

- Reuse of existing structure in proposal
- Use of screwed steel connectors
- Collaboration with Contractor

Figure 3.30 Glulam beams with metal connections, Bullitt Center (Courtesy of Bullitt Center, photos by John Stamets).

Fielden Fowles Architecture Studio (2016)
Architects - Fielden Fowles; Engineers – Structure Workshop

This studio space, designed to be demountable, is made from Douglas fir timber frame and clad with corrugated bitumen sheets. An internal datum of 2440mm and a structural grid of 1830mm, full and three-quarter plywood sheet respectively, were chosen to minimise cuts, wastage, and material use. The internal walls are lined with plywood boards which are 610mm wide, or a quarter of a ply board.

The structure consists of paired 300 x600mm beams supported by paired columns, also 300mm x 60mm. Steel T-Sections are used as window frames. Primary beams are set at 1800 centres, purlins at 600 centres and noggins at staggered 2400mm centres, all to align with the plywood butt joints and limit cutting (Figure 3.31). At the end of the lease, it is intended that the structure will be dismantled and erected elsewhere.

- Demountable
- Modular System
- Reusable in alternative location
- Lightweight structure
- Repeated connection
- Standardised dimensions

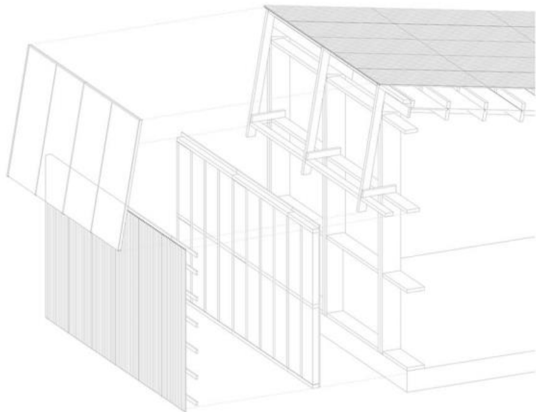


Figure 3.31 Fielden Fowles Architecture Studio (Source: Johnson et al. 2020)

Temporary Market Hall, Östermalm, Stockholm (2017)
Architects – Tengbom; Structural Design – Loostrom and Gelin

During the refurbishment of an existing market hall, a temporary home was created for the traders. The façade is fabricated using untreated cedar cladding on plywood at a lower level with clear storey utilised modular polycarbonate sheeting. Internally, the structure is exposed with a latticework of glulam beams resting on columns of CLT (Figure 3.32). This grid again utilises a modular mounting system which provides for erection and dismantling with the possibility for subsequent reuse at another location. The use of timber means a relatively light weight structure, reducing the need for foundations. The building's roof structure consists of 1.2m long LVL beams and glulam columns. Key strategies included:

- Demountable
- Modular System
- Reusable in alternative location
- Lightweight structure
- Repeated connection
- Standardised dimensions

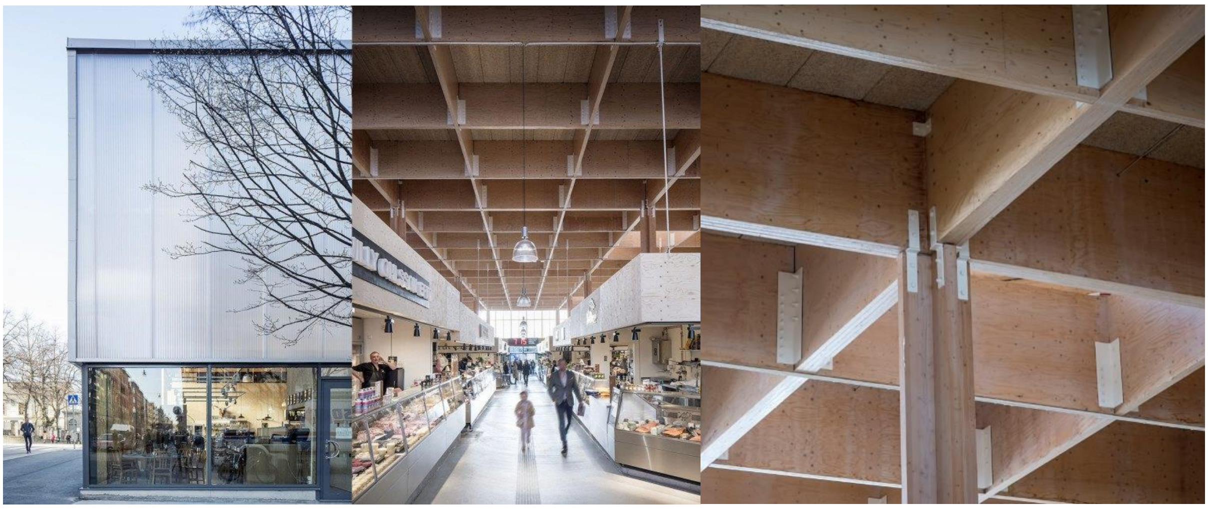


Figure 3.32 Temporary Market Hall, Östermalm (Photographer: Felix Gerlach)

Building D-mountable, Delft (the Netherlands 2020)
Architects: Architectenbureau cepezed

This is a four-storey office building that has a hybrid structure combining a steel frame with wooden elements (Figure 3.33). The architects designed the building with a view to flexible and modular construction, with a minimum of materials. The building has a systematic, rational and uncomplicated design. The key strategies used were:

- Materials minimised
- Light structure
- Modular dry mounted construction (apart from ground floor slab)
- Building only as large as needed
- Easily removable bio-based dry screed (gravel-like granules in a cardboard honeycomb structure with gypsum fibreboards on top)
- No typical window frames; the glass fixed directly to steel frame

- Integrated construction process

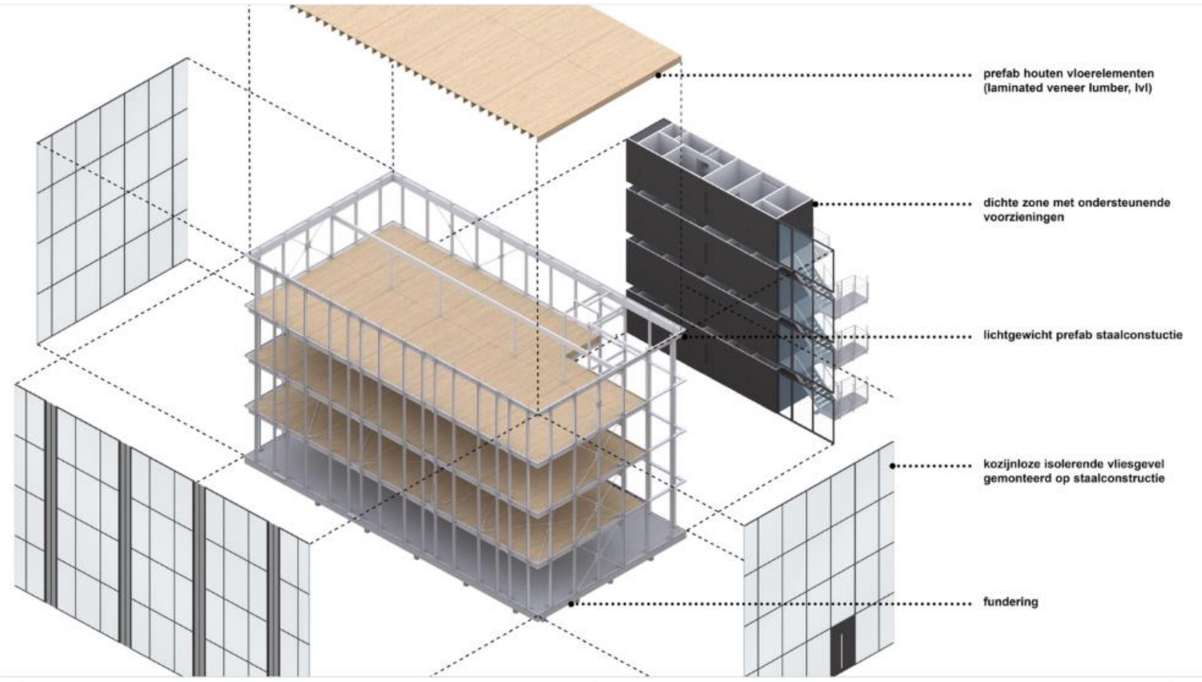


Figure 3.33 Building D-mountable 2020, Delft, Holland. © architectural office cepezed (Photo: MetsäWood 2020)

3.3. Benefits and obstacles for reuse of structural timber

3.3.1. Benefits of reuse of structural timber

There are many benefits of implementing a reversible design that would prepare a building for the reuse of structures showed a vast study during the BAMB project by Debacker and Mashnova (2016). The study not only identified these benefits but also looked at their relation to the knowledge about them, the market and the acceptance by society.

In theory, structural timber reuse is the best option for maximising the recovery potential of the building, because timber has the highest preferred reuse percentages among all construction materials (Hradil et al. 2014). Given that the World Bank has projected that global timber demand may quadruple by 2050, there is a growing threat to the sustainable management of the world’s forest resources if virgin resources alone are to fulfil this demand, making the reuse of harvested timber products increasingly important (Adhikari and Ozarska, 2018). This is echoed in the recent EU Circular Economy Action Plan, which propose revising material recovery targets set in EU legislation for construction and demolition waste, the introduction of recycled content requirements for certain construction products and promoting measures to improve the durability and adaptability of buildings and developing digital logbooks for buildings to track material use and reuse (CEAP, 2020).

An increased level of reuse and recycling would provide obvious benefits for the environment and could significantly reduce disposal costs. Cruz Rios et al. (2015) suggested that generally deconstruction is a cost-effective alternative to demolition, with case studies undertaken by the American Environmental Protection Agency and it is influenced primarily by the resale value of salvage material and the reduction in waste disposal costs. However, an efficient disassembly requires an efficient assembly, thus timber construction might have an advantage over some other materials, such as concrete and blockwork, which is more difficult to disassemble due to the mixture of wet and dry construction systems.

In a survey made of the Finnish construction and recycling industry (Hradil et al. 2014) the potential for structural steel and timber (beams, columns, CLT) were seen as nearly equal by respondents. It was especially clear among respondents that timber should be reused by 2050, as it had the highest preferred reuse percentages of all the materials identified. The survey provided a number of practical concerns and ideas regarding reuse, including a suggestion that only non-weather-exposed loadbearing structural elements should be reused (Hradil et al. 2014).

In light of the EU ambition for the increased use and effectiveness of digital tools, such as log books for buildings (CEAP, 2020), to encourage more effective resource management, current Building Information Management (BIM) tools could be effectively utilised to enable detailed documentation about the use and performance of recycled and reused building components. This form of 'material passport' (Debacker and Manshoven, 2016) could be used to track the use and reuse of materials, potentially leading to a greater acceptance of recycled materials and reused components in the future. It has been suggested by Webster (2007) that buildings with DfDR features may have a greater market value (Cruz Riosa et al. 2015).

3.3.2. Obstacles for the reuse of structural timber

Hradil (2014) identifies four categories of obstacles for reuse of building structures:

- economic
- social
- environmental
- technological

The results of a survey conducted by Hradil on the reuse of structures showed that some of the most important barriers in Finland are considered cost, legislation and standards which aligns with surveys conducted in Sweden on the potential re-use of CLT (Brismark 2020). The cause of the economical barrier is the lack of current demand for recovered wood in countries with a lot of forest that usually exports wood such as Finland and Sweden (Hradil et al. 2014, Brismark 2020) and that also have a good network of combustion plants.

Debacker and Mashnova (2016) also looked at the obstacles in implementing reversible design. Although there now is a Circular Economy Action Plan (CEAP, 2020) most of the obstacles identified in 2016 still exist in 2020 in Europe such as :lack of robust and standardised data/ information over the entire value chain of the product/building, linear construction models, higher complexity of disassembly compared to demolition, lack of certification and quality assurance for reclaimed products and recycled materials and the general perception that reversible design solution entail high financial costs.Some of the difficulties that need to be overcome for successfully implement a large-scale reuse of timber structural components will be studies and hopefully impacted by our the project such as: hindrances in building regulations, demolition practices, architectural/technological obstacles. They are briefly discussed below:

Hindrances in building regulations

For successful reuse of timber structural elements, the strength of reclaimed timber needs to be assessed. Generally, the same procedure should be used as for the grading of new timber; however, due to possible damage from construction, ageing, and the lack of background information, proper grading according to existing standards is not currently considered feasible. Thus, new rules for grading reused timber needs to be developed taking into account these effects, which will be addressed in Work Package 5 of the InFutUReWood project.

In Europe, standards for timber grading typically do not allow grading of used wood and there are restrictions on possibilities to use waste. Furthermore, European standards do not allow the use of recovered timber in CLT production, which will be addressed in Work Package 3 of the InFutUReWood project. There might also exist further restrictions on national level. For example, in the UK the possibilities to use waste materials are quite limited. The National House Building Council (NHBC), the biggest insurance provider for new houses in the UK, only allows the reuse of materials with their prior agreement.

More insights on this topic will be provided in Deliverable D3.2, D5.2 and D5.3 of the InFutUReWood project.

Demolition Practices

The Irish Environmental Protection Agency (EPA) have noted in *Design Out Waste Factsheet*, that

> … the fundamental design decision to reuse an existing building or demolish it for a new building will determine, to a large extent, the level of waste prevention in a project. In accordance with the waste hierarchy, the design team should explore reuse, recovery and recycling opportunities. (EPA, 2015b)

Current demolition practices will play a key role in the recovery of quality reusable timber components, yet demolition is rarely considered in the design and construction of buildings. In conjunction with this, construction practices over the last 50 years have changed, resulting in less salvage and reuse. Before the 1970s, Addis notes that a large proportion of demolition was undertaken by hand, apart from the very final stages when a 'ball and chain' method might have been used, and as a consequence items were more frequently salvaged undamaged (Addis, 2006). He highlights some changes to the industry, with potentially contrasting implications suggests some reasons for this:

- Pressure to reduce demolition and disposal costs
- Pressure to reduce the timescales
- Impetus to improve Health & Safety
- Change of perception from 'Demolition' to Material recovery & disposal Activity'.
- Greater environmental concerns, including an awareness of materials 'whole life cycle'
- Global market for demolition

Across Europe, the legislative and regulatory context within which Demolition occurs has become more complex. A range of legislative structures impact the process, including:

- General Health & Safety Legislation
- Project Supervisor Design Process (PSDP) / Project Supervisor Construction Stage (PSCS) (Construction design & Management) Regulations
- Management H&SW Regulations
- Construction H&SW Regulations
- Control of Substances Hazardous to Health (COSHH) Regulations
- Asbestos Regulation

Addis' (2006) study has found that demolition methods are very much project specific, with several factors influencing the chosen method; however, the most decisions are entirely driven by the economics of the process. Yet, there is a growing legislative and economic pressure on the demolition and waste companies to ensure as little waste as possible goes to landfill. The demolition and waste treatment practices are influenced by the following factors.

- Cost: Pressure to reduce costs.
- Budget and Programme: Will it be easier or more economic (see below) to demolish by hand, with expensive labour, or pull down with an excavator to be picked apart.
- Economic: economic value placed on segregation based on skip/landfill costs
- Building Construction; How is the building constructed? Can it be easily disassembled or stripped to an extent that will make it more efficient?
- Site Constraints: Is the building in a built-up location which might inform method of deconstruction?
- Phasing: Can space be made available for greater segregation?

Addis notes (2006) that this has resulted in:

- Reduced labour onsite, prioritising remote working i.e. 'one man and machine'
- Development of advanced demolition equipment, such as 'super long reach' and 'remote controlled machines'
- More demolition rather than deconstruction with fewer recovered components and materials.

Architectural/technological obstacles

Hradil et al. (2014) examined the reuse potential of timber to identify obstacles to reuse and postulate solutions that could be used by designers interesting in using salvaged timber in new designs. Beyond the question of assessing the timber grade, or structural properties, the dimensions (variability of length, shortness of length, depth and width of section sizes) of recovered timber appeared to be a significant obstacle (Hradil et al. 2014).

Huuhka (2018) developed the findings in Hradil et al. (2014) and concluded that the obstacles also include issues linked to architectural design such as inconsistent quality, inconsistent quantity and difficulty of dimensional coordination. To overcome this, Huuhka (2018) defines ten universal architectural design principles from the students' architectural applications for the use of salvaged timber to accommodate these inherent limitations under the umbrella of "Tectonic thinking for architectural reuse of salvaged timber":

1. Divide the spatial programme into smaller rooms or volumes
2. Split the structure into smaller sections
3. Avoid equal spans and dimensions
4. Split the structure according to the function
5. Utilize efficient forms that allow using smaller pieces for longer spans
6. Define ranges instead of fixed properties
7. Rotate and repurpose
8. Select the application according to the properties
9. Combine creatively
10. Let the patina speak.

Being a biological building material prone to biotic degradation, timber needs special care and control. Of especial importance in the acceptance of recovered wood on the market is assuring that reused products do not represent an environmental health-threaten, a source of mould, fungi or insects contamination. In Sweden Johansson studied mould growth on and proposed a structure of how timber should be handled. This idea will be further developed in WP5.

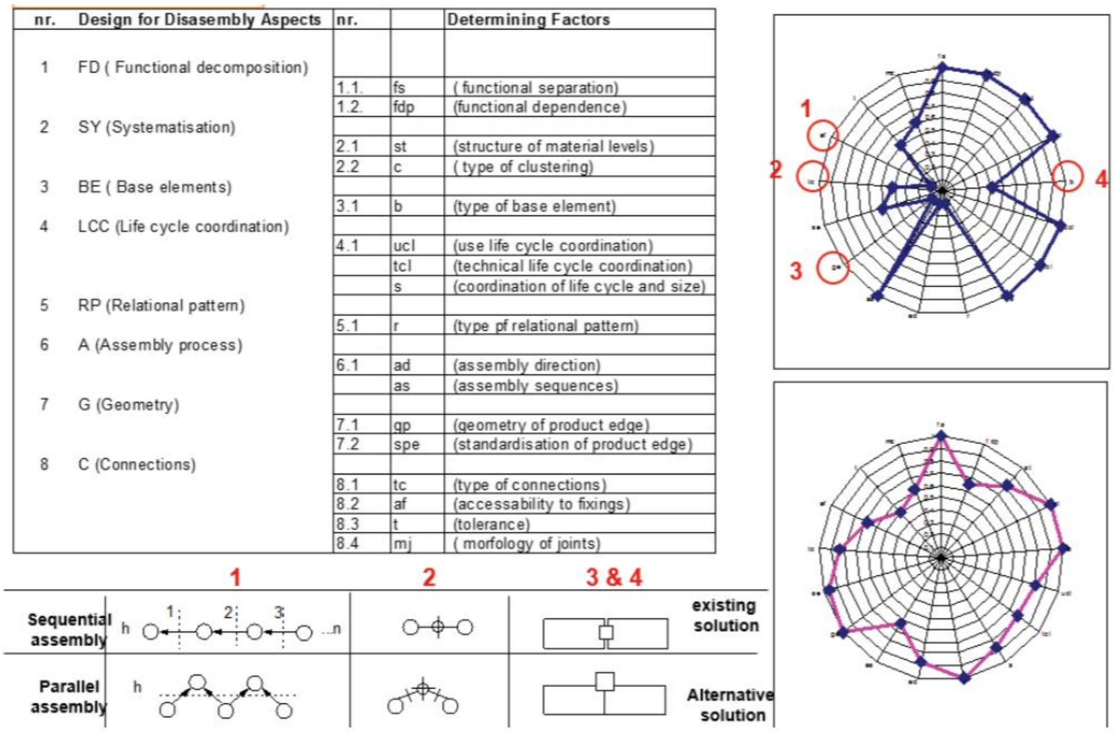
Some companies found a solution in using heating chambers to assure that the delivered recovered wood pieces of large dimensions are heated. Other companies offer information about how to deal with wormwood. It is positive that second hand wood trading companies in Europe are aware of the issue and offer both solutions and information on how to avoid further deteriorating of wooden material

4. Principles, indicators and guidelines for Design for deconstruction and reuse (DfDR)

To identify challenges and possibilities in DfDR, different approaches may be adopted. One approach would be to formulate generic principles applicable for any design concept. For practical use, these could then be developed into performance indicators to form the basis of a structured conceptual design process and highlighting areas of possible improvements.

Another approach would be to carry out a deeper but less structured analysis of a specific building system in form of a case study, which would then identify critical details in a specific design. The connections between the elements are considered a key factor to enable effective deconstruction including their ease of access and the type used.

To be able to evaluate the suitability of various design concepts for future deconstruction and reuse, during BAMB project (Durmisevic et al. 2017) a set of indicators has been developed which can measure the level of fulfilment of several important aspects relevant for the purpose. Figure 4.1 presents how design decisions influence assembly/disassembly sequences and how the type of connections leads towards improvements made from a reference initial solution to the improved alternative.



nr.	Design for Disasembly Aspects	nr.		Determining Factors
1	FD (Functional decomposition)			
		1.1.	fs	(functional separation)
		1.2.	fdp	(functional dependence)
2	SY (Systematisation)			
		2.1	st	(structure of material levels)
		2.2	c	(type of clustering)
3	BE (Base elements)			
		3.1	b	(type of base element)
4	LCC (Life cycle coordination)			
		4.1	ucl	(use life cycle coordination)
			tcl	(technical life cycle coordination)
			s	(coordination of life cycle and size)
5	RP (Relational pattern)			
		5.1	r	(type pf relational pattern)
6	A (Assembly process)			
		6.1	ad	(assembly direction)
			as	(assembly sequences)
7	G (Geometry)			
		7.1	gp	(geometry of product edge)
		7.2	spe	(standardisation of product edge)
8	C (Connections)			
		8.1	tc	(type of connections)
		8.2	af	(accessability to fixings)
		8.3	t	(tolerance)
		8.4	mj	(morfology of joints)

Figure 4.1 ***Assessment model with related spin diagram offering information on aspects that can be improved in order to increase the disassembly of structures and their associated reuse potential. (Durmisevic, 2019)***

According to Durmisevic (2019) during the design process indicators of reversibility are used as design aspects while at the end of the design phase, design solutions are assessed using a “Reuse potential tool” which has integrated reversible building design indicators as criteria for evaluation. Such evaluations systems highlight strengths and weaknesses of the “reversibility” concept in the BAMB project (having the same understanding as the DfDR concept in the literature), contributing to optimized designs with respect to deconstruction and reuse.

Currently there is a high interest in implementing a 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. Recently the International Standard Organisation (ISO) launched a suite of eleven documents dealing with sustainability in construction works (ISO, 2020). One of the standards in this suite is dedicated to DfD/A (design for Disassembly and Adaptability). ISO declares that “the document is intended to provide a framework of the DfD/A principles and the key issues that should be considered by the different actors, particularly designers involved in the project. It is equally important that this knowledge base is continually added to by those implementing these principles, and associated activities, for example, by knowledge sharing through the creation of case studies and associated journal articles” (ISO 2020). The standard contains a matrix for the assessment of components/assemblies for specific DfD/A principles and WP2 intention is to participate to the further development of the matrix.

As a means of addressing the negative environmental effects of construction and building use, several sustainability certification systems have developed and used rating tools since the 1990s with the aim of objectively assessing the green building credentials of designs and the long term impact of a development. These rating systems include BREEAM by the Building Research Establishment in the UK and LEED by the US Green Building Council, and the online green building rating and certification by Green Globes (Green Building Initiative). In Scandinavia, the Nordic Swan Ecolabel has been used for the evaluation of entire buildings and the rating gives points for using reused raw materials or construction products (outside the vapour barrier) in projects, including timber and timber products. The Nordic Ecolabelled buildings are required to have a logbook, of all the products that are built in, with information about the product id, the main constituent materials and the place in the building (Nordic Ecolabel, 2020). That means that today’s Nordic Ecolabelled buildings come with an inventory of all the products that are made of timber, their name and place in building. Many of the sustainability certification systems for buildings and building products are in the process of integrating DfDR credits yet specific DfDR strategies for timber are limited.

Addressing generic principles applicable for any design concept there are several existing studies in the literature, such as Crowther (2005), Guy and Ciarimboli (2008), Hradil et al. (2014).

Through studying historic examples Crowther (2005) identifies common patterns in DfDR which are translated into basic principles that might guide architects and building designers. The result is a detailed list about relevant aspects of DfDR and their relevance to the various levels of construction circularity, such as material recycling, component remanufacture, component reuse and building relocation. Those aspects that are found relevant or highly relevant for disassembly (D) and component reuse (R) include:

- Minimise the number of different types of components (D, R)
- Use mechanical not chemical connections (D)
- Use an open building system not a closed one (R)
- Use modular design (R)
- Design to use common tools and equipment, avoid specialist plant (D, R)
- Separate the structure from the cladding for parallel disassembly (D)
- Provide access to all parts and connection points (D)
- Make components sized to suit the means of handling
- Provide a means of handling and locating
- Provide realistic tolerances for assembly and disassembly (D)
- Use a minimum number of connectors (D)
- Use a minimum number of different types of connectors (R)
- Design joints and components to withstand repeated use (R)
- Allow for parallel disassembly (D)
- Provide identification of component type (R)
- Use prefabrication and mass production (D, R)
- Use lightweight materials and components (D)
- Identify points of disassembly (D)
- Retain all information of the building components and materials (R)

The list, however, is very generic and does not differentiate the various aspects based on if they are related to disassembly and/or reuse. Such a differentiation is indeed not straightforward or, in some cases possible and may not always be necessary. An attempt is made here by indicating D for disassembly and R for reuse in parentheses. Furthermore, there could be cases when the Crowther's principles are in conflict. For example, minimising the number of components used could contradict the principle of using lightweight items.

A more concise list is presented by Guy and Ciarimboli (2008) as the ten key principles of Design for Disassembly (DfD):

1. Document materials and methods for deconstruction
2. Select materials using the precautionary principle
3. Design connections that are accessible
4. Minimize or eliminate chemical connections
5. Use bolted, screwed and nailed connections
6. Separate mechanical, electrical and plumbing (MEP) systems
7. Design to the worker and labour of separation
8. Simplicity of structure and form
9. Interchangeability
10. Safe deconstruction

If these are considered as main indicators of appropriateness of design concerning Deconstruction and Reuse, they might be arranged in groups, which then possibly could lead to a hierarchy of indicators (Figure 4.2).

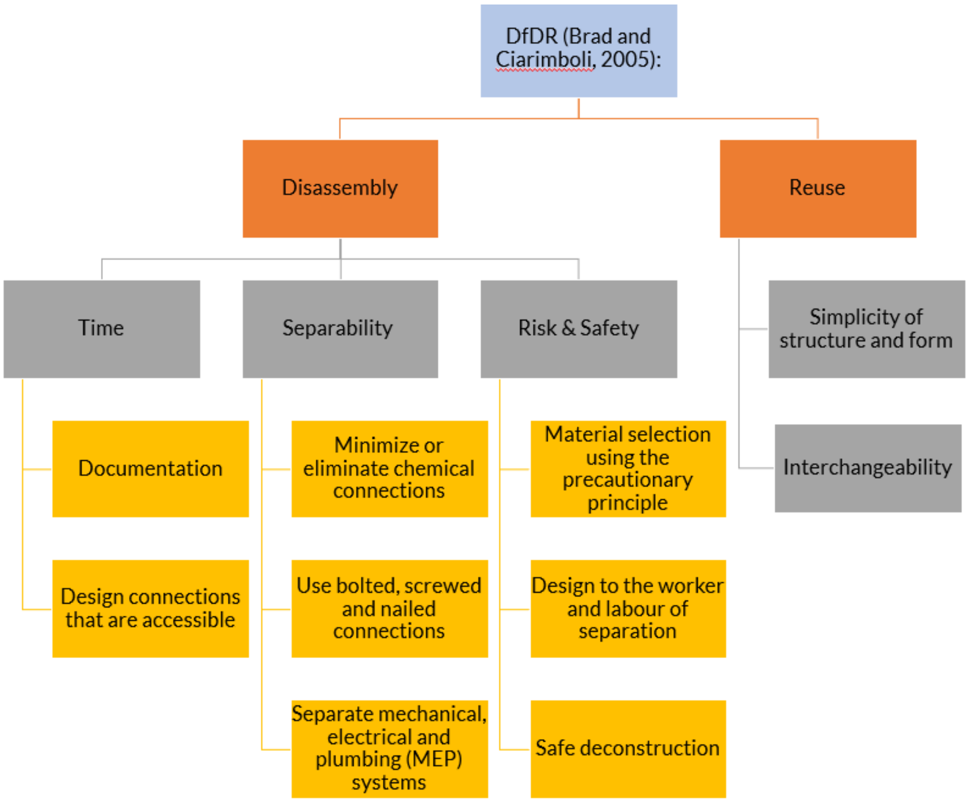


Figure 4.2 The ten main principles of DfDR (Guy and Ciarimboli, 2008) seen as indicators of Design for Deconstruction and Reuse (Source: RISE)

Although primarily focusing on recycling, rather than reuse, based on these principles Thormark (2001) suggested a simple method for assessment of the ease of disassembly of building constructions. As opposed to product design, besides the time requirement other parameters are also found important for buildings, such as:

- Risks in the working environment
- Time requirement
- Tools/equipment requirement
- Access to joints
- Damage to the material caused by disassembly

The presented method suggests assigning scores for each of these parameters.

A similar assessment method, referred as 'reusability indicator', is suggested by Hradil et al. (2017) concerning the reuse of components and structures of steel-framed buildings. The indicator is based on assigning scores and weight to the following categories:

- Separation and cleaning

- Handling and manipulation
- Quality control
- Geometry checking
- Redesigning
- Repurposing
- Modification

These two “scoring systems”, i.e. Thormark (2001) and Hradil et al. (2017), could be seen as the main indicators of Deconstructibility and Reusability (Figure 4.3)

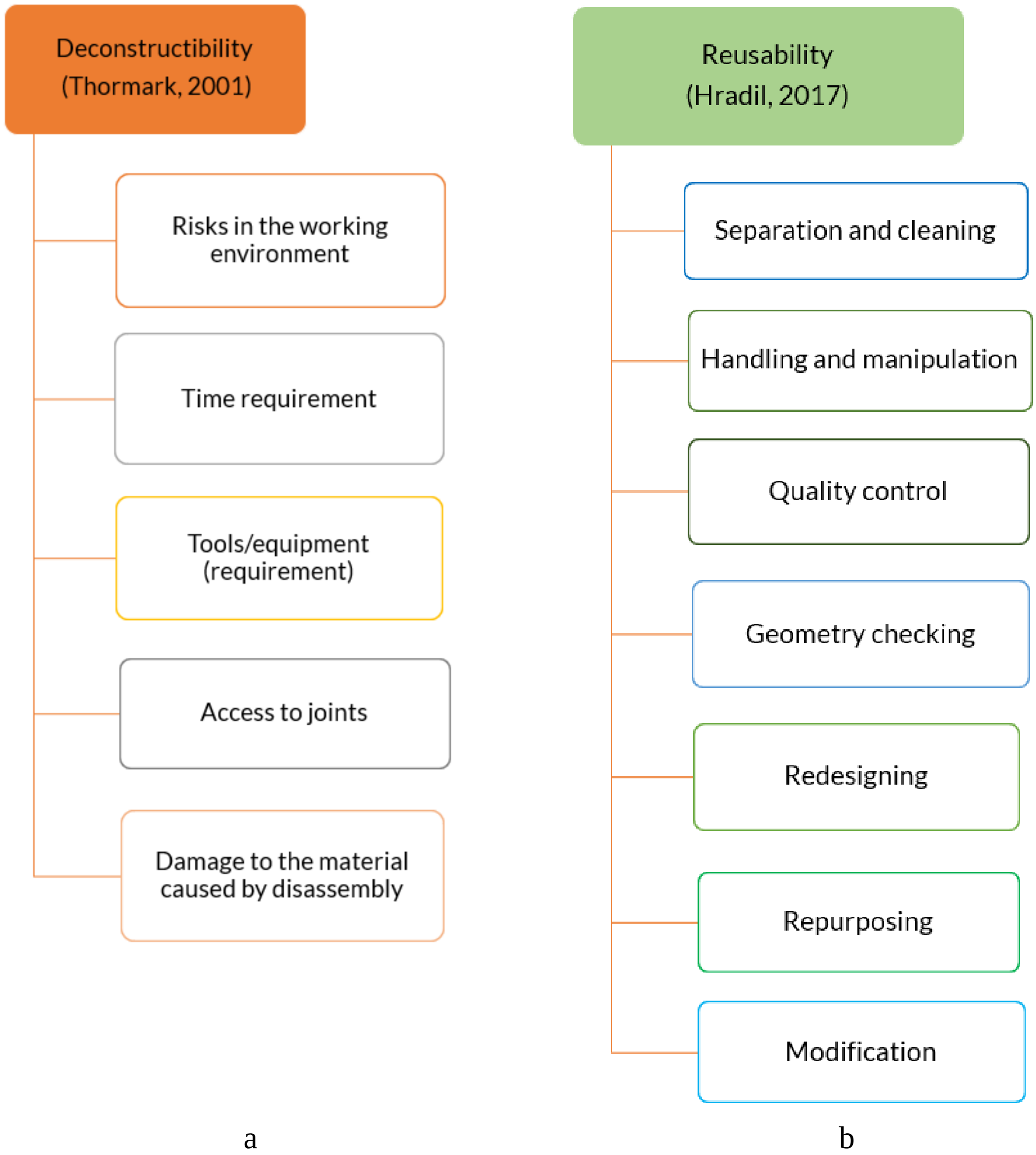


Figure 4.3 Main indicators of a) Deconstructibility (Thormark 2001) and b) Reusability (Hradil et al. 2017)

From the above examples it seems that it is most important that connections and structural systems should be easy to disassemble and then reuse. This could be facilitated by:

Ease of disassembly

- Low weights and small sizes for easy dismantling
- Accessibility of joints
- Separability of subcomponents for easy dismantling
- Low susceptibility against damage during disassembly

Reusability (including repurposing of individual structural elements)

- Repetitiveness (number of similar elements)
- Similarity (variation of elements)
- Standardization level (shapes, sizes, elements)
- Low exposure to deterioration processes
- Expected long-term deformations are not significant
- Transportability (except low weights and sizes again): remoteness of the building
- Documentation about design and maintenance

4.1. Case Study Approach

As mentioned before, another possible approach of improving design with regard to DfDR, as opposed to the generic indicator system-based approach, is to carefully analyse a specific design case and identify weak spots to be enhanced.

Chisholm (2012) reports on a case study and shows how the design can be improved in terms of design for dismantling. Chisholm studies The Sigma Home, a concept for a three-storey house with timber frame that comprises of two semi-detached dwellings. She uses four different analysis techniques to identify the most DfDR sensitive detail and then compares it to a modified DfDR-enhanced version.

The first analysis concerns the building layers and the lifespan vs. durability of the materials and products. The second analysis regards the manufacturing process and aims at highlighting DfDR issues and potential areas of improvement. Three obstacles to DfDR were found: the first concerned factory fixing using nails and nail plates, the second concerned the sequential production of components in the factory where each layer was fixed to the one below and the third concerned supplementary work done on site without guidance on fixings. The third analysis aims at identifying component dependencies. The fourth analysis is a calculation of the embedded energy in the different components (mid-floor cassette, internal non-load bearing wall, roof cassette, party wall, etc.).

The result of the different analysis methods highlighted the importance of designing the mid-floor cassettes, external walls and party walls for deconstruction. The detail found to be most DfDR-sensitive was a meeting/joint between these components. For this detail, DfDR issues were identified and a modified design was presented, including: an L-shaped joint that renders the components suitable for reuse, a floating floor construction that eliminates the need of fixing battens with nails and of gluing chipboard, a closed panel system that removes a site-built installation space with poor thermal performance and floor cassettes arriving on site with a preinstalled airtightness membrane. A detailed cost analysis was carried out showing that the modified design would save time as well as money.

This methodology could be adopted to investigate other timber construction typologies, such as post and beam or mass timber construction, to identify and isolate problematic junctions in an effort to define better design and detailing protocols.

Bergås and Lundgren (2020) also discuss the options an architect has when planning a DfDR-type of building at the earliest stage based on a case-study in WP 2. They assess three relevant choices: the type of joints, the prefabrication level and the building system using. For the case studied of a multi-storey building that will hopefully be built in Kiruna, Sweden, they chose 2D elements from CLT. "Fast assembly time at the building site gives plane modules lower cost, compared to separate pieces. As it simplifies the disassembly, it can make the decision of choosing a disassembly rather than a demolition easier. Compared to volume modules, working with plane modules will give more architectural freedom when designing spaces" (Bergås and Lundgren, 2020). In their assessment of the different building systems they assess not only the technical issues but also the environmental, economical and esthetical impact of each of the proposed scenarios.

5. Conclusions

There has been considerable research in the last 25 years which have identified key principles as well as several specific strategies that can inform DfDR. While there have been practical applications of some of these principals and strategies in built projects, as seen in the case studies, nevertheless, much of the work remains at the level of hypothesis rather than being actively applied in practice. Though many of the principles outlined by Thormark (2001), Crowther (2005), and Hradil et al. (2017), are useful reference points, and offer some high-level strategic guidance, for this thinking to be operationalised in the design and construction sectors a more directed decision-making tool, developed according to phases of design and construction work is required. Kibert's early definition of stages (Development, Planning, Design, Construction, Operation, Deconstruction) is a useful starting point, but to be considered as valid, for designers, be they architects or engineers, a finer grain of stages, linking principles, strategies and specific tactics appropriate to each stage, is required to properly direct their decision making in designing DfDR buildings.

It is 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 (2014) Hierarchy of building components 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 viewing this as the optimum solution.

As the InFutUReWood project proceeds, we will examine a more granular approach to DfDR, relating it to the actual construction stages used in practice, developing a general template to be appropriated and adjusted to account for regional variations in construction. A strategic matrix is in development which will provide designers with a methodology based on relating principles, strategies and specific tactics to the typical design stages, to aid design decisions that promote DfDR. The key criteria in the development of the matrix are:

- Relate to the typical stages of design and construction (currently based on Irish and UK statutory bodies RIAI/RIBA but must be adjustable to other regions); To ensure that opportunities to implement strategies are not missed, the matrix will be applicable to a project timeline which will enable a project team to identify strategies relevant to the project stage
- Accessible; Due to the impact of time and cost on the pace of design, any proposed strategy to increase the reuse of timber in construction must be easy to use and accessible.
- Specific to timber construction; It should also be as specific as possible to timber construction so that practitioners can easily comprehend what opportunities exist

for a particular use. Many of the current strategies are unspecific and assessment for usefulness takes resources.

- Refer to key DfDR principles; There are a number of principles which recur in relevant literature, such as 'layers of shear' and designing for maximum flexibility. Though general, these should also be included and linked where possible to specific strategies and tactics.
- Provide a framework to discuss with other consultants, particularly a structural engineer; Some options for DfDR might not be feasible in a given project, however a matrix of options will allow for a holistic discussion with consultants about the potential areas for use on a specific project
- Enable engagement with contractor regarding feasibility of strategies; Contractor engagement is important in achieving any DfDR goals
- Potentially include guidance on the reuse of existing material in the design
- Transferrable to other materials
- Adaptable to other regions
- Enable designers to review project holistically

Coupling such a decision matrix to an indicator system, such as the one developed by BRE (2020) or the indicator system currently in development in the InFutUReWood project, which could verify the projected design and highlight areas of possible improvements could help to transfer the considerable body of knowledge developed by researchers in the field of DfDR into practice more effectively. To be truly effective as a tool, the more specificity the matrix has, the more useful it will become.

There are variables influencing the success of DfDR projects in the long term, however, which cannot be addressed through a decision matrix or indicator system, as they are beyond the control of the designer. Without clear guidance and grading systems for recaptured wood the reuse of the material stored in DfDR buildings is jeopardized. This will be addressed in Work Packages 3 and 5 of the InFutUReWood project. When solved, this could facilitate the development of a market for reused wood, which will help to close the loop described by Crowther (2005) and allow this material to be cycled back into new DfDR buildings. There are, in addition, regulatory and practical challenges to the recapture of wood in current demolition practice. Though DfDR buildings may facilitate deconstruction over current demolition practice, this will in practice be influenced by the existence of a market for reused timber that is sufficiently profitable that it diverts recaptured timber away from the energy sector, where current regulations on renewable energy use is driving an uptake in timber consumption.

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7. Annex 1

Table 7.1 Glossary of Definitions

Term	*Definition*	*Source*	*Category*
Adaptability	The capacity of buildings to accommodate substantial change.	Moffatt and Russel (2001)	Building circularity
	Adaptable: an assembly of building materials that can be altered with a minimum of material flows initiated to support changes in needs and requirements. Adaptability is the degree to which an assembly is adaptable.	BAMB (2018)	
Adaptive Reuse	A process that changes a disused or ineffective item into a new item that can be used for a different purpose. Sometimes, nothing changes but the item's use.	Department of the Environment and Heritage 2004	Building circularity
Basic structural element	The basic elements can be used and designed alone to carry the load. It is possible to trim and cut such elements to smaller sizes on site to fit the new design.	Hradil (2014)	Timber structures
	The loadbearing parts of a building that cannot be decomposed into different parts, e.g. beams or columns.	ISO 10303-225 (1999)	
Building	The whole buildings or standalone building modules can be technologically very easy to disassembly and re-use. However, the flexibility of new design is very limited.	Hradil (2014)	Timber structures
	Construction work that has the provision of shelter for its occupants or contents as one of its main purposes, usually partially or totally enclosed and designed to stand permanently in one place. Includes building envelope and all technical building systems.	ISO 6707-1 (2020), ISO 16818 (2008)	
Building block	These elements are typically small and lightweight blocks that are joined together to form a bigger part. They can be re-used for a large variety of structural and non-structural applications.	Hradil (2014)	Timber structures

Term	*Definition*	*Source*	*Category*
Building Information Modelling	A methodology, accompanied with processes and techniques, that aims to represent, store and manage essential builiding design and project data in digital format over a building's life-cycle.	Van den Berg (2019) - PhD, Twente Univ- NL	Circular building projects
Building frame	Structure composed principally of linear or curved structural members.	ISO 6707-1 (2020)	Timber structures
Circular economy	In Circular Economy, value is created using the tightest possible loops for both technical and biotic nutrients. For the technical cycle, the loop with the most value is that of product maintenance and repair, followed by the reuse and redistribution loop, the refurbishing and remanufacturing loop and finally, the recycling loop. For the biotic cycle, biochemical feedstock production is the loop with the most embodied value, followed by renewable energy supply through biogases and finally agricultural amendment use. Cycling longer, cascading and toxicity reduction are also value creation drivers.	CIRAIG (2015), Polytechnique Montréal + Université du Quebec a Montréal	Life cycle thinking, engineering and social sciences
	A multi-level, socio-constructed concept that can either be considered a paradigm shift, a new toolbox, a conceptual umbrella or a portmanteau discipline. It is an idea or concept that is currently being developed, with moving and adaptable content as well as blurred boundaries, feeding from multiple and rich conceptual sources. As a response to resource scarcity and eroding profits, Circular Economy provides an attractive response to a global economic crisis but manages to leave behind some important issues (such as the social dimension of sustainability).	CIRAIG (2015), Polytechnique Montréal + Université du Quebec a Montréal	
	An industrial system that is regenerative by intention and design through decoupling resource depletion and economic growth. Proposed alternative for the linear economy.	Van den Berg (2019) - PhD, Twente Univ- NL	Circular building projects
Circularity	Degree to which a product or process is aligned with the circular economy		

Term	*Definition*	*Source*	*Category*
Compatibility	Building parts that are designed in accordance with dimensional and possibly other standards, to ensure they are interchangeable or easy to combine.	BAMB (2018)	Building circularity
Connectivity	Capability of a system or device to be attached to other systems or devices without modification	ISO/IEC 2382-1 (1993)	Building circularity
Cradle-to-cradle	A framework to design production processes in which materials flow in closed-loop cycles.	Van den Berg (2019) - PhD, Twente Univ-NL	Circular building projects
Design for Change	The design strategy based on the principle that our needs and requirements for the built environment will always change; its aim is to create buildings that support change effectively and efficiently.	BAMB (2018)	Building circularity
Design for Deconstruction/ Design for Disassembly	Design of the building so that the parts are easily dismantled and separated from each other for re-use or recycling.	Moffatt and Russel (2001)	Building circularity
	Design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials.	Guy and Ciarimboli (2006)	Building circularity
	The primary goal of deconstruction is to reuse the dismantled components; however, recycling can also be considered as a secondary objective. The term disassembly is often used in a wider context and typically enables the possibility of recycling of recovered building materials into new components or reprocessing into new materials. Thus, disassembly is typically less environmentally friendly than deconstruction as it preserves less embodied energy and requires additional energy for reproduction. However, throughout this report the two terms are used as synonyms.	Chapter 2 – InFutURe Wood	
Design for dismantling	Synonym for Design for disassembly/ Design for deconstruction		

Term	*Definition*	*Source*	*Category*
Design for Future Adaptive Reuse	Design with future adaptive reuse in mind. Incorporates design principles like adaptability, compatibility and generality that allow adaptive reuse of buildings and components with minimal material intervention.		Building circularity
Design for Reversibility	'Reversibility' is defined as a process of transforming buildings or dismantling its systems, products and elements without causing damage. Building design that can support such processes is reversible (circular) building design.	Durmisevic (2019)	Building circularity
Destruction	Process of turning material into waste, which may or may not be recycled.	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity
Dismantling	Deconstruction or disassembly and removal of any structure, system, or component during the renovation, alteration or removal of a building.	Adapted from ISO 12749-3 (2015)	
Disposal	Any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy.	EC (2008)	Waste management - generic
Generality	Generic: a building or space that supports changing needs and requirements without physical alterations and the initiation of new material flows. Generality is the degree to which a building or space is generic.	BAMB (2018)	Building circularity
Information	Data which are relevant, accurate, timely and concise	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity
Linear economy	An industrial system that follows a "take – make - dispose" model of resource consumption	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity
Object	Any physical part of a building that can be handled separately	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity

Term	*Definition*	*Source*	*Category*
Modularity	Exhibiting separable functions embodied within discrete and removable components (modules).	Adapted from ISO 22902-1 (2006)	Building circularity
Preparing for reuse	Checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing.	EC (2008)	Waste management - generic
Prevention	Measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of harmful substances in materials and products.	EC (2008)	Waste management - generic
Reclaimation (reclaiming), Recapture	Collection of products, components or materials with the intention of avoiding waste and with the purpose of reuse or recycling	BS 8001 (2017)	Waste management - generic
Recovery	Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy.	EC (2008)	Waste management - generic
	Process of collecting material with the aim to substitute virgin materials in construction. Always precedes reuse.	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity
Recycling	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.	EC (2008)	Waste management - generic
Reduce	Process of decreasing the use of materials		

Term	*Definition*	*Source*	*Category*
Repurposing	Reclamation of a building, assembly or object to a productive condition with minimal material intervention, corresponding with a use alternative to the previous use.	Adapted from ISO 20305 (2020)	Building circularity
Reuse	Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived.	EC (2008)	Waste management - generic
	Process in which materials is reprocessed into raw material that can serve as inputs for new products.	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity
Reversible building	A type of building that is specifically designed to enable transformations, disassembly and reuse of building objects.	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity
Salvage	Removal of disassembled building materials for the purpose of reuse, refurbishing, or recycling.	Sparandara et al. (2019)	Waste management - generic
Structural member / structural element	Physically distinguishable part of a structure, e.g. a column, a beam, a slab, a foundation pile.	Comité européen de normalisation (2010)	Timber structures
	Such elements are designed with well-defined shape and fitted connections. They can be composed from more materials or smaller elements. The members can be repaired if they are damaged during the disassembly, but their modification needs to be carried out in the workshop.	Hradil (2014)	
Structural system	Load-bearing members of a building or civil engineering works and the way in which these members function together.	Comité européen de normalisation (2010)	
Structure	Organised combination of connected parts designed to carry loads and provide adequate rigidity.	Comité européen de normalisation (2010)	Timber structures

Term	*Definition*	*Source*	*Category*
	Structures are typically composed of more structural members and need to be disassembled before re-using. They can be re-used in a different building design, but their spans and connection points should be carefully taken into account.	Hradil (2014)	
	The foundation and load-bearing elements are perilous and expensive to change so people don't. These are building. Structural life changes from 30 to 300 years (but few buildings make it past 60, for other reasons).	Brand (1994)	
Upgradability	Upgradable: an assembly of building materials of which the condition and performance can be improved efficiently. Upgradability is the degree to which an assembly is upgradable.	BAMB (2018)	Building circularity
Waste hierarchy	An order of prevalence for different end-of-life strategies	Van den Berg (2019) - PhD, Twente Univ-NL	Building circularity