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Circularity concepts in wood construction

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Abstract

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Executive Summary

When it comes to sustainability and circularity, wood as a natural raw material has a number of advantages over other building materials. The natural cycle of wood begins in the forest as trees grow, with solar energy and carbon dioxide as key inputs to wood formation. The cycle continues with conservative harvesting from sustainably managed forests and use of wood in producing a broad range of products. When used in the industry in a cascaded way, wood circulates in the technical cycle where it can be recovered either at the end of its first useful life, or in the form of residues or by-products from production processes. Wood used in construction can be applied in diverse functions, as parts of buildings (e.g., for structural frames, decking, flooring, wall and roof sheathing, window frames, doors, and more) or at different stages of construction processes (e.g., for foundation framework supports and scaffolding).

Whether or not a practice is sustainable rests on three pillars: environmental protection, economic viability, and social equity. Wood fares well in all these categories. The fact that wood is renewable and can be converted to useful products using relatively little fossil energy makes it less environmentally impacting than such materials as steel, masonry, and reinforced concrete. These things, of course, translate to environmental advantage only if wood is produced in a sustainably managed and responsively harvested forest or plantation. But here too, wood has an advantage in that third party oversight of forest management is widely practiced via forest certification programs that have been in place for almost three decades. Providing for rigorous evaluation of all aspects of forest management, including impacts to soil health, water quality, fish and wildlife habitats, rare and endangered flora and fauna, cultural and historical sites, and more, these programs provide a means of ensuring attention to important issues while producing sustainable volumes of wood and other products and services. They also provide a social context for wood production, bringing to the fore common social concerns and allowing external overview of industry practices.

In many parts of the UNECE region wood dwelling units account for only 10-11% of new construction, or less. Limitations on building with wood, including limits on construction height also exist in many places.

The new types of wood products that have enabled wood to replace in certain stances steel and reinforced concrete in tall buildings are all the result of extensive research over many years. And they are the result of focused attention to obtaining greater uniformity of properties than exhibited by solid wood. The cumulative result of many decades of research – and more than a century since the issuance of a German patent for glue laminated timber - mass timber buildings today contribute to circularity and environmental sustainability while also providing a highly engineered and high performing material for construction. Mass timber allows for the beneficial use of renewable resources which can be fashioned into useful products with less manufacturing waste than previous

forms of structural wood products, provide low carbon-emission alternatives to reinforced concrete and steel, and store massive quantities of carbon for as long as they remain in existence.

Modern wooden construction methods have been developed with economic pragmatism in mind, intuitively applying sustainability and circularity principles at the same time. New technologies incorporating a high degree of prefabrication are employed that speeds construction processes, provides for precision sizing of modules and connections – thereby promoting energy efficiency of completed buildings, greatly reduces waste, and protects prefabricated modules from the effects of weather.

Responsible wood use in construction is more circular and sustainable than use of other common building materials. Wood has inherent advantages and provides multiple benefits because it is a natural material, can be fashioned into useful building components with minimal climate impact, and can be incorporated into buildings which have lower lifecycle energy consumption and lower CO_2 emissions than non-wood structures. Substitution of wood for reinforced concrete or steel in construction results in reduced embodied carbon emissions. Significant additional carbon storage could occur within the built environment with the use of wood in construction with the caveat that it is important that the wood not go to landfill at the point of building demolition or deconstruction. Wood use in the construction sector results in lower use of fossil fuel energy and lower embodied fossil energy in the built environment. The reduced greenhouse gas emissions and use of renewable bioenergy in wood products manufacturing contribute to circularity and sustainability.

Although wood use in construction offers substantial sustainability and circularity benefits, there is also additional innovation that is needed. Currently, waste from building deconstruction is not being recovered effectively. Designing for building adaptability or disassembly and effective material recovery needs to be accomplished to improve the circularity of wood in the construction sector. The data suggests that there is considerable room for improvement in wood recovery and recycling at the end of life of buildings. The greatest opportunity for improved circularity of wood in existing buildings is in the recovery and reuse or recycling of building demolition waste.

However, for an overall transition of the wood construction sector to a more circular model, a systemic approach is needed to enhance increased integration across and along value chains. Such approach should move away from the business-as-usual towards a more cross-cutting collaboration among different actors within and outside the construction sector. An increased collaboration of designers, architects, urban planners, engineers, municipality actors and legislators would contribute to achieving greater sustainability and circularity at different stages of construction value chains.

Contents

1. CHAPTER 1 Setting a stage for circularity in wood construction

1.1. Understanding Circularity and Sustainability

Many of the global priorities imbedded in the 2030 Agenda for Sustainable Development[1] and the Sustainable Development Goals (SDGs) relate to forests and forestry, to forest-based industries and to bioenergy. SDG 15 Life on Land directly refers to the need for sustainable use of ecosystems, sustainable management of forests, and to reversing the land degradation ceasing the biodiversity loss. SDG 13 that is dedicated to Climate Action cannot be achieved without resilient forests and responsible forestry practices, while SDG 6 clearly mentions the need for protection and restoration of water-related ecosystems, including forests, wetlands, rivers, and lakes.

Existing, linear production and consumption patterns, based on "make, use, dispose" models are no longer sustainable and many key economic sectors and industries, including those using forest-based products, such as construction, furniture manufacturing, and pulp and paper industry, contribute in a significant way to pollution and waste generation. SDG 12 that calls for responsible production and consumption refers to circularity principles and sustainable use of natural resources. It points out the need of increasing resource efficiency, promoting sustainable lifestyles, producing more with less, and decoupling economic growth from environmental degradation in the long-term.

The achievement of many of these objectives in the context of increasing use of forest resources and growing environmental challenges, linked with greenhouse gas emissions and waste generation, requires application production and consumption models based on sustainable use of natural resources and the regeneration of biological systems.

Although the term "circular economy" does not appear in the 2030 Agenda for Sustainable Development, circular economy practices can contribute to achieving a number of SDGs. A study by Schroeder *et al*., 2019[2] noted that the strongest relationship exists between circular economy and SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Production and Consumption) and SDG 15 (Life on Land) (UNECE/FAO 2022)[3].

A transition towards a sustainable, bio-based, circular economy at the global level is often perceived as a way to achieve an economic model which can increase sustainability at the environmental, economic, and social levels, and, at the same time, reduce the global economy's dependence on non-renewable resources in the long term.

The circular economy model coexists in the policy space and in research with a number of concepts that have been developed earlier or simultaneously to it. The origins of circularity itself are older and more diverse than it is commonly perceived and are rooted in ecological and environmental

[1] https://www.un.org/sustainabledevelopment/development-agenda/

[2] Schroeder, P., Anggraeni, K., Weber, U., 2019. The Relevance of Circular Economy Practices to the Sustainable Development Goals. Journal of Industrial Ecology 23, 77-95.

[3] UNECE/FAO, 2022. Circularity Concepts in Forest-based Industries. https://unece.org/sites/default/files/2022-05/Circularity%20concepts%20in%20forest-based%20industries%20ECE_TIM_SP_49.pdf

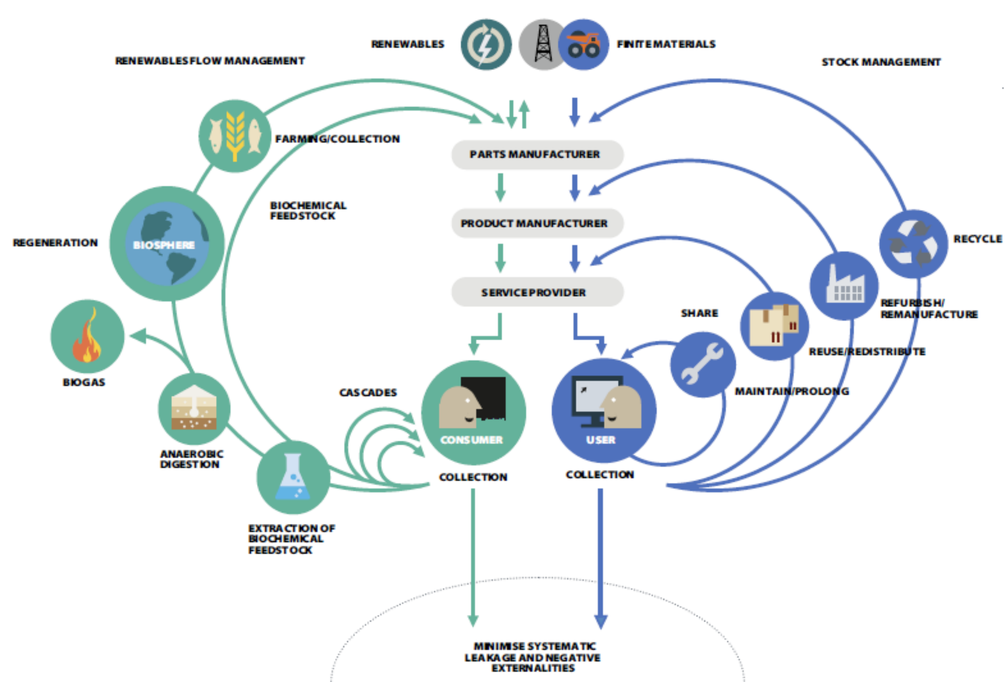
economics as well as industrial ecology (UNECE/FAO, 2022). Concepts regularly used today, such as circular economy, green economy, bioeconomy, and sustainable economy differ, but are consistent with each other since they all aim at synchronized optimization of ecological economic and social objectives at different levels (Durocher, 2021)[4] in the same way as the 2030 Agenda for Sustainable Development does.

For the needs of this study the concept of a circular economy based on the model of the Ellen MacArthur Foundation (Figure 1) is used as described in UNECE/FAO (2022) and takes into consideration its modifications by Oneil and Russel (2020)[5] presented below.

The Ellen MacArthur Foundation model distinguishes between technical (blue) and biological (green) cycles. This interpretation of circularity involves materials of biological origin that can return to the biosphere in the form of nutrients, and technical materials that cannot biodegrade but can circulate in closed loops thanks to circular practices.

Figure 1.

Biological and technical cycle in a circular economy model by the Ellen McArthur Foundation.



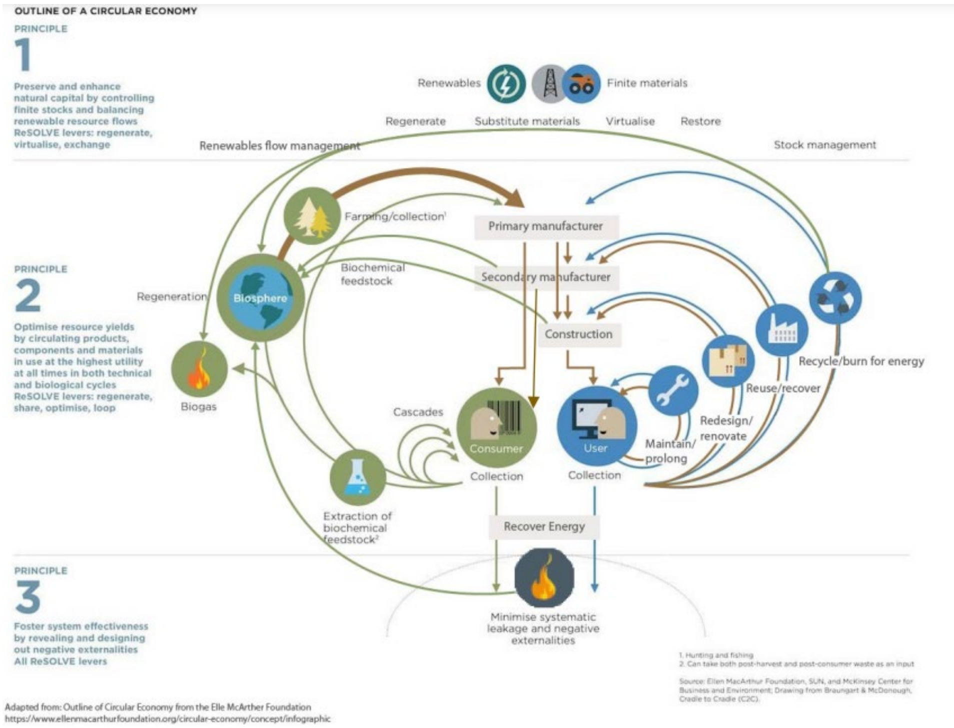
Source: https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic. Copyright © Ellen MacArthur Foundation (2017).

Oneil and Russel (2020) applied the Ellen MacArthur Foundation model for the use of wood in construction, furniture manufacturing and bioenergy production to illustrate the flow of wood from the biological to the technical cycle and back and within the technical cycle (Figure 2).

[4] Claude Durocher, 2021. State of the Global Forest Bioeconomy.

[5] Elaine Oneil, Jennifer Russel. 2020. A Framework for Incorporating Wood into the Circular Economy.

Figure 2.



Source: Oneil, Russel (2020)

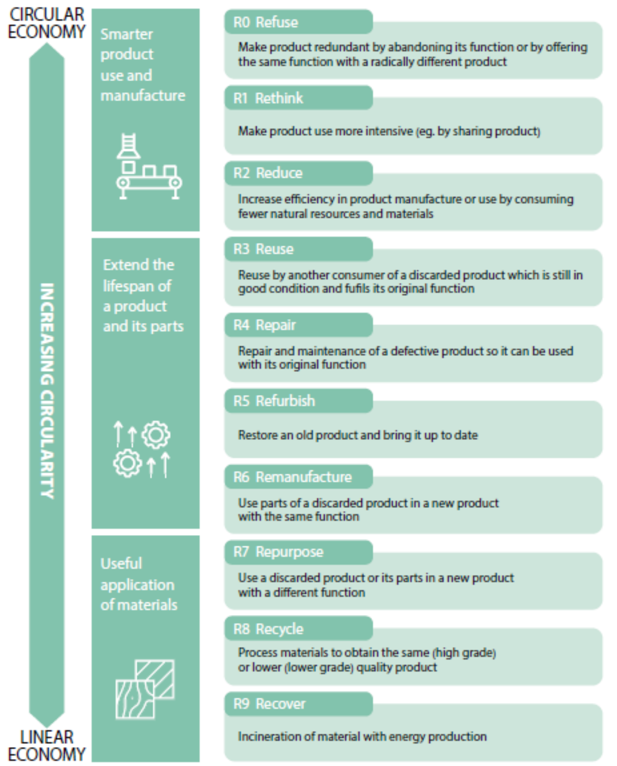
This modification of the Ellen MacArthur Foundation model acknowledged that wood begins its life cycle as a renewable resource (green cycle) and then crosses over into the technical (blue) cycle, where it splits into two distinct streams: 1) solid and engineered wood circulating in the technical (blue) cycle and 2) by-products and residues crossing back to biomaterials (green) cycle. In both cases wood continues its lifecycle through cascading use until it is recovered for bioenergy at the end of life, when CO_2 is released to the atmosphere and made available for trees to begin a new cycle (Oneil, Russel. 2020).

Based on this model, this study also makes an assumption that emissions associated with resources extraction and waste management linked to the use of non-renewable materials will decrease with a measured optimization of resources extraction and a steady replacement of non-renewable materials by renewable resources in the long term. This way a new economic model will be not only circular but also bio-based and more sustainable.

In this study the "circularity and sustainability practices" are understood by the application of the 9R approach (Figure 3) at different stages of the construction value chains, as presented in UNECE/FAO (2022) with the recognition that the focus has been made on analyzing industry practice, without considering forests and forest operations, to which a separate study will be dedicated (see below).

Figure 3.

Circularity and the 9Rs.



Source: UNECE/FAO, adapted from Ellen MacArthur Foundation (https://www.ellenmacarthurfoundation.org)

While the 9R model will be the basis for consideration of circularity and sustainability in the wood construction sector, it is understood that many of these R-approaches should be seen differently than in the case of many technical materials. It is due to the fact that once wood is transformed, it spans through several reuse, recovery, and recycling processes, in a cascading use before it is shredded or incinerated in order to feed back into the biological cycle of wood growth, before it is ready to be used by the technical cycle again. That is contrary to many technical materials that, once they enter the technical cycle, they can be recycled and transformed into materials similar to their origin without leaving the technical cycle.

1.2. Circularity and Sustainability in Wood Construction

Construction is a complex undertaking due to the diversity of materials, methods, and products used, and the combination thereof. Wood has been used in building for centuries and it is still one of the most widely used materials. It can be applied in a variety of structures thanks to the variety of properties offered depending on the type of wood. Also, with the appearance of engineered wood products the interest in the use of wood has been growing in the last few decades.

The concept of a circular economy is already familiar to some in the construction industry although its exact meaning is still vague. Circularity approaches are traditionally present in wood construction through practices such as rebuilding from used lumber or logs from recovery of old wood buildings (Antikainen *et al*, 2017)[6]. In modern construction types (residential, industrial, commercial, and civil engineering) environmental arguments favor the shift to wood construction and the advances in construction techniques and productivity emphasize resource efficiency objectives and minimization of production waste both overall and at the construction site.

Together with the sector's adoption of engineered wood, attention is being given to waste reduction in the construction process, including with the development of modular prefabricated construction techniques which ease the disassembly in the end-of-life stage. Recently, attention has also been given to sustainable material and product development, with the use of CLT and glulam in building construction, CLT being a trend that started in Europe, and which is linked with high-rise (tall wood) construction and increasing interest in prefabricated residential and non-residential buildings. Related to this, a high degree of customization and application of wood for nearly any building part, including load-bearing structures, is transforming the wood construction sector and is contributing to material efficiency (FAO, 2022)[7].

Applying circularity approaches to construction value chains through innovative design, regular maintenance, adaptive reuse, refurbishment, repair, recovery, and recycling can help to recapture some of its value (Delphi Group, 2021)[8]. However, wood can be considered a renewable material only when it is sourced responsibly from sustainably managed forests. Combined with sustainable spatial planning and eco-design, it is a durable, reusable, and recyclable resource, fitting the principles of a circular economy, contributing to sustainable use of natural resources and the mitigation of climate change.

Being a natural, bio-based raw material, wood has a potential to play a central role in a transition to a sustainable, bio-based, circular economy. In addition, apart from being a natural and biodegradable, wood is also a readily available construction material which is economically competitive in many parts of the world, and a strong and durable material in relation to its weight and environmental impact.

After the adaptation of the Ellen MacArthur Foundation circular economy model to represent the wood flows, Oneil and Russel built on the same model to present a lifecycle of solid wood products destined for building construction (Figure 4). The model shows the life cycle of products coming from working forests and flowing to the construction uses, through cascading value retention processes in the technical (blue) cycle until end-of-life and then into the biological (green) cycle at the end of its useful life (Oneil, Russel, 2020).

Figure 4

[6] Antikainen, Riina; Dalhammar, Carl; Hildén, Mikael; Judl, Jáchym; Jääskeläinen, Tiina; Kautto, Petrus; Koskela, Sirkka; Kuisma, Mika; Lazarevic, David; Mäenpää, Ilmo; Ovaska, Jukka-Pekka; Peck, Philip; Rodhe, Håkan; Temmes, Armi; Thidell, Åke. 2017. Renewal of forest-based manufacturing towards a sustainable circular economy, Reports of the Finnish Environment Institute 13/2017, http://hdl.handle.net/10138/186080

[7] Verkerk, P.J., Hassegawa, M., Van Brusselen, J., Cramm, M., Chen, X., Maximo, Y. I., Koç, M., Lovrić, M. and Tegegne, Y. T. 2022. The role of forest products in the global bioeconomy – Enabling substitution by wood-based products and contributing to the Sustainable Development Goals. Rome, FAO. https://doi.org/10.4060/cb7274en

[8] Delphi Group, 2021. Circular economy and the built environment sector in Canada

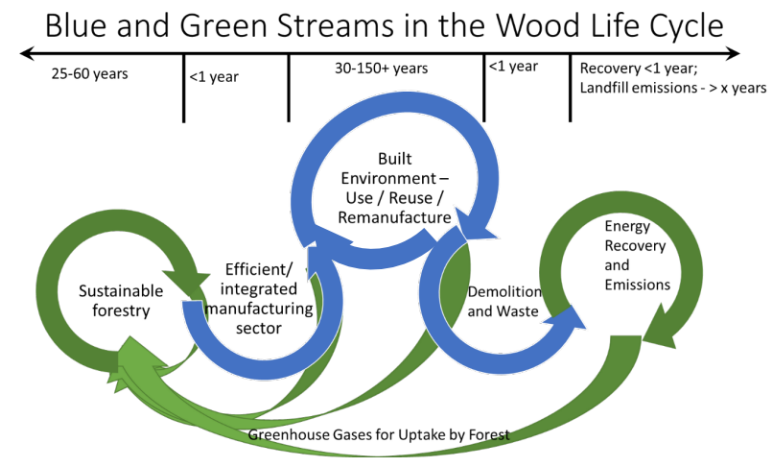


Figure 4 Life cycle of a solid wood product destined for building construction showing the cross-over from green to blue material flows vis a vis EMF circular economy model.

Source: Oneil, Russel (2020)

The model illustrates a more inclusive view on a circular economy, compared to existing circular economy models. It takes into consideration the energy recovery and the CO_2 absorption by forests, highly relevant for circularity in the forest sector, because of wood's characteristics as a material that is a subject to cascading use, with bioenergy at the end of life and the emissions coming back to forests to initiate a new cycle.

1.3. Background and objectives of the study

The study aims to provide a comprehensive overview of how circularity concepts and sustainability practices, based on models presented above, can be applied in wood construction. The work on the study results from a mandate given by the Committee on Forests and the Forest Industry (COFFI) of the United Nations Economic Commission for Europe and the European Forestry Commission (EFC) of the Food and Agriculture Organization of the United Nations, during their Joint Session in November 2021 to "(a) prepare a series of studies further reviewing the application of circular models in specific forest-based industries, including through identification of case studies and best practice (b) take into consideration the whole forest-based value chain and bring attention to the circular nature of wood as a renewable resource and the role of sustainable forest management"[9].

The focus of the studies has been identified through consultations with the UNECE/FAO Team of Specialists on Sustainable Forest Products between April and June 2022 and validated by the Joint UNECE/FAO Working Party on Forests Management, Economics and Statistics during its session in June 2022. The series will include the following studies:

- Universal preconditions of circularity in forest-based industries
- Circularity concepts in the wood construction sector as an example of long-lived products value chain

[9] (ECE/TIM/2021/2 FO:EFC/2021/2)

- Circularity concepts in pulp and paper industry as an example of a group of commodities with short life span

The studies build on the previous UNECE/FAO study "Circularity concepts in forest-based industries" (2022) and aim to present a more detailed insight into the circularity issues in forest-based value chains. They contribute to the "research and guidance for policymaking" activities of the UNECE/FAO Integrated Programme of Work 2022-2025, implemented by the UNECE/FAO Forestry and Timber Section in Geneva.

1.4. Scope and limitations

This study examines the benefits of wood use in construction as bio-based material, compared to other construction materials, from the perspective of circularity, sustainability, and climate change mitigation. It considers circularity practices at different stages of construction value chains, including retrofitting and deconstruction, and the end-of-life solutions. Different construction types (residential, industrial, commercial, civil engineering) and construction methods are analyzed to provide evidence how construction design, planning and practices contribute to circularity and how circularity concepts can be further promoted in the construction industry.

The study, as part of a series, focuses on the use of wood in construction as an example of a long-lived wood-based products value chain. Analysis is supported with examples of good practice in the construction sector. Building on existing circular economy models, the focus of this study is on analyzing circularity in the industry context, rather than the optimal use of forest resources for construction. This limitation was adopted as the implications of circular approaches on forest health and the sustainability of wood provision, in particular the balance between the use of wood and other forest ecosystem services, will be given due attention in a separate study of the series, analyzing universal preconditions of circularity in forest-based industries.

While this study presents the current industry context and points out opportunities and challenges in transition to a more sustainable and circular economy, it is important to note that circularity does not always equate to environmental sustainability or climate neutrality. Therefore, an effort has been made to recognize that successful implementation of circularity principles in the wood construction sector should also take into consideration a variety of aspects, such as the impact on environment and human health as well as their practicality and economic feasibility, often not included in theoretical models. Consequently, the objective of this study is to understand how wood flows in the construction sector and how it contributes to the renewal and sustainability of construction value chains.

1.5. Methods and data sources

Evidence and information reviewed in this study comes mainly from desk research, a review of the scientific literature, and subject matter knowledge. Additional information has been provided from government information sources and partnering organizations, including invited case studies and examples of good practice.

[To be completed after the COFFI session]

1.6. Structure of the study

Chapter 1 sets out the context and the objectives of the study and provides information on what is the understanding of the circular economy for the needs of this study…

Chapter 2 describes the benefits of wood in the construction sector…

Chapter 3 discusses the circularity practices applied in the wood construction sector…

Chapter 4 provides examples of concrete projects and case studies which implement the principles of circularity and sustainability in the wood construction sector…

Chapter 5 presents the study's conclusions and recommendations…

[To be completed after the COFFI session]

2. CHAPTER 2 The role of wood construction in a circular economy

2.1. History of Wood Use in Construction

Wood has long been widely available, relatively abundant worldwide, renewable, light weight yet strong, readily fashioned into useful products, and esthetically pleasing. Wood is today, and has been for many centuries, the dominant material used in construction of homes (i.e., single family residences) and some types of commercial buildings, including low-rise buildings in many regions of the world. As reported by Cabral and Blanchet, 2021, wood buildings account for 90% of single-family homes in Canada and the United States of America, 45-70% in parts of Europe, and 45% in Japan. Such use of wood in construction is likely to continue due to the basic characteristics of wood, its availability, and the growing interest in circularity and sustainability.

Figure 5
On-site Construction Typical of the United States of America and Canada

The type of wood construction varies widely by region. Wood post and beam construction is, for instance, typical in Japan, with prefabrication of building components common. In post and beam construction, timber is the main structural material, with wall elements typically non-loadbearing. In contrast, in the United States of America and Canada, single family homes, and other low rise residential structures are commonly platform frame construction built of wood, with much of the component assembly done on site with the exception of prefabricated floor and roof trusses. In Northern Europe, homes are also constructed dominantly of wood, although wall assemblies tend to be more robust than in Canada and the United States of America, with the vast majority of homes constructed off-site in some form, including sectionalized and modular components (Hedges and LaVardera, 2017). In many other parts of Europe, and especially Southern Europe, wood construction is less common. In Germany and the United Kingdom of Great Britain and Northern Ireland, for instance, wood dwelling units account for 10-11% of new construction, in Italy and France 7% and 4%, respectively, and in Spain and other parts of Europe 2-3% (Hildebrandt, Hagemann, and Thrän, 2017).

Across Europe, local regulations and other considerations have generally not constrained the height of wood structures. An exception is Germany where federal rules have limited the construction of wood framed houses to a height such that the flooring of the upper level that contains a living space be no more than 13 metres above the ground level. Other jurisdictions in Europe have required the installation of sprinkler systems for wood buildings taller than several storeys (Mahapatra, K. and Gustavsson, L, 2009). In Canada and the United States of America, codes for many years specified maximum building heights of no more than 4 storeys, a limit that in recent decades was increased to 6 storeys in some jurisdictions, particularly with the advent of podium slab construction in some regions wherein wood construction rises above one or two storeys of reinforced concrete. Still, the allowable height of wood structures has historically been effectively almost universally limited due to concerns about safety in the event of a building fire.

Development of a number of new types of wood-based mass timber products have created opportunities for wood construction at greater heights while meeting other objectives including addressing safety requirements. Over the past four decades innovation in wood products has culminated in unprecedented change in possibilities for wood use in construction, and particularly for use of wood in construction of tall buildings. The latest editions of the US-based International Building Code and the Canadian National Building Code have both adopted new provisions allowing mass timber structures as high as 18 storeys in the United States of America and 12 storeys in Canada. These new products also allow improved utilization of varied wood species, sizes, and grades to contribute to less waste and greater circularity. The use of these products contributes to sustainability goals through their market-based support for forest management and investments in forest-based businesses and green jobs. Many of these new products are structural wood composites, produced by assembling small wood pieces and particles, or larger wood members, into much larger products with the capacity to be used in new ways as structural components of buildings.

To create some of today's innovative wood construction products relatively small pieces of wood are glued together, with the grain of all pieces parallel to one another, to form large wood beams and columns. These kinds of products and techniques have been used for over 100 years to construct spectacular roofs of church buildings and other types of structures. In the mid- to late 20^{th} century wood scientists began to experiment with ways to create large structural wood members from relatively small trees. With initial work done primarily in the United States of America and Canada, a number of new products were introduced, including various forms of structural composite lumber created from multiple layers of veneer (laminated veneer lumber or LVL), or from thousands of thin strands of wood compressed into large members such as laminated strand lumber (LSL), and parallel strand lumber or (PSL). These products, which can be made to virtually any size, also eliminated the problem of large variation in wood strength due to natural features of solid wood. By eliminating or dispersing knots, holes, slope of grain, and other limiting factors, these new products offered uniform strength and other properties, establishing wood for the first time as an engineering material, with predictable features and comparable applications to steel and structural concrete.

The development that served to change the potential for use of wood in tall buildings is one that had its beginnings in Europe – and that is the introduction of Cross Laminated Timber (CLT). First used for roof systems in Germany in the early 1970s, then further developed in Germany, Austria, and Switzerland during the 1990s (Karacabeyli and Douglas, 2013), CLT is made of a number of layers of lumber, glued together with the grain of alternate layers laid at right angles to one another, much like the veneers of plywood. CLT panels today can be as large as 0.5 x 6 x 18 metres. Also known as mass timber, CLT offers many advantages in the form of large size load-bearing panels that provide building stability, fire resistance, long-term carbon storage, and renewability. A related product, made by nailing wood components together, is marketed as Nail Laminated Timber or NLT. Engineers and architects soon discovered that through the use of CLT and NLT panels, in combination with large-engineered wood columns and beams, wood buildings could be constructed to previously unimagined heights.

Photo: naturallywood.com Photo courtesy of Lever Architecture

Figure 6. Cross Laminated Timber (CLT)

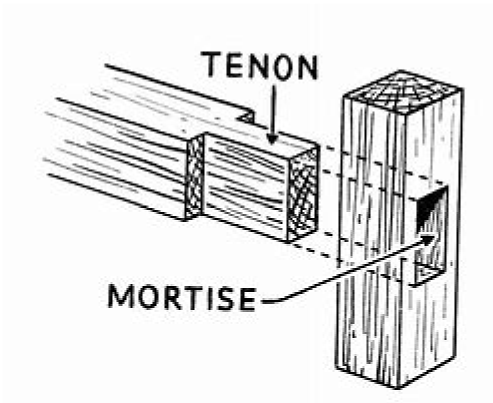
Within a period of less than two decades mass timber buildings have transformed the skylines of modern cities around the world. Such constructions have appeared in Canada, Norway, Sweden, the United Kingdom of Great Britain and Northern Ireland, and the United States of America (Verkek *et al*., 2021). Mass timber construction, which typically involves use of CLT in combination with other structural wood composites, is increasingly finding application in large scale structures, including multi-storey residential buildings and industrial and commercial structures, as well as in construction of civil engineering work. The transformation of construction to incorporate greater use of wood offers opportunities to enhance circularity and sustainability throughout the built environment and the related industries.

2.2. Traditional Construction Methods

Wood structures have been built for thousands of years. One of the first documented examples is Europe’s Neolithic longhouse, a freestanding timber building constructed about 5,000-6,000 BCE (Cochran, n.d.). In many parts of the world, where timber was abundant, early inhabitants used wood in many forms to build simple structures including log buildings for shelter. Over time, log construction became more sophisticated as logs were flattened on two sides, or fashioned into square timbers, to improve continuity of wall surfaces and provide greater protection from wind, rain, and heat loss.

At some point timbers began to be formed into structural frames, incorporating both horizontal and vertical members, with connections made using notching, mortise and tenon joints, and wood pegs (Figure 12). Timber framing later spread to Central Europe and soon thereafter to northern regions of the continent (Cochran n.d.).

Figure 12
Mortise and Tenon Connection



Wood buildings made in this way have been found to weather frequent earthquakes and typhoons better than structures constructed of non-wood materials (Animo, 2004).

In its early form, timber frame construction is described as half-timbered. In the half-timbered form timber provided the structural frame of the building and the spaces between the frames were filled with plaster, brick or wattle and daub. The half-timbered method of construction was common in parts of Europe, that are now France, Germany, and the United Kingdom of Great Britain and Northern Ireland in particular until the 17th century. After 1400, many European houses were made of masonry on the first floor – thereby providing greater protection from bands of marauders - with half-timber construction above. (Chisholm, 1911).

By the early 1600s, several factors contributed to a shift away from wood construction, and from wattle and daub, in much of Europe. A major factor was that there was a lack of established sustainable forestry practice and an overuse of wood for a myriad of uses, including production of charcoal, home heating, and building construction, led to a strain on supplies of timber. Another factor was changing fashion, which led to imitation of Mediterranean construction and increased use of clay or stone in construction (WoodMasters, 2015).

Through succeeding centuries and to the present, sustainable forestry practices have become widespread, timber supplies have recovered, and timber framing has remained the most common form of wood construction in Central Europe. Mortise and tenon connections have been replaced with various types of metal connectors, and infill with non-load bearing wall framing sections which are anchored to vertical elements of the timber frame. Many houses also continue to be built in the half-frame style wherein a frame of wood timbers provides the structural strength, and infill consists of non-wood materials such as stone, concrete block, or brick. Another form of construction involves stacking of squared timbers to create walls (sometimes both interior and exterior). Roof structures are wood and with wide overhangs common. In northern Europe, post and beam construction is common, with heavy timbers supporting the building; heavy wood framing or timbers typically fill spaces between timbers, with extensive attention to tight construction and insulation.

As Europeans began migrating to North America in the early 1600s, they brought with them knowledge of construction methods from their home countries. German settlers to what would become the State of Pennsylvania often constructed precision-built log homes (Youngquist and Fleischer, 1977), and Scandinavians for the most part also opted for log buildings (Carlsen 2008). Those from other areas and especially from today's United Kingdom of Great Britain and Northern Ireland, built half-frame structures using wattle and daub as infill. But those in half-frame houses in the northern reaches of the Americas soon found that the wall construction methods that had proven adequate in United Kingdom of Great Britain and Northern Ireland and southern France did not provide sufficient protection from the cold in their new location. Consequently, timber frame buildings began to be sheathed with solid wood siding of oak or pine, sometimes with narrow strips of wood underneath (Youngquist and Fleischer, 1977). Log and half-frame construction remained dominant in the eastern half of North America through the early 1800s, when dramatic change came about due to three developments, which in combination effectively changed everything (Carlsen 2008).

First, automation brought mass production of nails, which previously had to be hammered out on a forge, one-by-one. Thus, whereas nails had previously been relatively scarce and quite expensive, they became plentiful and inexpensive. At about the same time, a number of sawmills converted to steam power rather than waterpower, meaning that these mills no longer needed to be located near rivers, and could instead be situated more closely to where lumber was needed. The result was an increase in the number and availability of sawmills which could quickly convert logs into long, narrow pieces of lumber often referred to as dimension lumber. That development, in turn, led to the introduction in 1830 of a building technique known as balloon frame construction, a form of timber frame building (Carlsen 2008).

Similar to platform construction in common use today, balloon frame construction involved assembly of wall sections, using nails, composed of vertical members connected at each end by top and bottom plates. Wall sections were assembled on the ground, with these walls subsequently raised into place by a team of workers. Each vertical member was cut to the full height of the wall, from sill to roof line. As houses were commonly built to two storeys, this meant that vertical members were 20 to 30 feet in length. The fact that wall supports were the full height of walls marks the key difference between balloon frame construction and platform framing which came later. The method allowed rigid construction of buildings involving relatively few people, and because of these efficiencies in labor and materials it became the dominant form of home construction in the United States of America and remained so well into the 20th century (Carlsen 2008).

By the 1940s, platform framing - a refinement of timber frame construction - had largely displaced balloon framing. Using this method, buildings were constructed one floor at a time. After putting in foundations and floor platforms, walls were assembled as before, but in this case wall supports were cut to the height of the one floor being added. This was followed by the addition of another platform and another set of walls, and so on. While fire concerns limited wood building height to only 2-3 storeys, from an engineering perspective the method allowed for much taller buildings. Soon after the shift to platform construction softwood plywood came onto the market, allowing for rapid sheathing of exterior walls, which were then covered by siding or other weather resistant materials (Carlsen 2008). Other than a few changes designed to enhance energy efficiency and prefabrication of some building elements such as roof and floor trusses, this form of construction is representative of most homebuilding, including multi-storey, multi-family construction, in the United States of America and Canada today.

Despite examples of deforestation and forest degradation in some parts of the world over centuries, traditional wood construction in many regions followed circular and sustainable approaches in the light of today's concepts and definitions. In many areas it was based on local sourcing of raw material, whereas buildings were repaired, refurbished and reused for different purposes and over decades.

2.3. Benefits of Wood Use in Construction

Responsible wood use in construction is more circular and sustainable than use of other common building materials. Wood has inherent advantages and provides multiple benefits because it is a natural material, can be fashioned into useful building components with minimal climate impact, and can be incorporated into buildings which have lower lifecycle energy consumption and lower CO_2e emissions than non-wood structures.

Where wood is produced in sustainably managed and responsibly harvested forests or plantations, there are many environmental advantages of wood as a construction material. Wood is:

2.3.1. Produced by Solar Energy

Wood is, moreover, a material produced by the process of photosynthesis – a process driven by solar energy. At a time when society is increasing interested in effectively harnessing solar energy for power generation, the forest is already engaged in the routine production of wood through capture of solar energy. The natural, solar energy-based process of tree growth provides a extraordinary sustainability advantage for wood. As a consequence of utilization of freely available, zero impact energy by growing trees, even after further processing, the additional energy, and in particular the fossil energy, required to produce wood building components is typically significantly lower than for other major construction materials. Additionally, in many cases utilization of solar energy in the forest is supplemented by use of renewable biomass energy in wood processing facilities. Thus, wood building materials often require less energy to produce than available alternatives, and decidedly less fossil-fuel derived energy as well. As an added bonus, which no other material can duplicate, the natural process of photosynthesis which results in wood production in the forest is accompanied by production and release of oxygen.

2.3.2. Largely Composed of Captured and Stored Carbon

The fact that wood is produced as a result of photosynthesis translates to another key advantage: growing trees capture carbon dioxide from the air, sequestering much of that carbon in the form of wood. Among all species of wood found in the world, carbon composes on average one-half of its dry weight. When trees are subsequently harvested to produce wood products, the carbon within their trunks continues to be sequestered in the products made from it for as long as those products last, which in the case of buildings can be 100 years or more. Therefore, when wood is used in construction, specific buildings and even entire neighborhoods become additional carbon storage pools to those in the form of forests and grasslands. In the United States of America, where wood is dominant in homebuilding, the quantity of CO_2e[10] represented by the carbon contained in wood in use in 2020 was estimated at 1.5 trillion tonnes, or over 10% of the quantity contained in above-ground forest biomass, with an annual flux of 20 million tonnes (USEPA, 2022).

The magnitude of carbon storage in wood is also exemplified by Sherrill and Bratkovich (2018), who determined that a single white oak dining room table with ten chairs sequesters approximately 331 kg of CO_2e. The reality is that wood is composed of a great deal of carbon. By combining carbon capture during tree growth with the effect of delayed emissions due to the carbon storage in the provided wood products the use of wood in the circular economy contributes to immediate benefits as well as long term and extended climate mitigation goals.

2.3.3. Renewable

A key advantage of wood in comparison to other materials commonly used in building construction is that wood is renewable. Where forests or plantations from which wood is obtained are sustainably managed and responsibly harvested, the availability of wood for human use can be sustained for the long term at the same time that other critical values and amenities of forests are retained. Wood is the major construction material that provides multiple sustainability benefits

[10] Carbon dioxide equivalent: a unit for comparing the radiative forcing of a greenhouse gas to carbon dioxide. (ISO 6707-3:2017, 3.7.35)

throughout its production cycle as the use of wood requires the continuous growth of trees and support of associated biodiversity.

2.3.4. Strong, Yet Light Weight

It has long been known that wood has high strength in relation to its weight. In the emerging era of mass timber and tall wood buildings this reality has come into focus to many in the building design and engineering community. What this means is that wood buildings of comparable strength to buildings constructed of alternative materials weigh considerably less. One study, which compared a multistorey mass timber building with an otherwise identical reinforced concrete building, determined that the mass timber building weighed 67% of the reinforced concrete equivalent (Chen et al., 2020). As a result, buildings of great height that incorporate large amounts of wood can be built with less massive foundations, footings, and pilings than would otherwise be required (Gosselin *et al*., 2017). Wood is also a natural choice when additional storeys are desired on a building in which foundation and footings are not sufficiently robust for a functionally equivalent addition of upper floors built of steel or reinforced concrete. This advantage can result in tangible reduction of energy intensive building materials and concrete in particular. The reduced reliance on concrete can positively influence the carbon footprint of a building and contribute to circularity and sustainability of the construction sector.

2.3.5. A Natural Thermal Insulator

2.3.6. Wood and products made from it provide natural protection from heat transfer and loss. This is due to the fact that wood fibers are hollow, creating air pockets which serve to protect against heat transfer. Although modern building standards require greater protection from heat loss than wood alone can provide, the quantity of additional and often energy-intensive insulation needed in wood exterior walls is generally significantly less than in walls of concrete or those framed in steel. The use of wood and the benefits of its natural insulating properties can contribute to reduced use of other insulation materials that have associated climate impacts. The natural thermal insulator attribute of wood contributes to its value in reducing the environmental impacts of the built environment. There are also innovative opportunities for the development of insulation materials made from wood and wood fibre. The future development of wood fibre insulation can further advance circularity and sustainability in the construction sector. Recyclable

At the end of useful life of a structure made wholly or partially of wood, building components may be recovered for reuse and recycling. While reuse and recycling of wood at end of life is today relatively rare in developed countries, considerable potential exists for such use in a circular economy. Although reuse and recycling is also possible for many other categories of materials, wood has the advantage of also storing carbon and energy through its life. The potential for energy recovery from wood, which for one reason or another, cannot be reused or recycled, adds another dimension to end-of –life possibilities. Combustion with energy recovery is commonly practiced today, although there exists again great potential for expansion of end-of-life conversion to energy. The many alternatives for what can be done with wood after its first useful life offers circularity and sustainability benefits that are suitable for diverse situations, including where renewable energy generation is a priority or where avoidance of waste and reuse of materials is essential.

2.3.7. Esthetically Pleasing and Beneficial to Human Health

Many studies have found positive effects of exposure to wood on human health and well-being. Findings include those that have documented increase in human comfort (i.e., satisfaction with room conditions such as lighting, noise, temperature) when in spaces with extensive wood surfaces as compared to spaces containing no visible wood (Watchman, Potvin, and Demers, 2017). Positive effects on human health have been documented as well. For example, research has reported that the presence of visual wood surfaces in a room lowered activation of the sympathetic nervous system, a system which is responsible for physiological stress responses in humans (Fell, 2010). Kotradyova *et al*., 2019, similarly found that inclusion of wooden materials in medical facilities has a "regenerative and positive impact on the human nervous system", citing a range of factors from appealing aesthetics to contact comfort, and acoustics. Circularity and sustainability objectives are often focused on the resiliency of the economy and reduced impacts to the natural environment. However, the human experience, emotional, and mental and physical health aspects of sustainability are also critically important and can be supported with wood in construction.

2.4. Circularity and Sustainability of Wood Use in Comparison to Other Construction Materials

The discussion that follows focuses on the quantity of energy used, and carbon dioxide equivalent emissions generated, in the process of producing building components and constructing various types of buildings using wood, steel, and concrete. Comparisons can be tricky, in that modern buildings are virtually never constructed of only one material. Instead, builders and designers tend to use various materials in various proportions so as to take maximum advantage of the unique properties and construction benefits of each material. This is often true of both structural and non-structural elements. For purposes of this discussion, and the several case studies referenced herein, the type of building is defined by the dominant material used to construct the load-bearing frame.

2.4.1. Relative Impacts of Building Materials

Examples provided below are based on extensive analyses involving the application of life cycle assessment (LCA), a science-based tool specifically designed to allow for determination of multiple specific environmental impact indicators and interrelationships. With roots in the 1970s, but increasingly employed in the 21st century, LCA provides a mechanism for systematically evaluating environmental impacts linked to a product, from raw material procurement, transport, manufacturing, use, maintenance, and all the way to end-of-life treatment, e.g., re-use, recycling or disposal to landfill. The use of LCA is applicable to evaluation of products from as small as a pencil to as large as a tall building. Application of LCA yields definitive information regarding such indicators impact on climate change, water use, acidification, eutrophication, fresh water eco-toxicity, particulate emissions, ozone depletion, fossil fuel depletion, human toxicity, and more. Throughout this chapter, LCA-based findings are frequently referenced in discussions of how enhanced and optimized use of wood in construction can help to reduce greenhouse gases emissions and climate change. The application of LCA is also a key strategy for supporting circularity and sustainability because the LCA findings inform actions that improve the outcomes of material use and recovery.

As noted previously, there are three primary structural materials used in construction: steel, steel reinforced concrete, and wood. Energy consumption and carbon emissions linked to production of various materials (commonly referred to as *embodied energy* and *embodied carbon*, respectively), as determined by LCA, on both a mass and volume basis, are shown in Table 1. Although this data is specific to the United Kingdom of Great Britain and Northern Ireland, values are comparable to those of other European countries. In view of this, and although various materials are not used in equal mass and volume when constructing functionally equivalent buildings or components, the figures nonetheless provide insights into relative impacts of key structural materials.

Table 1 shows the embodied energy and embodied carbon associated with production of various materials. To apply this information effectively in the quantification of construction impacts it is important to know how materials are being utilized in a building. These comparisons are discussed in detail in the next sections. Also note that Table 1 differentiates between the carbon emissions associated with wood product manufacturing between those resulting from combustion of fossil fuels or of woody biomass used as fuel. The carbon emitted from combustion of wood residues is designated "bio" in reference to biogenic carbon which is unique from fossil-carbon sources.

Table 1
Embodied Energy and Carbon in Common Construction Materials

Material	MJ/kg	$kgCO_2e/kg$	MJ/m^3	$kgCO_2e/m^3$
Concrete	0.75	0.107	1,805	258
Steel reinforced concrete	1.79	0.184	4,550	837
Steel (virgin)	35.40	2.890	277,890	22,687
Steel (100% recycled)	9.40	0.470	73,790	3,690
Steel (structural)	13.10	0.720	102,835	5,652
Steel (galvanized rolled)	22.60	1.540	180,800	12,230
Softwood lumber	7.40	0.20 + 0.39 (bio)	3,774	102 + 199 (bio)
Laminated veneer lumber (LVL)	9.50	0.33 + 0.32 (bio)	4,845	168 + 163 (bio)

Glue laminated timber (Glulam)	12.00	0.42 + 0.45 (bio)	6,120	214 + 230 (bio)
Cross laminated timber (CLT)	27.20	0.80 + 0.93 (bio)	12,792	373 + 438 (bio)

Source: Inventory of Carbon and Energy (ICE) Database, Bath University (2010). Hammond and Jones (2008).

2.4.1.1. Steel

The environmental impact of steel construction materials is highly dependent upon recycled content. Energy consumed in making steel is considerably greater if producing from iron ore versus from steel recovered for recycling. As shown in Table 1 the impacts of new steel can be nearly 4 times greater than a fully recycled steel. Impacts also vary depending upon the types and quantities of metals used in creating different alloys of steel. Whether compared on a weight or volume basis, the production of steel requires greater energy consumption and results in greater CO_2 equivalent emissions that does production of steel reinforced concrete. However, steel does not substitute for concrete on a kilogram to kilogram or cubic metre to cubic metre basis. When functionally equivalent structures of steel and concrete are compared, results almost always show lower embodied energy and emissions for steel structures. Comparison of structural steel and structural composites such as LVL and Glulam show similar embodied energy on a weight basis, but vastly lower emissions (for wood) on a volume basis. But again, the weight and volume of functionally equivalent wood and structural steel are quite different; in this case, both embodied energy and emissions linked to production of engineered wood are consistently lower than for structural steel.

The recycled content of steel is dependent upon the intended use of a specific steel product. The degree to which recycled content steel can be incorporated into new steel products is limited by the extent to which alloying metals are present. Because current technology does not result in complete removal of all alloying metals, recovered steel is becoming increasingly contaminated with each recycling. One consequence is that the recycled content of thin steel used in making such things as wall framing and auto bodies is by necessity quite low (and thus embodied energy high). The recycled content of large cross-section structural steel components is thus far not constrained, although at some point will likely be in the future.

2.4.1.2. Concrete

The environmental impacts linked to production of concrete depend upon designed strength, which in turn is defined by the water to cement ratio. The greater the quantity of cement, the greater the impact. Reinforcing steel used in structural concrete also adds to overall impacts. Comparisons of embodied energy and CO_2e emissions in reinforced concrete and various wood products (Table 1), indicate that on a kilogram to kilogram, or cubic metre to cubic metre basis, concrete is a lower impact material than wood. But because of high strength to weight ratios, building modules made of wood are both less massive and far lighter than a functionally equivalent module of concrete.

On both measures, wood consistently outperforms both structural and non-structural concrete, and often by a substantial margin.

2.4.1.3. Wood

Lumber has the lowest environmental impact and offers the greatest contribution to sustainability of any structural wood product. Lumber production is highly technical, engineered, and exacting, but it is not an energy intensive heavy manufacturing process. Lumber production involves only sawing of logs, trimming and shaping of the pieces produced, and drying. Engineered structural wood products such as laminated veneer lumber (LVL), made by first separating solid wood into small pieces and then recombining the pieces using adhesive, or end-jointing lumber made into longer laminations and face gluing laminations to create glue laminated timber (glulam), increase the magnitude of embodied energy. With these additional processing steps and the use of adhesives these materials have associated impacts that are higher than for lumber (Table 1). Production of cross laminated timber (CLT) results in significantly greater impact per kilogram or cubic metre than lumber alone, even though the product is composed largely of layers of lumber. The difference is due to use of resin and/or large metal fasters to bind components together.

Of the three primary structural materials, wood is the only one that is composed of substantial quantities of carbon. About one-half the oven dry weight of wood is carbon, and wood continues to store that carbon as long as it exists, or throughout the life of the building or building component made of it. Wood is the only principal building material that stores substantial carbon, and as noted previously, significantly less carbon is emitted in the manufacture of wood building materials than available alternatives. While some types of steel are classified as high carbon products these contain only very small quantities of carbon.

2.4.2. Relative Impacts of Building Structures

The differences shown in Table 1 are large as a result of comparisons based on weight and volume. But when material use is viewed in the context of an actual building the significance of these differences become clearer. What follows are three examples of wood (or largely wood) buildings that have been constructed in recent years. These examples illustrate that in real-life situations the use of wood in construction compares favorably to available alternatives and contributes significantly to circularity and sustainability.

2.4.2.1. Wood Construction on the Rise

Brock Commons

Brock Commons is an 18 storey student residence built on the campus of the University of British Columbia (UBC) in Canada. The 54-metre-tall UBC Brock Commons residential complex includes housing for 404 students, assembly spaces, quad units (two per floor) which contain a pass-through kitchen, bathroom and bedroom, assembly and study rooms, and a student study-social lounge, in addition to mechanical spaces. This building is a hybrid, composed of a combination of mass timber (CLT, and glulam), structural steel and reinforced concrete.

The wood in the building (2,233 cubic meters of CLT and glulam) has captured 1,753 metric tons of CO_2 that will be stored throughout the life of the structure, and potentially beyond depending upon fate of materials at the end of building life. In addition, extensive use of wood in the structure rather than steel and concrete served to avoid 679 tonnes of CO_2e. The total carbon benefit of this building adds up to 2,432 tonnes of CO_2e. Expressed differently, the carbon savings from selection of wood rather than more concrete and steel are equivalent to not driving a typical passenger vehicle in Canada 18,713 km.

Figure 7 Brock Commons Photo courtesy Canadian Wood Council

John Hope Gateway Entrance to Royal Botanical Gardens, Edinburgh

Figure 8
John Hope Gateway

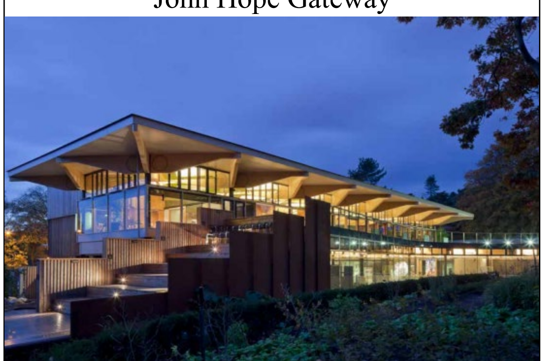


Photo: 100 Projects UK CLT, p. 274.

In this project CLT panels supported by a diagonal lattice of 117 exposed tapered glulam beams were used to create a dramatic effect above a restaurant and other areas associated with the John Hope Gateway Entrance to the Royal Botanical Gardens in Edinburgh, Scotland. The CLT forms a single horizontal timber plane that is accentuated by the supporting glulam beams that are used in conjunction with slender steel columns. A total of 674 cubic metres of wood were incorporated in this structure, that resulted in long-term sequestration of 366 tonnes of CO_2e. An additional 142 tonnes of emissions were avoided as a result of the selection of wood, rather than steel or reinforced concrete for the roof of the building.

Roof Beams – Gardermoen Airport Terminal Building, Oslo

In designing the roof structure for an addition to the Gardermoen airport terminal in Oslo, Norway, a question arose as to what material to use for roof-support beams: steel or glulam timbers. Assessment of steel versus glue-laminated spruce beams found that the manufacturing of steel beams for that project would have required 2–3 times more energy and 6–12 times more energy from fossil fuels than would functionally equivalent glulam beams. Analysts noted that if virgin rather than recycled steel were used, the differences as indicated above would be substantially greater. In the most likely scenario, steel beam manufacture was estimated to result in a fivefold increase in GHG emissions in comparison to glulam. The structure was subsequently built using spruce glulam beams (Petersen and Solberg, 2002).

Figure 9. Terminal 2, Gardermoen Airport, Oslo, Norway

These examples have highlighted the GHG emissions savings when using CLT and engineered wood compared to other construction materials. Further examples illustrate that any wood structure exhibits similar carbon advantage over structures constructed of alternative materials.

2.4.3. GHG Emissions and Climate Change

As the previous examples have illustrated, substitution of wood for reinforced concrete or steel in construction results in reduced carbon emissions. In creating a building, the mass of material used to construct it varies considerably depending upon the materials used. For instance, the weight of functionally equivalent structural framing made of concrete, steel, or wood vary greatly. Concrete structures weigh more than steel and far more than wood. This difference in weight has a direct bearing on embodied energy and overall environmental impact (see again Table 1). International Organization for Standardization (ISO) compliant comparative life cycle assessments have consistently shown lower climate impact of wood buildings than those constructed of concrete and steel.

The brief summaries that follow address research findings that have considered energy consumption from the point of raw material extraction (or recovery and recycling of raw materials if applicable) to completion of building construction.

- A Dutch study of four house types modeled with increasing quantities of wood used in construction found that a 12% reduction of CO_2 emission related to material use for residential buildings would be possible in the near term through an increase of wood use in residential buildings. (Goverse *et al*., 2001).
- A comprehensive assessment of single-family residential homes in two regions of the United States of America (Lippke *et al*., 2004) showed carbon emissions, from raw material procurement through completion of finished structure, to be 31% lower for wood in comparison to a concrete structure and 26% lower for wood in comparison to a steel structure. Because all of the structures analyzed had concrete foundations, the relative emissions as noted above were masked by the influence of emissions linked to use of concrete. Analysis of only the above-ground portions of structures, that eliminated the common foundation element, showed CO_{2e} emissions differences between wood and concrete, and wood and steel, to be 80% and 33%, respectively.
- A Swedish study of concrete and wood-framed buildings (Gustavsson, Pingoud, and Sathre, 2006) found higher energy and CO_2 balances for concrete structures (with differences in the range of 30–130 kg C per m^2 of floor area) and concluded that reducing the proportion of concrete building materials relative to wood building materials would be an effective means of reducing fossil fuel use and CO_2 emissions
- A study in the United States of America in which six commercial buildings representing different functionalities, material systems, and building techniques were redesigned through modelling to determine the impact on climate change potential (global warming potential) of substituting wood for steel and concrete in construction found an average reduction in climate change potential due to wood substitution of 60% across all building types examined (Milaj *et al*., 2017).
- A Swedish examination of a number of life cycle studies of multi-storey CLTbuildings (Younis and Dodoo, 2022) compared to equivalent structures made of alternative materials found notable savings in GHG emissions associated with the use of CLT. Reported emission reductions associated with CLT construction averaged 40%, primarily in comparison to concrete buildings, with differences greatest when carbon sequestration was considered in the analysis.
- A Canadian assessment of relative environmental impacts of a mid-rise office building constructed alternatively with structural concrete, versus CLT and engineered wood determined that the global warming potential of the concrete design was almost four times greater than for the CLT/engineered wood design (Robertson, Lam, and Cole, 2012.)
- A study in which conventional buildings of 8, 12, and 18 storeys, constructed with concrete and steel, were compared with otherwise identical buildings constructed of mass timber for

three regions of the United States of America, found that over all regions and building heights, embodied carbon in mass timber buildings was 22% to 50% lower than otherwise identical steel reinforced concrete buildings (Puettmann *et al*., 2021). In all of the mass timber buildings studied, carbon storage was determined to be greater than the carbon released in the process of product manufacture (including both fossil and biogenic carbon). In other words, the net global warming potential of the structure itself at the end of building life was net negative. The study concluded the carbon storage benefit of mass timber construction more than offset greenhouse gas emissions from manufacturing.

- A Norwegian study involving a comparative LCA of structural frames of timber, steel, and reinforced concrete for commercial structures found net negative climate change potential for timber framing, as defined in terms of CO_2e emissions per m^2 of building. The net negative climate change potential of timber frame was compared to significant emissions for steel and reinforced concrete frames, and the margin of difference was considerable. The difference in greenhouse gas emissions between wood and steel, and wood and concrete widened as the designed length of span increased (Hegeir et al., 2022).

Many more examples of consistent and replicable research findings could be given. As noted, buildings constructed of wood in any form consistently show lower embodied energy and carbon emissions than buildings of concrete or steel. This is particularly the case when analysis factors out confounding effects of common concrete foundations. Based on a large body of scientific studies, it is clear that the more wood is used in creating s structure, the lower the impact on the climate and the greater potential for circularity and sustainability benefits.

2.4.3.1. Carbon Storage

As noted previously, about 50% of the oven dry weight of wood is composed of carbon that was captured from the atmosphere in the process of tree growth. This sets wood apart from other construction materials that contain little or no carbon and are not derived from a natural and renewable growth process. For example, even high-carbon steel beams and columns contain only 0.6% to 2.0% carbon as a percentage of total weight. In the case of concrete, the production of which involves massive release of carbon dioxide, the finished product contains virtually no carbon, although carbon is slowly regained through carbonation[11] over the life of concrete products. Consequently, increased use of wood in construction could substantially increase the volume of carbon stored in buildings.

An example of the carbon storage potential is provided by a study conducted by the Potsdam Institute for Climate Impact Research_in Germany, and as reported in the journal *Nature Sustainability* (Churkina et al., 2020). This study examined four possible scenarios of timber use in buildings over the succeeding 30 years, with results compared to what was described as "business as usual: 0.5% of buildings constructed of wood, with the vast majority remaining constructed of concrete and steel". For comparison, scenarios were developed in which 10%, 50%,

[11] chemical reaction of carbon dioxide

and 90% of new building were of timber construction. Results showed the potential for as much as 55 million tons of additional carbon storage in buildings across Europe per year. This result corresponded to the 90% wood buildings scenario and 55 million tons is an amount equivalent to about half of annual European cement industry CO_2e emissions. Among the studies' conclusions was that the carbon storage capacity of buildings is far more determined by the number and the volume of wooden elements used in the structural and non-structural components used, than by building type, size, or species of wood. This conclusion suggests that in any kind of building a reasonable carbon strategy is to incorporate as much wood as possible.

2.4.3.2. Building Lifecycle Emissions

The energy and emissions embodied at the construction stage of a building are viewed as increasingly important. In view of consistently lower embodied greenhouse gas emissions of wood structures, the climate advantages of wood construction are widely recognized today by architects and engineers and considered in building design. The embodied emissions advantage of wood, combined with carbon storage within the material itself, translates to lower emissions for wood structures throughout building life (Chen *et al*., 2020; Duan, Huang, and Zhang, 2022). The improvement in building life cycle emissions between mass timber and reinforced concrete has generally been found to be 20-35% (Durlinger, Crossin, and Wong, 2013; Jayalath *et al*., 2020). A comparison of building life cycle emissions of mass timber and steel structures of 5 and 12 storeys determined 31-41% lower greenhouse gas emissions for mass timber structures (Allan and Philips, 2021). Given that operational energy consumption within a building tends to be quite similar regardless of the primary building material employed, significantly lower embodied fossil energy and associated lower greenhouse gas emissions at the point of construction completion lead to superior climate performance throughout the life of a building. Therefore, wood use in the construction sector results in lower use of fossil fuel energy and lower embodied fossil energy in the built environment, thus contributing to its sustainability.

2.4.4. Energy Efficiency

The energy efficiency of a building is defined by two primary factors: embodied energy and operating energy. As previously indicated, embodied energy is the sum of all energy expended in the production (raw material extraction through finished product), transport, and on-site assembly of building materials into a building structure. Operational energy is all energy expended thereafter to heat, cool, maintain, and otherwise occupy and operate the building.

2.4.4.1. Operational Energy

Energy efficiency codes and standards for buildings require design for comparable performance regardless of the primary building material used. The operational energy consumption of buildings constructed dominantly of wood is often equivalent to operational energy consumption of buildings constructed of alternative materials; however, wood buildings can require less insulation to attain required energy performance due to lower conductivity of wood and wood building materials compared to concrete or steel.

Table 2 shows the thermal conductivity of common construction materials. The right-hand column illustrates the thickness of each material that would be needed to provide the same insulation value as 25mm thick softwood lumber – the common material with the greatest inherent thermal resistance. The conductivity value for softwood lumber also applies to wood construction materials such as cross-laminated timber (CLT), laminated veneer lumber (LVL), glue laminated timber (glulam), and plywood. The thermal conductivity of composite wood products such as laminated strand lumber is about 8% higher than of solid softwood (Tripathi and Rice 2017).

Structural components of buildings (and metals in particular) are not commonly directly exposed to outdoor environments in modern construction. Nonetheless, structural materials can serve as a conduit of heat transfer across a building envelope and bridging between the interior and exterior of the building. This can lead to heat loss in winter and heat gain in summer. For high conductivity materials, such as steel, added insulation is needed to obtain comparable energy efficiency to buildings characterized by materials of lower conductivity. The addition of insulation increases the embodied energy and carbon impacts of building with non-wood materials.

Table 2
Thermal Conductivity of Selected Construction Materials

Material	Avg. Conductivity (W/m K)*	Relative Thickness Required to Equal Thermal Resistance of 25mm Thick Softwood Construction Lumber
Softwood construction lumber	0.1-0.14	1
Aerated Concrete	0.16	1.3
Concrete (light)	2.0	4.8
Concrete (limestone)	1.2	9.6
Concrete	0.6	16
Carbon steel	60	480
Aluminum	180	1,440

* The lower the conductivity value, the greater the resistance to heat transmission or loss
Source: Straube, J. 2016. Heat Flow Basics for Architectural Calculations.

That wood buildings require less in the way of added insulation than buildings constructed of alternative materials is one reason why wood buildings are associated with lower embodied energy than other types of buildings. The embodied energy difference is often substantial as described in the following discussions.

2.4.4.2. Embodied Energy and Associated Emissions

As demonstrated by the many studies cited previously under the heading "GHG Emissions and Climate Change Potential," climate warming emissions linked to mass timber buildings have been consistently found to be lower than for functionally equivalent buildings constructed of steel and concrete. Many other similar studies have confirmed these findings.

Most of these same studies have also found, however, that embodied energy associated with wood buildings is greater than for structures constructed of alternative materials when all energy sources are treated the same. The higher embodied energy findings are due to the use of renewable woody fuel for energy generation during wood product manufacturing, which is less efficient than energy generation from fossil fuels that typically fuel steel and concrete manufacturing. Total primary energy requirements for creation of wood buildings, and mass timber buildings in particular, is typically higher than for buildings constructed of concrete and/or steel (Liang *et al*., 2020; Felmer *et al*., 2022; Duan, Huang, and Zhang, 2022). The Duan *and colleagues* study, which involved an extensive review of LCAs of mass timber construction, found that average reported embodied energy of mass timber buildings at the point of completion of building construction was, on average, 23% higher than for equivalent reinforced concrete buildings, but that embodied greenhouse gas emissions of reinforced concrete buildings were more than 42% higher than for mass timber.

The reason for the apparent anomaly is that fossil emissions associated with production of wood building components and subsequent construction are significantly lower than for buildings constructed of alternative materials. Steel and concrete manufacturing currently rely on fossil fuels for thermal and electric energy needs. Wood product manufacturing includes the utilization of the byproducts of sawmilling (bark, trimmings, chips) to generate renewable bioenergy. But how much difference does this make when considering lifecycle emissions of a building when considering construction as well as heating/cooling cycles and building operation through the end of useful life of the structure?

For buildings constructed prior to the implementation of strict energy codes in the 1980s, the answer to this question usually was "not much." In older buildings embodied energy commonly accounts for only a small fraction (10-20%) of total energy consumed throughout the life of a building (Dimoudi and Tompa, 2008; Ramesh, Prakash, and Shukla, 2010). However, as building energy efficiency has increased, as measured by consumption of operational energy, embodied energy has become much more significant. Today, embodied energy of buildings accounts for a much greater portion of total energy consumed within the built environment. Chastas, Theodosiou, and Bikas, 2016, through an extensive review of literature, found an increasing share of embodied energy in the transition from older building designs to low energy and net zero buildings. They reported the share of embodied energy in modern low energy buildings to range from 26%-57%, and in net zero energy buildings from 74%-100%.

The adoption of strict energy codes has helped reduce the operational energy use and associated impacts of buildings during their useful life. As this change has occurred, the significance of the material-related embodied energy impacts has increased. This recognition has elevated the importance of material selection during building design and construction and highlights the importance of wood use and wood preferences in construction. The use of wood in construction contributes to reducing embodied energy while still achieving the same operational energy goals, and thus to sustainability in the built environment.

The consideration of embodied energy is becoming more important, and increasingly recognized. While attention to and regulation of embodied carbon reporting is beginning to appear in Canada and the United States of America and Europe, "only 5 EU countries – Sweden, Denmark, France, Finland, and the Netherlands – have introduced regulation on whole-life carbon emissions, meaning both operational and embodied emissions" (Petersen, Ekman, and Espersen, 2022). Similar action is reported for the cities of Vancouver, British Columbia, Canada and Oslo, Norway (World Green Building Council. 2019). The Netherlands regulations are particularly notable. In 2018, what is known as the Netherlands Building Decree required accounting for all new residential and office buildings of embodied carbon emissions as well as data in ten additional impact categories using an established national LCA methodology. France has also taken steps to substantially reduce embodied carbon emissions in building construction through its *Réglementation environnementale*[12] RE2020 regulation set for implementation in 2022); the measure calls for a 52% reduction in embodied carbon emissions by 2031 in comparison to an established baseline (Bourgeon and Giddings, 2021).

Definitive determination of energy embodied in construction materials is made possible through use of LCA in planning and design of buildings. In view of this, adoption on the part of the European Commission, in its Renovation Wave strategy, of the principle of "life cycle thinking and circularity" with a goal of reducing the carbon intensity of buildings over their full life cycles is viewed by many as an important step forward. Proposed are mandatory minimum energy performance standards that incorporate LCA and circularity goals (UNEP, 2021). However, enthusiasm for this initiative is tempered in some quarters by the fact that while reporting on whole-life carbon is required, there is no mention of embodied carbon (Petersen, Ekman, Espersen, and Garver, 2022), an omission which is likely to result in general inattention to this issue.

[12] https://www.ecologie.gouv.fr/reglementation-environnementale-re2020#scroll-nav__2

2.4.5. Fire Performance

Perhaps the most questioned aspect of greater use of wood in the construction sector is that of fire performance. It is well known that wood burns and other major construction materials do not, so wood buildings are often assumed to be inherently more dangerous in a fire. Less generally known is that unprotected steel reacts immediately to the high temperature of a fire in ways that change its structural integrity. Steel exposed to the heat of a fire exhibits linear expansion that can buckle support walls and then ductility that leads to a complete loss of strength and then collapse. In contrast, wood of large cross section and mass reacts to fire by forming an outer char layer that greatly slows the fire impact and protects the interior of the wood material. The charring reaction of wood allows exposure to fire for extended periods of time without sacrificing structural integrity. The result is that wood of large cross-section, such as CLT, will retain its strength after other materials have failed. This is true even without encapsulation with non-combustible materials as is usually required when using steel. If extra protection from fire is desired, wood can be covered with sheetrock[13] to provide even greater fire resistance.

Extensive fire testing of CLT and engineered composite timbers has occurred in many countries over the past decade (Kippel *et al*., 2014; Barber, 2017); Su *et al*., 2018; Zelinka, Hasburgh, and Bourne, 2020; Ronquillo, Hopkin and Spearpoint, 2021). These have included numerous tests of furnished compartments under various conditions. Data gathered from these tests have informed code development worldwide and provided a basis for adoption of new tall wood construction provisions within building codes in Canada and the United States of America. With provisions which mandate fire testing of adhesives used in CLT panel production and limit the extent to which wood surfaces can be exposed in finished structures, one building code extensively adopted across the United States of America, the International Building Code, in 2021 adopted provisions permitting mass timber construction up to 18 storeys. Even taller wood buildings have been constructed in some jurisdictions in accordance with local regulations or approved code exceptions.

Research continues to investigate fire risk and behavior in wood construction. Investigations in Canada have focused on evaluating fire performance in full scale tests that are more typical of modern mass timber office buildings. In a 2022 fire test conducted by the Canadian National Research Council and the Canadian Explosives Research Laboratory a substantial fire load of simulated furniture and other contents was set ablaze in a two storey mass timber structure. More than 150 experts from across Canada, including fire officials, building regulators, insurance industry representatives, engineers, and architects, were on hand during the test in which the mass timber building withstood full burnout of the furnishings of the building, whereupon the fire quickly subsided and burned out without any manual suppression or intervention. Burn-out largely

[13] a type of plasterboard made of gypsum layered between sheets of heavy paper

occurred within the first hour, but the test was continued for a full four hours to monitor for any potential re-ignition. The test indicated that the fire performance of the mass timber structure was similar to that of non-combustible construction by showing the capacity of the timber structure to survive full burn-out (Canadian Wood Council, 2022; Renew Canada, 2022).[14]

2.4.6. Durability of Wood Structures

Recent efforts to promote the use of engineered wood products in construction of tall buildings and supportive research findings may be changing perceptions and attitudes about the performance and benefits of wood structures. However, a turn of the century survey of architects, structural engineers, builders, and developers in the United States of America and Canada regarding building durability revealed a pervasive perception that nonresidential wood buildings would last for far shorter periods than buildings constructed of other materials. Compilation of responses from 683 respondents indicated an average expected life for wood buildings of 46 years, whereas useful lives of steel, masonry, and concrete buildings were estimated at 77–87 years (Gaston *et al*., 2001 as reported by O'Connor 2004). A more recent survey (Conroy, Riggio, and Knowles, 2018) identified wood durability as a continuing concern among architects in Canada and the United States of America. Gosselin *et al*., 2017, cited 16 studies of architect and civil engineer perceptions of wood as a construction material in which wood durability was cited as a concern. Another study (Viholainen *et al*., 2021) delved into perceptions of the public in Austria, Denmark, Finland, Germany, Norway, Sweden, and the United Kingdom of Great Britain and Northern Ireland. In this study, durability was identified as one of the top five concerns in every country involved. It is important to note that these were all studies of perceptions and not of actual buildings and their durability. These studies indicate that decision makers and influencers in the construction sector hold concerns about the durability and useful life of wood buildings.

One definitive study of actual rather than perceived building durability by primary type of material used in construction has been conducted. The study involved an examination of 227 building demolitions (both residential and commercial structures) in Minneapolis/St. Paul, Minnesota located within the north central region of the United States of America, for the years 2000–2003 (O'Connor 2004). About two-thirds of the studied buildings were wood, one-fourth were concrete, and the remainder were steel or various combinations of wood, steel, and concrete.

About half (105) of the buildings studied were nonresidential. Of these, the structural systems of 54 were concrete, 10 were steel, and 30 were wood, for a total of 94 non-residential buildings in these three categories. Of the other 11 nonresidential buildings in the study, the structure of one building was aluminum and the rest had structural systems of various combinations of concrete,

[14] Research summary available here: https://www.renewcanada.net/performance-of-mass-timber-during-fire-test-similar-to-non-combustible/ Also see the complete Mass Timber Fire Test Program information here: https://firetests.cwc.ca/

steel, and wood. Comparing the age of demolition by type of structural material with the concerns of design professionals revealed a wide gap between perception and reality. Only one-fifth of the steel buildings were more than 50 years old at the time of demolition, with half of these no more than 25 years old. Similarly, only a third of concrete structures reached an age of 50 years or more prior to being demolished. In contrast, over 60% of the wood buildings were older than 50 at demolition, with the largest group demolished at 76–100 years of age.

Investigation into the reasons for demolition revealed that most buildings were demolished for reasons that had nothing to do with the physical state of the structural systems. About 60% of structures were removed because the buildings no longer fit the needs of the owner or tenant due to changing land values, because of socially undesirable use, or inability to economically bring a building up to code. Structural failure was identified as the primary reason for demolition for only 8 of the 227 buildings studied, and in all but one of these the problem was foundation failure. In one building wood decay was identified as the problem. Fire damage was reported as the reason for demolition of 3.5% of the buildings studied. A greater percentage of steel buildings were demolished because of fire damage than of buildings constructed of wood or concrete.

This study led to a conclusion that despite a widely held perception that the useful life of wood structures is lower than other building types, no meaningful relationship exists between the type of structural material and average service life. Results also showed that wood structural systems are fully capable of meeting longevity expectations. The reality of the durability of wood construction is conclusively illustrated by the Butler Building—an eight-story, brick clad, 46,500 m^2 building in Minneapolis which was built of heavy timbers in 1906, and which remains as sound today as its date of completion (Figure 10). The building interior was recently renovated with the resulting design exposing the timber structure inside to be visually enjoyed by tenants and visitors. The building is in the urban center of the city and occupants include businesses, professional services, restaurants, shops, and a United States Postal Service center.

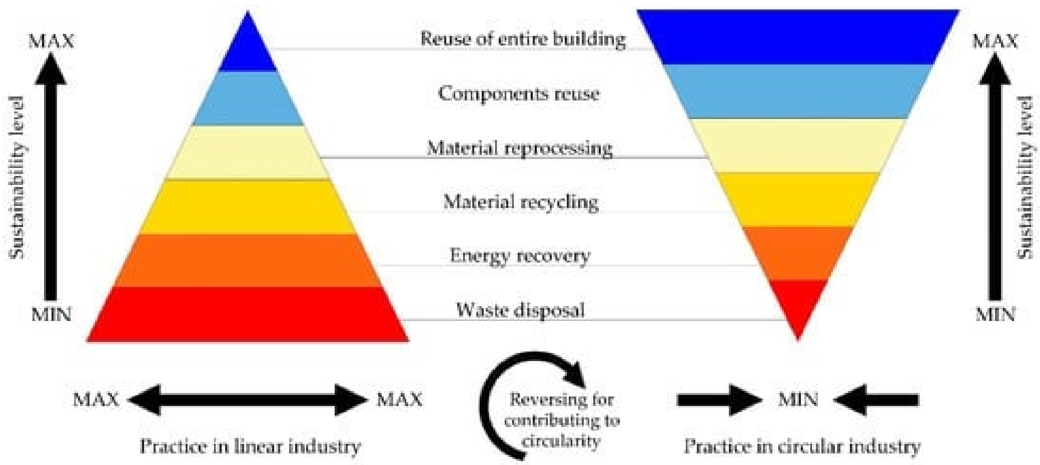
Figure 10, Butler Building, Minneapolis, MN

3. CHAPTER 3 Circularity and Sustainability in Wood Construction Practices

3.1. Circularity of Wood Material

Bertino *et al.*, 2021 modified circularity principles to express the hierarchy of options available at the end of useful life of a building (Figure 11). In accordance with 9R circularity principles they graphically expressed what practices should look like in a circular economy (right side of Fig. 11) vs. practice in what they described as a linear industry (left side of graphic). As a building material, wood performs well relative to potential alternatives in a number of aspects. It is a natural, renewable material; is light but strong requiring relatively low mass of materials for a given job; and results in lower impacts to the environment in many impact categories, including lower climate-impacting emissions.

Figure 11
Circularity Considerations at the End of Building Life



Source: Bertino *et al.*, 2021

Circular design considers the possible fate of a product. In the case shown in Figure 11, the product is a building at the end of its useful life. The possibilities include the prioritization of reuse through a variety of approaches. Materials may be repaired, refurbished, and rehomed so as to extend the life of materials involved. To support these possibilities at the end of a material's useful life the initial design of the material or its use may need to change. Through changes in design and use it can be possible to facilitate deconstruction and reconfiguration to adapt to shifting needs. If the goal of reuse is not achieved, the next possibility to consider is to recycle the material into another product. If that is not possible, then the recovery of embodied energy can be done by utilizing the material in energy production (thermal and/or electric). Landfilling and eventual biodegradation is a last resort outcome within the circularity hierarchy and, to be avoided if at all possible. The use of wood in these buildings creates circularity possibilities at all levels. Wood can be reused, recycled, or the embodied energy of wood can be recovered. As shown in Figure 11, each of the considerations of circularity can be applied to buildings at the end of life.

The importance of reuse, recycling, or energy recovery to climate impact reduction have been examined via several analyses of end-of-life scenarios for wood buildings. These reviews have confirmed the sustainability advantages of material reuse over recycling, recycling over combustion for energy recovery, and energy recovery over landfilling. Most building lifecycle studies incorporate an assumption that carbon contained in wood elements will be retained at the end of building life. If that is not the case, or if materials are at a minimum incinerated without energy recovery, then the lifecycle carbon advantage over alternative materials becomes much smaller. Darby, Elmualim, and Kelly, 2013, for example, calculated net carbon emissions for a CLT multi-storey residential building using various end of life scenarios. They evaluated reuse of building components, recycling, incineration, incineration with energy recovery, and landfilling. The results showed that net emissions remained net negative in all scenarios (carbon storage exceeded emissions) except incineration without energy recovery. However, combustion with energy recovery reduced the CO_2e emissions advantage of wood to one-half of what it would have been if wood were reused or recycled. These results further reinforce the hierarchy of the circularity principles. Another study which examined this issue (Durlinger *et al*, 2013) found a 22% building life cycle emissions advantage of a CLT building over one built of reinforced concrete, but that this advantage dropped to 13% if carbon is not retained within wood at end of building life. What happens at the end of the useful life of a structure is vitally important to the goal of circularity.

With thoughtful design when wood is used in the construction sector the principles of circularity can be followed; however, while sustainable design is critical in all value chains, the construction sector in particular appears to need support in the form of coordinated efforts regarding reuse and material recovery during retrofitting and demolition to improve material circulation where possible.

In view of the importance of the end-of-life fate of building components, and especially the circularity benefits of reuse and repair, a relevant consideration is the state of current practice. Unfortunately, current practice in the sector is much more linear than circular and looks much more like the left side of Figure 7 than the right. For instance, in the United States of America in 2018, 75% of wood contained within construction and demolition waste was landfilled, 19% combusted for energy recovery, and only 9.4% recycled (USEPA 2020). There is, moreover, only limited use of waste to energy technologies in Canada and the United States of America. Landfilling continues to be common practice for many materials, including wood waste.

The situation is somewhat better in the European Union (EU), with far lower volumes of wood waste sent to landfill. An EU BioReg' project's report (Borzecka, 2018) stated that 54.8 million tonnes of wood waste were generated EU-wide in 2016 of which 48 million was treated (87%). Included in this figure was wood contained in municipal solid waste, construction and demolition waste, and wood products mill residues. Of the wood that was reported as treated, 49% was recycled, 48% combusted for energy recovery, and 3% landfilled or incinerated. The fate of the 6.8 million tonnes of waste wood which were not treated is unclear. Practices were reported to vary widely across Europe, with material and energy recovery much more common in Northern and Western Europe than in Eastern and Southern regions where landfilling was much more common (Borzecka, 2018; Besserer *et al*., 2021).

Other countries have made greater progress with wood waste recovery. Recycling of C&D waste in Japan was reported at 80.3% in 2008, a figure that encompassed energy recovery, conversion to mulch, and reuse in manufacture of particleboard and other products (Japan Ministry of the Environment, 2014).

For most countries for which data is available, and that includes almost all countries of the BioReg project[15], the greatest contribution to wood waste is C&D waste (Borzecka, 2018). Of that, by far the greatest volume arises from demolition of existing buildings rather than new construction. The data suggests that there is considerable room for improvement in wood recycling at the end of life for buildings. The greatest opportunity for improved circularity for wood is in the recovery and reuse or recycling of building demolition waste.

3.2. Sustainability of Wood Material

Whether or not construction design, panning and practice are sustainable rests on three pillars: environmental protection, economic viability, and social equity. Wood fares well in all these categories. The fact that wood is renewable, is produced using solar energy, is composed of captured and stored carbon as it is formed within growing trees and can be converted to useful products using relatively little fossil energy all add up to define a material that is less environmentally impacting than such materials as steel, masonry, and reinforced concrete. These things, of course, translate to environmental advantage only if wood is produced in a sustainably managed and responsibly harvested forests or plantations. But here too, wood has an advantage in that third party oversight of forest management is widely practiced via forest certification this has been said before and can be cut short here. programs that have been in place for almost three decades. Providing for rigorous evaluation of all aspects of forest management, including impacts to soil health, water quality, fish and wildlife habitats, rare and endangered flora and fauna, cultural and historical sites, and more, these programs provide a means of ensuring attention to important issues while producing sustainable volumes of wood and other products and services. They also provide a social context for wood production, bringing to the fore common social concerns and allowing external overview of industry practices.

[15] Countries of the BioREg project include Sweden, Germany, Italy, Austria, France, Portugal, Poland and the United Kingdom of Great Britain and Northern Ireland. https://www.bioreg.eu/index.php

While wooden structures have been built for centuries, the concern about the circularity of materials used is a relatively new concept. Even as recently as several generations ago, the human population was far below today's and most of the world's economies were characterized by only minimal consumption. As a result, raw materials of all kinds were relatively more plentiful and less expensive than today, with little concern about future raw material supplies, particularly in high consuming nations.

Despite examples of deforestation and forest degradation in some parts of the world over centuries, traditional wood construction in many regions had actually followed circular and sustainable approaches in the light of today's concepts and definitions. This included on the local sourcing of raw material, buildings being repaired, refurbished and reused for different purposes and over decades.

3.3. Circularity of Modern Construction Methods

Today, mass timber buildings contribute to circularity and environmental sustainability while also providing a highly engineered and high performing material for construction. Table 3 presents an overview of different modern construction types and methods.

Table 3 Construction types and methods

	Construction Characteristics and Methods
Residential Includes single family homes, duplexes, triplexes, fourplexes, condos, low rise apartment complexes, tiny homes, mobile homes (mostly United States of America), large multi-storey apartment buildings.	• Single family and low-rise residential structures largely constructed on site. Significant shift toward factory built (panelized, modular) in Sweden, Japan, Germany, and United Kingdom of Great Britain and Northern Ireland. Use of wood is dominant in residential construction in Canada, the United States of America, Northern Europe, Japan. Wood construction generally uncommon across Europe with some local exceptions. Large multi-story apartment buildings constructed mostly of reinforced concrete and steel. • Exceptions are Canada and the United States of America where wood frame residential, and mixed-use residential and commercial construction up to 6 stories over one or two storeys of concrete construction is common. Tall (8-18 storeys) Mass timber construction at very early stages of market penetration. • Mass timber construction for multi-storey residential most advanced in Northern Europe and Canada.

Commercial Includes office buildings, hospitals and clinics, restaurants, hotels, entertainment centers, retail establishments.	• wide range of construction methods • Construction of larger buildings largely done on site, with incorporation of modular units gaining greater acceptance in some regions. Smaller buildings, and particularly chain restaurants and coffee shops, often panelized or modular construction. • Reinforced concrete and steel construction dominant, particularly for large multi-storey structures. In Canada and the United States of America, light frame wood construction common for hotels of 4-6 stories and low-rise commercial buildings of all kinds. Mass timber construction for these types of buildings overall at early stages of market penetration.
Industrial Includes manufacturing, warehouses, distribution centers, flex space buildings	Common building methods for these types include reinforced concrete and steel frame construction and reinforced concrete tilt-up construction. Steel clad pole buildings also common in some localities. Very little use of wood in construction of these types of buildings at present.

Mass timber allows for the beneficial use of renewable resources which can be fashioned into useful products with less manufacturing waste than previous forms of structural wood products, provide low carbon-emission alternatives to reinforced concrete and steel, and store carbon for as long as they remain in existence. Modern wooden construction methods also address some circularity questions as they incorporate a high degree of prefabrication that speeds construction processes, provides for precision sizing of modules and connections, thereby greatly reducing waste.

However, for an overall transition of the wood construction sector to a more circular model, a systemic approach is needed to enhance increased integration across and along value chains. Such approach should move away from the business-as-usual towards a more cross-cutting collaboration among different actors within and outside the construction sector. An increased collaboration of designers, architects, urban planners, engineers, municipality actors and legislators would contribute to achieving greater sustainability. From a design for durability of materials and building structures, to an improved recovery of materials, reuse of structure components to recycling of wood from construction and demolition. The degree to which a building can be built and used in a sustainable manner depends on the awareness of these different actors about the opportunities and limitations to applying different circular approaches at different stages of construction value chains. Circularity in Material and Product Development

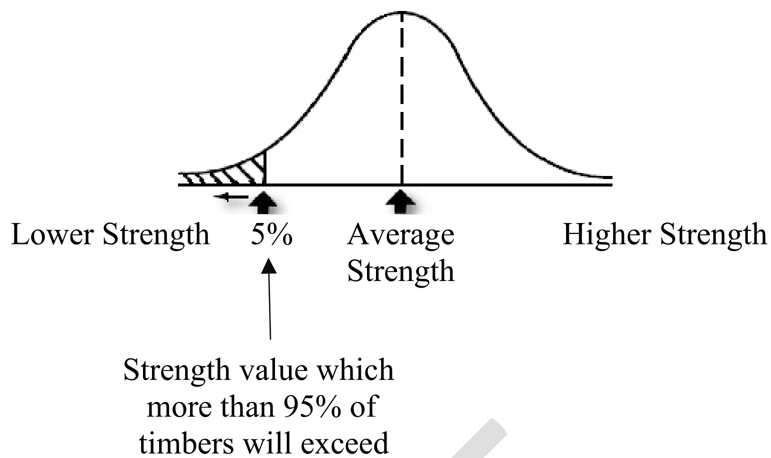
The cumulative result of many decades of research – and more than a century since that first patent – provide evidence that mass timber buildings today contribute to circularity and environmental sustainability while also providing a highly engineered and high performing material for construction. Mass timber allows for the beneficial use of renewable resources which can be fashioned into useful products with less manufacturing waste than previous forms of structural wood products, provide low carbon-emission alternatives to reinforced concrete and steel, and store massive quantities of carbon for as long as they remain in existence.

Therefore mass timber can be a more sustainable alternative for some of the steel and concrete that goes into buildings. It is safe, fire-resistant, and is of comparable strength. It’s lighter weight and factory-built, precisely manufactured timber construction can make better use of resources and reduce the number of deliveries to a building site, in turn decreasing overall vehicle emissions. Mass timber building systems can be disassembled and refurbished with relative ease or used in different ways. Their value can be re-captured at the end of life and scraps can be repurposed or used as bioenergy.

The new types of wood products which have enabled wood to replace in some stances steel and reinforced concrete in tall buildings are all the result of extensive research over many years. All of them, involve taking solid wood apart and then reassembling the pieces into forms that look like solid wood of various sizes, which moreover have more uniform and predictable performance properties. Using wood in buildings in addition to private homes creates chances for greater circularity. Therefore, the following chapter will briefly review the various innovations and progress made in the engineering and development of wooden building materials.

Disassembling and then reassembling wood results in better, more durable thus more sustainable products because, although wood, as it is sawn from round logs, is a very useful material, it can also be somewhat unpredictable. Even among trees of the same species, as well as in different locations within a single tree, the wood produced can vary considerably in density and strength. These variations can sometimes cause the wood to warp or twist unpredictably as well. Variation can be due to a number of factors, including variation in grain direction around locations where branches result in knots, stress zones traceable to weather events during the life of the tree, sharp differences in density and dimensional stability properties near the centers of trees or in sections of leaning trees, and more (Bowyer, Shmulsky and Haygreen, 2007). As a result, tests of thousands of samples of wood have been conducted from which average strength values were obtained for different kinds of wood. Those tests have also revealed variation in strength, yielding information that can be graphically expressed as in Figure 13.

Figure 13
Typical Variation in Strength of Wood of a Single Species



In designing a structure, a common practice is to use a strength value which over 95% of lumber or timbers of that species would exceed (i.e., a strength value for which there is a very low chance that strength of the member might actually be lower than assumed). This way solid wood members used in strength critical applications are almost universally larger than they need to be to meet strength and durability requirements. One solution to optimize wood use has been mechanical and other forms of testing to narrow uncertainty regarding particular individual timbers strength properties. Nonetheless, construction wood has generally not been viewed by architects and engineers as having sufficiently uniform and predictable properties comparable to reinforced concrete or steel. It is primarily this characteristic that led to development of structural wood composites and suite of engineered wood products. Another driver was interest in creating large structural members from relatively small diameter trees as depicted in Figure 14.

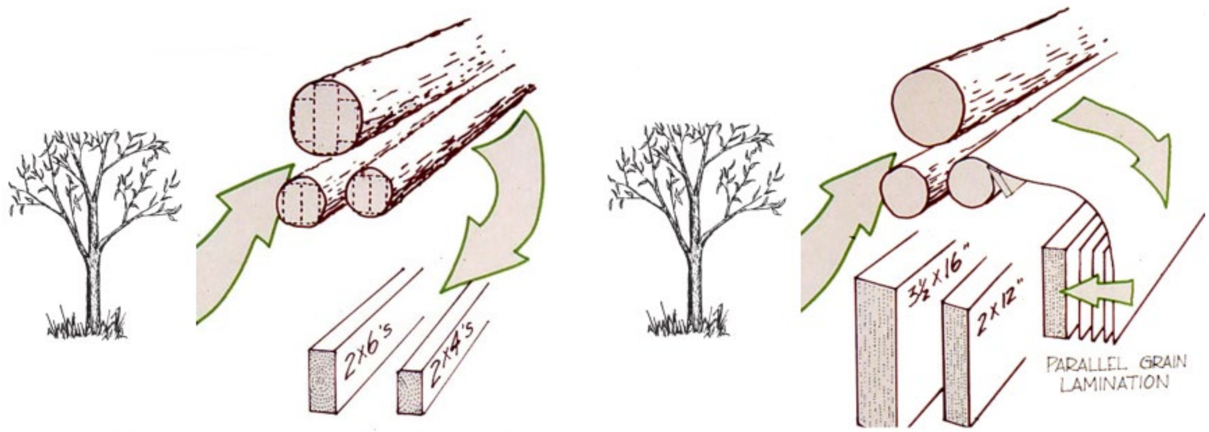
One advantage of disassembling wood before reassembly is that some of the defects, such as knots, can be removed. Secondly, disassembly provides an opportunity to break up zones of weakness as well as to mix component parts of one tree with another. In addition, there is also an opportunity to reassemble wood in such a way as to optimize desired properties. One of the best examples of what is gained in creation of a new engineered product is the effect on wood strength. Whereas wide variability of wood of a given species is normal in solid wood, engineered wood products have a much narrower range of variability, with the result that such products can now compete directly with materials long viewed as superior due to uniform and predictable properties.

Innovation contributes to circularity and sustainability of wood construction. These include:

- The idea of creating large wood members from smaller pieces of wood is first documented in 1901 when a German carpenter and inventor obtained a patent for a straight beam composed of smaller pieces of wood bonded together using adhesives. More recently known as glulam, this product is commonly used today (Lehman 2018).
- Softwood plywood was another innovation which made use of small pieces of wood to make larger items. Plywood displaced the use of boards for bracing of light frame buildings in the United States of America and Canada beginning in the mid-1940s. Although modern plywood is based on the same principles used in creating plywood as far back as the time as the Pharaohs, the emergence of construction plywood didn't occur until development of the rotary lathe[16] made production of large sheets of veneer quick and inexpensive (Wood, 1963). This is the same mechanical innovation that led to development of laminated veneer lumber (LVL).
- LVL, patented in 1968, was developed specifically to create "lumber" of more uniform strength than solid wood, while at the same time permitting the manufacture of large-size timbers from relatively small diameter logs (Figure 10). Although LVL, like plywood, is made of veneer, the grain directions within veneer layers are lined up parallel to one another, rather than at alternating 90-degree angles as in plywood. The result is a product that, like solid wood, is much stronger along the length than across the width (solid wood is 1-20 times stronger along the grain rather than across it). The advantage of LVL over solid wood is that large defects are removed from veneer before reassembly, with any remaining defects dispersed throughout the product. The result is a superior product of uniform strength which does not warp or twist as moisture levels change (Bowyer, Shmulsky and Haygreen, 2007).

Figure 14
Laminated Veneer Lumber – Large Timbers from Small Trees

[16] Prior to processing on a rotary lathe bark is removed from logs which are then immersed in heated water in order to soften the wood. Then chucks are pressed into the each end of the log to be processed which provide torque to enable turning of the log. As the log turns it is steadily moved toward a sharp knife which extends the length of the log, with the result that thin veneer is produced. In the manufacture of construction plywood or LVL individual veneers are cut to 2.5-3 mm in thickness.



Small trees allow production of only small-sized lumber if sawing logs, but unlimited sizes if "lumber" is produced from veneer.

- The next steps in development of engineered wood trace back to the introduction of softwood plywood. As plywood quickly gained wide adoption in the construction industry in Canada and the United States of America, a new product – waferboard panels – made of ultra-thin slices of wood (also called "wafers") (0.5mm) were first commercially manufactured in 1955. Ongoing development further led to the discovery that making of long (150mm)-thin wafers allowed alignment of grain, even layering of various grain angles, similar to plywood. These insights led in the early 1980s to emergence of oriented strand board (OSB) panels 6-18mm thick, which closely approximated the properties of plywood, but at much lower cost. This innovation allowed the economical use of small trees of relatively low inherent strength in production of high-strength products that previously required large diameter logs of high strength species reduction of wastes in the production process in comparison to plywood (Bowyer, Shmulsky and Haygreen, 2007).
- The success of OSB led to yet another round of innovation. Why, some researchers wondered, might it not be possible to make assemblies far thicker than 18mm which could then be sawn into timbers and "lumber" of any desired size? This kind of thinking and subsequent research resulted in "lumber" products such as oriented strand lumber (OSL) and laminated strand lumber (LSL). Yet another product is parallel strand lumber (PSL), made of thin strands of veneer of about 300mm in length, and produced in an extrusion process. All of these products were commercialized by the mid-1980s in the United States of America and Canada (Bowyer, Shmulsky and Haygreen, 2007).

In **Europe**, the significance of engineering wood innovation was recognized years later and resulted first in what would become known as cross laminated timber (CLT) - Switzerland and Austria. CLT was first used for roof systems in Germany in the early 1970s, then further developed in Germany, Austria, and Switzerland during the 1990s[17]. Subsequently, a three storey house was constructed in Bavaria. A period of experimentation in Germany, Austria, and Switzerland followed that led to initiation of full-scale production of CLT in the early years of the 21st century (Karacabeyli and Douglas, 2013). The construction of tall buildings using CLT began, first in Europe, then in Canada, and thereafter in countries all over the world. Combined with an extensive use of other engineered wood products, this building method is described as **mass timber construction** and with its growing popularity the production of CLT expanded rapidly, first in Europe, then Canada, the United States of America, and in Asia.

Global CLT production capacity in 2020 was estimated at 2.8 million m^3 2020, with 48% in Europe, 43% in North America, 6% in Oceania and 3% in Asia. Actual production is estimated to have exceeded 2 million m^3(Forest Business Network, 2020). In Europe, most of the production facilities and installed capacities of CLT are located in Germany, Austria and Switzerland, as well as in Italy and in the Czech Republic. Slightly more than 1 million m3 of CLT was produced in these five countries in 2020, which was 15% more than in 2019. This growth trend is expected to continue in the coming years, (Gaston, Pahkasalo, and Zhu, 202118).

3.3.1. Circularity and Construction Techniques

Although "stick"[19] building remains dominant in many countries, and most notably in Canada and the United States of America, alternative methods of building are becoming of interest, in part because of a scarcity of skilled construction labor, but also because of the potential advantages for circularity and sustainability thanks to greater off-site prefabrication of building components (i.e., increased precision of connections and fittings, speed of construction, and potential material waste reduction). These factory-built, precisely manufactured timber constructions can make better use of resources and reduce the number of deliveries to a building site, in turn decreasing overall vehicle emissions. In addition, modular and panelized building systems can be disassembled and refurbished with relative ease and used for different purposes.

Stick building often incorporates some prefabricated components such as floor and roof trusses. However, systems sometimes referred to as "modern" construction – panelized, mass timber (for wood construction), and modular construction –involves a far greater level of off-site prefabrication (Figure 15).

Figure 15
Modular, Mass Timber, and Modular Construction

[17] https://sites.cnr.ncsu.edu/clt-panels/history-of-cross-laminated-timber/

[18] UNECE (2022). Forest products annual market review 2020- 2021. United Nations Economic Commission for Europe. Downloaded 28 Feb 2022 at: https://unece.org/sites/ default/files/2021-11/2114516E_Inside_Final_web.pdf

[19] The term "stick building" refers to construction wherein most or all of the building materials are delivered to the construction site unassembled.

In some parts of the world prefabrication, either in the form of panelization or modular construction, has gone mainstream. Sweden reportedly ranks as the leading country in the implementation of prefabricated building systems, with eight out of 10 detached houses built using modern methods. Offsite manufacturing is also used in Sweden to build at least 30% of new-build multi-residence buildings (Modor Intelligence, 2021). In Japan, more than 15% of nearly 1 million new homes and apartments built in 2016 were made inside factories, either as stackable modular blocks or panelized walls and floors (Berg, 2017). The homebuilding sectors in Germany and the United Kingdom of Great Britain and Northern Ireland also represent significant markets for prefabricated building components (Globe NewsWire 2021) with Scotland showing a strong lead.

3.4.2.1. Panelized construction

Panelized construction can involve the off-site prefabrication of simple framed and sheathed wall and roof sections delivered to the building site with pre-cut window and door openings, to prefabrication of engineered floor systems, roof trusses, and completely finished wall and roof sections that incorporate windows, doors, and exterior and interior finishes. Subsequent on-site work is similar to stick-built construction. Both methods typically involve installation of the foundation as a first step, with prefabricated components carefully sized to precisely match foundation dimensions.

Panelized construction process depends upon the degree to which panels and other elements have been prepared off-site. Typically, a factory manufactured floor system would be first installed on top of a pre-laid foundation, with wall panels erected as a next step. Once wall panels are in place, usually with temporary bracing, either floor trusses for a next floor, or roof trusses are placed, and roof sheathing then installed. In instances where wall panels as delivered to site consist only of framing and perhaps sheathing, and are delivered to site along with roof trusses, on site construction proceeds much as described below (Lack, 2020):

Once the exterior walls and roof trusses and sheathing are set, extensive on-site work is required which closely approximates stick building from that point forward. The same is true if wall panels include windows, doors, and exterior siding, although in this case the structure can be rapidly enclosed to protect against the weather. However, when wall panels are completely finished within the factory, to include finishing of both interior and exterior surfaces, the time to completion of the building on site is reduced considerably.

Panelized construction is typically faster and less expensive than "stick built" construction with faster and more resource efficient in-plant assembly of components than on-site assembly. In-plant assembly is independent of weather or other delays allowing for faster on-site weather tight assembly. In terms of circularity, material waste is reduced, and waste generated more easily collected for reuse or recycling.

With regard to costs, a study in the United States of America found that construction costs of panelized single-family homes were less than 80% that of traditionally construction homes. Nonetheless, only a small percentage (3-4%) of homes constructed in the country used this technology in 2015 (Ghosh, Bigelow, and Patel, 2021).

3.4.2.2. Mass Timber

Mass timber construction, like all other forms of construction, may involve use of concrete and/or steel along with mass timber elements. Concrete is almost universally used in creating the building foundations. CLT panels can be used as horizontal elements only (floors, ceilings, and roof) or also as exterior and interior walls, staircases, and other parts of a building. CLT panels are generally delivered to the building site with all openings' precision pre-cut, and with individual panels identified as to exact placement in the erection process (Souza, 2018, Delheim, 2017).

CLT panels can be as large as 50cm x 3 m x 18 m, and typically weigh about 1,800-2,250 kg or roughly 2 tonnes. At the construction site cranes are used to lift them into place as building proceeds, typically involving two construction crew members; two to four others work to guide the panels into place and secure them. Construction typically proceeds quickly and coudo result over time in additional gains in productivity, and construction cost savings than concrete and steel construction methods due to the large-sized engineered panels that characterize this method (Mallo and Espinoza, 2015; Smith *et al*., 2018). This is particularly the case when CLT is used for exterior walls, floors and roofs. Numerous case studies have documented reductions in construction time compared to construction. One example is provided by construction of a project in which 418 m^2 (4,500 ft^2) of CLT floors were installed in less than 3 hours (Dalheim, 2017).

In addition to reduced construction time, mass timber construction involves fewer construction trades and smaller on-site crews for erection which likewise reduces construction costs. On-site waste is also reduced (Smith *et al*., 2018; Abed *et al*., 2022). Fewer construction trades also contribute to reduced use of natural resources that are essential to building construction. Smaller on-site crews translate into lower environmental impact of transport and on-site facilities during construction time. While mass timber construction is promoted for low-rise buildings, it requires substantially greater volumes of wood than light frame construction. For this reason, it is likely to be used more for tall multi-story structures, rather than in buildings of less than 4-6 stories in height (Ramage *et al*., 2017).

3.4.2.3. Modular construction

With modular construction the vast majority of work occurs off-site. Modules typically come to the building site in finished form, with finished interiors and exteriors. One European manufacturer even offers units complete with furniture. This form of construction is employed with all building types, ranging from single family homes, schools, and commercial structures to multistory residential, office, and hospital structures.

In this type of construction, building components are assembled almost entirely in a factory. In its ultimate form, separate three-dimensional, box-like modules, including attached walls, floor, ceiling, wiring, plumbing and interior fixtures, are produced off-site before transport to the building site where modules are connected to create a finished structure. In some cases, modular units are used in conjunction with panelized construction, with modules employed only for bathrooms or kitchens. Modular are designed for connection end-to-end, side to side, or one on top of another to create different configurations (eArchitect, 2021).

The design phase is particularly important with this type of construction since it is critical that assembly tolerances are controlled, and misalignment of modules and connections be avoided. Sophisticated tools are used, including computer aided design (CAD) systems, additive manufacture (3D printing) and manufacturing control systems, and design for manufacture and assembly practices are followed (TWI, Ltd. 2022).

Production of building modules begins with the floor system, which like other building elements is precision built within a factory. Production using jigs that provide a width and length template ensure that floor systems are constructed to exact measurements within pre-established tolerances. Walls are similarly manufactured, often with interior gypsum board included, and then lifted onto the floor system and fastened directly to it. Next comes the roof and ceiling system which is constructed at the same time as the floor and wall sections before lifting into place to enclose the module. Plumbing and water lines are then added, if part of the module. Windows and doors are then added, followed by insulation, sheathing, and exterior siding. At the same time, work proceeds in the interior of the module. Preparation of interior drywall (gypsum) is completed, cabinets are installed, interior trim is added, and painting and finishing done. Electrical, water, and plumbing connections are also made and checked. Finally, modules are cleaned and wrapped for transport to the building site.

Modules are delivered sequentially to the construction site in accordance with planning. As they are set into place they are connected to adjoining modules, with linkages made as needed to wiring, water, and plumbing lines. With proper planning, setting and connection of modules can be completed within a day or two. Work is then done to finish the joints between units, ensure that wiring, water, and plumbing connections are complete and tested, conduct a final inspection, and do a final cleaning. With ideal conditions and no weather or other construction delays, construction time from initiation of foundation installation to occupancy can be as short as 4-6 weeks, although 2-3 months is reported as typical. In comparison, the same process using panelized construction is likely to extend 4-7 months (Kline, 2020).

As early as 1837, modules were produced in London for shipment to Australia for assembly as cottages (REDS10, 2014). While modular construction came in and out of fashion all over the word over the years it became over the years largely a provider of temporary structures for various needs such as temporary classrooms, job site structures, communication pods, and show rooms (Smith, 2016).

More recently, modular construction has been employed for permanent structures. Described in 2016 as having flourished for a decade or more in Europe and gaining in popularity in Canada and the United States of America, modular construction is today used in construction of multistory multi-family structures, government buildings, health care facilities, schools, hotels, and other building types (Smith, 2016).

Similar to panelized constriction, weather and other factor independence allow for more resource and time efficiency, durability, and sustainability of the end product (TWI, Ltd., 2022):

In terms of material waste reduction, Loizu *et al*., 2021, in two case studies comparing waste from modular and traditional construction found a waste reduction from modularization of 81.3% and 83.2%. They also examined five previous studies of waste reduction with modularization and found waste reduction levels ranging from 20.1% to 92%.

The many benefits of modular construction can be exemplified by the experience of the National Health Service (NHS) of the United Kingdom of Great Britain and Northern Ireland. As reported by eArchitect, 2022, the NHS has benefitted greatly by the material and cost-efficiency of modular construction. Facing a substantial bed shortage, and the need for rapid, inexpensive construction, NHS found modular construction to be 60% faster, and 30% less expensive than traditional methods. Moreover, this building technique resulted in reduced on site construction activity, resulting in minimal disruption to the ongoing work of NHS hospitals. All these characteristics place the modular construction as an interesting circular solution with comprehensive benefits contributing to not only the optimization of natural resources use and the reduction of pollution but also implying cost and time efficiency.

Healthcare is just one of the sectors that experiences rapid technological advances, and construction needs to evolve with these changes. The modular units are flexible and can be easily adapted as an internal space as the demands on the space change. They can be used in lieu of other renovation techniques which require more resources, time and contribute to the generation of pollution (e.g., concrete dust) or waste

3.3.2. Opportunities for Greater Use of Wood in Buildings

As indicated in Table 3, there is considerable potential for making the construction sector more circular and sustainable by increasing the use of renewable wood in residential and commercial construction. The potential for incorporation of greater quantities of wood in construction are greatest in residential and commercial buildings. With regard to tall buildings, although recent design and construction projects have demonstrated the potential for very tall buildings made dominantly of wood, based on a survey of commercial buildings in the United States of America, it is buildings of less than 10-storeys in height or less which represent the greatest opportunity for expansion of wood use (Figures 17-19). Structures of this height dominate the multi-storey building scene both in terms of numbers of buildings and floor space.

Figure 17
Commercial Buildings in the United States of America:
Number of Buildings by Height, 2012

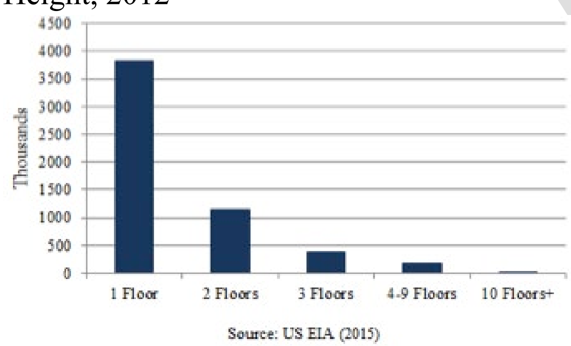


Figure 18
Commercial Buildings in the United States of America
Floor Space in Buildings by Height, 2012

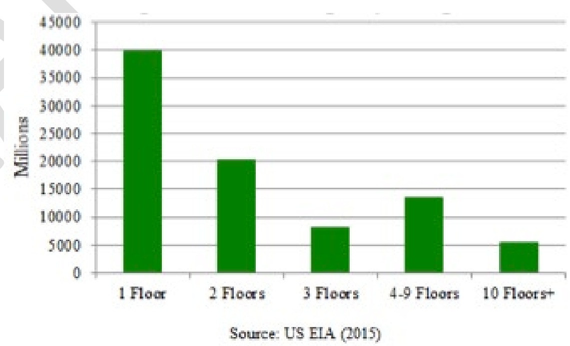
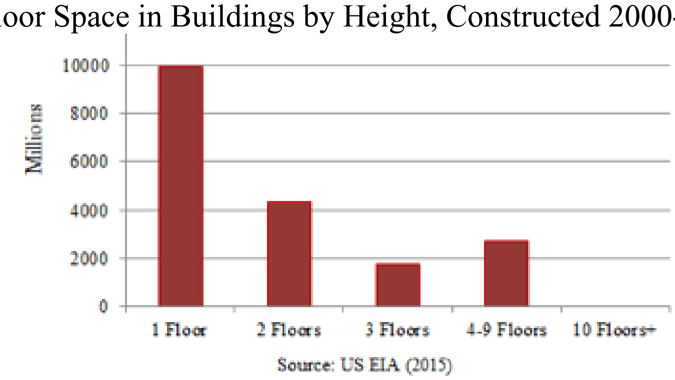


Figure 19
Commercial Buildings in the United States of America
Floor Space in Buildings by Height, Constructed 2000-2012



3.3.3. Opportunities for Greater Application of Modern Building Methods

For all building types, and in some regions to a greater extent than others, application of panelized, mass timber, and modular construction methods remains on the periphery. Likely to be driven by primarily by shortages of skilled labor, the share of construction projects employing off-site construction methods is expected to rise in the years ahead (Business Wire, 2021; Future Market Insights, 2022; Globe Newswire, 2022). Likewise, further adoption of mass timber construction for multi-storey buildings is likely based on increasing recognition of the climate and other sustainability and circularity beneficial aspects of mass timber (Business Wire, 2021; Future Market Insights, 2022; Globe Newswire, 2022).

3.4. Retrofitting, Deconstruction, and Demolition

As discussed under the topic "Circularity" and depicted in Figure 11, an ideal pathway for circular use of wood in construction would involve repair, refurbishment, and rehoming as top priorities at the end of first useful life. Recycling into some other kind of useful product would be a lower priority due to the greater additional energy and other resources that are needed. Finally, recovery for energy generation would be a desirable outcome at the point that all other potential reuse possibilities had been exhausted. This kind of ideal pathway for wood circularity is far from reality today.

3.4.1. Wood in the Waste Stream

The data for the EU (Borzecki *et al*., 2018) show annual production of 52.9 million tons of wood waste in the EU-28. Of this waste, 48% is contained in municipal solid waste (MSW), 38% in construction and demolition waste (CDW), and the remainder as wood industry waste. With regard to CDW in particular, wood accounts for only 2-4% of such wastes in most countries (Diyamandoglu and Fortuna, 2015), but as high as 25-30% in the Nordic countries where wood construction is dominant (Jetsu, Vilkki and Tiihonen, 2020). As a component of MSW, wood is estimated to comprise 7.5% to 11% of the waste stream (Boulday, 2018). Various reports indicate the fate of wood wastes in the EU. The percent of wastes recycled, primarily into particleboard, is reported at 31-35%, with processing for energy recovery estimated at 33-34% (Adamopoulos, 2015; Diyamandoglu and Fortuna, 2015; Besserer *et al*., 2021). The same sources variously indicate the percent of wood wastes landfilled, composted, or incinerated without energy recovery at 28-37%, although a steady decline in these disposal methods is ongoing within the EU (Abis *et al*., 2020).

Data for Japan are somewhat dated. Wood waste was reported as 6.3 million tonnes, or 6.5% of CDW in Japan in 1995, with a small amount originating from what was described as civil engineering projects and most from building deconstruction and renovation (Nakajima and Futaki, 2001; Asakura *et al*., 2010). Recycling rates of 69% and 37% were reported for the two sources, respectively. Volumes reported as recycled included wood converted to mulch (Nakajima and

Futaki, 2001). More recent reports indicate recycling rates of construction generated wood at 80.3% (Japan Ministry of Environment, 2014), and significant growth in use of domestically generated waste wood for energy generation in recent years, and in volumes exceeding earlier estimates of total wood waste (Aikawa, 2021).

In the United States of America wood wastes amounted to 64 million tonnes in 2010. Of this, 22.5% was contained in MSW, 51.5% in construction and demolition waste, and the rest in the form of yard waste, which includes woody trimmings of trees and brush (Falk and McKeever, 2012). More current statistics (USEPA, 2022) show a similar percentage of wood wastes in municipal solid waste, with 17% recycled, 16% combusted for energy recovery, and 67% landfilled. Most of the wood counted as recycled was used as animal bedding or mulch. Almost all of construction and demolition waste generated in 2018 (27 million tonnes) was sent to landfill (Dunkerly, 2021). Increasing volumes of waste wood find their way to reuse via more than 900 retail *ReStore*[20] facilities in the United States of America operated by the non-profit Habitat for Humanity. About half (55%) of yard waste in 2010 was recycled into bedding or mulch (Falk and McKeever, 2012). The situation is similar in Canada.

3.4.2. Potential for Deconstruction and Cascading Wood Use

An assessment of recovered wood from building deconstruction in Germany (Höglmeier, Weber-Blaschke, and Richter, 2017), found significant quantities of wood (26%) in suitable condition for further use, with over a quarter of this having potential for high value secondary use. Another study (Merl, 2007) analyzed wood materials recovered from deconstruction of a 120-year-old alpine cottage, determining that many of the components were in good condition, with large portions fit for reuse. A demonstration project involving deconstruction of a two storey, 93 m^3 wood-framed residential structure in the United States of America resulted in complete deconstruction over a 12 ½ hour period using a crew of 26 workers. The sales value of salvaged materials was double that of labor costs, indicating economic potential for building deconstruction (Falk, 2002). Yet another European study chronicled widespread use of recovered wood for particleboard manufacture, noting that whereas 100% of particleboard manufactured in Italy, and 50% of particleboard manufactured in Germany, Denmark, and the United Kingdom of Great Britain and Northern Ireland are made of recovered wood, nearby countries use little or none for this purpose (Besserer *et al*., 2021).

Figure 20
Deconstruction for Building Materials Recovery

[20] https://www.habitat.org/restores

3.4.3. Benefits of Retrofit and Deconstruction

Several studies have identified the p**otential benefits of retrofitting or deconstructing buildings** [Figure 16]. Schwartz, Raslin and Mumovich, 2022, evaluated refurbishment vs. replacement of two housing archetypes, finding reductions in greenhouse gas emissions of 10-30% through refurbishment. One study applied life cycle assessment to evaluation of deconstruction and determined that separation of materials in demolition operations and subsequent recycling and/or reuse resulted in reductions of 77% for climate change potential, 57% in acidification potential and 81% in summer smog creation as compared to demolition without recycling (Coelho and de Brito, 2012). An assessment of deconstruction examined environmental impacts from deconstruction site through delivery of reclaimed materials to a storage facility; findings showed cumulative energy consumption in producing new framing lumber and wood flooring to be about 11 and 13 times greater, and global warming potential 3 to 5 times greater, than reclaiming these materials (Bergman et al., 2010). These results indicate that reclaimed framing lumber and wood flooring have a significantly lower environmental impact than their two new or fresh wood alternatives.

Another study, which also employed a life cycle approach, found that **cascading wood use** could increase wood use efficiency in the European wood sector by 23-31%, with reductions in global warming potential of 42-52% (Bais-Moleman et al., 2018). Yet another study compared cascading use of wood from deconstruction with no wood reuse, finding 7% reduction in global warming potential and a savings of up to 14% of the annual primary wood supply of the study area (Höglmeier et al., 2015). Risse, Weber-Blaschke, and Richter, 2017, who conducted a case study in Germany, determined that cascading use of wood resulted in significantly greater resource efficiency and lower resource consumption as compared to the use of new wood. An examination of particleboard production using recovered wood found that production from wood wastes resulted in −428 kg CO_2-eq compared to particleboard from fresh woods, and combined heat and power energy production using wood wastes yielded −154 kg CO_2-eq emissions compared to use of fresh wood (Kim and Song, 2014). Several studies, however, identified cautions in approaching deconstruction. Bais-Moleman and colleagues, for instance, noted that while cascading would provide substantial wood use efficiency and greenhouse gas reductions, these benefits would be largely negated in the short term because of diversion of wood from renewable energy production and resulting increases in CO_2-e emissions from fossil-based energy production. And Cohello and Brito, 2012, cautioned that what they described as "shallow, superficial, selective" demolition might actually result in a heightened environmental impact due to extra transportation needs.

3.4.4. Barriers to Greater Levels of Cascading Use

Asked why so much deconstruction waste is landfilled, rather than recovered for reuse, in the United States of America, the president of an organization that encourages recovery, reuse, and recycling of building materials replied that "One of the biggest challenges is we're working against a system that's been completely designed to make it easy for people to throw things away." (Cochran, 2022). In Canada, where less than 8% of landfills are reportedly recycling wood waste, low tipping fees, relatively cheap availability of timber, and ease of obtaining open burn permits are identified as disincentives to wood waste recycling (Donaldson, 2022).

Growing demand for wood for energy generation also presents a challenge. For instance, Bergeron, 2014, noted that the presence of a robust thermal treatment sector in Switzerland, combined with an established pattern of wood waste exportation, add up to no amount of waste wood being available for recycling in that country. Exports are largely driven by markets for wood for energy production (Junginger *et al*., 2019).

Another factor is that deconstruction is difficult. buildings are usually not constructed with dismantling in mind. Instead, are designed with performance, customer satisfaction, and long-term durability as objectives. As reported by Bertino *et al*., 2021, less than 1% of existing buildings are fully demountable. Among the problems are that older buildings contain materials that are today recognized as environmental hazards; structural components are penetrated by electrical, plumbing, and heating, ventilation, and air conditioning (HVAC) systems throughout, resulting in damage to material and difficulty in separation at the point of deconstruction; construction adhesives, such as those used to create stiff floors, make separation of components virtually impossible; and many connectors are inaccessible and/or difficult to remove, often resulting in damage during deconstruction (Guy and Shell, 2002).

3.4.5. Design for Disassembly

Recognizing current problems in building deconstruction considerable effort has been devoted in recent decades to examination of how buildings might be constructed so as to facilitate deconstruction at end of useful life. Literally hundreds of reports have been published on this topic, and numerous architectural firms and professional associations around the world are devoting attention to this issue. Where this will all lead is at this point uncertain but given the level of attention this issue is attracting, changes in future building design and construction standards are likely.

4. CHAPTER 4 Examples of Good Practice

This Chapter provides an overview of currently observed strategies and activities undertaken by different policy and economic actors which have an impact on the construction sector, in particular the wood construction. These strategies and activities showcase efforts made by policy makers and industry actors alike, at the planning, the construction and demolition stages of building processes. They aim to reduce resources consumption, including energy consumption and to extend the life of products, where it is possible.

These concrete projects and case studies, implementing principles of circularity and sustainability in the wood construction sector, have been collected through desk research and personal communication with forest sector professionals in different countries of the UNECE region.

List of case studies:

1. Austria – wooden building in Vienna (final)
2. Austria –policy supporting substitution with wood (final)
3. Canada – Unbuilders (draft)
4. Czechia - public procurement policy supporting substitution with wood (final)
5. Poland – wooden building in Jata (final)
6. Poland – wooden building in Plonsk (final)
7. Serbia – use of CLT (final)
8. Turkey – to be completed after COFFI
9. UK - Sustainable Materials Library (draft)
10. Study on wooden buildings performance in16 countries (draft)

Policy supporting wood construction, AUSTRIA
Introduction/Background
The Austrian Wood Initiative is a project that contributes to the implementation of a bio-based circular economy and climate protection by promoting the use of wood as raw material for construction, and the research on production of gas, biofuels and hydrogen from wood. It has been established as part of the Governmental Programme 2020–2024 within the Austrian Bioeconomy strategy[2] (2019) which includes a commitment to achieve climate neutrality by 2040 and provides guidelines for the implementation of the Agenda2030 and the SDGs. It covers all industrial and economic sectors that produce, process, handle or use biological resources[2] and aims to replace fossil raw materials and energy resources with renewable resources. Through several flagship projects, the strategy aims to optimize synergies among SDGs. In Austria, the federal states are responsible for building regulations based on the Guideline from the Austrian Institute of Construction Engineering in timber construction. The Guideline serves to harmonize the building regulations, prescribe fire protection in construction and provides classification of buildings. In 2021, the framework for timber construction of the guideline was simplified allowing constructing more than three floors' buildings.
Circular approaches and practice applied
The Austrian Wood Initiative includes the following bioeconomy and circular economy measures [2]: <u>Governance</u> • Development of a national timber policy i.e., contribution to European and global level and the creation of a Wood Policy Platform (European and global). • Improving the framework conditions for sustainable building, securing, equipping, and furnishing. • Coordination, further development and harmonization of standards and regulations at national and international level. • Establishment of an Austria-wide consulting network for wood and timber construction. • Establishment of a platform fostering and connecting bioeconomy-related clusters and initiatives. <u>Wood construction</u> • Promotion of wooden buildings (CO_2 Bonus) by promoting the use of wood by the public sector (federal government, province, municipality, school buildings, kindergartens). • The CO_2 bonus provides investment premium of 1€ per 1kg certified wood (and up to 50% funding) and in case renewable materials are used for insulation the subsidy increases to 1.10 € per 1kg certified wood. • An additional condition is that at least 80% of the wood must be harvested and processed in a proximity of no more than 500 km from the construction site[21]. <u>Innovation</u>

- Research – in the framework of the Forest Fund a regular call for research projects is provided. Most recent one is "Increased use of wood as raw material" (THINK.WOOD. Innovation[3]) where the goal is development and innovation in the value chain for multiple use of wood as a raw material.
- Digitalization in the procurement, planning and the production process as well as in construction and facility management.
- Bioeconomy – substitution of basic and other materials in energy intensive buildings.

Education

- Educational and awareness-raising measures regarding active sustainable forest management and wood use with regard to climate protection in the Primary, Secondary and Tertiary schools.
- Communication
- Promotion of events, public relations and social media, related to awareness raising in use of wood as construction material.

Results and benefits

The foreseen effects of the Austrian Wood Initiative project include[2]:

- Wood as building material is used in the best possible way, considering sustainability criteria.
- The trend towards timber construction continues to gain momentum.
- Income and jobs are secured and created. Currently, 7 % of the workforce in Austria works along the wood-based value chain.
- CO_2 storage effects (carbon sink) are improved, and CO_2-intensive materials are substituted in the best possible way. Today, 10% of Austria's total annual greenhouse gas emissions (eight million tons of CO_2) are already avoided each year by substituting finite raw materials with wood products.

Unique or can be replicated

The Austrian Wood Initiative can be replicated in the EU countries (based on similarity in policies and legislation) and especially in countries with similar wood resources.

Contacts & sources

Contacts:

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E-mail: paul.ehgartner@bmlrt.gv.at

Links:

[1]https://info.bml.gv.at/themen/wald/wald-in-oesterreich/wald-und-zahlen/forstwirtschaft-zahlen-und-fakten-2021.html

[2]https://www.bmk.gv.at/en/topics/climate-environment/climate-protection/bioeconomy/flagship-projects.html

[3] https://www.ffg.at/programm/thinkwoodinnovation

https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.filipovic-savjetovanje.hr%2Fpresentations%2F2022%2FPaul%2520Ehgartner_Austrian_Wood_Initiative_ZagRE_2022_Conference%2520Real_Estate_Development.pptx&wdOrigin=BROWSELINK

Wood based building in Vienna, AUSTRIA
Introduction/Background
The Seestadt Aspern is a district in Vienna currently under construction. It is one of the largest urban development projects in Europe. One of its buildings, the HoHo, is characterized by an innovative approach of timber construction. It shows advantages of hybrid wood construction compared to pure timber construction. Reinforced concrete cores are used for vertical development and supply, providing sustainability and saving of CO2 emissions. The building is mostly made of wood (74%) and shows that wood as building material can be used both ecologically and economically. Building features (Endre, 2017): • Construction time: from October 2016 to summer 2019 • Construction costs: 65 million € • Underground floors: 2 floors • Floors above ground: 24 floors; Building height: 84.00 m • Gross floor area: approx. 25,000 m² • Net floor area: approx. 19,500 m² • Wood: 74%, 6000 m³ • Energy standard: Passive house standard It is a pioneering project, because it is one of the first buildings mostly made of wood with more than eighty meters height (Endre, 2017; Woschitz, 2015) which stands out as the 2nd tallest wooden skyscraper in the world.
Circular approaches and practice applied
The HoHo building integrates wood as a sustainable alternative to conventional building materials. Special value is placed on prefabrication of wood and the construction efficiency resulting from the use of modular systems, which contribute to a simple and resource-efficient construction. Use of concrete only where absolutely necessary, translates to a significant reduction in the overall CO_2 emissions. Compared to traditional construction methods, production of this building is estimated to result in avoidance of 2.800 tons of CO_2 emissions in additional to emissions reduction from use of fewer truck transports compared to conventional buildings Adoption of a modular design resulted in a significant reduction in energy consumption during the construction phase, equivalent to 40 km driven daily in a car over 1,100 years (Holzbau Austria). Separation of the reinforced concrete construction from production of mass timber elements allows parallel production and thus contributes to an optimal and shorter construction process. Reduction of construction time is accompanied by savings of energy. During construction of the primary structure on site, the prefabricated timber components were manufactured in a factory independent of weather conditions, which helped to assure quality. The clear load bearing structure ensures simple and thus economical assembly logistics on site, which also means e.g., less dust- and reduced noise pollution. The static load-bearing system consisting of glulam columns, prefabricated concrete girders as ceiling finishes and the timber-concrete composite ceiling elements have a fire resistance duration of 115 minutes, which gives to the fire brigade 25 minutes more time for evacuation and firefighting than required by the OIB guidelines. The OIB is the Austrian Institute for

Building Technology (Oesterreichisches Institut für Bautechnik), which issues guidelines for the standardization of structural requirements.

Results and benefits

The advantages of using wood for HoHo building:

- Efficient construction through the use of modular systems in timber construction.
- Use of domestic wood as a renewable raw material form sustainably managed forest.
- Replacing of CO_2 intensive materials and reducing the environmental footprint.
- Avoidance of long transport routes by using local wood and security of the value chain.
- Significantly higher CO_2 storage capacity compared to conventional building materials.
- The project illustrates that sustainable building is possible without loss of comfort.
- The heating demand for the HoHo is 19.8 kWh/year/m^2, which is more than 20% below the low energy house minimum standard of 25 KWh/year/m^2.
- Certification by the ÖNGB (Oesterreichische Gesellschaft fuer nachhaltiges bauen - Austrian society for sustainable building): 924 from 1000 points. In particular, the economy, resource efficiency and the area of energy requirements offer big advantages.

Unique or can be replicated

The construction method can be replicated.
This construction system is not patented and can be accessed by the client and by competitors (Endre 2017, 109).

Contacts & sources

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R. Woschitz, E-mail: office@woschitzgroup.com

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Unbuilders, CANADA
Introduction/ Background
The demolition industry generates millions of tonnes of waste annually in Canada, 37%[22] of which is valuable lumber. Unbuilders is a salvage experts' company, build of former-carpenters, roofers, framers, and tradespeople who have made the switch from construction to deconstruction. The company focuses on deconstruction and remanufacturing in lieu of demolition and disposal of construction materials.
Circular approaches and practice applied
Unbuilders focus on end-of-life management of construction products. The team disassemble homes, layer-by-layer, upcycling them into the supply chain. In their practice, most of the building's components can be deconstructed and salvaged yielding less than 5% waste on average. The company sells a selection of reclaimed wood that comes directly from deconstruction projects with a variety of sizes, types, and dimensions of reclaimed wood, including original fir and oak flooring. These include: Dimensional lumber Shiplap and strapping Large posts, beams, joists Salvaged and wide plank flooring
Results and benefits
On each project, Unbuilders report to divert 50 tonnes of waste and salvage 10 tonnes of lumber. The service benefits from tax credits that make it more affordable than traditional demolition. Often harvested raw material has also historical value. Much of our lumber comes from buildings that were constructed with ancient trees. The company also provides jobs to a young team of professionals and allows young workers to contribute meaningfully to lessening waste in the construction sector.
Unique or can be replicated
It can be replicated in different countries
Contacts & sources
https://unbuilders.com/

[22] Source will be completed

Sustainable Procurement Law, CZECHIA
Introduction/Background
Czechia introduced a new regulation on public procurement on 1 January 2021[23]. According to this regulation, new requirements supporting sustainable and circular approaches in procurement for construction projects came into force. They include social and environmental sustainability criteria related to environmental impacts of a project, sustainability and life cycle costs of supplied products, services, or construction work. In support to the new regulation the Ministry of Agriculture published guidelines[24] supporting its implementation. They include: • Brief introduction on the possibilities and reasons for the use of wood in public procurement contracts • Examples of good practice (e.g., public procurement documentation modelled on wood building projects documentation) • Design, building materials and techniques of the construction (e.g., procuring organization can define purpose, scope, performance, and functional parameters including the share of used wood) • Preliminary market consultation (procuring organization gathers information from suppliers on incorporating procurement goals in their projects related to e.g., environmental, and social sustainability, or innovation) • Procuring organizations are allowed to define sustainability criteria needed for specific project e.g., establish the condition of wood use as a technical condition defining the subject of the public procurement or define criteria for evaluation (e.g., life cycle costs, share of used wood)
Circular approaches and practice applied
The new procurement regulation creates a policy environment promoting the use of wood and the circular economy approaches such as life cycle evaluation or the share of used wood in public procurement construction projects.
Results and benefits
The new Sustainable Procurement law and the presented guidelines are going to support fulfilment of the Strategy of the Ministry of the Czech Republic with the outlook to 2030 and one of its strategic goals “competitiveness of the forest-based value chain”. Both documents also support Conception of the State Forestry Policy until 2035, where “strive for the inclusion of a minimum proportion of renewable raw material use in construction contracts (emphasis on wood) implemented under the Public Procurement Act” is defined as one of the sub-goals.
Unique or can be replicated
Can be replicated
Contacts & sources

[23] 134/2016 Sb. Zákon o zadávání veřejných zakázek (nový) (zakonyprolidi.cz)
[24] METODIKA_VYUZITI_DREVA_VE_VZ.pdf (eagri.cz)

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Wood Promotion Centre in Jata, POLAND

Introduction/Background

The Wood Promotion Centre in Jata, built by the State Forests is a building located in eastern Poland. The facility is a passive energy office and educational building, using wood for construction and finishing purposes. It is an example of the use of environmentally friendly technologies such as heating systems, photovoltaics and recuperation for minimising energy consumption and the building's impact on the environment.

Circular approaches and practice applied

In accordance with the investor's assumption, the designed building is an energy-efficient, timber-framed building. The energy-saving solutions adopted are confirmed by the Passivhaus Institut Darmstadt[25] certification.

The facility makes maximum use of wood as a building material, in the structure, in the thermal insulation layer and as a roofing finishing and aesthetic material. Furthermore, the beneficial impact on the environment includes:

1. Location of the building. The building was positioned on the plot to maximise the use of solar energy. Orienting the longer axis of the building in an east-west direction allows the surface of the longer southern elevation to absorb energy gains from solar radiation. On this side, a full-height glass façade was used in the multipurpose room, large windows in the office room and atrium, and a system of photovoltaic panels on the roof slopes. To prevent the building from overheating in the summer, sun breakers in the form of vertical blades were designed on the glass facade.
2. Compact building shell and thermal insulation. In order to eliminate potential energy losses, the building shell was designed to be compact. All of the building external compartment were made airtight and thermally insulated to such an extent that the U-value of the entire building body ≤ 0.15 W/(m2K) and air infiltration ≤ 0.6 h-1 by volume of the entire building.
3. STEICO[26] system. The building uses a bridgeless construction and insulation system consisting of wood and wood-based elements, in which load-bearing properties are provided by I-beams and glued laminated timber elements (columns and beams), while thermal insulation properties are provided by wood chip elements (boards and mats).
4. Energy efficient joinery. The window and door joinery used in the building, in addition to thermal insulation, ensures maximum use of solar energy. The windows (glazing and frames) have U-values ≤ 0.80 W/(m2K) and g-values ≈ 50%.
5. Renewable energy solutions:
    a. The building is equipped with a vertical ground heat exchanger with 3 boreholes to a depth of 100 m with a collection well. The energy extracted

[25] https://passiv.de/

[26] System certified by the Passivhaus Institut Darmstadt, confirming energy-efficient standards in construction https://www.steico.com/en/solutions/new-construction/the-steico-construction-system

from the ground exchanger will be used to heat the building and for domestic hot water.

b. The building is founded on a heating and cooling foundation slab, with thermal accumulation parameters ensuring the maintenance of comfort in both winter and summer.
c. The building uses a mechanical ventilation system with heat recovery - recuperation. The heat present in the air removed from the rooms is transferred to the incoming fresh air (building heat recovery efficiency of at least 80%).
d. The building has been equipped with a 4 kWp photovoltaic system, which is used to produce and transmit electricity to the existing internal electrical installation (on-grid installation) and allows excess energy produced by the micro-installation to be exported to the power grid.
e. A low energy consumption LED lighting system has been designed for the building.
f. The electrical appliances that equip the building are characterised by an energy class of A +++ (if an energy class is defined for them).

Results and benefits

The building is energy passive and ensures low maintenance costs and high comfort. It is sustainable and environmentally friendly over the entire life cycle. The storage of CO2 in wood for many decades is significant. The reduction in CO2 emissions is linked to a shorter construction process compared to a conventional construction material. The educational nature of the facility further emphasises the role of wood in construction and changes public awareness. The following parameters have been set for the building:

- U max for the external compartments Umax=0.15 W / m2K
- U max for the window and external door package (glazing and frame) Umax=0.8 W / m2K
- Energy requirement for heating max. 15 kWh/(m2a) or heating power max. 10 W/m2
- Airtightness of building n50 ≤ 0.6 h-1
- Energy need for cooling max. 15 kWh/(m2a)
- Primary energy demand ratio max. 120 kWh/(m2a)

The building was awarded at a national competition “Modernisation of the Year and Construction of the 21st Century”[27] in the category of wooden buildings, in 2020

Unique or can be replicated

The solutions used in the facility, as well as its educational value in the context of timber promotion, are intended to encourage people to follow this timber construction technology.

Contacts & sources

General Directorate of the State Forests in Poland / Forest District Łuków

[27] https://www.modernizacjaroku.org.pl/

Office building of the Płońsk Forest District, POLAND

Introduction/Background

The new headquarters of the Forest District Płońsk is located in central Poland. The building is an example of sustainable construction with the highest environmental standards and emphasises the importance of the ecological aspect in modern construction. It was built with an objective to create an ecological, zero-energy building with no negative impact on the environment, either during its construction or in its subsequent use.

Circular approaches and practice applied

Wood is the main building material (with the exception of the staircase and foundations). The building was designed and constructed using prefabricated timber frame technology. Assembly and prefabrication of the finished elements (walls and ceilings) took place in closed conditions in a factory environment.

The prefabrication of the elements, wooden walls and ceilings, (including windows) filled with thermal insulation material and assembled in an airtight manner ensures the rigidity of the walls and the entire building. Thermalised timber was used on the facade.

The building is equipped with modern ventilation systems with heat recovery and renewable energy sources. Heating is provided by ground source heat pumps powered by electricity produced by photovoltaic cells installed on the building. An additional advantage is the absence of greenhouse gas emissions and very high energy efficiency close to zero-energy building.

The building incorporates modern technology and uses renewable energy sources:

1. 36.3 kW photovoltaics, (134 panels) - The project has taken care to use environmentally friendly, renewable energy sources. The electricity supply will be supported by photovoltaic panels on the roof of the building, with a maximum capacity of 36.3 kW.
2. Underfloor heating using ground source heat pumps, (nine heat pumps were used to heat the building with a total heating capacity of 40 kilowatts and a cooling capacity of 30 kilowatts. With the assumed heating capacity at this level, nine boreholes each 92 metres deep were required)
3. The building is also equipped with mechanical air exchangers to ensure comfortable living and avoid unnecessary heat loss. There are three mechanical supply and exhaust ventilation systems with heat recovery, and one mechanical exhaust ventilation system for the sanitary facilities and utility rooms, as well as an air-conditioning system for cooling the server room. The supply and exhaust ducts are fitted with appropriate dampers to reduce noise and ensure the comfort of the building's occupants.
4. Care has also been taken to use rainwater in the irrigation system. Rainwater is collected in closed tanks and used to maintain the green areas within the plot next to the office.

The building is an energy-efficient building as evidenced by the fact that the heat transfer coefficient of the external partitions (roof, floor on the ground, external walls) meets the standards in force in Poland from 2021. All partitions are filled with mineral wool insulation and the external partitions are diffusively open.

Results and benefits

- Wood is a renewable, naturally occurring raw material, warm, ecological, human friendly and this is also why houses made of wood are more environmentally friendly. The trees from which wood for construction is obtained sequester CO_2 during their growth process – carbon which can be stored in houses and other wooden structures for decades or even hundreds of years.
- The strength parameters and insulating properties of wood make it possible to build much lighter and more energy-efficient structures than the equivalent concrete or masonry structures.
- Timber can be easily reused after demolition.
- The facade was finished with thermised board, a material with greater dimensional stability and better insulating properties while being resistant to the growth of rot fungi. Heat treatment modifies the properties of the wood by means of high temperatures and steam. Heat treatment reduces the wood's ability to absorb water and increases its insulating capacity by up to 25 %.
- The building is equipped with electrical and lightning protection, water and sewage system and rainwater system, and mechanical ventilation with recuperation and air conditioning.

Heat transfer coefficients:

1. external walls (Umax W/m2K) - <0.20

2. roofs - <0.15

3. windows, balcony doors - <0.90

Basic building parameters:

Built-up area: 654,32 m2

Usable area: 749,24 m2

Internal volume: 2637.72 m3

Gable height: 5.18 and 7.15 m

Fire resistance class of the building - "D".

The building was awarded the title “Building of the 21st century” in the category "Low-emission construction and renewable energy sources" during a national competition “Modernisation of the Year and Construction of the 21st Century”.

Unique or can be replicated

The building is currently being used as a demonstrator due to the high level of interest from other State Forests units and will be replicated by others in the near future.

Contacts & sources

General Directorate of the State Forests and Forest District Płońsk
https://www.youtube.com/watch?v=OycUmk-vf8o

CLT Construction, SERBIA

Introduction/Background

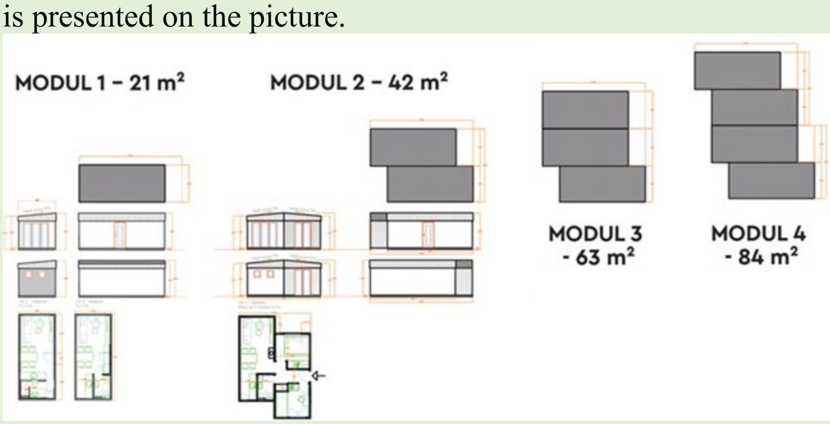
The tradition of building with wood in Serbia is several centuries long. During that period, the trends in wood construction changed both to the advantage and to the disadvantage of wood. In the second half of the 20th century, the construction of wooden buildings was stagnant due to the dominance of concrete, brick and other materials. The situation began to change in favor of wood in the last twenty years when wood experienced a renaissance in the construction of family houses and tourist facilities. This was supported by the trends of returning to tradition and nature in all spheres of society. There are numerous examples of touristic facilities (hotels, restaurants, viewpoints at picnic areas, etc.) as well as an increasing number of family residential facilities that are built of wood. Their construction is characterized by the use of wood in a traditional way i.e., by a large consumption of wood per unit area of the object in which the wood is installed.

With the construction of the first CLT factory in Serbia in 2019, the situation began to change. CLT is gradually being accepted by architects, builders and investors as the material of the future, with advantages compared to the traditional construction method, as well as its importance for the development of the circular concept in building with wood.

Circular approaches and practice applied

Innovative construction with CLT panels made of solid wood is based on the modular house construction system developed by the Kolarević company, which is currently the only producer of this type of engineered wood products in the Southeastern Europe.

The modular building system allows for a large number of combinations of basic modules in order to obtain the desired square footage and functionality of the space. In this way, the space solution in the interiors is tailored to the individual needs and wishes of users. Once built, the house can be extended and expanded by adding suitable modules, and that is an important advantage compared to building houses with other materials. A schematic representation of modular construction with CLT panels developed by the Kolarević method is presented on the picture.



The constructive joints of the modules enable high compactness of the assembled units during transport from the factory to the installation site. This significantly shortens the installation time of the facility on the site. Currently, the primary area of use of CLT in Serbia is the construction of individual family houses.

Results and benefits
The results of the building construction with CLT of this method show that construction with CLT is 5 times faster, that construction costs are lower by 5-10% and that they have 5 times better insulating properties compared to concrete construction for the same building. Additionally, the significant savings in CO_2 emissions are reached with CLT, and the buildings made of CLT fulfill the majority of the 9R principles of circularity. The up-to-date experience in the construction of buildings with CLT shows a significantly lower consumption of structural material compared to traditional wood construction, measured per unit area of the building. For example, for a building of 56 m^2, 17 m^3 of CLT is consumed, while the same building in the traditional construction system would require 33 m^3 of wood (wooden houses made from rough lumber). This example clearly shows the contribution of CLT construction to the rational usage of wood and the preservation of forest resources, which is one of the principles of the circular economy.
Unique or can be replicated
Can be replicated
Contacts & sources
info@kolarevic.co.rs https://www.kolarevic.co.rs

Library of Sustainable Building Materials (UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND)
Introduction/Background
Library of Sustainable Building Materials is a web-based resource established in Scotland in 2012 by Architecture and Design Scotland, an executive Non-Departmental Public Body set up by the Scottish Government. The Library showcases information about sustainable, traditional, innovative, recycled, and low carbon building materials. This service is relevant to construction professionals, architects, builders, homeowners, and students. It offers the visitors an opportunity to: Browse and compare materials Search materials by type, origin and typical use View case studies of the materials in use in Scottish projects, from houses to visitor centres View relevant events and training Find related publications and guidance on construction innovation, sustainable design, resource efficiency and low carbon buildings.
Circular approaches and practice applied
The Library of Sustainable Building Materials provides information about commonly used construction materials, including wood as regards: - their origin - embodied energy - recycled content - if it is a renewable or finite product - if it is processed or treated product - their suitability for deconstruction - their suitability for disposal - if there are subject of any sustainability certification - their lifespan - It also includes photos of each product.
Results and benefits
The Library contributes to knowledge-sharing and raising awareness on sustainable materials characteristics and applications. It is available to the public for free.

Unique or can be replicated
This type of information-database is relevant for the local and national market. It can be extended, or similar database created with information about other materials and species typical for other regions of the world.
Contacts & sources
https://www.ads.org.uk/ https://materials.ads.org.uk/

Life assessment of the softwood multiresidential building PAL6 from 16 countries

Introduction/Background

The case study demonstrates two objectives. 1) The six-storey multi-residential building is made of lightweight wood to show that it is possible to build above four levels in softwood in Quebec in 2016. 2) The life-cycle assessment (LCA) was performed was 16 countries from the perspective of the practitioners. The end-of-life scenario selected by the countries are reported, which is a first step to consider a circular building design.

Circular approaches and practice applied

The case study shows that the countries are using different LCA approach and end-of-life management of the wood. The case study reports:

Life cycle assessment and methodological approach,

Material substitution (some element of the concrete structure by wood),

End of life management (recycling, landfill, incineration),

Raising awareness.

Need for policy.

Results and benefits

The quantitative results are the share of recycled at the end-of-life in the participating countries.

Many countries are not considering recycled wood, which is an important information at this stage. Recycling wood prolongs the duration of the fixation of biogenic carbon in the wood. The wood industry can better position in the perspective of product stewardship and the circular economy.

Unique or can be replicated

The multiresidential building in a softwood structure of 6 levels can be replicated.

The study is unique because it discussed the life cycle assessment of biogenic carbon from lightweight wood structure from the practitioners in 16 countries.

Contacts & sources

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Conclusions

[This text has been drafted as background for COFFI discussion. It will be completed following COFFI comments and recommendations]

When considering sustainability and circularity in the construction sector, wood is an apparent choice. It is a natural raw material has a number of advantages over other building materials. First, it is derived from the natural growth cycle. Where forests are sustainably managed, enough wood can be grown in the long-term to meet the increasing demand for construction wood in many regions of the world. In regions where deforestation and forest degradation are currently primary concerns, sustainability and land use considerations include the need to stabilize and reverse these trends and further develop forest restoration capacities and associated policies or incentives.

Second, as forests are a natural carbon sink, wood is a part of the natural carbon cycle and actively contributes to climate protection. The natural cycle of wood begins in the forest as trees grow, with solar energy and carbon dioxide as key inputs to wood formation. The cycle continues with conservative harvesting from sustainably managed forests and use of wood in producing a broad range of products. When used in the industry in a cascaded way, wood circulates in the technical cycle where it can be recovered either at the end of its first useful life[28], or in the form of residues or by-products from production processes. In addition, pertinent construction design can contribute a sustainable use of wood raw materials and ensure a high degree of its recovery and recyclability. At the end of useful life, wood can be biodegraded or converted into bioenergy, this way returning to nature and closing its natural cycle.

Third, wood used in construction can be applied in diverse functions, as parts of buildings (e.g., for structural frames, decking, flooring, wall and roof sheathing, window frames, doors, and more), in building interiors in a myriad of ways (flooring, cabinets, paneling, trim) or at different stages of construction processes (e.g., for foundation framework supports and scaffolding) which contributes to lower impacts on environment and climate. Modern wood construction methods incorporate a high degree of prefabrication which speeds construction processes, provides for precision sizing of modules and connections – thereby promoting energy efficiency, circularity and greatly reduced waste generation.

This study examined the benefits of wood use in construction as bio-based material compared to other construction materials, analyzed different construction methods and circularity practices at

[28] Useful life refers to the amount of time an asset is expected to be functional and fit-for-purpose. With regard to the life of building, useful life can be defined by the number of years before a building deteriorates to the point that it is no longer safe or desirable to continue using, the point at which it no longer meets existing code requirements and would be too costly to bring up to code, the point in time at which other uses for the building site are more financially viable than keeping the existing building in place, and so on.

different stages of construction, retrofitting, deconstruction and demolition. The evidence provided has led to the following conclusions:

Better design, innovation and environmental impact: Over the past four decades innovation in engineered wood products for construction has culminated in an **unprecedented change in possibilities for wood use in construction and in particular of tall buildings**.

- The use of these innovative products contributes to sustainability goals through their market-based support for forest management and investments in forest-based industries and green jobs.
- Use of wood from sustainably managed forests in buildings results in lower CO_2 emissions and lower lifecycle energy consumption compared to other construction materials.

Reuse and the recycling of wood at the end of life is relatively low and therefore constitutes a considerable potential, provided economic and environmental efficiency are met.

Current and future potential: The potential for incorporation of greater quantities of wood in construction are the highest in residential and commercial buildings of 10 stories in height or less. Numerous case studies presented in this publication depict successful examples of hybrid construction with steel and concrete as well as mass timber. The increased recognition of climate and other sustainability benefits coming from the use of wood will likely contribute to further adoption of mass timber in construction for multi storey buildings, while the share of construction projects employing off-site methods will likely rise due to shortages of skilled labour.

- Although stick building technique remains dominant in most counties, recent construction techniques such as modular, mass timber and panelized construction techniques are becoming of interest, because of the advantages related to increased precision of design, the speed of construction and reduction of waste, thus contributing to a more circular and sustainable management of natural resources, of human capital and a lower impact on natural environment.
- The design is particularly important in these types of innovative construction techniques since it is critical that assembly tolerances are controlled, and misalignment of modules and connections be avoided, contributing to the reduction of material waste in the construction phase and in the long term the durability of construction structures during the use phase

Wood waste landfilled, composted or incinerated: Today, the data on the share of the latter varies according to different sources, however a steady decline in volumes can be observed. More information is needed to track these waste streams in a detailed way.

Deconstruction projects and reuse: Studies have shown examples of successful deconstruction projects where most of the materials recovered were fit for reuse with their market value exceeding the cost of the project, making it economically viable.

- Some studies assessed that the environmental impacts e.g., cumulative energy consumption or greenhouse gas emissions from deconstruction and material recovery were lower than producing new lumber.
- Despite these advances, deconstruction practices are not common in the sector. First, it is because buildings are usually not constructed with dismantling in mind and second the growing market for wood energy discourages other destinations of wood waste.

In sum: The study has shown that implementation of the above-mentioned approaches varies greatly among countries. Some measures, such as those related to the extending the life of products, including reuse, recycling and energy recovery are known in the industry practice, while others, including waste management, need further promotion and mainstreaming every time they make sense from the economic, social and environmental point of view.

Above all, a systemic change of mindsets and an integrated management of all process and activities by which companies add value to their construction materials and services along value chains are needed. This implies a new perspective on construction processes and redefines relations among different value chains' actors, from concept through completion to demolition and recovery of materials.

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