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CIRCULARITY CONCEPTS IN WOOD CONSTRUCTION

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CIRCULARITY CONCEPTS IN WOOD CONSTRUCTION

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ABSTRACT

When it comes to sustainability and circularity, wood as a natural raw material has several advantages over other building materials. As a bio-based resource, it has considerable benefits concerning greenhouse gas emissions, carbon-storing, thermal insulation as well as human health and well-being compared to other construction materials. New types of wood products, being the result of extensive research, enable the extensive use of wood in tall buildings. At the same time, innovative wood products provide less manufacturing waste, low carbon-emission alternatives and store massive quantities of carbon while new technologies speed construction processes, promote energy efficiency and minimize waste. This study examines the benefits of wood as a construction material and discusses practices applied in the wood construction sector from the perspective of circularity, sustainability and climate change mitigation. It analyses how circularity concepts can be applied in the construction industry using different construction methods and at different stages of value chains. The study describes how different construction techniques and practices contribute to the renewal and sustainability of construction value chains. The analysis is supported by examples of good practice in UNECE member States.

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The authors are:

Jim Bowyer

Katie Fernholz

Alicja Kacprzak

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GLOSSARY

Acidification – Refers to the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides.

Balloon frame construction – An early form of construction in the United States of America and Canada in which vertical members are cut to the full height of walls, from sill to roof line. 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.

Balloon framing – Refers to balloon frame construction.

Bio-based – Refers to commercial or industrial products that are composed in whole, or significantly, of biological products or renewable domestic agricultural or forestry materials.

Bioeconomy – This term refers to the share of the economy based on products, services and processes derived from biological resources (e.g., plants and microorganisms).

Cascading use of wood (Cascaded use) – Cascaded use refers to the use of material resources in such a way as to create the most economic value over multiple lifetimes with energy recovery as the last option and only after all potential for higher-value products and services has been exhausted.

Circular economy – A circular economy is one in which materials and products are kept in circulation for as long as possible. Such an economy uses a systems-focused approach and involves industrial processes and economic activities that are restorative or regenerative by design. This enables resources used in such processes and activities to maintain their highest value for as long as possible and aims to eliminate waste through the superior design of materials, products and systems (including business models).

Circularity – Refers to the use of materials and products in alignment with the principles of a circular economy.

Carbon dioxide equivalent (CO_2e) – A term used in reference to greenhouse gas emissions, based on the reality that other compounds have greater climate warming potential than CO_2 and calculated by weighting the volumes of various gases emitted with their potency as a greenhouse gas.

Cross-laminated timber (CLT) – This term is used synonymously with mass timber. Both terms refer to large structural panels made by assembling layers of dimension lumber that are glued or nailed together, or connected by dowels, with the grain of alternate layers laid at right angles to one another, much like the veneers of plywood.

Deconstruction – Refers to the selective dismantlement of building components, specifically for reuse, repurposing, recycling and waste management. It differs from demolition where a site is cleared of its building by the most expedient means.

Demolition – A description of the action taken at the end of a building's useful life with little or no regard for the potential reuse, recovery, repurposing or recycling of its components.

Embodied carbon – The sum of CO_2 equivalent emissions associated with materials and construction processes throughout the whole lifecycle of a product, building or piece of infrastructure, including the emissions resulting from the manufacturing of component materials (material extraction, transport to manufacturer, manufacturing), the transportation of those materials to a manufacturing or work site as well as all activities involved in secondary manufacturing, assembly or construction.

Embodied energy – The sum of energy consumption associated with materials and construction processes throughout the whole lifecycle of a product, building or piece of infrastructure, including emissions resulting from the manufacturing of component materials (material extraction, transport to manufacturer, manufacturing), the transportation of those materials to a manufacturing or work site as well as all activities involved in secondary manufacturing, assembly or construction.

Engineered wood – Refers to products made of wood elements that have been reformed using adhesives or other means of assembly to create a more useful product.

Eutrophication – A process involving a transfer of nitrogen and/or phosphor-containing compounds into fresh or ocean water ecosystems that can result in accumulating and decaying mats of algae which consume dissolved oxygen from the water and cause death of fish and other aquatic organisms.

Freshwater ecotoxicity – An indicator of the potential impact on freshwater organisms of toxic substances released into the environment.

Glulam – A stress-rated engineered wood beam composed of wood laminations, or 'lams', that are bonded together with durable, moisture-resistant adhesives. The grain of the laminations runs parallel with the length of the member. Glulam has versatile forms, ranging from simple, straight beams to complex, curved members.

Half-timbered construction – A construction where timber provides the structural frame of a building while the spaces between the frames are filled with plaster, brick or wattle and daub.

Laminated veneer lumber (LVL) – LVL is made from multiple layers of softwood veneer aligned such that the gain directions of all layers are parallel and aligned with the long axis of the lumber. LVL is a part of a family of products, namely structural composite lumber (SCL), that are made of dried and graded wood veneers, strands or flakes that are layered upon one another and bonded together with a moisture resistant adhesive into large blocks known as billets. Other products in this group include oriented strand lumber (OSL) and parallel strand lumber (PSL).

Life cycle assessment (LCA) – Refers to an environmental accounting and management approach that systematically considers all aspects of resource use and environmental releases associated with a product or industrial system from the defined beginning and ending points. Assessment through an entire life cycle considers the environmental impacts resulting from the procurement of raw materials as well as the production and distribution of energy, transportation, manufacturing, assembly and product use through to the end of its useful life.

Light frame construction – Refers to typical platform frame construction wherein wall sections are constructed with evenly spaced (usually 40 to 50 cm) vertical elements that are affixed to upper and lower horizontal elements.

Mass timber – A term used synonymously with 'cross-laminated timber' or CLT. Both terms refer to large structural panels made by assembling layers of dimension lumber that are glued or nailed together, or connected by dowels, with the grain of alternate layers laid at right angles to one another, much like the veneers of plywood.

Mass timber construction – Construction in which mass timber panels are the predominant or major building material, typically in combination with other engineered wood beams or columns such as glulam, parallel strand lumber and laminated veneer lumber.

Modular construction – A type of construction involving the assembly of building components almost entirely in a factory to manufacture separate, three-dimensional, box-like modules, including attached walls, floor, ceiling, wiring, plumbing and interior fixtures. These modules are then transported to a building site where they are positioned on a previously constructed foundation system and interconnected to create a finished structure.

Oriented strand board (OSB) – Refers to an engineered wood panel that is manufactured from thin, narrow wood strands 100 to 150 mm in length that are arranged in cross-oriented layers and bonded by waterproof heat-cured adhesives. Its strength and performance characteristics are similar to that of construction-grade plywood.

Oriented strand lumber (OSL) – Refers to a product made from thin, narrow wood strands 100 to 150 mm in length that are arranged with the long axis of the strands parallel to the long axis of the 'lumber'. The thin stands are combined with a structural adhesive before being oriented and formed into a large mat or billet and pressed. The resulting billet is then sawn into sizes similar or identical to that of construction lumber or timbers. Oriented strand lumber has high strength, stiffness and dimensional stability with consistent and predictable mechanical properties.

Oven dry weight – Refers to the weight of wood achieved through drying of wood to a constant weight in a ventilated oven at a temperature generally above the boiling point of water (103° +/- 2°C).

Panelized construction – A type of construction involving off-site prefabrication of building components, ranging from simple framed and sheathed wall and roof sections delivered to a building site with pre-cut window and door openings, to prefabricated floor systems, roof trusses and finished wall and roof sections that incorporate windows, doors and both exterior and interior finishes. Site delivery follows the on-site construction of a foundation system and is followed by the assembly of the prefabricated sections.

Parallel strand lumber (PSL) – Similar to laminated strand lumber (LSL) and oriented strand lumber (OSL), PSL is made from flaked wood strands that are arranged parallel to the longitudinal axis of the member and have a length-to-thickness ratio of approximately 300. The wood strands used in PSL are longer than those used to manufacture LSL and OSL. Combined with an exterior waterproof phenol-formaldehyde adhesive, the strands are oriented and formed into a large billet then pressed together and cured using microwave radiation. The resulting billet is then sawn into sizes similar or identical to that of construction lumber or timbers. PSL has high strength, stiffness and dimensional stability with consistent and predictable mechanical properties.

Particleboard – Refers to a panel product made by compressing thin shavings, flakes or slivers of wood while simultaneously bonding them with an adhesive. Many types of particleboards can differ greatly concerning the size and geometry of particles, the amount of adhesive used and the density to which panels are pressed, all of which can have a significant impact on its strength, other properties and potential uses.

Platform frame construction – In platform frame construction, the exterior, and some interior walls, carry the load of the upper levels and roof. Vertical wall elements are the height of one level of the building and capped by a floor system, with each successive floor created by the addition of another platform, another set of walls and so on. Wall sections are constructed with evenly spaced vertical elements that are affixed to upper and lower horizontal elements.

Post and beam construction – Refers to a type of construction where a building is supported by a structural frame with wall elements typically being non-loadbearing.

Primary energy – Refers to energy in the form that it is first accounted for in a statistical energy balance, before any transformation to secondary or tertiary forms of energy. For example, coal can be converted into synthetic gas, which can then be converted into electricity; in this case, coal is primary energy, synthetic gas is secondary energy and electricity is tertiary energy.

Structural composite lumber (SCL) – Refers to a family of products that are made of dried and graded wood veneers, strands or flakes that are layered upon one another and bonded together with a moisture resistant adhesive into large blocks known as billets. Other products in this group include laminated veneer lumber (LVL), oriented strand lumber (OSL) and parallel strand lumber (PSL).

Timber construction – Often used synonymously with 'wood construction'.

Timber frame construction – Refers to a construction method where the structural frame, consisting of both horizontal and vertical members, is made of large cross-section wood members (timbers), with connections made using notching, mortise and tenon joints and/or wood pegs.

Useful life – Refers to the amount of time an asset is expected to be functional and fit-for-purpose. With regard to a building, useful life can be defined as the number of years before the building deteriorates to the point that it is no longer safe or desirable for continued use, 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.

Wattle and daub – Refers to infill in the walls of buildings where a woven lattice of wood strips called wattle is thickly covered with a sticky material usually made of a combination of wet soil, clay, sand, animal dung and straw. Used mainly prior to the 17th century in parts of Europe.

Waferboard – Refers to a type of structural panel made from thin wood wafers roughly square in shape bonded together with waterproof phenolic resin under extreme heat and pressure that briefly appeared in commercial markets prior to replacement by oriented strand board (OSB).

ABBREVIATIONS

CAD	computer aided design
CDW	construction and demolition waste
CLT	cross-laminated timber
COFFI	Committee on Forests and the Forest Industry
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
EFC	European Forestry Commission
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GEF-7	Global Environment Facility, seventh replenishment
GHG	greenhouse gases
Glulam	glue laminated timber
HVAC	heating, ventilation and air conditioning
IEA	International Energy Agency
ISO	International Organization for Standardization
LCA	life cycle assessment
LSL	laminated strand lumber
LVL	laminated veneer lumber
mm	millimetres
MSW	municipal solid waste
NHS	National Health Service of the United Kingdom of Great Britain and Northern Ireland
NLT	nail laminated timber
OSB	oriented strand board
OSL	oriented strand lumber
PSL	parallel strand lumber
SCL	structural composite lumber
SDG	Sustainable Development Goals
SFM	sustainable forest management
UBC	University of British Columbia
UNECE	United Nations Economic Commission for Europe
USEPA	United States Environmental Protection Agency
3D	three dimensions

EXECUTIVE SUMMARY

When it comes to sustainability and circularity, wood as a natural raw material has several advantages over other building materials. The natural cycle of wood begins in forests as trees grow, with solar energy and carbon dioxide (CO_2) as the key inputs for wood formation. The cycle continues with harvesting from sustainably managed forests with the wood being used to produce a broad range of products. When used in 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 formwork 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 into useful products using relatively little fossil energy makes it less environmentally detrimental than materials such as steel, masonry and reinforced concrete. These aspects, of course, only translate to environmental advantage if wood is produced in a sustainably managed forest or plantation. Furthermore, wood has an advantage in that third-party oversight of forest management is widely practiced via forest certification programmes that have been in place for almost three decades. These programmes provide for rigorous evaluation of all aspects of forest management, including impacts on soil health, water quality, fish and wildlife habitats, rare and endangered flora and fauna, cultural and historical sites, among others. Doing so results in a means of ensuring attention to important issues while producing sustainable volumes of wood and other products and services. The programmes also provide a social context for wood production, bringing to the fore common social concerns and allowing an external overview of industry practices.

In many parts of the UNECE region, wood dwellings account for only 10 to 11 percent, or less, of new construction while 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 steel and reinforced concrete in tall buildings are all the result of extensive research over many years and are the result of focused attention on 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 (glulam) - mass timber buildings today contribute to circularity and environmental sustainability while also providing a highly engineered and high-performance material for construction. Mass timber allows for the beneficial use of renewable resources that can be fashioned into useful products with less manufacturing waste than previous forms of structural wood products, provides low carbon-emission alternatives to reinforced concrete and steel while also storing massive quantities of carbon for as long as they remain in existence.

Innovative wood 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 speed construction processes, provide for precision sizing of modules and connections - thereby promoting the energy efficiency of completed buildings, greatly reducing waste and protecting prefabricated modules from the effects of weather.

Wood use in construction is more circular and sustainable than the use of other common building materials. Wood has inherent advantages and provides multiple benefits because it is a natural material, can be fashioned into a diverse array of building components with minimal climate impact and can be incorporated into buildings which have lower lifecycle energy consumption and CO_2 equivalent[1] (CO_2e) emissions than non-wood structures. The substitution of wood for concrete or steel in construction results in reduced embodied CO_2 emissions. Significant additional carbon storage could occur within the built environment with greater use of wood in construction, with the caveat that the wood does not go to landfill following 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-product manufacturing contribute to circularity and sustainability.

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[1] A number of compounds are classed as GHGs. Although CO_2 is predominant in terms of volume, other compounds, such as methane, nitrous oxide and fluorocarbons, though emitted in lesser quantities than CO_2, are far more potent. Methane and nitrous oxide, for example, have 28 and 265 times the warming potential as CO_2 over a 100-year time horizon. In calculating the potential greenhouse effect of emissions from an industrial operation or other activity, the volumes of various gases emitted are weighted by their potency as a GHG to calculate carbon dioxide equivalent emissions, expressed as CO_2e.

Although wood use in construction offers substantial sustainability and circularity benefits, additional innovation is needed. Currently, waste from building deconstruction is not being recovered effectively. Designing for building adaptability, disassembly and effective material recovery would 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 buildings' end of life. The greatest opportunity for improved circularity of wood in existing buildings is in the recovery, reuse and/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 an approach should move away from business-as-usual towards more cross-cutting collaboration among different actors within and outside the construction sector. Increased collaboration of building research organizations, designers, architects, urban planners, engineers, municipality actors and legislators would contribute to achieving greater sustainability and circularity at different stages of construction value chains.

CHAPTER 1
Setting the stage for circularity in wood construction

1.1 Understanding Circularity and Sustainability

Many of the global priorities embedded in the 2030 Agenda for Sustainable Development[2] and the Sustainable Development Goals (SDGs) relate to forests and forestry, forest-based industries and bioenergy. SDG 15 Life on Land directly refers to the need for the sustainable use of ecosystems, the sustainable management of forests and the reversing of land degradation and biodiversity loss. SDG 13 is dedicated to Climate Action and cannot be achieved without resilient forests and responsible forestry practices, while SDG 6 clearly mentions the need to protect and restore 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 the pulp and paper industry, significantly contribute to pollution and waste generation. SDG 12 calls for responsible production and consumption and refers to circularity principles as well as the sustainable use of natural resources. It points out the need to increase resource efficiency, promote sustainable lifestyles, produce more with less and decouple economic growth from environmental degradation in the long-term.

The achievement of many of these objectives in the context of the increasing use of forest resources and growing environmental challenges, linked with greenhouse gas (GHG) emissions and waste generation, requires the application of production and consumption models based on the 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 several SDGs. A study by Schroeder Anggraeni and Weber 2019 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).

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 while at the same time reducing the global economy's dependence on non-renewable resources in the long term.

Different circular economy models coexist in the policy space and in research with a number of concepts that have been developed earlier or simultaneously. The origins of circularity itself are older and more diverse than it is commonly perceived and are rooted in ecological and environmental economics as well as industrial ecology (UNECE/FAO, 2022). Concepts regularly referenced today, such as circular economy, green economy, bioeconomy and sustainable economy, all differ but are consistent with each other since they all aim at the synchronized optimization of ecological economic and social objectives at different levels (personal communication Durocher, 2021)[3] in the same way as the 2030 Agenda for Sustainable Development does.

In this study, the concept of a circular economy used is based on the model of the Ellen MacArthur Foundation (Figure 1), as described in UNECE/FAO (2022), and takes into consideration its modifications by Oneil and Russel (2020) 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 while technical materials that cannot biodegrade can still circulate in closed loops thanks to circular practices.

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 as well as within the technical cycle (Figure 2).

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 biological (green) cycle. In both cases wood continues its lifecycle in a cascaded way until it is recovered for bioenergy at the end

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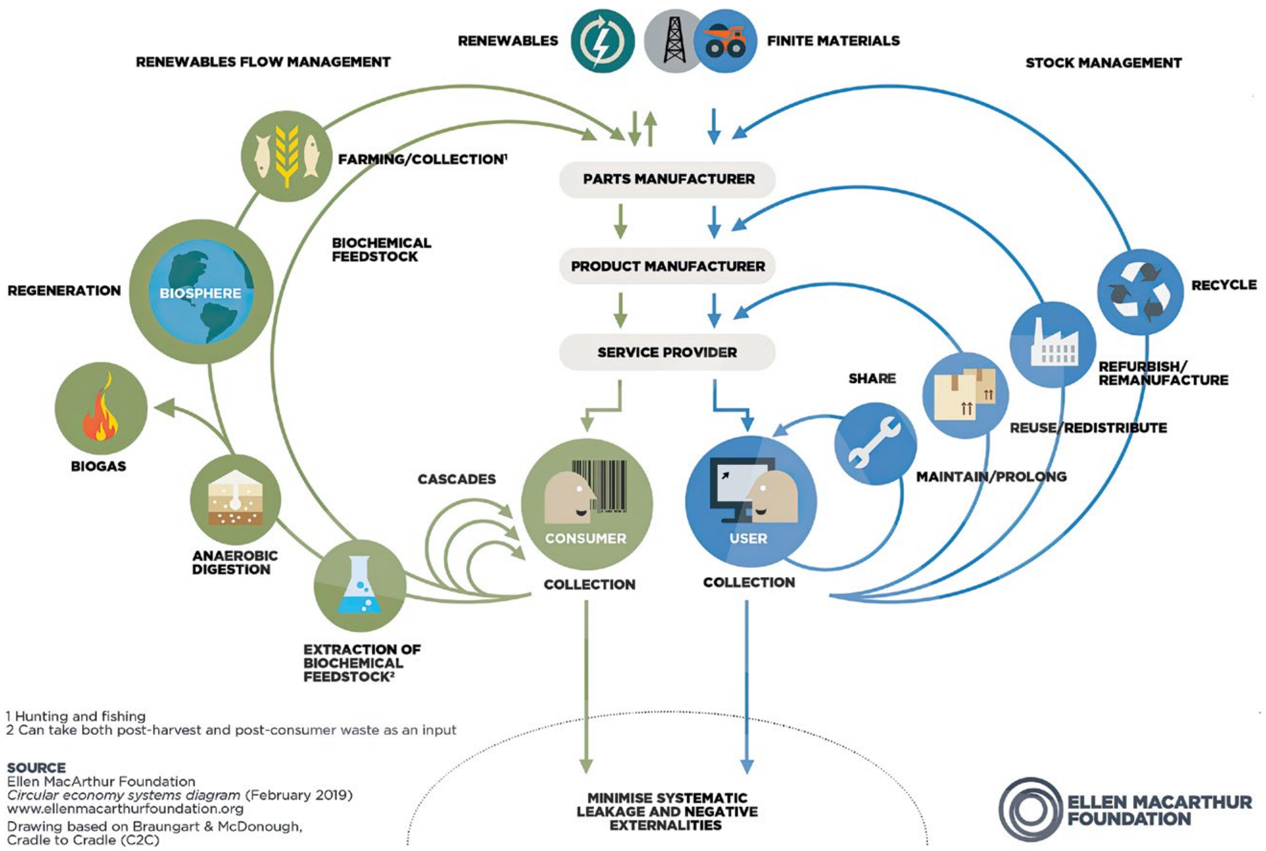
[2] https://www.un.org/sustainabledevelopment/development-agenda/

[3] Claude Durocher, unpublished study. State of the Global Forest Bioeconomy.

FIGURE 1 Biological and Technical Cycle in a Circular Economy Model by the Ellen MacArthur Foundation



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

of its life, at which point CO_2 is released to the atmosphere and made available for trees to begin a new cycle (Oneil and Russel. 2020).

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

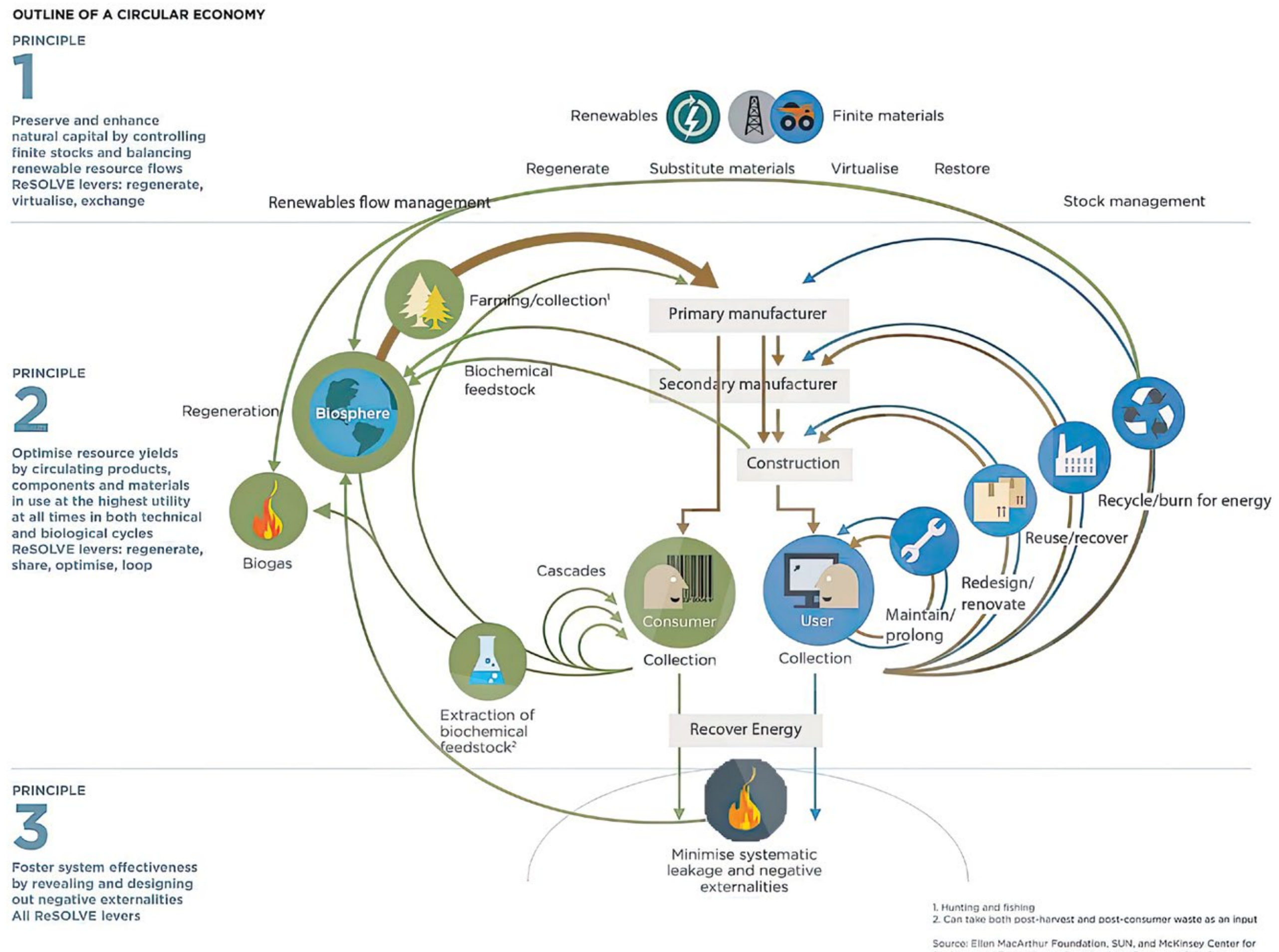
In this study, the 'circularity and sustainability practices' are understood by the application of the 9R approach (Figure 3) at different stages of construction value chains, as presented in UNECE/FAO (2022). This was done with the recognition that the focus is on analysing industry practice, without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

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 when applied to many technical materials. This is because once wood is transformed, it spans through several reuse, recovery and recycling processes in a cascaded way before it is shredded or incinerated for energy production. This allows it to feed back into the biological cycle of wood growth before it is ready to be used by the technical cycle again. In contrast, many technical materials, such as steel, aluminium and glass used in different elements of buildings, once they enter the technical cycle can be recycled and transformed into materials similar to their original form 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 as well as the combination thereof. Wood has been used in building for centuries and it is still one of the most widely used materials, however, with the appearance of engineered wood products, interest in the use of wood as a construction material is growing.

FIGURE 2 Circular Economy in the Wood Construction Sector



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Adapted from: Outline of Circular Economy from the Elle McArther Foundation
https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic

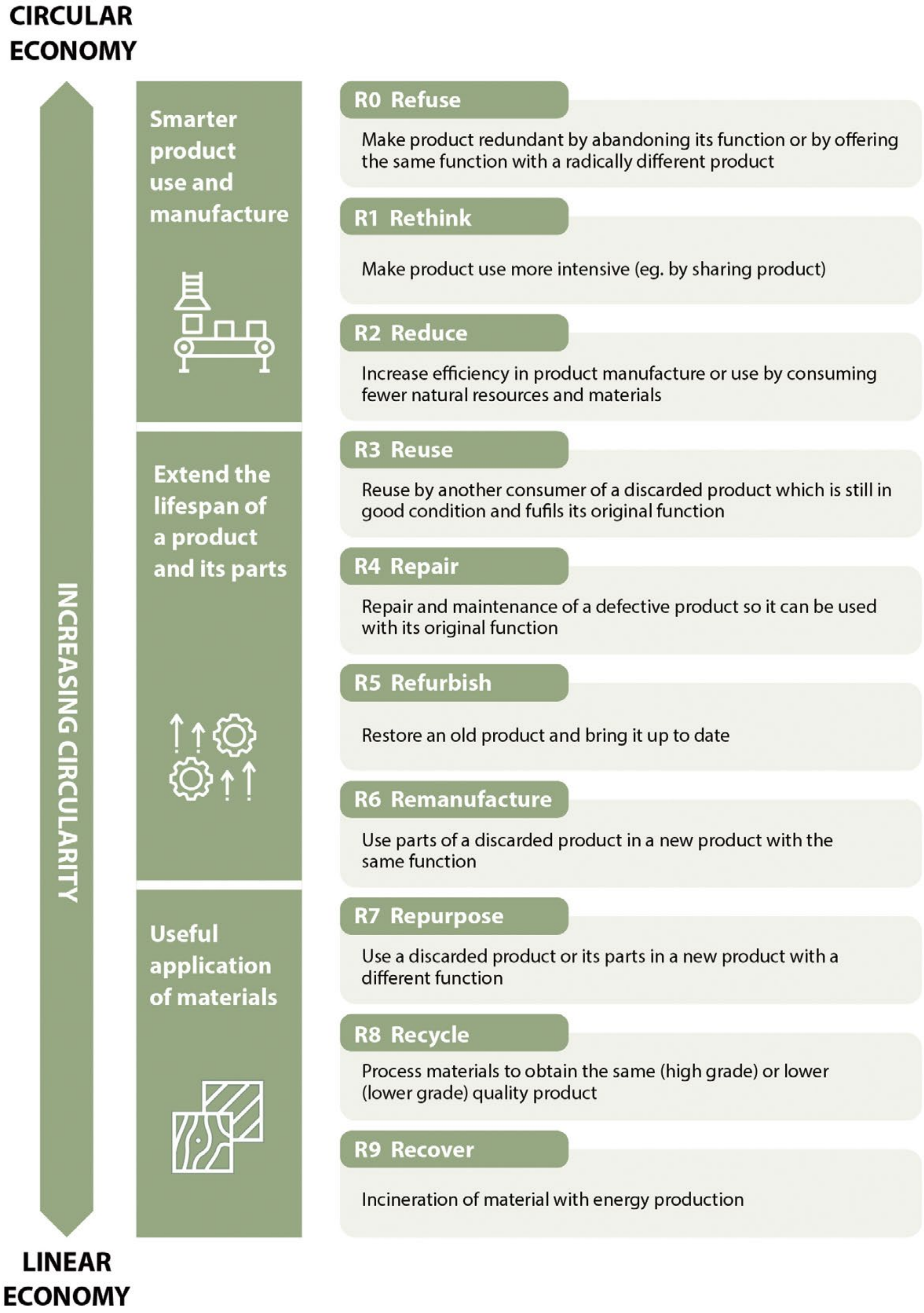
Source: Oneil and Russel, 2020

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 recovered from old wood buildings (Antikainen *et al.*, 2017). More recently, environmental arguments favour a shift to the use of more wood in construction based on advances in wood-based building materials and construction techniques while seeking gains in resource efficiency objectives as well as minimization of production waste both off site and at the construction site.

Together with the sector's increased adoption of engineered wood, attention is being given to waste reduction in the construction process, including the development of modular prefabricated construction techniques which ease disassembly at the end-of-life stage. Recently, attention has also been given to increased use of sustainable material and product, including cross laminated timber (CLT) and engineered wood timbers in building construction. CLT was invented in Europe and was the key development which allowed high-rise (tall wood) construction while also stimulating 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 (Verkek *et al.*, 2022).

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 the value of the built environment, including wood buildings (Delphi Group, 2021). However, wood can be considered a renewable material only when it is sourced from sustainably managed forests. Combined with sustainable spatial planning and eco-design, it is a durable,

FIGURE 3 Circularity and the 9Rs



CIRCULAR ECONOMY

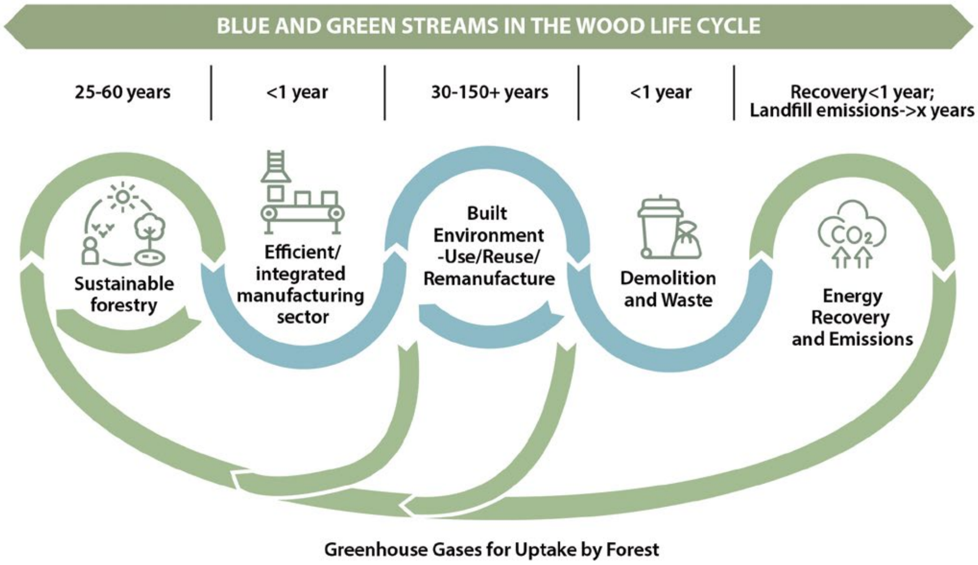
INCREASING CIRCULARITY

Smarter product use and manufacture	**R0 Refuse**	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (eg. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend the lifespan of a product and its parts	**R3 Reuse**	Reuse by another consumer of a discarded product which is still in good condition and fufils its original function
	R4 Repair	Repair and maintenance of a defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of a discarded product in a new product with the same function
Useful application of materials	**R7 Repurpose**	Use a discarded product or its parts in a new product with a different function
	R8 Recycle	Process materials to obtain the same (high grade) or lower (lower grade) quality product
	R9 Recover	Incineration of material with energy production

LINEAR ECONOMY

Source: UNECE/FAO, 2022

FIGURE 4 Wood Life Cycle in the Circular Economy



Source: Oneil and Russel, 2020

reusable and recyclable resource, fitting the principles of a circular economy, contributing to the sustainable use of natural resources and the mitigation of climate change.

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

After the adaptation of the Ellen MacArthur Foundation circular economy model to represent 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 construction uses through cascaded value retention processes in the technical (blue) cycle until their end of life and then into the biological (green) cycle at the end of their useful life (Oneil and Russel, 2020).

This model illustrates a more inclusive view of a circular economy, compared to existing circular economy models. It takes into consideration 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 suited to cascaded use, with bioenergy production coming at its end of life and the emissions returning to forests to initiate a new cycle.

1.3 Background and Objectives of the Study

This study aims to provide a comprehensive overview of how circularity concepts and sustainability practices, based on the models presented above, can be applied in wood construction. The work on the study resulted 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, COFFI and EFC requested UNECE and FAO to "(a) prepare a series of studies further reviewing the application of circular models in specific forest-based industries, including through the identification of case studies and best practice, and (b) to 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"[4].

The focus of the studies was 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

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

- Circularity concepts in the wood construction sector as an example of a long-lived products value chain
- Circularity concepts in the pulp and paper industry as an example of a group of commodities with a 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 Joint UNECE/FAO Forestry and Timber Section in Geneva.

1.4 Scope and Limitations

This study examines the benefits of wood use in construction as a 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, as well as end-of-life solutions. Different construction types (residential, industrial, commercial, civil engineering) and construction methods are analysed to provide evidence of how construction design, planning and practices contribute to circularity and how circularity concepts can be further promoted in the construction industry.

This 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 where 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 analysing circularity in an 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. This balance will be given due attention in a separate study of the series.

While this study presents the current industry context and points out opportunities and challenges in a 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 the 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 come 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.

1.6 Structure of the Study

Chapter 1 sets out the context and the objectives of the study. It defines a circular economy as referenced in this study and how it applies to the forest sector, in particular to wood construction.

Chapter 2 describes the benefits of wood use in the construction sector. It examines the benefits of wood, as a bio-based material and compared to other construction materials, on GHG emissions, carbon storage, thermal insulation as well as human health and well-being. It takes into consideration the perspective of circularity, sustainability and climate change mitigation.

Chapter 3 discusses the circularity practices applied in the wood construction sector. It describes how wood flows in the construction sector as a material and how different construction techniques and practices contribute to the renewal and sustainability of construction value chains.

Chapter 4 provides construction project experiences and case studies in the UNECE region in which the principles of circularity and sustainability were implemented in the wood construction sector.

Chapter 5 presents the study's conclusions and recommendations.

CHAPTER 2

The role of wood construction in a circular economy

2.1 History of Wood Use in Construction

Wood is widely available, relatively abundant worldwide, renewable, light weight yet strong, readily fashioned into useful products and aesthetically pleasing. Wood is today, and has been for many centuries, the predominant material used in the 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 percent of single-family homes in Canada and the United States of America, 45 to 70 percent in parts of Europe and 45 percent in Japan. Such use of wood in construction is likely to continue due to its basic characteristics, its availability and the growing interest in circularity and sustainability.

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

Source: Depositphotos

The type of wood construction used varies widely by region. Wood post and beam construction is, for example, typical in Japan along with the prefabrication of building components common. In post and beam construction, timber is the main structural material, with wall elements typically non-loadbearing. In contrast, single-family homes and other low-rise residential structures in the United States of America and Canada are commonly platform frame construction built of wood (sometimes referred to as light frame construction). Using this method, exterior and some interior walls carry the load of the upper levels and roof with wall sections usually constructed with evenly spaced (usually 40 to 50 cm) vertical elements that are affixed to upper and lower horizontal elements (Figure 5). Much of the component assembly typically occurs on-site, the exception being prefabricated floor and roof trusses.

In Northern Europe, homes are also constructed predominantly 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 to some degree, 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 example, wood-dwelling units account for 10 to 11 percent of new construction, in Italy and France it is 7 percent and 4 percent respectively while in Spain and other parts of Europe 2 to 3 percent (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. This limit was increased in recent decades to 6 storeys in some jurisdictions, particularly with the advent of podium slab construction wherein wood construction rises above one or two storeys of reinforced concrete. Nevertheless, the allowable height of wood structures has historically been effectively almost universally limited due to safety concerns in the event of a building fire.

The development of a number of new types of wood-based mass timber products has 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 led to unprecedented changes in the possibilities for wood use in construction, particularly regarding its use in the construction of tall buildings. The 2021 edition of the US-based International Building Code and the 2022 edition of 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 the pieces running 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 roof supports for church buildings and other types of structures. In the mid- to late 20th 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 (SCL) created from multiple layers of veneer referred to as laminated veneer lumber (LVL). Other products were formed from thousands of thin strands of wood compressed into large members, such as oriented strand lumber (OSL) and parallel strand lumber (PSL), which can be made to virtually any size and eliminate the problem of large variations in wood strength due to the 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 that established wood, for the first time, as an engineering material with predictable features and comparable applications to steel and structural concrete.

As noted previously, the development that served to change the potential use of wood in tall buildings had its beginnings in Europe, namely the introduction of CLT or mass timber. 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). This product 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. Panels made from CLT today can be as large as 0.5 x 6 x 18 metres and offer many advantages as load-bearing components 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 (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 unfeasible heights.

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

2.2 Traditional Construction Methods

Wood structures have been built for thousands of years, with one of the first documented examples being Europe's Neolithic longhouse, a freestanding timber building constructed between 5000 and 6000 BCE (Cochran, n.d.). In many parts of

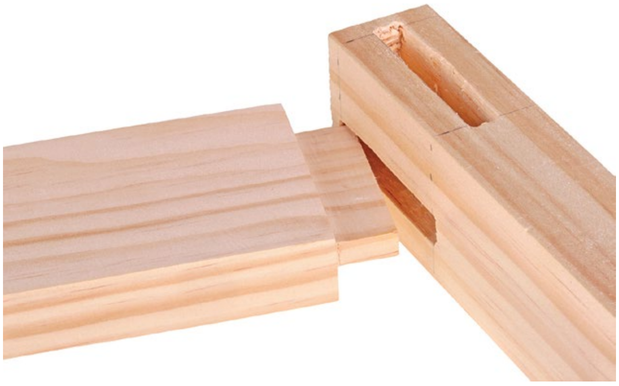
FIGURE 6 Cross-Laminated Timber (CLT)

Source: Depositphotos

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 the continuity of wall surfaces and provide greater protection from wind and rain as well as 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 as well as wood pegs (Figure 7). Timber framing later spread to Central Europe and soon thereafter to northern regions of the continent (Cochran n.d.).

FIGURE 7 Mortise and Tenon Connection



Source: Depositphotos

In its early form, timber frame construction is described as half-timbered as timber provided the structural frame of the building while 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 until the 17th century in modern-day France, Germany and the United Kingdom of Great Britain and Northern Ireland in particular. 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 the use of 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 purposes, including the production of charcoal, home heating and building construction, which led to a strain on the supplies of timber. Another factor was changing fashion, which led to an imitation of Mediterranean construction and the increased use of clay and stone in construction (WoodMasters, 2015).

Through succeeding centuries and up to the present day, sustainable forestry practices have become widespread, timber supplies have recovered, and timber framing has continued to be the most common form of wood construction in Central Europe. Mortise and tenon joints have been replaced with various types of metal connectors while what was wattle and daub infill is now 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-timber 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 squared timbers to create walls (sometimes both interior and exterior). Roof structures are wood and 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 in 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-timber structures using wattle and daub as infill. But those in half-timber houses in the northern reaches of the Americas soon found that the wall construction methods that had proven adequate in the 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 predominant 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 the 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 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 frame construction in common use today, balloon frame construction involved using nails in the assembly of wall sections 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 the sill to the roof line. As houses were commonly built to two storeys, this meant that vertical members were approximately six to nine meters in length. The fact that wall supports were the full height of walls marks the key difference between balloon frame construction and platform framing, another construction method that came later. Balloon framing allowed rigid construction of buildings involving relatively few people and, because of these efficiencies in labour and materials, it became the predominant 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 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, platform framing allowed for much taller buildings than balloon framing. Soon after the shift to platform frame construction, softwood plywood came onto the market, allowing for the 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 the prefabrication of some building elements, such as roof and floor trusses, this form of construction is representative of most current homebuilding in the United States of America and Canada, including multi-storey and multi-family construction.

In conclusion, 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 materials, whereas buildings were repaired, refurbished and reused for different purposes 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, is renewable and can be fashioned into useful building components with minimal climate impact. Also, it can be incorporated into buildings that have lower lifecycle energy consumption and lower CO_2e emissions than non-wood structures.

Where wood is produced in sustainably managed forests or plantations, there are many environmental advantages of wood as a construction material. Below are key characteristics of wood.

2.3.1 Produced by Solar Energy

Wood is a material produced by the process of photosynthesis; a process driven by solar energy. The natural, solar energy-based process of tree growth provides an extraordinary sustainability advantage for wood. As a consequence of trees utilizing freely available, zero-impact energy, the additional energy used, in particular the fossil energy, in processing wood into building components is typically significantly lower than for other major construction materials. Additionally, in many cases, the utilization of solar energy in the forest is supplemented by the use of renewable biomass energy in wood processing facilities, further adding to this reduced use of fossil-fuel-derived energy. As an added bonus, and one which no other building material can duplicate, the natural process of photosynthesis which results in wood production is accompanied by the 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 CO_2 from the air, sequestering much of that carbon in the form of wood. Among all species of wood found in the world, carbon composes an average of one-half of its dry weight. When trees are subsequently harvested to produce wood products, the carbon within their wood 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 alongside forests and grasslands. In the United States of America, where wood is predominant in homebuilding, the quantity of CO_2e represented by the carbon contained in wood in use in 2020 was estimated at 1.5 trillion tonnes, or over 10 percent of the quantity contained in above-ground forest biomass, a figure that is increasing annually at a rate of about 20 million tonnes (USEPA, 2022b).

The reality is that wood stores a great deal of carbon, the magnitude of that storage 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. By combining carbon capture during tree growth with the effect of delayed emissions due to carbon storage in wood products, the use of wood brings immediate benefits and contributes to long-term and extended climate mitigation goals consistent with circular economy principles.

2.3.3 Renewable

A key advantage of wood in comparison to other materials commonly used in building construction is that wood is renewable. If forests and 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 without sacrificing other critical values and amenities provided by forests. Wood is the major construction material that provides multiple sustainability benefits throughout its production cycle as the use of wood requires the continuous growth of trees and the support of associated biodiversity.

2.3.4 Strong, Yet Light Weight

It has long been known that wood has a high strength-to-weight ratio. In the emerging era of mass timber and tall wood buildings, this reality has come into focus for 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 percent 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 an existing building in which the foundation and footings are not sufficiently robust for the addition of functionally equivalent upper floors built of steel or reinforced concrete. This advantage can result in a tangible reduction in the use of energy-intensive building materials, concrete in particular. A reduced reliance on concrete can positively influence the carbon footprint of a building and contribute to the circularity and sustainability of the construction sector.

2.3.5 A Natural Thermal Insulator

Wood and products made from it provide natural protection from heat transfer and loss. This is because wood fibres are hollow, creating air pockets which serve to protect against heat transfer. Although 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 concrete walls 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 insulation 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. Future development of wood-fibre insulation can further advance circularity and sustainability in the construction sector.

2.3.6 Recyclable

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

2.3.7 Aesthetically Pleasing and Beneficial to Human Health

As reported by Lowe (2020), many studies have found positive effects on human health and well-being from exposure to wood. Findings include those that have documented increases in human comfort (i.e. satisfaction with room conditions such as lighting, noise and 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 also been documented where, for example, research has reported that the presence of visual wood surfaces in a room lowered the activation of the sympathetic nervous system, a mechanism which is responsible for physiological stress responses in humans (Fell, 2010). Kotradyova *et al.*, 2019, similarly found that the inclusion of wood 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 on the natural environment however, human emotional, mental and physical health aspects are also important for sustainability 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 CO_2e emissions generated in the process of producing building components and constructing various types of buildings using wood, steel and concrete. Comparisons can be challenging as modern buildings are virtually never constructed of only one material. Instead, builders and designers tend to use various materials in various proportions 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 this discussion and the several case studies referenced herein, the type of building is determined by the predominant 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 LCA, a science-based tool specifically designed to allow the 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 and maintenance through to end-of-life treatment, e.g., re-use, recycling or disposal to landfill. The use of LCA is beneficial in the evaluation of products that are as small as a pencil or as large as a tall building. Application of LCA yields definitive information regarding such indicators as 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 GHG emissions and climate change. The application of LCA is also a key strategy for supporting circularity and sustainability because 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 CO_2 emissions linked to the 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 the relative impacts of key structural materials.

Table 1 shows the embodied carbon associated with the 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.

TABLE 1 Embodied CO_2e in Common Construction Materials

Material	**kgCO_2e/kg 1/**	**kgCO_2e/m^3 2/**	**kgCO_2e/kg 1/**	**gCO_2e/m^3 2/**
	Carbon (CO_2e) stored in material not included		Carbon (CO_2e) stored in material included	
Steel reinforced concrete	0.149	354	--	--
Precast concrete	0.172	409	--	--
Precast concrete beams and columns	0.194- 0.249	462-593	--	--
Hollow core, reinforced concrete for flooring applications 3/	--	373	--	--
Steel (structural)	1.210	9,498	--	--
Softwood lumber	0.263	126	-1.29	-619
Laminated veneer lumber (LVL)	0.504	242	-1.25	-600
Glue laminated timber (glulam)	0.512	246	-0.90	-432
Cross laminated timber (CLT)	0.437	210	-1.20	-576

1/ Source: Jones, C. and Hammond, G. 2019. Inventory of Carbon and Energy (ICE) Database, v. 3.0. Bath University/Circular Ecology. Value for hollow core reinforced concrete adapted from ICE data per m^2.

2/ Conversion from kg/kg to kg/m^3 based on a concrete mass of 2,380 kg/m^3; a steel mass of 7,850 kg/m^3 for structural steel; and for wood products of specific gravity of 0.48. Structural steel is assumed to be comprised of 85 percent recycled material.

2.4.1.1 Steel

The environmental impact of steel construction materials is highly dependent upon their recycled content. The energy consumed in making steel is considerably greater if it is produced from iron ore versus from steel recovered from recycling. The impacts of producing new steel can be nearly 4 times greater than producing the equivalent quantity from 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_2e emissions than the production of steel-reinforced concrete. However, steel does not substitute for concrete on a kilogram to kilogram or m^3 to m^3 basis. The greater ability to span long distances without intermediate support (as required in concrete construction), coupled with requirements for substantially smaller beam dimensions than when designing in concrete, give steel an environmental advantage. When functionally equivalent structures of steel and concrete are compared, results almost always show lower embodied energy and CO_2e emissions for steel structures. Conversely, comparisons of structural steel with structural composites, such as LVL and glulam, show similar embodied energy on a weight basis but vastly lower emissions for the composites on a volume basis. Having said that, the weight and volume of functionally equivalent wood and structural steel are quite different; in this context, both the embodied energy and emissions linked to the 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 the complete removal of all alloying metals, recovered steel becomes increasingly contaminated each time it is recycled. 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 the embodied energy is high). The recycled content of large cross-section structural steel components is thus far not constrained, although it will likely become so at some point in the future.

2.4.1.2 Concrete

The environmental impacts linked to the production of concrete depend upon its desired strength which is, in turn, determined by the water-to-cement ratio. The greater the quantity of cement, the greater the impact and adding reinforcing steel to structural concrete further adds to the overall impact. Comparisons of embodied 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. However, because of high strength-to-weight ratios, building modules made of wood are both less massive and far lighter than functionally equivalent concrete modules. On both measures, wood consistently outperforms both structural and non-structural concrete, often by a substantial margin.

2.4.1.3 Wood

Lumber has the lowest environmental impact and offers the greatest contribution to the sustainability of any structural wood product. Lumber production is highly technical, engineered and exacting, using sophisticated scanning and computer control technology but does not entail an energy-intensive manufacturing process. Lumber production involves only sawing logs and then trimming and shaping the pieces produced before undergoing a drying process. Engineered wood products, such as LVL, involve first cutting solid wood into thin veneers and then recombining these veneers using adhesive, or in case of glulam, end-jointing lumber made into longer laminations and face glueing laminations to create glulam. This process increases the magnitude of the embodied energy and with these additional processing steps, combined with the use of adhesives, these materials have associated impacts that are higher than that of lumber (Table 1). For example, the production of CLT results in a 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 the use of resin and/or large metal fasters to bind components together.

Of the three primary structural materials (concrete, steel and wood), 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, therefore also 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 smaller quantities of carbon than wood.

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. However, when material use is viewed in the context of an actual building, the significance of these differences becomes 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 favourably 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 Brock Commons residential complex includes housing for 404 students, assembly spaces, and units that each serve four student rooms (two per floor) which contain a pass-through kitchen, bathroom and bedroom, assembly and study rooms as well as a student study-social lounge, in addition to mechanical spaces. This building is a hybrid structure composed of a combination of mass timber (CLT and glulam), structural steel and reinforced concrete.

FIGURE 8 Brock Commons, University of British Columbia, Canada

Source: Brudder Productions, courtesy naturallywood.com

As detailed by Pilon *et al.*, 2017 and Pilon, Teshnizi and Lopez, 2018, the wood in the building (2,233 cubic meters of CLT and glulam) contains 1,753 tonnes of CO_2 that will be stored throughout the life of the structure and potentially beyond, depending upon the fate of the materials at the end of the building's life. In addition, the extensive use of wood in the structure rather than steel and concrete avoided 679 tonnes of CO_2e emissions, meaning the total carbon benefit of this building equates to 2,432 tonnes of CO_2e. Expressed differently, the carbon savings from the selection of wood rather than more concrete and steel are equivalent to not driving a typical passenger vehicle in Canada 18,713 km.

John Hope Gateway Entrance to Royal Botanical Gardens, Edinburgh

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 into this structure, resulting in the long-term sequestration of 366 tonnes of CO_2e. An additional 142 tonnes of CO_2e emissions were avoided as a result of the selection of wood rather than steel or reinforced concrete for the roof of the building.

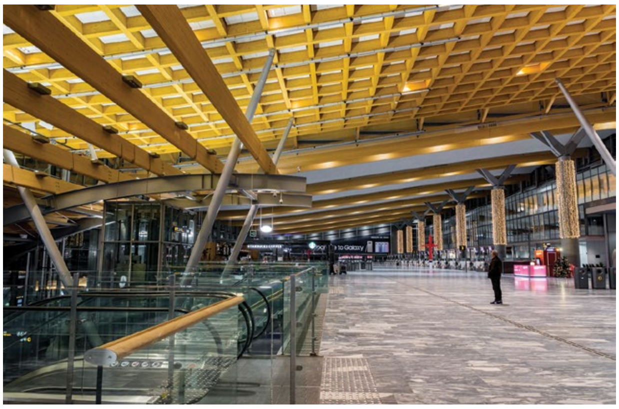
FIGURE 9 John Hope Gateway, Edinburgh, United Kingdom of Great Britain and Northern Ireland

Source: Paul Raftery

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 the roof-support beams: steel or glulam timbers. An assessment of the impacts of using steel versus glue-laminated spruce beams found that the manufacturing of steel beams for that project would have

FIGURE 10 Terminal 2 Gardermoen Airport, Oslo, Norway



Source: Depositphotos

required 2 to 3 times more energy and 6 to 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 indicated above would be substantially greater. In the most likely scenario, manufacturing steel beams for this project was estimated to result in fivefold more GHG emissions than if glulam was used. The structure was subsequently built using spruce glulam beams (Petersen and Solberg, 2002).

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 a similar carbon advantage over structures constructed of alternative materials.

2.4.3 GHG Emissions and Climate Change

As the above examples have illustrated, the substitution of wood for reinforced concrete or steel in construction results in reduced CO_2 emissions. In creating a building, the mass of material used to construct it varies considerably depending upon the materials used. For example, the weight of functionally equivalent structural framing will vary greatly depending on whether it is made of concrete, steel or wood. Concrete structures weigh more than steel and far more than wood, this difference in weight has a direct bearing on embodied carbon and the overall environmental impact (Table 1). The International Organization for Standardization (ISO) compliant comparative LCAs have consistently shown there are lower climate impacts from wood buildings than those constructed of concrete and/or 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) through to the completion of various building projects.

- A Dutch study of four house types modelled with increasing quantities of wood used in construction found that a 12 percent reduction of CO_2 emission related to material use for residential buildings would be possible in the near term through increased 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 CO_2 emissions from raw material procurement through to completion of a finished wood structure to be 31 percent lower than for that structure to be made of concrete and 26 percent lower than if it was made of steel. Because all of the structures analysed had concrete foundations, the relative emissions noted above were affected by the influence of emissions linked to this use of concrete. Analysis of only the above-ground portions of these structures, hence eliminating the concrete foundation element, showed CO_2e emissions differences between wood and concrete, and wood and steel, to be 80 percent and 33 percent, 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 to130 kg CO_2 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 having 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. The study found an average reduction in climate change potential due to wood substitution of 60 percent across all building types examined (Milaj *et al.*, 2017).
- A Swedish analysis of a number of life-cycle studies of multi-storey CLT buildings (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 percent, primarily in comparison to concrete buildings and where the differences were greatest when carbon sequestration was considered in the analysis.
- A Canadian assessment of the relative environmental impacts of a mid-rise office building constructed with structural concrete as opposed to CLT and engineered wood determined that the global warming potential of the concrete design was almost four times greater than the CLT/engineered wood design (Robertson, Lam and Cole, 2012.)

- A study compared conventional buildings of 8, 12 and 18 storeys, constructed with concrete and steel with otherwise identical buildings constructed of mass timber in three regions of the United States of America. The analysis found that in all regions and building heights, embodied carbon in mass timber buildings was 22 percent to 50 percent lower than in otherwise identical steel-reinforced concrete buildings (Puettmann *et al.*, 2021). Furthermore, 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 a net negative. The study concluded the carbon storage benefit of mass timber construction more than offset GHG 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 frames was compared to significant emissions for steel and reinforced concrete frames with the margin of difference being considerable. The difference in GHG emissions between wood and steel, and wood and concrete widened as the designed length of span increased (Hegeir *et al.*, 2022).

Practical limits prevent more examples of consistent and replicable research findings from being given. However, as seen from the above examples, buildings constructed of wood in any form consistently show lower embodied energy and CO_2 emissions than buildings constructed from concrete or steel. This is particularly the case when analysis factors out the confounding effects of common concrete foundations. Based on a large body of scientific studies, it is clear that the more wood is substituted for steel or concrete in creating a 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 percent 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 percent to 2 percent carbon as a percentage of their total weight. In the case of concrete, the production of which involves massive releases of CO_2, the finished product contains virtually no carbon, although carbon is slowly regained through carbonation[5] over the life of concrete products. Consequently, the increased use of wood in construction could substantially increase the volume of carbon stored in buildings.

An example of this 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 percent of buildings constructed of wood, with the vast majority remaining constructed of concrete and steel". For comparison, scenarios were developed in which 10 percent, 50 percent and 90 percent of new buildings were of wood construction. Results showed the potential for as much as 55 million tonnes of additional carbon storage in buildings across Europe per year. This result corresponded to the scenario where 90 percent of new buildings were made of wood, however, 55 million tonnes is an amount equal to about half of Europe's cement industry's annual CO_2e emissions. Among the study's conclusions was that the carbon storage capacity of buildings is far more determined by the number and the volume of wood elements used in the structural and non-structural components than by building type, size or the species of wood used. This conclusion suggests that in any kind of building, a reasonable carbon strategy is to incorporate as much wood as possible as a replacement for steel or concrete.

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 GHG emissions of wood structures, the climate advantages of wood construction are widely recognized today by architects and engineers and are increasingly 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 a given building's 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 to 35 percent (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 that there were 31 to 41 percent lower GHG 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

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[5] chemical reaction of CO_2

GHG 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 to finished product), transport and on-site assembly of building materials into a completed structure. Operational energy is all the 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 predominantly of wood is often equivalent to the operational energy consumption of buildings constructed of alternative materials; however, wood buildings can require less insulation to attain the required energy performance due to the lower thermal 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 construction lumber – a common material with the greatest inherent thermal resistance. The conductivity value for softwood lumber also applies to wood construction materials such as CLT, LVL, glulam and plywood. The thermal conductivity of composite wood products such as LSL is about 8 percent higher than that of solid softwood (Tripathi and Rice 2017).

Structural components of buildings (and metals in particular) are not commonly directly exposed to outdoor environments. 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 thermal conductivity. The addition of insulation increases the embodied energy and carbon impacts of building with non-wood materials.

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.

TABLE 2 Thermal Conductivity of Selected Construction Materials

Material	Average Conductivity (W/m K)*	Relative Thickness for Equal Thermal Resistance of 22mm 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
Aluminium	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.

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," 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 the creation of wood buildings, and mass timber buildings in particular, are 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 *et al.* study, which involved an extensive review of LCAs of mass timber construction, found that the average reported embodied energy of mass timber buildings upon completion of building construction was, on average, 23 percent higher than for equivalent reinforced concrete buildings. However, embodied GHG emissions of reinforced concrete buildings were more than 42 percent higher than for mass timber.

The reason for the apparent anomaly is that fossil emissions associated with the production of wood building components and subsequent construction are significantly lower than for buildings constructed of alternative materials. For the most part, steel and concrete manufacturing currently rely on fossil fuels for the process' thermal and electric energy needs. Wood product manufacturing includes the utilization of the byproducts of sawmilling (such as bark, trimmings and chips) to generate renewable bioenergy. The question then arises, 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 to the end of the 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 to 20 percent) 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 the consumption of operational energy, embodied energy has become much more significant. Today, the embodied energy of buildings accounts for a much greater portion of the total energy consumed within the built environment than it did in previous decades. 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 low-energy buildings to range from 26 to 57 percent and in net-zero-energy buildings from 74 to 100 percent.

The adoption of strict energy codes has helped reduce the operational energy use and associated impacts on 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, further highlighting 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, thus adding to sustainability in the built environment.

Consideration of embodied energy is becoming both more important and increasingly recognized. While attention to and regulation of embodied carbon reporting is beginning to appear in Canada, the United States of America and Europe, regulation of CO_2 emissions is not yet common. As reported by Petersen, Ekman and Espersen, and Garver 2022, "only 5 EU countries – Sweden, Denmark, France, Finland, and the Netherlands – have introduced regulation on whole-life CO_2 emissions, meaning both operational and embodied emissions". Similar action is reported for the cities of Vancouver in Canada and Oslo in Norway (World Green Building Council. 2019). In this context, 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 CO_2 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 CO_2 emissions in building construction through its *Réglementation environnementale* RE2020 regulation set for implementation in 2022 (French Ministry of Ecological Transition and Territorial Cohesion, 2020); the measure calls for a 52 percent reduction in embodied CO_2 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 the use of LCA in the planning and design of buildings. In view of this, adoption on the part of the European Commission, in its "Renovation Wave for Europe - greening our buildings, creating jobs, improving lives" 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 (European Commission, 2020) is viewed by many as an important step forward. Mandatory minimum energy performance standards have been proposed 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.

2.4.5 Fire Performance

Perhaps the most questioned aspect of the 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 followed by collapse. In contrast, wood with a large cross-section and mass reacts to fire by forming an outer char layer that greatly slows a fire's impact and protects the interior of the wood material. This charring reaction allows wood to endure exposure to fire for extended periods without sacrificing structural integrity. The result is that wood with a 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[6] 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 the adoption of new tall wood construction provisions within building codes in Canada and the United States of America. This has resulted in 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.

Research continues to investigate fire risk and behaviour in wood construction. Investigations in Canada have focused on evaluating fire performance in full-scale tests that are more typical of 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 the full burnout of its furnishings, whereupon the fire quickly subsided and burned out without any manual suppression or intervention. Burnout largely occurred within the first hour, however, 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 burnout (Canadian Wood Council, 2022; Renew Canada, 2022).[7]

2.4.6 The Durability of Wood Structures

Recent efforts to promote the use of engineered wood products in the 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. The compilation of responses from 683 respondents indicated an average expected life for wood buildings of 46 years, whereas the average useful lives of steel, masonry and concrete buildings were estimated at 77–87 years (Gaston *et al.*, 2001 as reported by O'Connor 2004). Another 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 the perceptions of the public in Austria, Denmark, Finland, Germany, Norway, Sweden and the United Kingdom of Great Britain and Northern Ireland. In this study, wood's 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 or building durability. Nevertheless, 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 from 2000 to 2003 (both residential and commercial structures) in Minneapolis/St. Paul, both located in Minnesota in the central-north region of the United States of America (O'Connor 2004). Approximately 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.

Almost half (105) of the buildings studied were nonresidential and, of these, 54 had concrete structural systems, 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 aluminium and the rest had structural systems of various combinations of concrete, 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 percent of the wood buildings of more than 50 years old at demolition, with the largest group demolished being aged between 76 and 100 years.

Investigation into the reasons for the demolitions revealed that most buildings were demolished for reasons that had nothing to do with the physical state of the structural systems.

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[6] Sheetrock is a type of plasterboard made of gypsum layered between sheets of heavy paper.

[7] 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/

Approximately 60 percent of the structures were removed because the buildings no longer fitted the needs of the owner or tenant due to changing land values, because of socially undesirable use or the economic unviability of bringing a building up to code. Structural failure was identified as the primary reason for demolition for only 8 of the 227 buildings studied, the problem here was foundation failure in all but one building where wood decay was identified. Fire damage was reported as the reason for the demolition of 3.5 percent of the buildings studied, with a greater percentage of steel buildings being 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 a building's 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 using heavy timbers in 1906 and which remains as sound today as it was when completed. The building's 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 centre of the city and occupants include businesses, professional services, restaurants, shops and a United States Postal Service centre.

FIGURE 11 Butler building, Minneapolis, United States of America

Source: Wikimedia Commons

CHAPTER 3
Circularity and Sustainability in Wood Construction Practices

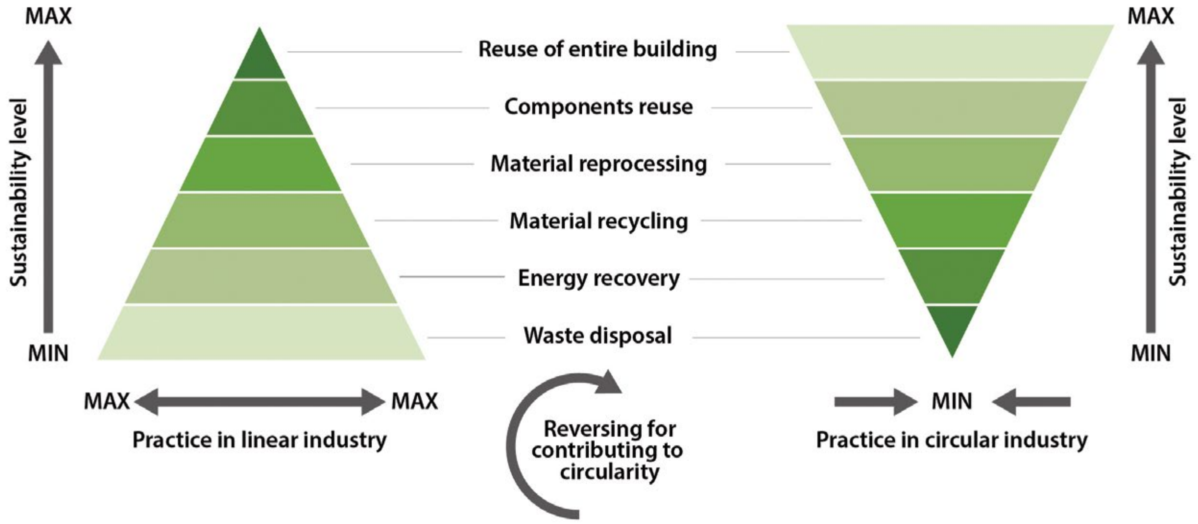
3.1 The Circularity of Wood Material

Bertino *et al.*, 2021 modified circularity principles to express the hierarchy of options available at the end of useful life of a building (Figure 12). In accordance with 9R circularity principles, they graphically expressed what practices should look like in a circular economy (right side of Figure 12) versus 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 a relatively low mass of materials for a given job, which results in lower impacts on the environment in many impact categories, including lower climate-impacting emissions.

A circular design considers the possible fate of a product, namely, the options that come into play at the point that a structure reaches the end of its useful life, including the prioritization of reuse through a variety of approaches. Materials may be repaired, refurbished and/or rehomed to extend the life of the materials involved. To support these options at the end of a material's useful life, the initial design of the material or the way it is used 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 is to be avoided if at all possible. The use of wood in buildings creates circularity possibilities at all levels as it can be reused, recycled or its embodied energy can be recovered. As shown in Figure 12, each of the considerations of circularity can be applied to buildings at the end of life.

The importance of reuse, recycling and 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,

FIGURE 12 Circularity Considerations at the End of Building Life



Source: Bertino et al.*, 2021*

calculated net CO_2 emissions for a CLT multi-storey residential building using various end-of-life scenarios. They evaluated the reuse of building components, recycling, incineration with and without energy recovery as well as landfilling. The results showed that net emissions remained net negative in all scenarios (carbon storage exceeded emissions) except incineration without energy recovery. However, even incineration with energy recovery reduced the CO_2e emissions advantage of wood to one-half of what it would have been if the wood had been 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 percent building life cycle emissions advantage of a CLT building over one built of reinforced concrete, however, this advantage dropped to 13 percent if carbon is not retained within the wood at the 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 12 than the right. For example, in the United States of America in 2018, 75 percent of wood contained within construction and demolition waste (CDW) was landfilled, 19 percent combusted for energy recovery, and only 4.9 percent was recycled (USEPA 2020). Moreover, there is only limited use of waste-to-energy technologies in both Canada and the United States of America while landfilling continues to be a common practice for many materials, including wood waste.

The situation is somewhat better in the 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 were treated (87 percent). Included in this figure was wood contained in municipal solid waste (MSW), CDW, and wood products mill residues. Of the wood that was reported as treated, 49 percent was recycled, 48 percent combusted for energy recovery and 3 percent landfilled or incinerated. The fate of the 6.8 million tonnes of waste wood that 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 CDW in Japan was reported at 80.3 percent in 2008, a figure that encompassed energy recovery, conversion to mulch and reuse in the manufacture of particleboard and other products (Japanese Ministry of the Environment, 2014).

In most countries for which data is available, and that includes almost all countries of the BioReg project[8], the product contributing the most to wood waste is CDW (Borzecka, 2018). Of that, by far the greatest volume arises from the 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, including CDW. As such, the greatest opportunity for the improved circularity of wood is in the recovery, reuse and/or recycling of CDW.

3.2 Sustainability of Wood Material

Whether or not construction design, planning and practice are sustainable rests on three pillars: environmental protection, economic viability and social equity. Wood fares well in all these categories given that it is renewable, is produced using solar energy, is composed of carbon captured within growing trees and wood can be subsequently converted into useful products using relatively little fossil energy. This all adds up to define a material that has less negative environmental impacts than materials such as steel, masonry and reinforced concrete. These potential advantages, of course, only translate to environmental benefits if wood is produced in sustainably managed forests and plantations. Regarding this latter point, wood has another advantage in that, as indicated previously, third-party oversight of forest management is widely practiced via forest certification.

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

Despite examples of deforestation and forest degradation in some parts of the world over the centuries, traditional wood construction in many regions had followed circular and

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[8] 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

sustainable approaches in the light of today's concepts and definitions. This included local sourcing of raw materials and the repair, refurbishment and reuse of buildings for different purposes over decades.

3.3 The Circularity of Modern Construction Methods

Today, mass timber panels, posts and beams contribute to circularity and environmental sustainability while also providing a highly engineered and high-performance structural elements for construction. Table 3 presents an overview of different modern construction types and methods.

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, providing low carbon-emission alternatives to reinforced concrete and steel while also storing carbon for as long as they exist. Modern wood construction methods also address some circularity questions as they incorporate a high degree of prefabrication that speeds construction processes and provide for precision sizing of both 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 an approach should move away from business-as-usual toward a more cross-cutting collaboration among different actors within and outside the sector. Increased collaboration between designers, architects, urban planners,

TABLE 3 Building Types and Construction Methods

	Construction Characteristics and Methods
Residential Includes single-family homes, duplexes, triplexes, fourplexes, condos, low-rise apartment complexes, tiny homes, mobile homes (mostly in the United States of America) and large multi-storey apartment buildings.	• Single-family and low-rise residential structures largely constructed on-site. A significant shift toward factory built (panelized, modular) in Sweden, Japan, Germany, and the United Kingdom of Great Britain and Northern Ireland. The use of wood is predominant in residential construction in Canada, the United States of America, Northern Europe and Japan. Wood construction is 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, with over one or two storeys of concrete construction, are common. Tall (8- to 18-storey) mass timber construction is at the very early stages of market penetration. – Mass timber construction for multi-storey residential is most advanced in Northern Europe and Canada.
Commercial Includes office buildings, hospitals and clinics, restaurants, hotels, entertainment centres and retail establishments.	• Wide range of construction methods • Construction of larger buildings is primarily done on-site, with the incorporation of modular units gaining greater acceptance in some regions. Smaller buildings, particularly chain restaurants and coffee shops, are often panelized or utilize modular construction. • Reinforced concrete and steel construction are predominant, particularly for large multi-storey structures. In Canada and the United States of America, light frame wood construction is common for hotels of 4-6 stories and low-rise commercial buildings of all kinds. • Mass timber construction for these types of buildings overall is at the early stages of market penetration.
Industrial Includes manufacturing, warehouses, distribution centres and flex space buildings	• Common building methods for these types include reinforced concrete and steel frame construction as well as reinforced concrete tilt-up construction. Steel-clad pole buildings are also common in some localities. There is very little use of wood in the construction of these types of buildings at present.

engineers, municipality actors and legislators would contribute to achieving greater sustainability. The degree to which a building can be built and used sustainably depends on the awareness of these different actors about the opportunities for and limitations of applying different circular approaches at different stages of construction value chains. In short, whether designing for the durability of materials and building structures, seeking to improve the recovery of materials and reuse of structural components or increasing the recycling rates of wood from construction and demolition, there is room for improvement.

Circularity in Material and Product Development

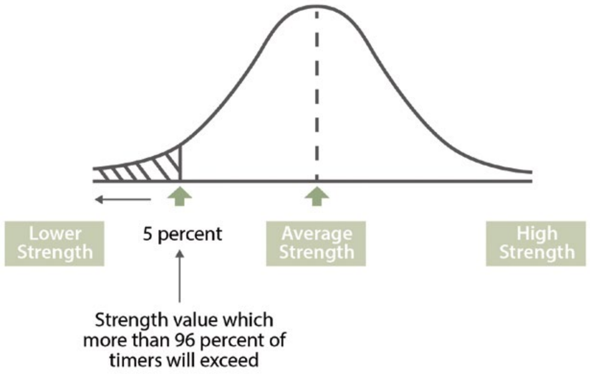
The cumulative result of many decades of research – and more than a century since that first patent – provide evidence that mass timber buildings today contribute to circularity and environmental sustainability while also providing a highly engineered and high-performing material for construction.

Therefore, mass timber can be a more sustainable alternative than the steel and concrete that commonly goes into buildings at present. It is safe, fire-resistant and of comparable strength. Mass timber building systems can also theoretically be disassembled and refurbished with relative ease or used in different ways. Their value can be recaptured at the end of life and scraps can be repurposed or used for bioenergy.

The new types of wood products which have, in some instances, enabled wood to replace 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 but which have more uniform and predictable performance properties. Using wood in more buildings than just private homes creates opportunities for greater circularity. Therefore, the following chapter will briefly review the various innovations and progress made in the engineering and development of wood building materials.

Disassembling and then reassembling wood results in better, more durable and thus more sustainable products because less processed wood derived from round logs, while a very useful material, 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 sometimes causing, for example, the wood to warp or twist unpredictably. Variation within wood can be due to a number of factors, such as disparities in grain direction around locations where branches emerge resulting in knots, stress zones traceable to weather events during the life of the tree, sharp differences in density and dimensional stability properties near the centres of trees or in sections of leaning trees (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 variations in strength, yielding information that can be graphically expressed, as done in Figure 13. Extensive testing of 50 species of wood has determined that maximum load-carrying capacity, bending strength and compression strength commonly varies by 16, 22 and 28 percent respectively in defect-free solid wood. However, these values can be far greater when knots, the slope of the grain or various hidden defects are present (Bowyer, Shmulsky, and Haygreen, 2007). Consequently, allowable design values are based on a consideration of the natural variation in defect-free wood, the variation in the strength of full-size timbers due to the presence of defects in timbers of various grades and the inclusion of a substantial margin for safety. The result is that allowable design stresses for solid wood are only a fraction of clear (defect-free) wood strength.

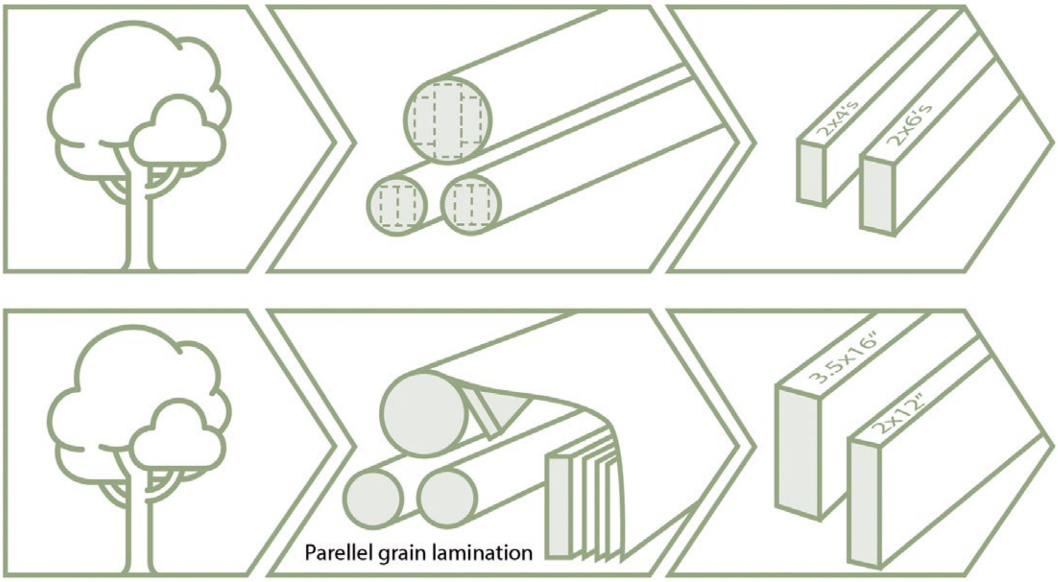
FIGURE 13 Typical Variation in Strength of Wood of a Single Species



Source: Author's notes

In designing a structure, a common practice is to use a strength value that over 95 percent of the lumber or timbers derived from that species would exceed (i.e., a strength value for which there is a low probability that the strength of the member may actually be lower than assumed). In doing so, 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 timber's strength properties. Nonetheless, construction wood has generally not been viewed by architects and engineers as not being sufficiently uniform and predictable when compared to reinforced concrete and steel. It was primarily a desire to address this characteristic that led to the development of structural wood composites and a suite of engineered wood products. Another driver was the interest in creating large structural members from relatively small-diameter trees, as depicted in Figure 14.

FIGURE 14 Laminated Veneer Lumber - Large Timber from Small Trees



Source: Author's notes

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 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 the creation of a newly engineered product is the effect on wood strength. Whereas a wide variability of strength in the solid wood of a given species is normal, engineered wood products have a much narrower range of variability, with the result that such products can now directly compete with materials long viewed as superior due to their uniform and predictable properties.

Innovations have contributed to the circularity and sustainability of wood construction. These innovations include:

- The idea of creating large wood members from smaller pieces of wood was 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. Later 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. Beginning in the mid-1940s, plywood displaced the use of boards for bracing in light-frame buildings in the United States of America and Canada. Although today plywood is based on the same principles used in creating plywood as far back as the time of the Pharaohs, the emergence of construction plywood did not occur until the development of the rotary lathe[9] made the production of large sheets of veneer quick and inexpensive (Wood, 1963). This is the same mechanical innovation that led to the development of LVL.
- First patented in 1968, LVL was developed specifically to create 'lumber' of more uniform strength than solid wood while simultaneously permitting the manufacture of large-size timbers from relatively small diameter logs (Figure 14, right side). 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 up to 20 times stronger along the grain rather than across it). The advantage of LVL over solid wood is that large defects are removed from veneers 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).

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[9] Prior to processing on a rotary lathe, bark is removed from logs which are then immersed in heated water to soften the wood. Then, chucks are pressed into each end of the log being processed to provide a means of delivering torque to turn the log. As the log turns, it is steadily moved toward a sharp blade which extends along 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 that range from 2.5 to 3 mm in thickness.

- Another innovation in the development of engineered wood traces back to the introduction of softwood plywood. As plywood was quickly adopted for use in the construction industry in Canada and the United States of America, a new product called waferboard panels, made of ultra-thin slices of wood (0.5mm thick and called 'wafers') were first commercially manufactured in 1955. Ongoing development led to the discovery that the making of long (150mm)-thin wafers allowed the alignment of the grain, even allowing the layering of various grain angles, similar to plywood. This development led, in the early 1980s, to the emergence of oriented strand board (OSB) panels that are 6 to 18mm thick that closely approximated the properties of plywood but can be manufactured at a much lower cost. This innovation made the use of small trees with relatively low inherent strength economically viable in the production of high-strength products that previously required large-diameter logs of high-strength species. Furthermore, this technique resulted in a reduction of waste generated in the production process in comparison to plywood (Bowyer, Shmulsky and Haygreen, 2007).
- The success of OSB led to yet another round of innovation. Some researchers began to wonder if it may 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 new 'lumber' products, such as oriented strand lumber (OSL) and laminated strand lumber (LSL). Yet another product that can trace its origin back to OSB is parallel strand lumber (PSL), which is made of thin strands of veneer of approximately 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 innovation in engineered wood products was recognized years later and resulted in what would become known as CLT. This product was first used for roof systems in Germany in the early 1970s before being further developed in Germany, Austria and Switzerland during the 1990s. Following the construction of a three-storey house in Bavaria using CLT, a period of experimentation in Germany, Austria and Switzerland followed that led to the 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 in Europe and then spread to Canada before being employed in countries all over the world. Combined with the extensive use of other engineered wood products, the production of this mass timber product expanded rapidly, again first in Europe, then in Canada, the United States of America and Asia.

Global CLT production capacity in 2020 was estimated at 2.8 million m³ 2020, with 48 percent in Europe, 43 percent in North America, 6 percent in Oceania and 3 percent in Asia. Actual production in 2021 is estimated to have exceeded 1.85 million m^3 (imarc, 2022). In Europe, most of the production facilities and installed capacities for CLT are located in Germany, Austria and Switzerland, with Italy and the Czech Republic also contributing. Slightly more than one million m³ of CLT was produced in these five countries in 2020, which was 15 percent more than in 2019, a growth trend that is expected to continue in the coming years (Gaston, Pahkasalo and Zhu, 2021).

3.3.1 Circularity and Construction Techniques

Although 'stick building'[10] remains predominant in many countries, 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 labour but also because of the potential advantages for circularity and sustainability thanks to the advantages of off-site prefabrication of building components (i.e. increased precision of connections and fittings, speed of construction and potential reduction of material waste). These factory-built, precisely manufactured wood 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 –involve a far greater level of off-site prefabrication (Figure 15).

In some parts of the world prefabrication, either in the form of panelization or modular construction has gone mainstream.

FIGURE 15 Modular Mass Timber Construction

Source: Depositphotos

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

Sweden reportedly ranks as the leading country in the implementation of prefabricated building systems, with eight out of ten detached houses built off-site. Offsite manufacturing is also used in Sweden to build at least 30 percent of new-build multi-residence buildings (Modor Intelligence, 2021). In Japan, more than 15 percent of nearly one 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.

3.3.1.1 Panelized Construction

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

Panelized construction typically involves the installation of a factory-manufactured floor system on top of a pre-laid foundation as the first step, followed by the erection of prefabricated wall panels. Once wall panels are in place, usually held with temporary bracing, either floor trusses for the next floor or roof trusses are placed before the roof sheathing is then installed. In instances where wall panels delivered to a site consist only of framing and perhaps sheathing, and are delivered to the site along with roof trusses, on-site construction proceeds much as described below:

Once the exterior walls, 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 finished in the factory, including the finished 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 factory assembly of components than on-site assembly. Factory assembly is independent of weather or other delays allowing for faster on-site weather-impacted assembly. In terms of circularity, material waste is reduced, and waste generated is 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 percent of traditionally construction homes. Nonetheless, only a small percentage (3 to 4 percent) of homes constructed in the country used this technology in 2015 (Ghosh, Bigelow and Patel, 2021).

3.3.1.2 Mass Timber

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

Cross-laminated timber panels can be as large as 50 cm x 3 m x 18 m, and typically weigh about 1800 to 2250 kilograms, or approximately 2 tonnes. At the construction site, cranes are used to lift them into place as building proceeds, typically involving two construction crew members and two to four others who guide the panels into place and secure them. Construction typically proceeds quickly and can contribute to additional gains in productivity and construction cost savings than concrete and steel construction methods due to the large-sized 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 other construction methods. One example is provided by the construction of a project in which 418 m^2 (4500 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, both of which reduce construction costs. On-site waste is also reduced (Smith *et al.*, 2018; Abed *et al.*, 2022). Fewer construction trades also contribute to a reduced use of natural resources that are essential to building construction. Smaller on-site crews translate into lower environmental impacts associated with transport and on-site facilities during the construction period. While mass timber construction is promoted for low-rise buildings, it requires substantially greater volumes of wood per unit of floor area than light-frame construction, commonly used for low-rise buildings. High-rise wood construction, on the other hand, is only made possible through the use of mass timber. For this reason, it is likely to be used more for tall multi-story structures, rather than in buildings of less than 4 to 6 stories in height (Ramage *et al.*, 2017).

3.3.1.3 Modular Construction

With modular construction, the vast majority of work occurs off-site as modules typically come to the building site in finished form, including 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 that include attached walls, floor, ceiling, wiring, plumbing and interior fixtures are produced off-site before transport to the building site where the modules are connected to create a finished structure. In some cases, modular units are used in conjunction with panelized construction, with the modules employed only for bathrooms and/or kitchens. Modules are designed to connect end-to-end, side-to-side, or one on top of another, which allows the creation of 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 any misalignment of modules and connections are precluded. Sophisticated tools are used to achieve this, including computer aided design (CAD) systems, additive manufacture (3D printing) and manufacturing control systems while good design for manufacture and assembly practices are also 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 ensures 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 they are a required part of the module. Windows and doors are added next, followed by insulation, sheathing and exterior siding. At the same time, work proceeds in the interior of the module. Preparation of the interior drywall (gypsum) is completed, cabinets are installed, the interior trim is added before painting and any finishing touches are made. 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 modules in place and connecting them can be completed within a day or two. Work is then done to finish the joints between the modules and ensure that wiring, water and plumbing connections are complete and tested before conducting a final inspection and 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 to 6 weeks, although 2 to 3 months is reported as typical. In comparison, the same process on a similar building using panelized construction is likely to extend to 4 to 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 has been in and out of fashion around the world over the years, its history is largely that of a provider of temporary structures for various needs such as short-term 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 the construction of multistory multi-family structures, government buildings, health care facilities, schools, hotels and other building types (Smith, 2016).

Similar to panelized construction, independence from inclement weather and other negative factors allows 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 percent in one study and 83.2 percent in the other. They also examined five previous studies of waste reduction with modularization and found waste reduction levels ranging from 20.1 percent to 92 percent.

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 from the material and cost-efficiency of modular construction. Facing a substantial bed shortage and the need for rapid, inexpensive construction, the NHS found modular construction to be 60 percent faster and 30 percent 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 modular construction as an interesting circular solution with comprehensive benefits contributing to not only the optimization of natural resource 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 to keep pace with these changes. 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 and time as well as contribute to the generation of pollution (e.g., concrete dust) and/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 is greatest in residential and commercial buildings. With regard to tall buildings, recent design and construction projects have demonstrated the potential for very tall buildings made predominantly of wood. However, based on a survey of commercial buildings in the United States of America, it is buildings of 10 storeys or less which represent the greatest opportunity for expansion of wood use (Figures 16 to 18. This is because structures of this height dominate the multi-storey building scene both in terms of the number of buildings and floor space.

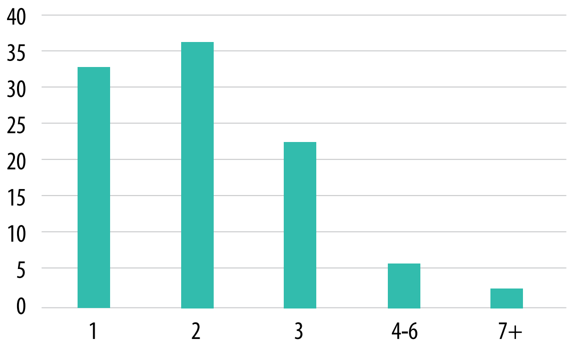
3.3.3 Opportunities for Greater Application of Innovative Building Methods

For all building types, and in some regions to a greater extent than others, the application of panelized, mass timber and modular construction methods remains on the periphery. However, likely driven primarily by shortages of skilled labour, 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, the further adoption of mass timber construction for multi-storey buildings is also 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

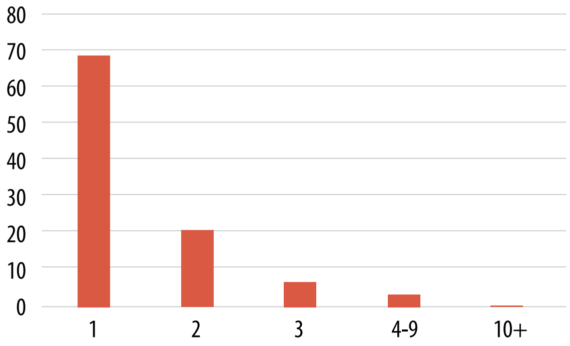
As discussed under the heading "Circularity of wood material" and depicted in Figure 12, an ideal pathway for a circular use of wood in construction would involve repair, refurbishment and rehoming as top priorities at the end of its first useful life. Recycling into some other kind of useful product 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 have been exhausted. However, this kind of ideal pathway for wood circularity is far from reality today.

FIGURE 16 Percentage of Housing Units in the United States of America by Number of Storeys, 2020



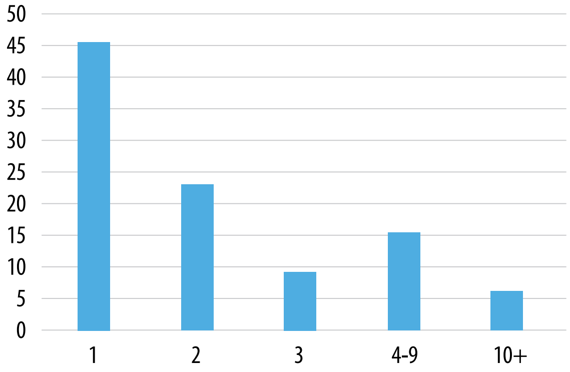
Source: Potter, 2020

FIGURE 17 Percentage of Commercial Buildings in the United States of America by Number of Storeys, 2020



Source: Potter, 2020

FIGURE 18 Percentage of Floor Area in Commercial Buildings in the United Stated of America by Number of Storeys, 2020



Source: Potter, 2020

3.4.1 Wood in the Waste Stream

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

In the United States of America, wood waste amounted to 64 million tonnes in 2010. Of this, 22.5 percent was contained in MSW, 51.5 percent in CDW and the rest in the form of yard waste, which includes woody trimmings from trees and brush (Falk and McKeever, 2012). More current statistics (USEPA, 2022a) show a similar percentage of wood wastes in MSW, with 17 percent recycled, 16 percent combusted for energy recovery and 67 percent landfilled. Most of the wood counted as recycled was used as animal bedding or mulch. Almost all CDW generated in 2018 (27 million tonnes) was sent to landfill (Dunkerly, 2021). Increasing volumes of waste wood find their way into reuse via more than 900 retail *ReStore*[11] facilities in the United States of America operated by the non-profit Habitat for Humanity. Approximately half (55 percent) 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 Use of Wood

An assessment of recovered wood from building deconstruction in Germany (Höglmeier, Weber-Blaschke and Richter, 2017), found significant quantities of wood (26 percent) in suitable condition for further use, with over a quarter of this having potential for high-value secondary use. Another study (Merl, 2007) analysed wood materials recovered from the deconstruction of a 120-year-old alpine cottage, determining that many of the components were in good condition with a large portion fit for reuse. A demonstration project involving the deconstruction of a two-storey, 93 m³ wood-framed residential structure in the United States of America resulted in its complete deconstruction over a 12.5-hour period using a crew of 26 workers. The sales value of salvaged materials was double that of the labour costs, indicating the economic potential for building deconstruction (Falk, 2002). Yet another European study chronicled the widespread use of recovered wood for particleboard manufacture, noting that whereas 100 percent of particleboard manufactured in Italy, and 50 percent 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 no recovered wood for this purpose (Besserer *et al.*, 2021).

3.4.3 Benefits of Retrofit and Deconstruction

Several studies have identified the potential benefits of retrofitting or deconstructing buildings (Figure 19). Schwartz, Raslin and Mumovich, 2022, evaluated refurbishment versus replacement of two housing archetypes, finding reductions in GHG emissions of 10 to 30 percent through refurbishment. One study applied LCA to the evaluation of the deconstruction and determined that the separation of materials in demolition operations and subsequent recycling and/or reuse resulted in reductions of 77 percent for climate change potential, 57 percent in acidification potential and 81 percent in summer smog creation when compared to demolition without recycling (Coelho and de Brito, 2012). Another assessment of a deconstruction examined the environmental impacts from the deconstruction site through to the delivery of reclaimed materials to a storage facility; findings showed that 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 significantly lower environmental impacts than their two new or fresh wood alternatives.

Another study, which also employed a life cycle approach, found that a cascading use of wood could increase wood use efficiency in the European wood sector by 23 to 31 percent with the added benefit of reductions in global warming potential of 42 to 52 percent (Bais-Moleman *et al.*, 2018). Yet another study compared a cascading use of wood from deconstruction with no wood reuse, finding a 7 percent reduction in global warming potential and a saving of up to 14 percent 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 the cascading use of wood they analysed resulted in significantly greater resource efficiency and lower resource consumption when compared to the use of new wood. An examination of particleboard production using recovered wood found

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

that production from wood wastes resulted in –428 kg CO_2e compared to particleboard made from fresh wood. Furth to this, the combined heat and power energy production using wood wastes yielded –154 kg CO_2e emissions compared to the use of fresh wood (Kim and Song, 2014). Several studies, however, identified the need to be cautious in approaching deconstruction. Bais-Moleman *et al.*, for example, noted that while a cascading use of wood would provide substantial wood use efficiency and GHG reductions, these benefits would be largely negated in the short term because of the diversion of wood from renewable energy production that would result in increases in CO_2e emissions from fossil-based energy production. Furthermore, Coellho and Brito, 2012, cautioned about that what they describe as "shallow, superficial, selective" demolition that may actually result in heightened environmental impacts due to extra transportation needs.

3.4.4 Barriers to Greater Levels of Cascading Use of Wood

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 such building materials stated: "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 percent of landfills are reportedly recycling wood waste, the combination of low tipping fees, the availability of relatively cheap timber and the ease of obtaining open burn permits are identified as disincentives to wood waste recycling (Donaldson, 2022).

The growing demand for wood for energy generation also presents a challenge. For example, Bergeron, 2014, noted that the presence of a robust thermal treatment sector in Switzerland combined with an established pattern of wood waste exportation mean that no waste wood was available for recycling in that country as wood waste exports are largely driven by markets of wood for energy generation (Junginger *et al.*, 2019).

Another factor limiting the cascading use of wood is that deconstruction is difficult. Buildings are usually not constructed with dismantling in mind, instead, they are designed with performance, customer satisfaction and long-term durability as objectives. As reported by Bertino *et al.*, 2021, less than 1 percent of existing buildings are fully demountable. Additional problems come as a result of older buildings containing materials that are now recognized as environmental hazards; structural components are penetrated by electrical, plumbing as well as heating, ventilation, and air conditioning (HVAC) systems throughout, resulting in damage to material and difficulty in separation at the point of deconstruction. Furthermore, older construction adhesives, such as those used to create stiff floors, make the 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

In attempting to recognize current problems in building deconstruction, considerable effort has been devoted in recent decades to examinations of how buildings may be constructed 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 is uncertain, however, given the level of attention this issue is attracting, changes in future building design and construction standards are likely.

FIGURE 19 Deconstruction for Building Materials Recovery

Source: Depositphotos

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 wood construction. These strategies and activities showcase efforts made by policymakers and industry actors alike, at the planning, construction and demolition stages of building processes. They aim to reduce resource consumption, including energy consumption, and to extend the life of products, where doing so is possible.

These tangible projects and case studies, implementing principles of circularity and sustainability in the wood construction sector, have been collected by the authors of this study through personal communication with public and private forest sector professionals in different countries of the UNECE region. Their accuracy and veracity have been verified by the contributors to this chapter cited in the "contacts and sources" of each case study and the full responsibility for the details cited remains with them.

4.1 Austria - Policy Supporting Wood Construction

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 the 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 (2019), which includes a commitment to achieve climate neutrality by 2040 and provides guidelines for the implementation of the Agenda2030 as well as the SDGs. It covers all industrial and economic sectors that produce, process, handle or use biological resources and aims to replace fossil raw materials and energy resources with renewable resources. Through several flagship projects, the strategy aims to optimise synergies among the 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. This guideline serves to harmonize building regulations, prescribe fire protection in construction and provide classifications for buildings. In 2021, the framework for timber construction in the guideline was simplified, allowing the construction of buildings with more than three floors.

Circular approaches and practice applied

The Austrian Wood Initiative includes the following bioeconomy and circular economy measures:

Governance

- Development of a national timber policy
- Improvement of framework conditions for sustainable building, securing, equipping and furnishing.
- Coordination, further development and harmonization of standards and regulations at the national and international levels.
- Establishment of an Austria-wide consulting network for wood and timber construction.
- Establishment of a platform fostering and connecting bioeconomy-related clusters and initiatives.

Wood construction

- Promotion of wood buildings (via a CO_2 bonus, detailed below) by promoting the use of wood by the public sector (federal government, province, municipality, school buildings, kindergartens).
- The CO_2 bonus provides an investment premium of EUR 1 per kg of certified wood (and up to 50 percent funding) and, in cases where renewable materials are used for insulation, the premium increases to EUR 1.10 per kg of certified wood. An additional condition is that at least 80 percent of the wood must be harvested and processed within a radius of no more than 500 km from the construction site.

Innovation

- Research – in the framework of the Forest Fund, a regular call for research projects is provided. The most recent one is "Increased use of wood as raw material" (THINK.WOOD. Innovation) where the goal is to spark development and innovation in the value chain for multiple uses of wood as a raw material.
- Digitalization in the procurement, planning and production processes 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 (SFM) and wood use with regard to climate protection in primary and secondary schools as well as tertiary education institutions.
- Communication via the promotion of events, engaging in public relations and posting on social media to raise awareness of the use of wood as construction material.

Results and benefits

The foreseen effects of the Austrian Wood Initiative project include:

- Wood as a building material is used in the best possible way, particularly considering sustainability criteria.
- The trend towards timber construction continues to gain momentum.
- Income and jobs are secured and created. Currently, 7 percent 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 percent of Austria's total annual GHG emissions (eight million tonnes 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 other EU countries (based on similarity in policies and legislation) and especially in countries with similar wood resources.

Contacts and sources

Contacts:

P. Ehgartner, Deputy Head, Wood-based Value Chain Division, Directorate General – Forestry and Sustainability, at the Ministry of Agriculture, Regions and Tourism.

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

Links:

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

https://www.ffg.at/programm/thinkwoodinnovation

https://view.officeapps.live.com/op/view.aspx?src=httpspercent3Apercent2Fpercent2Fwww.filipovic-savjetovanje.hrpercent2Fpresentationspercent2F2022percent2FPaulpercent2520Ehgartner_Austrian_Wood_Initiative_ZagRE_2022_Conferencepercent2520Real_Estate_Development.pptx&wdOrigin=BROWSELINK

4.2 Austria - Wood-based Building in Vienna

Background

Seestadt Aspern is a district in Vienna currently under construction and is one of the largest urban development projects in Europe. One of its buildings is a high-rise wood building the *Holzhochhaus* (HoHo), a structure characterized by an innovative approach to timber construction. It is taking advantage of the benefits of hybrid wood construction compared to pure timber construction. Reinforced concrete cores are used for vertical development and supply, providing sustainability and savings in terms of CO_2 emissions. The building is mostly made of wood (74 percent) and shows that wood as a building material can be used both ecologically and economically. Building features (Endre, 2017):

- Construction time: from October 2016 to summer 2019
- Construction costs: EUR 65 million
- Underground floors: 2
- Floors above ground: 24; Building height: 84 m
- Gross floor area: approximately 25 000 m^2
- Net floor area: approximately 19 500 m^2
- Wood: 74 percent, 6000 m^3
- Energy standard: Passive house standard

It is a pioneering project because it is one of the first buildings made primarily of wood with a height than exceeds eighty meters (Endre, 2017; Woschitz, 2015).

Circular approaches and practice applied

The HoHo building integrates wood as a sustainable alternative to conventional building materials. Special value was placed on the prefabrication of wood and the construction efficiency resulting from the use of modular systems, which contributed to a simple and resource-efficient construction process. The use of concrete only where absolutely necessary translated to a significant reduction in the project's overall CO_2 emissions. Compared to if it was constructed using traditional methods, this building is estimated to result in the avoidance of 2800 tonnes of CO_2 emissions in addition to the reduced emissions from the use of fewer transport trucks. The adoption of a modular design resulted in a significant reduction in energy consumption during the construction phase, this reduction equates to a car being driven 40 km per day for 1100 years (Holzbau Austria).

The separation of the reinforced concrete construction from the production of mass timber elements allowed parallel production and thus contributed to the optimal and shorter construction process which was accompanied by savings of energy. During the 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 ensured simple and thus economical assembly logistics on site, which also meant fewer issues common to construction sites, such as less dust and reduced noise pollution.

The static load-bearing system consists of glulam columns, prefabricated concrete girders as ceiling finishes and timber-concrete composite ceiling elements, all of which have a fire-resistance duration of 115 minutes, which gives emergency services 25 minutes more time for evacuation and firefighting than that 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 the HoHo building:

- Efficient construction through the use of modular systems in timber construction.
- Use of domestic wood as a renewable raw material from sustainably managed forests.
- Replacing CO_2-intensive materials has reduced the building's 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 percent 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) resulted in the building receiving 924 from a possible 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 and sources

Contacts:

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

Sources:

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Woschitz R. (2015). Holzhochhaus HoHo Wien. In 21 Internationales Holzbau Forum IHF 2015, 7p.

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4.3 Canada - Unbuilders - a deconstruction and salvaging company

Background

The demolition industry generates millions of tonnes of waste annually in Canada, 37 percent[12] of which is valuable lumber.

Unbuilders is a deconstruction and salvaging company, built of former carpenters, roofers, framers and tradespeople who have transitioned from construction to deconstruction. The company focuses on deconstruction and remanufacturing in lieu of the demolition of buildings and disposal of construction materials.

Circular approaches and practice applied

Unbuilders focus on the end-of-life management of construction products. The team disassembles buildings, layer-by-layer, upcycling the resultant material into the supply chain. In their practice, most of the building's components can be deconstructed and salvaged, yielding less than 5 percent waste on average.

Unbuilders parent company, Heritage Lumber, sells reclaimed wood products and a variety of sizes, types, and dimensions of a selection of reclaimed wood that comes directly from deconstruction projects, including original fir and oak flooring as well as:

- Wide-plank flooring
- Cladding
- Beam wrap
- Dimensional lumber
- Shiplap and strapping
- Large posts, beams and joists
- Salvaged flooring

Results and benefits

On each project, Unbuilders report that they divert 50 tonnes of waste and salvage 10 tonnes of lumber. In 2021 the company diverted 3600 tonnes of material, saving nearly 20 000 tonnes of CO_2 from decomposing into the atmosphere. The service benefits from tax credits that make it more affordable than traditional demolition in most cases.

The harvested raw material has historical value on top of its intrinsic economic value. Much of the company's lumber comes from buildings that were constructed with ancient trees, some as much as 2000 years old.

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 other countries

Contacts and sources

https://unbuilders.com/

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[12] Metro Vancouver Waste Report

4.4 Czechia - Sustainable Procurement Law

Background

Czechia introduced a new regulation on public procurement on 1 January 2021[13]. According to this regulation, new requirements supporting sustainable and circular approaches in procurements for construction projects came into force. They include social and environmental sustainability criteria related to the environmental impacts of a project as well as the sustainability and life cycle costs of supplied products, services and construction work.

To support the new regulation the Czech Ministry of Agriculture published guidelines[14] detailing its implementation. They include:

- A brief introduction to 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 organizations can define the purpose, scope, performance and functional parameters of the construction, including the share of wood used)
- Preliminary market consultation (procuring organizations gather information from suppliers on incorporating procurement goals in their projects related to, for example, environmental and social sustainability or innovation)
- Procuring organizations are allowed to define sustainability criteria needed for a specific project, for example, establishing the condition of wood use as a technical condition defining the subject of the public procurement or defining the criteria for evaluation (e.g., life cycle costs and the share of wood used)

Circular approaches and practice applied

The new procurement regulation creates a policy environment promoting the use of wood and circular economy approaches such as life-cycle evaluation and the share of wood used in public procurement construction projects.

Results and benefits

The new regulation on public procurement and the guidelines are tools to support the fulfilment of the Departmental Strategy of the Ministry of Agriculture of Czechia with outlook to 2030 and one of its strategic goals, namely "competitiveness of the forest-based value chain". Both documents also support the conception of the National Forestry Policy, which runs until 2035, and where "striving 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 and sources

Contact:

Pavel Broum, Ministry of Agriculture, Pavel.Broum@mze.cz
Tomáš Krejzar, Ministry of Agriculture, Tomas.Krejzar@mze.cz

Link:

METODIKA_VYUZITI_DREVA_VE_VZ.pdf (eagri.cz)

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[13] 134/2016 Sb. Zákon o zadávání veřejných zakázek (nový) (zakonyprolidi.cz)

[14] METODIKA_VYUZITI_DREVA_VE_VZ.pdf (eagri.cz)

4.5 Poland - Wood Promotion Centre in Jata

Background

The Wood Promotion Centre was built by the State Forests[15] in Jata, a village 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 photovoltaics as well as heating and recuperation systems to minimize energy consumption and the building's impact on the environment.

Circular approaches and practice applied

In accordance with the investor's vision, the building design is an energy-efficient, timber-framed construction. The energy-saving solutions meet the requirements of certification from the Passivhaus Institut Darmstadt[16].

The facility makes maximum use of wood as a building material, including in the structure, thermal insulation layer, roofing finishes and as an aesthetic material. This design choice to maximize the use of wood minimizes the building's impact on the environment, as does the:

1. Location of the building. The building was positioned on the plot to maximize 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 from solar radiation. On this side, a full-height glass façade was used in the multipurpose room, there are large windows in the office room and atrium and a system of photovoltaic panels were placed on the roof slopes. To prevent the building from overheating in the summer, sun breakers in the form of vertical blades were fitted to the glass facade.
2. Compact building shell and thermal insulation. To eliminate potential energy losses, the building shell was designed to be compact. All of the building's external compartments were made airtight and thermally insulated to such an extent that the U-value of the entire building body is ≤ 0.15 W/(m^2K) and air infiltration is ≤ 0.6 h-1 by volume of the entire building.
3. STEICO building system.[17] 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 the maximum use of solar energy. The windows (glazing and frames) have U-values of ≤ 0.80 W/(m^2K) and g-values of approximately 50 percent.
5. Renewable energy solutions:
    a. The building is equipped with a vertical ground heat exchanger employing 3 boreholes drilled to a depth of 100 m with a collection well. The energy extracted from the ground exchanger will be used to heat the building and supply 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 percent).
    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 installed throughout the building.
    f. The electrical appliances that equip the building are characterized by an energy class of A +++ (if an energy class is defined for them).

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[15] https://www.lasy.gov.pl/en

[16] https://passiv.de/

[17] 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

Results and benefits

The building is energy passive and ensures low maintenance costs and high user comfort. It is sustainable and environmentally friendly over its entire life cycle. The storage of CO_2 in the wood for many decades is significant. The reduction in CO_2 emissions during construction was linked to a shorter process than if the building had used conventional construction materials. The educational nature of the facility allows further emphasis to be placed on the role of wood in construction and helps to heighten public awareness. The following parameters have been set for the building:

- Umax for the external compartments Umax=0.15 W/ m^2K
- Umax for the window and external door package (glazing and frames) Umax=0.8 W/m^2K
- Energy requirement for heating, maximum 15 kWh/(m^2a) or heating power maximum 10 W/m^2
- Airtightness of building, n50 ≤ 0.6 h-1
- Energy needed for cooling, maximum 15 kWh/(m^2a)
- Primary energy demand ratio, maximum 120 kWh/(m^2a)

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 and sources

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

4.6 Poland - Office Building of the Płońsk Forest District

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 highlights the importance of the ecological aspect in modern construction. It was built to create an ecological, zero-energy building with no negative impacts on the environment during both its construction and subsequent use.

Circular approaches and practice applied

Wood is the main building material, although non-wood materials are the primary components of the staircase and foundations. The building was designed and constructed using prefabricated timber frame technology with the assembly and prefabrication of the finished elements (walls and ceilings) taking place in a factory environment.

The prefabrication of the various elements, wood 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 innovative 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. This leads to an absence of GHG emissions from the building and very high energy efficiency that makes it close to a zero-energy building.

The building incorporates innovative technology and uses environmentally friendly, renewable energy sources:

1. A 36.3 kW photovoltaic system of 134 panels was installed on the roof of the building.
2. Underfloor heating uses ground-source heat pumps. Nine heat pumps generate a total heating capacity of 40 kilowatts and a cooling capacity of 30 kilowatts. To create heating capacity at this level, nine 92-metre-deep boreholes were required.
3. The building is also equipped with mechanical air exchangers to ensure a comfortable internal environment 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. These are in addition to an air-conditioning system for cooling the server room. The supply and exhaust ducts are fitted with the appropriate dampers to reduce noise and ensure the comfort of the building's occupants.
4. Care has also been taken to allow the use of 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 energy-efficient, as evidenced by the fact that the heat transfer coefficient of the external partitions (roof, floor on the ground and external walls) meet the relevant standards in force in Poland since 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 wood 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 thermized board, a material with greater dimensional stability and better insulating properties that is also 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 percent.
- The building is equipped with electrical and lightning protection, a water and sewage system, a rainwater collection system and mechanical ventilation with recuperation and air conditioning.

Heat transfer coefficients:

1. External walls (Umax W/m^{2}K) - <0.20
2. Rooves - <0.15
3. Windows and balcony doors - <0.90

Basic building parameters:

Built-up area:	654.32 m^2
Usable area:	749.24 m^2
Internal volume:	2637.72 m^3
Gable height:	5.18 and 7.15 m

Fire resistance class of the building – D.

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 and sources

General Directorate of the State Forests and Forest District Płońsk

https://www.youtube.com/watch?v=OycUmk-vf8o

4.7 Russian Federation - Low-carbon construction material: Segezha Sokol CLT

Background

CLT panels and structures are manufactured at the Segezha Group plant in Sokol, Vologda Region. CLT production with a capacity of 50 000 m³ per year began operating in February 2021. The company procured its cutting-edge production equipment from leading European suppliers and the CLT has passed the European Technical Assessment (ETA) and received the CE certificate allowing for drawing up the declaration of performance and affixing the CE mark.

Circular approaches and practice applied

Panels produced at the Segezha Group plant are made of softwood boards. Sawn wood is preliminarily kiln dried until having a 12% (±2%) moisture content. Dry lamellae are processed, stacked and glued under press. Due to the criss-cross pattern of the layers, the panels have high bearing capacity and rigidity as the adhesive seams are stronger than wood. Only non-toxic European certified adhesive systems are used in the production process.

The panels can be used for the construction of individual family houses and multi-store buildings, as well as for the production of prefabricated house kits. Compared to reinforced concrete structures these CLT structures have less weight and exert less pressure on the soil.

Length up to 16 m; Width: up to 3.5 m

Layer thickness: 20 mm | 30 mm | 40 mm

Standard width: 2.40 m | 2.50 m | 2.70 m | 3 m

Purpose: Bearing and enclosing elements of walls, floors and rooves

Lamellae: Kiln drying | Sorted | Spliced

Wood species: Spruce

Lamella strength class: C24 according to GOST 33080-2014

Glue: Formaldehyde-free polyurethane adhesive – approved for indoor and outdoor use

Weight: About 470 kg/m^3 (to determine transport needs), 500 kg/m^3 (for static calculations)

Surface quality: Industrial and visual

Surface: Sand

Moisture content: 12% (± 2%)

Dimensional stability: Longitudinal (0.010 percent per each 1 percent change in moisture content) | Perpendicular (0.025 percent per each 1 percent change in moisture content)

Thermal conductivity: Approximately $\lambda = 0.12$ W/(m-K)

Specific heat capacity: Approximately $c = 1.60$ kJ/(kg-K)

Sound insulation: Dependent upon wall and/or ceiling design

Combustibility: G4 combustible

Charring rate: 0.8 mm/minute

Results and benefits

CLT structures are widely used in construction thanks to:

- The low weight, high stiffness due to layered design, and ability to withstand heavy loads without shrinkage or deformation,
- wide architectural applications, quick assembly on site and possible combination with other building materials,
- high energy efficiency and fire resistance characteristics,
- modern design solutions that allowing safe and durable structures, including in seismic zones.

CLT is a carbon-neutral material and its properties have been confirmed in the Inventory of Carbon & Energy 2019 database of the Circular Ecology and Bath University[18]. Based on average results of research on life-cycle assessment a value of approximately minus 610 kg of embodied carbon per m^3 of CLT is reported when compared to other construction materials that show values ranging from 300 to 13,000 kg of embodied carbon per m^3. This advantage comes from the CO_2 bio-sequestration by the photosynthesis in wood and its long-term preservation in CLT panels, a long-lived and innovative wood product.

The use of the Segezha Group CLT technology can address an urgent problem of obsolescence of the housing stock, which is especially acute in Russia's northern territories, where the construction season is abridged. The construction using CLT panels does not involve any wet processing; or welding; thus, one can use this construction material all year round. In addition, developers can mount CLT-based structures on old foundations, which provides remarkable advantages for housing renovation programmes.

In 2022, the first multi-storey wooden residential complex that extensively used CLT panels was built in Vologda region, northwestern Russia. The complex consists of two four-storey buildings, each with the height of 15 meters and providing 64 apartments.

Segezha Group is considering the possibility of the large-scale use of CLT in construction in the Arctic and northern territories, including using ready-for-use foundations, and the company will implement two more pilot CLT-panels constructions of multi-storey buildings. One is planned in the area of Norilsk, a city in the Krasnoyarsk Territory, and located some 300 km north of the Arctic Circle. The other pilot building will be in Baikalsk, a city in the Irkutsk Region in Eastern Siberia, located in the seismically active Baikal Rift Zone. This latter project entails the construction of a four-storey CLT building starting at the beginning of 2023 and will include tests on seismic resistance.

Unique or can be replicated

Can be replicated.

Contacts and sources

Ivanov Nikolay, Vice President for Implementation of State Programmes, Sustainable Development and Forest Industry Policy at Segezha Group, ivanov_nv@segezha-group.com

Alena Vysokikh-Al-Yasiri, Sustainable Development, vysokikh_aa@segezha-group.com

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[18] Inventory of Carbon & Energy 2019 is a database with aggregated figures for embodied carbon values for various construction materials, including: CLT-panels, bricks, concrete and steel. More information at Circularecology.com

4.8 Serbia - CLT modular building system Koralević

Background

The tradition of building with wood in Serbia is several centuries long. During that period, trends in wood construction changed, meaning that wood was used to a greater or lesser extent at different times. In the second half of the 20th century, the construction of wood buildings fell out of favour due to the dominance of concrete, brick and other materials. That situation began to change in the last twenty years as wood has experienced a renaissance as the material of choice in the construction of family houses and tourist facilities. This trend was at least partially triggered by a societal shift that saw a return to tradition and nature. There are numerous examples of tourist facilities (hotels, restaurants, viewpoints at picnic areas and so forth) as well as an increasing number of family houses that are built of wood. Their construction is characterized by the use of wood in a traditional way, namely by a large amount 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, CLT is gradually being accepted by architects, builders and investors as the material of the future, with advantages compared to the traditional construction methods, as well as its importance for the development of a 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 product in Southeastern Europe.

Kolarević's modular building system allows for a large number of combinations of basic modules 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 the occupants. Once built, the house can be extended and expanded by adding suitable modules, an important advantage when compared to building houses with other materials.

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

Results and benefits

The results from buildings constructed with CLT using this method show that construction is 5 times faster, costs are 5 to 10 percent lower and the modules have 5 times better insulating properties than if concrete was used to construct the same building. Additionally, there are significant savings in CO_2 emissions when using CLT and buildings made of CLT fulfil the majority of the 9R principles of circularity.

Current experience in the construction of buildings with CLT has shown that there is significantly lower consumption of structural material, when measured per unit area of the building, compared to traditional wood construction. For example, for a building of 56 m^2, 17 m^3 of CLT is consumed, while the same structure built using the traditional construction methods would require 33 m^3 of wood (wood houses made from rough lumber). This example clearly shows the contribution of CLT construction to a more rational usage of wood and the preservation of forest resources, which is one of the principles of a circular economy.

Unique or can be replicated

Can be replicated.

Contacts and sources

info@kolarevic.co.rs
https://www.kolarevic.co.rs

4.9 Türkiye - Public-private project promoting the Use of Wood

Background

In Türkiye, wood houses and structures have been used as living spaces, especially in villages for centuries. However, as the rate of wood structures among all buildings built in 2021 was less than 0.1 percent, they are under protection today.

To promote wood construction, a project entitled Promoting the Use of Wood was initiated by the Ministry of Agriculture and Forestry in 2018. It is expected that the percentage of wood structures in new buildings will increase to 5 percent by 2030, with the completion of the works carried out to start a return trend towards wood structures because they are good for human well-being, do not release carbon, are a part of Turkish culture and are resistant to earthquakes, given that Türkiye is located in an earthquake zone.

Circular approaches and practice applied

In the context of this project, three different studies were carried out with the cooperation of the General Directorate of Forestry of the Ministry of Agriculture and Forestry, UNDP, TORID (Turkish Forest Products Industrialists and Businessmen's Association) and UAB (National Wood Association), Boğaziçi University, Middle East Technical University, Kocaeli University, Gebze Technical University and Istanbul University - Cerrahpaşa.

1. The scope of the first study includes:
    - Determining the context of the wood sector - a sectoral report was prepared
    - Preparation of wood construction sample buildings - architectural and static projects are planned and the project drawings of them have been completed. These include a single-storey highland house, a 2-storey village house, housing up to 5 floors related to urban transformation, a school and a mosque.

    Preparation of the Regulation on the Design, Calculation and Construction Principles of the wooden structures, the Construction Principles and Construction Guides of the Standard Wooden Structures. These have been provided by the Ministry of Environment and Urbanization in collaboration with the above-cited universities.

2. The scope of the second study includes:

    Performing strength tests on six Turkish tree species (coniferous tree species cannot be used in buildings because their strength tests have not been undertaken). For this reason, C18[19], C20 and C25 shaped standards will be determined as in concrete and steel, which will pave the way for their use in buildings. Also, work has been initiated to harmonize them with European Union standards.

    Measurement studies of the mechanical tests of Anatolian Black Pine, Red Pine, Scotch Pine, Fir, Spruce and Cedar trees, which are the main tree species grown in Türkiye. Studies on Scotch Pine and Red Pine tree species have been completed and the application process for the standards has been started. Studies are continuing for other tree species.

3. The scope of the third study includes:

    A project on the construction of energy-efficient wood buildings was prepared and submitted for GEF-7, an external grant of USD 3.8 million. The project is still awaiting approval.

    The Ministry of National Education, government housing agency TOKİ, Boğaziçi University and municipalities will construct public buildings with at least six high-rise model wood structures to raise awareness.

    Studies will be carried out with the sector regarding the dissemination of information regarding the use of CLT and glulam. Loan opportunities will be provided to the sector to create support infrastructure.

    Training, booklets and TV programmes will be prepared to raise awareness about the value of wood in buildings in earthquake zones, something of particular relevance for Türkiye.

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[19] These codes describe the strength classes of the load bearing structural materials. The numbers indicate that the characteristic bending stress of the material is 18 Mpa, 20 Mpa and 25 Mpa.

Results and benefits

The project is in the implementation phase. The following outputs have been completed or are expected to be completed:

A face-to-face survey was conducted with representatives of 3200 companies in the woodworking sector. Its results revealed the situation of the sector.

Strength tests have been started for those tree species that are expected to be used, especially in high-rise buildings. The process has been completed for two tree species, a report has been submitted for the other two tree species and the process continues for the remaining two tree species.

Five wooden construction projects with differing numbers of floors were drawn and all needed calculations were made. This way a base for the construction of these wood buildings in the future was created.

Subject to the approval process of the GEF-7 project, studies on energy-efficient wood buildings will be carried out.

Also, an analysis of legislation gaps has been started.

Unique or can be replicated

The project can be replicated in other countries.

Contacts and Resources

General Directorate of Forestry, Ministry of Agriculture and Forestry, Türkiye
umitturhan@ogm.gov.tr; resatbenli@ogm.gov.tr

4.10 United Kingdom of Great Britain and Northern Ireland - Material Consideration: Library of Sustainable Building Materials

Background

Material Considerations: a Library of Sustainable Building Materials is a physical materials library and a web-based resource established in Scotland in 2012 by Architecture and Design Scotland, an executive Non-Departmental Public Body of Scottish Government in partnership with Scottish Forestry, Zero Waste Scotland and City of Glasgow College.

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 for materials by type, origin and typical use
- View case studies of the materials in use in Scottish projects, from houses to visitor centers
- Access relevant events and training options
- 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, with regard to their:

- Place of origin
- Embodied energy
- Recycled content
- Classification as a renewable or finite product
- Classification as a processed or treated product
- Suitability for deconstruction
- Suitability for disposal
- Status regarding sustainability certification
- Lifespan
- Physical appearance (photos of each product are available).

Results and benefits

The library is available to the public for free and contributes to knowledge-sharing as well as raising awareness of sustainable materials, their characteristics and applications.

Unique or can be replicated

This type of information database is relevant for the local and national markets. It can be extended, or similar databases created, with information about other materials and species typical for other regions of the world.

Contacts and sources

https://www.ads.org.uk/
https://materials.ads.org.uk/

CHAPTER 5
Conclusions

When considering sustainability and circularity in the construction sector, wood is a preferred choice. It is a natural raw material and has a number of advantages over other building materials. First, it is derived from a natural growth cycle and, where forests are sustainably managed, enough wood can be grown in the long term to meet the foreseeable increasing demand for construction wood in many regions of the world. In regions where deforestation and forest degradation are currently pressing concerns, sustainability and land use considerations include the need to stabilize and reverse these trends and further develop forest restoration capacities, associated policies and 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 CO_2 as key inputs leading to wood formation. The cycle continues with harvesting from sustainably managed forests and the 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. In addition, pertinent construction design can contribute to a sustainable use of wood raw materials that ensures that the majority of it can be recovered and/or recycled. At the end of its useful life, wood can be biodegraded or used to generate bioenergy, at which point it is returned to its natural cycle.

Third, wood used in construction can be applied in diverse functions, as structural parts of buildings (e.g., for frames, decking, flooring, wall and roof sheathing, window frames, doors and so forth), in building interiors in a myriad of ways (flooring, cabinets, paneling, trim) or to fulfil various functions associated with construction processes (e.g. foundation formwork supports and scaffolding) which contributes to lower impacts on the environment and climate. An emerging trend toward wood construction that incorporates a high degree of prefabrication, speeds construction processes and 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 a bio-based material when compared to other construction materials. Furthermore, it also analysed different construction methods and circularity practices at different stages of construction, retrofitting, deconstruction and demolition. The facts that were determined as a result of this examination have led to the following conclusions:

Better design, innovation and environmental impact: Over the past four decades, innovation in engineered wood products for construction has led to **unprecedented changes in the possibilities for wood use in construction, particularly in 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.
- The use of wood from sustainably managed forests in buildings results in lower GHG emissions and lower lifecycle energy consumption when compared to using other construction materials.

The rate of reuse and recycling of wood at the end of life is still relatively low and, therefore, represents considerable untapped potential for increasing circularity and sustainability, provided economic viability and environmental efficiency criteria are met.

Current and future potential: The potential for the incorporation of greater quantities of wood in construction are the highest in residential and commercial buildings of 10 storeys or less. Numerous case studies presented in this publication have demonstrated 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 the further adoption of mass timber in construction for multistorey buildings while the share of construction projects employing off-site methods will also likely rise due to shortages of skilled labour.

- Although the 'stick building' technique remains predominant in most counties, recent construction techniques, such as modular, mass timber and panelized construction techniques, are garnering interest because of the advantages related to being able to increase the precision of design, speed up construction and reduce waste. All of these factors contribute to a more circular and sustainable management of natural resources and human capital while simultaneously having a lower impact on the natural environment.

- The design phase is particularly important in innovative construction since it is critical that assembly tolerances are controlled and misalignment of panels, modules and connections be avoided to facilitate the reduction of material waste in the construction phase. Additionally, improved designs will contribute to the durability of structures, prolonging their use phase.

Wood waste landfilled, composted or incinerated: Although the evidence clearly demonstrates the differences in climate modifying emissions from discarding or incinerating wood rather than reusing, recycling or combustion for energy recovery, substantial volumes of wood continue to find their way into the waste stream. Progress is being made to change this reality, however, more remains to be done.

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 their recovery, making such projects economically viable.

- Some studies assessed that the environmental impacts, such as cumulative energy consumption or GHG emissions from deconstruction and material recovery, were lower than what would have resulted from producing new lumber.
- Despite these advances, deconstruction practices are not common in the sector. First, this is because buildings are usually not constructed with dismantling in mind and second, the growing market for wood-based energy discourages other destinations and uses for wood waste.

In summary: This study has shown that the implementation of the above-mentioned approaches varies greatly among countries. Some measures, such as those related to 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 wherever and whenever economically, socially and environmentally viable.

Above all, systemic changes in mindset and an integrated management approach to all the processes and activities that companies use to add value to their construction materials and services along value chains are needed. This requires a new perspective on construction processes and a redefining of the relations among different value chains' actors, from concept through to completion, demolition and recovery of materials.

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CIRCULARITY CONCEPTS IN WOOD CONSTRUCTION

When it comes to sustainability and circularity, wood as a natural raw material has several advantages over other building materials. As a bio-based resource, it has considerable benefits concerning greenhouse gas emissions, carbon-storing, thermal insulation as well as human health and well-being compared to other construction materials. New types of wood products, being the result of extensive research, enable the extensive use of wood in tall buildings. At the same time, innovative wood products provide less manufacturing waste, low carbon-emission alternatives and store massive quantities of carbon while new technologies speed construction processes, promote energy efficiency and minimize waste. This study examines the benefits of wood as a construction material and discusses practices applied in the wood construction sector from the perspective of circularity, sustainability and climate change mitigation. It analyses how circularity concepts can be applied in the construction industry using different construction methods and at different stages of value chains. The study describes how different construction techniques and practices contribute to the renewal and sustainability of construction value chains. The analysis is supported by examples of good practice in UNECE member States.

Information Service
United Nations Economic Commission for Europe

Palais des Nations
CH - 1211 Geneva 10, Switzerland
Telephone: +41(0)22 917 12 34
Fax: +41(0)22 917 05 05
E-mail: unece_info@un.org
Website: http://www.unece.org

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