Prolonged Carbon Storage and CO_2 Reduction by Circular Design with Wood

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https://doi.org/10.5755/j01.sace.35.2.35552

JSACE 2/35

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Received 2023/11/08

Accepted after revision 2024/03/06

Abstract

The benefits of circularity and biogenic carbon storage are often overseen. This study links the circular design of buildings with prolonged biogenic carbon storage. Circularity in architectural design can involve extending the service life of a building frame, whilst forests grow back and store more carbon. Following this approach, Stora Enso has developed a mixed-use building concept with flexible and adaptable structures. Static and dynamic life cycle assessment (LCA) has been carried out to assess different scenarios, modelling and quantifying its potential benefits regarding whole life carbon.

While whole life carbon is lower in all timber scenarios compared to conventional concrete buildings, dynamic LCA makes clear the benefits of carbon storage and carbon sequestration. Total emissions, considering a reference service life of 50 years, are 2,84 kg CO_2-eq./m² floor area/year, considering biogenic carbon storage and carbon sequestration in regrowing forests. An increase of the building lifetime to 80 years aligns with a longer rotation time of forest trees, resulting in whole life carbon of -0,09 kg CO_2-eq./m² floor area/year. This demonstrates that the effective implementation of built-in flexibility and adaptability can extend the service life of a building, unlocking environmental benefits of biogenic carbon storage of wood products in buildings.

Keywords: adaptable building; carbon sequestration; circularity; flexible design; whole life carbon.

Introduction

It is well established that timber construction is one of the most effective strategies to decarbonize construction, especially through reducing embodied carbon emissions. It has become one of the main arguments for property developers to shift towards building with wood, especially those who have carbon reduction as one of their key strategic goals. Using timber-based products sourced from sustainably managed forests (SMF) has many environmental benefits that go beyond reducing carbon emissions; however, there is still a long way to go until these potential environmental impacts can be properly accounted for in standardized frameworks. Currently, a more holistic and sensible approach and calculation methods of carbon emissions might be considered.

The interactions between sustainably managed forests, in which harvested trees are replanted, and timber products play a relevant role in carbon sequestration. Additionally, biobased products are unique as their biogenic carbon storage locks CO_2 away from the atmosphere for the length of the product's lifetime. With buildings, such storage durations typically last for decades if not centuries.

Journal of Sustainable Architecture and Civil Engineering
Vol. 2 / No. 35 / 2024
pp. 23-23
DOI 10.5755/j01.sace.35.2.35552

However, these facts are also being questioned via scientific publications that argue that these carbon storage and carbon sequestration are not relevant because it is not clear that trees regrow quickly enough in the forests to compensate for emissions connected to their harvesting. As a result, the biogenic carbon storage effect is frequently dismissed from the equation and therefore disregarded as a benefit of building with wood.

Background

Recent and upcoming regulations across Europe aim at transforming the way in which we understand and quantify how carbon is being released and captured in construction. One rather advanced example of this is France's Environmental Regulation 2020 (RE2020), which aims to improve the environmental performance of buildings throughout their entire lifecycle, from procurement of raw materials to construction, use of the facility and even the building's end-of-life. A particularly unique aspect within this regulation is that it requires the LCA to include the timing of building-related emissions. With this so-called dynamic LCA approach, emissions generated earlier in the project are weighted more heavily than future emissions, and the benefit of carbon-storing materials is recognized. These considerations make the choice of materials a key factor and can be a positive game changer for the sustainable timber industry. (Cabassud et al., 2022)

In this context, the application of flexible and adaptative design principles (as part of circular design) in buildings should help us further reduce carbon emissions by extending the lifecycle of timber-based products. Most buildings of any construction are demolished due to financial factors, especially that a building owner expects another building type to be more profitable on a given site. Given this context, a building adaptable to different uses should have a better chance of standing for longer. Much of the timber industry is not yet focused on this opportunity. Instead, a lot of effort is currently spent on re-use, recovery and recycling solutions of these materials, for instance via the project Timberloop led by the Austrian Forest Products Research Society.

Stora Enso, along with other industry partners, has developed a concept building to demonstrate how it is possible to design for mixed-use, flexible, and adaptable structures, allowing for future changes and repurposing. Chiefly, this concept establishes a building that can either be an office or a hotel, or both over its lifetime. This way of designing a timber structure should allow extending the service life of the building by delaying obsolescence. It should not be necessary to demolish and rebuild when the use of the building needs to change. (Fig. 1)

Fig. 1

Architectural design of the Concept Building for mixed-use, considering flexible and adaptable design for circularity (left). Column and beam based structure based on the Sylva ™ platform (right)

The built environment is currently responsible for 39% of global carbon emissions. On a global scale, 11% of it is directly contributed by the production of materials, transport, construction activities and demolition material. These emissions are what is referred to as embodied carbon. Considering that fact and the ambition of the EU and its member states to decarbonize the energy sector and improve building energy efficiency, the largest share of the total carbon emissions will shift continuously from operational energy to construction materials. (WorldGBC, 2019) With these two key factors, recognizing carbon storage and extending the lifetime of a building can significantly increase the way the environmental benefits of building with timber are evaluated and quantified.

Purpose

This study aims to understand and quantify how the use of timber for the structure of a building can reduce carbon emissions in comparison to the use of other conventional and widely used materials. To assess the real effect to the Global Warming Potential (GWP) of a timber structure, we need to understand the relation between the carbon sequestration of sustainably managed forests and the carbon stored in the building. (Helin et al., 2013)

Another relevant aspect is to better understand the potential climate mitigation effect of using flexible and adaptable architecture to extend the service life of buildings, in relation to sustainable forest growth as a holistic system. It also helps to better understand the Life Cycle Assessment (LCA) calculation methods required in current and upcoming building regulations and the importance of using biobased materials within those schemes. Additionally, a wider understanding of the dynamic LCA methodology on building level using timber construction products and considering different service lives will be created.

Methods

The study is based on the mixed-use building concept by Stora Enso that was designed by a team experienced in timber building design, including such other firms as Sweco Finland and INARO. This concept also includes a comparison building with standard mineral-based methods, which is used as benchmark for all evaluations.

The timber-based concept building and its benchmark are compared from different viewpoints and using different scenarios. Both building types were modelled and calculated according to the Method for the Whole Life Carbon Assessment of Buildings (the 2021 edition) issued by the Ministry of the Environment of Finland. (Kuittinen, 2019) This method is applied to better understand the regulations in the country where Stora Enso has its headquarters. The method is based on the Level(s) environmental reporting framework developed by the European Commission, which is further based on European sustainable construction standards, especially EN 15978. (Dodd et al., 2019)

To explore how a circular approach can contribute to decarbonization in the construction sector, it is important to consider time when assessing environmental impacts of buildings, especially when it comes to an increased use of timber or other biobased construction materials. Therefore, in addition to applying well-established and standardized static LCA methodologies, as used in the Method for Whole Life Carbon Assessment of Buildings, a dynamic LCA approach (Levasseur et al., 2010) is applied to understand the effect of timing on both buildings and on forest regrowth levels. (Lippke et al., 2011)

Understanding biogenic carbon in timber

Although standards for LCAs and EPDs have been developed over the last decades and the treatment of biogenic carbon in biobased products is regulated within calculation methods (EN 16449) and product category rules (EN 15804, EN 16485), the final application varies between countries and regulatory approaches. There is wide consensus on product level to apply a -1/+1 approach. That means that biogenic CO_2 which is captured during forest growth is stored as biogenic carbon and enters the product system in module A1. At the end-of-life of the product or building, this biogenic carbon leaves the system in modules C3 or C4, depending on the end-of-life treatment.

Contrary to this approach, there is still guidance to apply a 0/0 approach since there is a certain difficulty and probability of errors in applying the EN 15804 guidelines. Therefore, carbon neutrality is achieved by using a 0/0 approach, which means that no biogenic uptake and release is considered in the life cycle.

In both approaches, the carbon balance should be 0 over the whole life cycle. However, these approaches face similar criticism: that although both assume carbon neutrality of forests, they do not consider the timing of carbon uptake and release. (Hoxha et al., 2020)

To better tackle the topic of timing when CO_2 uptake and emissions occur, dynamic LCA approaches have been developed. This means that CO_2 emissions and sequestration must be differentiated by the year when they occur. Within this approach, two scenarios can be considered. The first one assumes that trees grow before they are harvested for use in timber products (growth scenario) while the second assumes that trees grow after harvesting (regrowth scenario). Stora Enso's approach is to only take wood from sustainably managed forests, in which new trees are planted to replace those harvested and accordingly maintain their biodiversity, productivity, regeneration capacity and vitality. (Stora Enso 2023) Thus, it can be assumed that trees will grow and regrow over centuries in the forest, from where the raw material for timber products is taken. Considering that fact and understanding the relevance of time in dynamic LCA, the regrowth approach is taken as scope for the study to highlight the differences in GWP over the reference service life of the buildings and to evaluate the impacts of CO_2 sequestration in the forests for the same period. (Hoxha et al., 2020)

Design for circularity

A key aspect of circularity in building construction is the use of a building and/or its materials for as long as possible. "Keeping buildings and materials in use reduces the need for new construction and material extraction, thereby limiting the associated negative impacts on biodiversity. Where new materials are needed, switching to renewable materials produced regeneratively can help the sector actively rebuild biodiversity and safeguard the health of ecosystems." (Ellen MacArthur Foundation, 2021) For the purposes of this concept building, the guidelines proposed by the Dutch environmental consultancies Metabolic and Copper8 are used to guide and describe the circularity approach taken by this design. Two main principles used are directly related with the embodied biogenic carbon and the lifespan of the building: 1) Design for maximal functional lifespan, and 2) Design with minimal amount of material. (Metabolic, 2023)

To design for maximal functional lifespan, the building's layout, structure and MEP (Mechanical, Electrical and Plumbing) and HVAC (Heating, Ventilation and Air Conditioning) systems have been designed simultaneously for office and hotel uses - both common city centre building types. A structural grid has been chosen that meets the requirements of office space for lease, and at the same time follows the rhythms of the many regular compartment walls required for hotel rooms. A delicate design negotiation process was needed to find a column layout that serves both uses. Probably the hardest design challenge was to find MEP and HVAC systems that can be adapted to both office and hotel uses with the fewest changes possible. A revision of the available heating, cooling and ventilation systems was done from the viewpoint of the adaptability, and then fitted into the layout and structures in a way that there is no collision between ducts or pipes and the timber structure. This was a deeply iterative process, showing that there is still much left to develop as such building adaptability goes against industry norms.

A beam and column structure was chosen to fulfil the requirements of the both design principles mentioned previously. As material quantity is a relevant cost driver, the reduction of the amount of material is well incentivized by the need to keep the cost competitiveness of the solution. Therefore, a relatively tight grid was chosen at 4 x 5.5 m and 6 x 4 m approx. By this means, the beams and floor elements remain thin reducing the amount of material required for the building structure.

With the timber superstructure, two concrete vertical cores for utilities and egress were designed in each building end as the most effective way to meet the fire safety requirements of both hotel and office functions and to keep separate distribution shafts for each use type, The MEP and HVAC systems can be connected from the main central lines to either side in order to maintain the same main lines despite functional changes. The secondary distribution pipes and ducts would need to be replaced, as they are too different in size, function, and location in both functions.

Through the aforementioned design principles, a design has been achieved that allows adaptivity, meaning the ability to undergo functional changes, and flexibility, referring to the ability to undergo spatial change. Because of this design feature, this study assumes that the building can extend its lifetime considerably, thus further storing the biogenic carbon, which will positively impact its LCA results.

LCA methodology and scenario set-up

A first baseline comparison with a reference service life of 50 years is carried out between the intended design (timber frame) with an alternative design (concrete frame); from this, it is assessed how this comparison changes when applying longer time frames, such as 80 years, which represents a typical rotation time of a forest stand.

Basic information of the timber building

The external non-load-bearing walls are foreseen as a timber frame structure with mineral wool insulation. The principle of the load-bearing structure follows a beam and column system. The columns and beams are GL24h GLT (Glue-laminated timber). The central beams are designed of LVL (Laminated Veneer Lumber). The upper floors are built from CLT (Cross-Laminated Timber) with a typical floor construction which varies between wet areas (bathrooms, washing rooms, etc.) and the areas which are used as offices or hotel rooms. The flat roof structure is based on CLT with mineral based insulation and roof membrane. The ground floor is identical for both building options.

Basic information of the concrete building

The concrete building is designed to represent a standard reinforced concrete frame, with non-load bearing external walls. The structural system is a column and slab structure, without beams supporting the floor from underneath, laterally stabilized with concrete circulation cores at the ends. The compartment floors and the roof structure comprise precast hollow-core concrete slabs, while the ground floor is slab on grade. The roof is finished with flat roof insulation and membrane.

General assumptions for both building types

It is assumed that the consumption of operational energy is the same in both design solutions. The emissions from energy generation are calculated according to the benefit-sharing approach presented in the construction emissions database. (CO_2DATA, 2022) The surface areas of the concrete- and wood-structured mixed-use building are almost identical and the scope of the calculation and building parts to be included in the building are the same. The assessment generally considers the entire building and main building service technology.

Scenarios and replacement assumptions

Four main scenarios are assessed within this study:

- Timber building with 50 years reference service life (RSL)
- Timber building with extended RSL to 80 years
- Concrete building with 50 years (RSL)
- Concrete building with extended RSL to 80 years

For each of above scenarios six different LCA approaches have been applied:

_ Dynamic LCA with 0/0 approach
_ Static LCA with 0/0 approach
_ Dynamic LCA with -1/+1 approach
_ Static LCA with -1/+1 approach
_ Dynamic LCA with -1/+1 approach including carbon sequestration (regrowth method)
_ Static LCA with -1/+1 approach including carbon sequestration (regrowth method)

Replacement scenarios applied:

Default values were applied via One Click LCA tool as well as some values are based on expert judgement for building elements. (Table 1)

Table 1

Replacement scenarios applied

Building element	Number of replacements	
	50 years scenario	80 years scenario
Doors	1	
Building technology	1	2
Accommodation	1	2
Elevator	1	1
Water vapour barriers	1	2
Bitumen waterproofing	2	3
Facade	0	1
Windows	0	1
External doors	0	1
Internal doors	0	1
Parquet flooring	0	1

LCA methodology

The scoping procedure and assumptions used in the calculation are determined in the Method for the Whole Life Carbon Assessment of Buildings (2021 edition) issued by the Ministry of the Environment of Finland. Whole life carbon considers the total amount of CO_2 emissions throughout the entire buildings lifetime, which means all impacts from material manufacturing, transportation to the construction site, construction works, the use phase of the building and after use activities like demolition and waste processing. It can be furthermore separated into embodied emissions, which are linked to materials emissions and operational emissions, which is considering the emissions from day-to-day occupancy like heating, cooling and electricity consumption. The assessment was done with automated One Click LCA calculation software, which focuses on assessments of construction and infrastructure projects and gives access to the largest database of environmental construction data. It includes various possibilities to connect directly with design tools and import data in the web platform. One Click LCA has integrated automatic checks on completeness and plausibility of the applied data to ensure LCA quality, hence this appears to be the most suitable tool for such types of projects. (One Click LCA 2023)

Dynamic LCA

Currently in static LCA, the Global Warming Potential (GWP) is assessed following the guidelines and characterization factors by the Intergovernmental Panel on Climate Change (IPCC). "GWP expresses the cumulative radiative forcing value caused by an emission of a unit mass of a given greenhouse gas (GHG) over a defined time horizon, relative to the equivalent value for CO_2." (Levasseur et al. 2010) The GWP results are quite sensitive when looking at different radiative forcing values, as, for instance, methane is quite short in the atmosphere (12 years) compared to CO_2 which will remain for thousands of years. That example underpins the importance of time in LCA; this led to the establishment of dynamic LCA analysis.

Within dynamic LCA (DLCA), specific dynamic characterization factors (DCFs), which differ from the static approach, are utilized. The life cycle of a product, building or service is divided in one-year time steps and specific factors (DCFs) for different greenhouse gases at each were developed. With that, it is possible to calculate the radiative forcing impact of greenhouse gas emissions at any time and that allows the GWP to be analyzed under different scenarios. This process leads to a better, more complete understanding of the complex effect of biogenic carbon storage and carbon sequestration. (Levasseur et al. 2010)

Based on the static LCA results calculated via One Click LCA, those values are further adopted using a well-developed DLCA spreadsheet to facilitate the calculation of time-dependent Absolute Global Warming Potential and Absolute Global Temperature Potential due to a temporally resolved (year by year) emissions inventory (CO_2, CH_4, other well-mixed forcers, and examples of short-life forcers). (Cooper 2020)

Results

The reduction of the whole life carbon is 11% from the mixed-use timber building concept against the concrete benchmark building, considering a RSL (Reference Service Life) of 50 years and applying traditional, static LCA. (EN 15804+A2 2019; EN 15978 2011) To better understand the impact of carbon storage and carbon sequestration in regrowing forests, variations of the RSL and LCA approaches are applied. DLCA demonstrates the benefit of using timber and the effect of biogenic carbon storage in the material for RSLs of 50 and 80 years. If the same amount of stored carbon in the installed timber elements in the building will be sequestered as CO_2 in sustainably managed forests after construction within the RSL of 50 years, the whole life carbon could be reduced by 74% from 10,79 to 2,84 kg CO_2-eq./m² floor area/year. This means that the upfront carbon (CO_2 emissions from stages A1-A3) is already offset by the carbon sequestration effect and leads to a positive GWP impact.

By applying circular design methods and assuming basic refurbishment after 50 years and extending the RSL to 80 years (**Table 1**), the whole life carbon results in 0,10 CO_2-eq./m² floor area/year, which means a nearly net zero contribution to the Global Warming Potential, although a conservative end-of-life scenario (incineration with energy recovery for wood products) is applied for the building. Applying same considerations (refurbishment after 50 years and RSL of 80 years) for the concrete benchmark, the whole life carbon results at 7,42 kg CO_2-eq./m² floor area/year, which is a reduction of 26% compared to the concrete benchmark building with 50 years RSL. (**Fig. 2**)

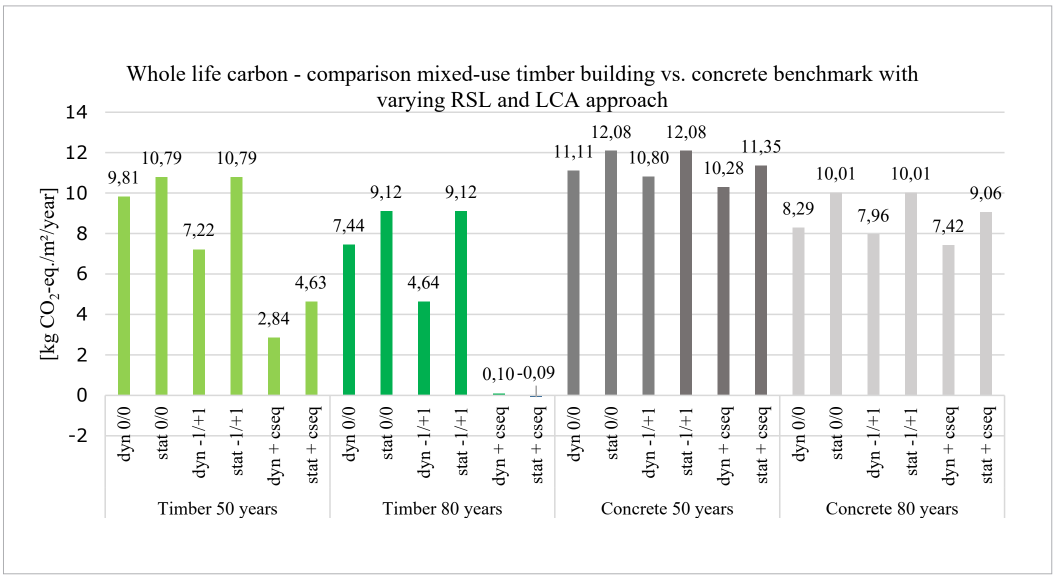


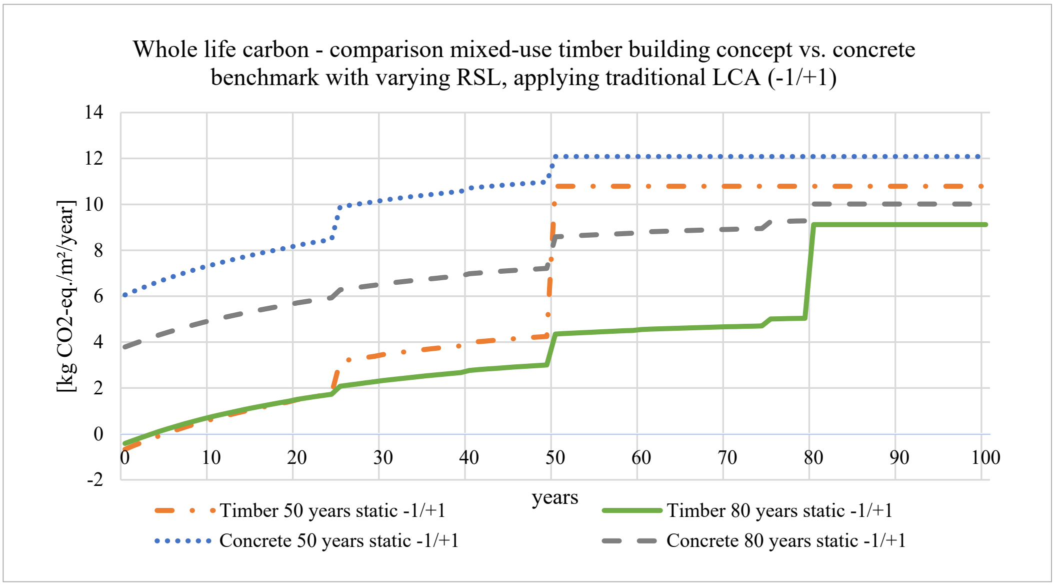
Fig. 2

Comparison of the whole carbon between mixed-use timber building concepts and benchmark buildings. (dyn = dynamic; stat = static; cseq = carbon sequestration)

Fig. 3 shows a static LCA approach where in the timber options more biogenic carbon is stored in the wood construction materials than emitted during the manufacturing of those products (A1-A3). Replacements and operational embodied carbon are the same in all options. The release of CO_2 after the buildings' lifetime is balanced out by the carbon stored in the construction materials, meaning that carbon neutrality is assumed over the whole life cycle. It does not consider the timing of uptake and release as well as what happens with the forests, from where the wood for the buildings originally is taken.

Fig. 3

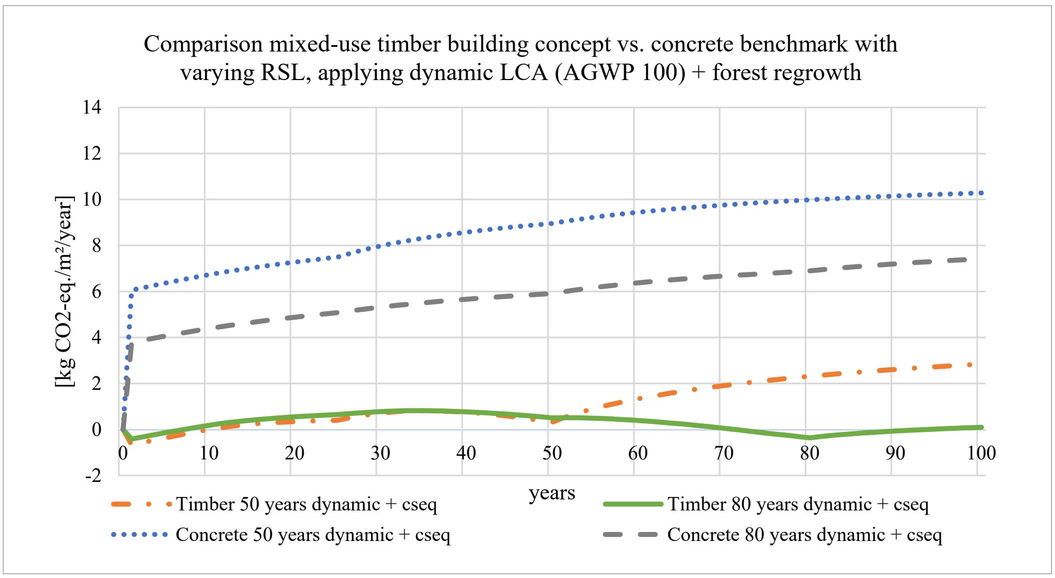
Comparison of LCA results between the mixed-use timber building concept and the concrete benchmark with varying RSL, applying traditional LCA (-1/+1)



On the contrary, **Fig. 4** reflects DLCA and the accompanying DCFs to show the consideration of the timing of CO_2 storage and release and the regrowth effect in forests, as well as when emissions occur. It's assumed that the same amount of wood needed to produce the timber construction materials for the building grows back over the building's lifetime. The lifetime extension of the building to 80 years allows the trees to reach full maturity and consequently leads to a positive contribution to the Global Warming Potential.

Fig. 4

Comparison of LCA results between the mixed-use timber building concept and the concrete benchmark with varying RSL, applying dynamic LCA (AGWP 100) + carbon sequestration



As a consequence from the application of the mentioned circular design principles, an extension of the RSL from 50 to 80 years, instead of building new in case of the mixed-use timber building concept, would also reduce the amount land used for sustainably managed forests. The number of trees needed to sequester the same amount of CO_2 from the atmosphere as it is stored in the timber building elements will be reduced by 52%. To express in a different way, more raw material is available for other timber buildings. (UBA 2020)

Discussions

The effects of using timber as the main material for building frames was compared to conventional concrete buildings by applying a common static LCA along with non-standardized dynamic LCA approaches. The expected carbon reduction benefit of using timber structures has been quantified and confirmed when comparing buildings with the same function but made from different materials. The reduction of GWP becomes significant when considering the effect of the prolonged carbon storage in timber materials. In the standard LCA approach (static and RSL of 50 years), the benefit of approximately 11% emissions reduction may not always be considered strong enough to justify the required transformation of the construction sector.

The implication of carbon sequestration leaves room for assumptions regarding tree rotation times, which are influenced by various parameters like location of the forest and species and which lack of standards or common rules - only recommendations exist for how to consider this key factor. Also having large bearing on the LCA results is the selection of timelines regarding climate aspects. The investigated time frame for the GWP was 100 years, which is common consensus for climate impact assessment. The change of the chosen time horizon to, for instance, 300 years would also affect the outcome of the study, as CO_2 endures over centuries in the atmosphere. It is of upmost importance to implement effective circular design strategies to make sure that this methodological change is reflected in practice, effectively extending the building life cycle. A significant shift in the real estate industry's mindset is fundamental to enabling this change.

Another aspect that significantly impacts LCA results is the end-of-life option for wood, which in this study is assumed to be conservative incineration. The ambitions of the wood industry to get more circular include increasing the re-use of building elements. Also, such cascading usages as recycling of timber construction elements like CLT for particleboards prolong the biogenic carbon storage, thus significantly influence the climate impact using DLCA. Additionally, the shift away from operational emissions to embodied emissions in the construction sector is considered. This is contemplated due to a benefit-sharing approach, which "provides emission values for energy services also for coming decades considering the targeted decarbonization of energy services". (CO_2DATA 2022)

The authors also emphasize that the Whole Life Carbon Assessment Method is used from them for the first time within this study and therefore some uncertainty within the results or building elements classification cannot be excluded. While for most materials values from the emissions database for construction published by the Finnish Environment Institute are applied, for some materials specific data from Stora Enso's EPDs was chosen. While the focus is on carbon sequestration and carbon storage effect in timber, carbonation was excluded as it would go beyond the scope of this study and based on Hawkins et al. it can be assumed that on both the concrete and timber building the effect on emissions would vary between 0 and 7,5% over the whole life cycle.

Conclusions and Outlook

This study makes evident that the current static LCA methods are overlooking some of the major benefits of building with timber and its linkage to sustainable forestry. This may likely influence the material choice negatively towards the use of timber and play against well-established environmental goals.

Carbon reduction potential by using timber shows clear advantages compared to conventional concrete buildings. (Churkina et al., 2020; Hawkins et al. 2021; Himes et al. 2020; Peñaloza et al. 2016)

This carbon reduction benefits can be significantly increased by implementing circular design principles, such as extending the building's service life, along with considering accompanying carbon sequestration. The real benefit becomes evident when linked to forest regrowth and development of dynamic LCA models. It is desirable that on the standardization level - for instance, in the further development of EN 16485, which is providing the product category rules for wood and wood-based products for use in construction – that dynamic LCA becomes visible. And even the mentioned RE2020 regulation is forerunner in considering time in LCA. More research is needed to improve data and links between construction and forest (re)growth and with that an opportunity and exercise to further develop more holistic methods.

In addition to pioneering countries like France, much regulatory action regarding whole life carbon is also ongoing at EU level through the European Green Deal. Hence, a link is needed between circular design, through which the effective implementation of built-in flexibility and adaptability can extend the service life of a building and consequently unlock the environmental benefits of biogenic carbon storage of wood products. This can significantly help decarbonize the construction sector and today's timber construction products in those buildings can serve as material banks for the future.

Acknowledgements

This research was supported by the project Timberloop under consortium leadership by the Austrian Forest Products Research Society. "This project is funded by the Forest Fund, an initiative of the Federal Ministry of Agriculture, Forestry, Regions and Water Management and is carried out as part of the Think.Wood program of the Austrian Wood Initiative.", supported by FAssociation of the Austrian Wood Industries..

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