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Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon

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ABSTRACT

This study conducted a consequential Life Cycle Assessment (LCA) on two similar mid-rise apartment buildings applying either concrete or cross laminated timber (CLT) as the main structural material. The study further investigated inclusion of biogenic carbon and how this affects environmental impacts related to Global warming. Thus, two assessment scenarios were applied: A Base scenario, without accounting for biogenic carbon and a Biogenic carbon scenario that include a GWP_{bio} factor to account for the use of biogenic carbon. The CLT building had the lowest impact score in 11 of 18 impact categories including Global warming. Operational energy use was the main contributor to the total impact with some variation across impact scores, but closely followed by impacts embodied in materials (incl. End-of-Life). An evaluation of the potential forest transformations required for fulfilling future projections for new building construction in 2060 showed that about 3% of current global forest area would be needed. This share was essentially independent of the selected building material as the main driver for forest transformation was found to be energy use during building operation. Thus, focus should primarily be on reducing deforestation related to energy generation rather than deforestation from production of building materials.

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1. Introduction

The building and construction sector is responsible for about 39% of the World's process and energy related CO_2-emissions and the emissions related to this sector appears to increase each year [1]. This is problematic as the continuous increase in greenhouse gas (GHG) emissions makes it increasingly difficult to achieve commitments on climate change, such as the Paris Agreement [2]. Moreover, it is estimated that ca. 230 billion additional m^2 floor area will be constructed in 2060 [1]. In this light, it is essential to identify solutions for decoupling the link between construction and GHG emissions to reduce overall emissions related to the building and construction sector. A common approach for quantifying environmental impact and evaluating options for reducing environmental impacts, such as global warming, of buildings is Life Cycle Assessment (LCA) [3,4]. In LCA, the flows of material and energy pertaining to a building are mapped throughout its full life-cycle starting with the extraction of raw materials for the production of building materials, over the use of the building and ending with the decommission of the building and final disposal and recycling of building materials.

Historically, timber has been a common construction material in buildings and different types of timber and different construction techniques have been commonly applied [5]. Cross Laminated Timber (CLT) is a relatively new wood construction material and can be used as the main loadbearing element in a building. Thus, CLT is seen as a relevant alternative to conventional mineral-based building materials, such as reinforced concrete, which are commonly used in today's buildings [5]. Previous studies have shown that timber in general, and CLT in particular, has a lower impact on the global warming compared to concrete [6–13]. For instance, Hart and colleagues [14]] evaluated carbon emissions from using steel, reinforced concrete, or engineered timber frames across the building life-cycle. However, the majority of studies were limited to assessing impacts related to climate change without considering the importance of other potential environmental impacts. Thus, potentially overlooking environmental trade-offs that can lead to unintentional shifting of the environmental burdens [15]. Indeed, an increased future use of CLT in the building and construction industry will increase the demand for timber production. Here, it is important that the increase in timber produc-

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tion is done on a sustainable manner to avoid potential deforestation where production exceeds the growth rate of new trees. Indeed, it is relevant to consider if the current pool of forest is sufficient for fulfilling future demands for timber in buildings. Lechón et al. [16] performed an assessment of single-family dwelling constructed using CLT and looked across 16 environmental impact categories. However, the results of the study cannot be extrapolated to multi-story dwellings and does not include a comparison with other structural materials, such as concrete. Moreover, the modelling of the life-cycle inventory appears to be based on an attributional approach, in contrast to a consequential approach, that seeks to model the environmental consequences of a decision. This is particularly important for evaluating the consequences of future constructions and the impacts of structural material selection. LCA on buildings are most often done using an attributional approach to provide an environmental account of the impacts that have gone into constructing the studied building. Still building LCAs using a consequential approach are becoming more common as decision-makers are interested in evaluating the potential environmental impacts of their decision. A number of studies have conducted consequential LCAs on wood-based buildings [6,10,17] or wood-based building materials or products [18–25].

Finally, the estimation of environmental impacts of CLT is not commonly agreed on in LCA as different approaches for handling biogenic carbon exists. Often the biogenic carbon in CLT is treated as being climate neutral where the carbon sequestrated during tree growth is released after final used of the timber, either via incineration or by natural degradation of the wood [10,26]. However, this approach has been questioned in a number of studies because factors, such as forestry management and time of temporary sequestration in the building are not properly accounted for [10,26–30]. Thus, it is relevant to evaluate how choices about modelling of biogenic carbon during the life-cycle impact assessment (LCIA) phase of the LCA will affect results for wood-based buildings and if this will affect the overall conclusions that can be drawn from this LCA-study.

Based on the existing state of the art, this study seeks to add to existing knowledge about the use of CLT and the potential environmental implications of using CLT compared to more conventional materials, such as concrete. This is done by performing a consequential LCA on two buildings constructed using CLT and concrete as structural material, using two approaches for considering biogenic carbon and taking into account all relevant impact categories. The results of the assessment are used to:

1) evaluate the importance of different approaches for handling biogenic carbon in a building LCA and if this will change the overall conclusions drawn from the LCA-study;
2) evaluate the potential environmental consequences of using CLT or concrete as the main structural materials and if selection of e.g. CLT will lead to environmental burden shifting, where reduction in one environmental issue is countered by increased impacts for the other issues;
3) evaluate the potential effect on deforestation and the forest area needed for satisfying future construction demand by extrapolating the case study results to cover projected future construction demand.

2. Materials and methods

2.1. Case study description

LCA was conducted on two case study buildings, which are located in the area Lilleby in Trondheim, Norway. The buildings were constructed between 2016 and 2018. The buildings are called *Maskinparken 2* and *Maskinparken TRE* and were constructed using two different structural systems. *Maskinparken 2* was constructed using a structural system of concrete and steel and *Maskinparken TRE* was constructed with CLT elements as the structural system. *Maskinparken TRE* and was the first mid-rise building constructed in CLT in Norway. Throughout this article *Maskinparken 2* and *Maskinparken TRE* are referred to as the "Concrete building" and the "CLT building", respectively.

The Concrete building consists of five floors and has a heated area of 2449 m^2. The CLT building consists eight floors and has a heated area of 3973 m^2. The two buildings share a large unheated basement, constructed in concrete, with a total area of 1395 m^2. The basement areas under the Concrete building and the CLT building are 700 m^2 and 695 m^2, respectively.

The two case study buildings are comparable due to a very similar design for the floor plan per story and the apartments, which vary between 1 and 4 rooms. The large similarity in design enable a comparative LCA of the Concrete building and the CLT building. See Supplementary Material (SM) 1 Section S1 for more details on the case study buildings.

2.2. Life cycle assessment

2.2.1. Goal and scope

This LCA follows the recommendations given in the ILCD LCA guidelines [31]. The scope of this LCA is defined as cradle-to-grave and results will be reported for all impact categories as characterized and normalized results. The primary function of the CLT and the Concrete building is to allow people to live in an apartment as their home. Thus, the functional unit (FU) was defined as "Use of 1 average m^2 of a mid-rise apartment building with 5 to 8 stories and apartment sizes ranging from 1 to 4 rooms for 100 years in the Scandinavian countries." The defined FU allows a comparison of the CLT building and the Concrete building in the LCA. The results are intended to support future decisions about using either concrete or CLT as the structural material for construction in order to reduce the environmental impacts associated with construction of new buildings. Therefore, the decision context for the LCA is defined as *Situation B* [31]. For *Situation B*, results of an LCA can be used to support decisions at meso- and macro-level, where decisions based on the results can cause structural changes in one or more processes of the systems that the studied product system interacts with [32]. In this case, the results of this study can lead to decisions about using either CLT or concrete as the common material in structural system for new mid-rise buildings. Such decision, will likely lead to structural changes for the material supplying timber and concrete industries. Therefore, we apply a consequential approach for constructing the life cycle inventory (LCI) for the two buildings. Multi-functional processes, such as recycled material, was handled by system expansion and crediting for substitution of production of primary materials. As a comparative LCA, the reference flows that are identical in both buildings can be excluded from the study. In this case study, the only material reference flows that are excluded are the technical installations. This is because data on the technical installations in the building was not available. However, the installations are likely to be identical and exclusion is, therefore, considered acceptable. The system boundaries for the LCA are indicated in Fig. 1 and include all life-cycle stages based on the European Standard EN15978 [33].

The unit processes in the foreground system shown in Fig. 1 are based on primary data from Veidekke. The foreground unit processes are specific to the Concrete and the CLT building, such as the building constructions, the electricity during construction and use of the building in terms of replacements, electricity and district heating. The electricity and heat generation processes are placed in the foreground system as these are modelled based on primary data from 2018 and future projections on the energy grid

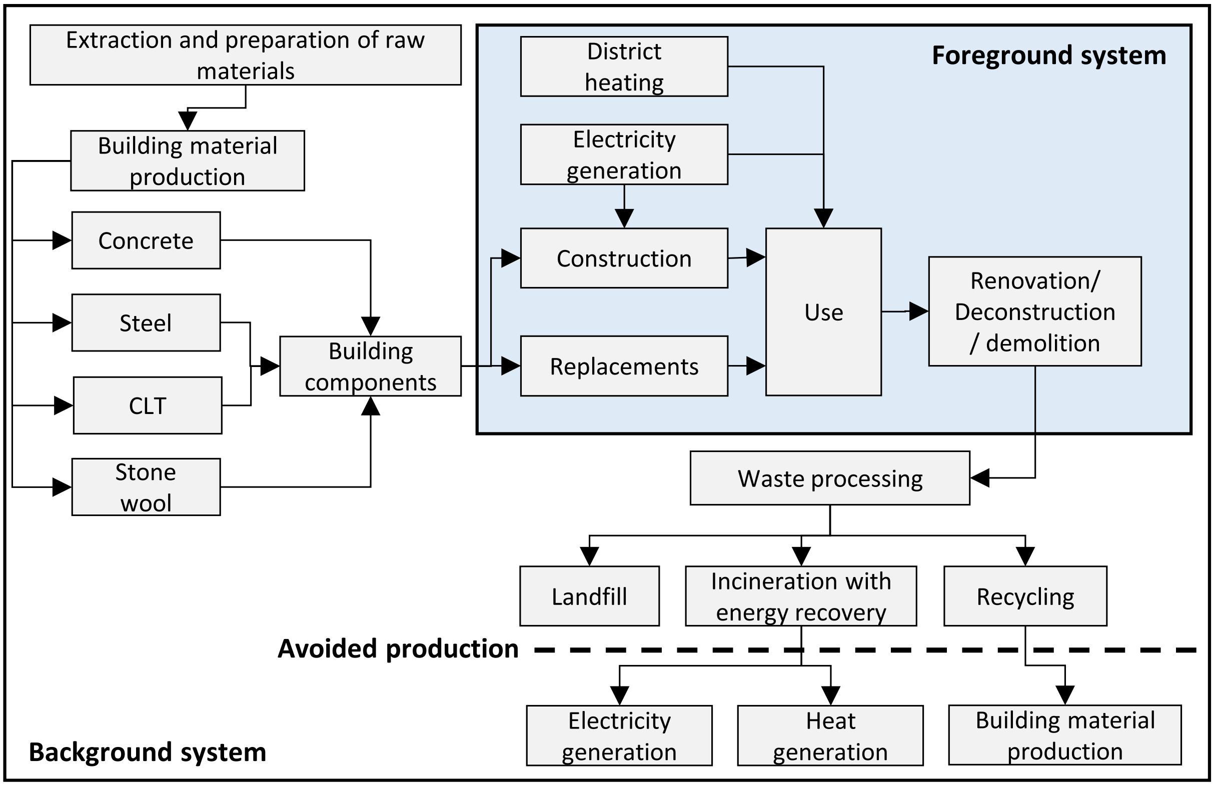

Fig. 1. System boundaries used in the LCA for the CLT and the Concrete building.

mix for 2035 and 2050 from the Danish Energy Agency [34,35] (see SM 1 Table S2 and Table S3 for details on the grid mixes used). Unit processes used in the background system are not specific to the Concrete and the CLT building. Here, all background data were based on ecoinvent v3.5 [36,37] using the ecoinvent consequential database. For example, primary data on manufacturing of building materials was not available. Therefore, we used relevant representative manufacturing processes from the ecoinvent v3.5 database to model the building material manufacturing (see SM 1 Section S4 for considerations about the representativeness of background unit processes). The ecoinvent consequential database deals with multi-functionality via substitution. The substituted processes are intended to reflect the consequences of small-scale, long-term decisions, by taking into account the constraints that are applicable at this scale and time horizon [36]. The ecoinvent consequential database is developed to correspond with the decision context Situation B and is the recommended approach by the ecoinvent Centre for consequential LCA modelling [36]. The product systems were modelled using SimaPro version 9.0.0.35 [38]. A full overview of the modelled production systems and the unit processes used for modelling the foreground system is given in SM 2

2.2.2. Life cycle inventory

The LCI was modelled per life-cycle stage. The LCI was modelled for intervals of 5 years from 0 to 100 years in order to show temporal development in potential impacts during the assessment period.

2.2.2.1. Product stage. Data on the amount of materials for the CLT and Concrete building was provided by Veidekke. The bill of materials provided by Veidekke was not fully complete for the two buildings. Thus, analysis of IFC models of the buildings in Revit was done to determine material geometries. Veidekke were able to provide Environmental Product Declarations (EPDs) on the majority of the materials. In this study, the LCA is modelled as a consequential LCA, hence marginal processes and not average processes are used. Therefore, EPDs, based on average data was not used. However, the EPDs were used to obtain information about specific material properties such as densities and thicknesses, which could be coupled with the material geometries to estimate the mass of different materials used in the two buildings. For wood material processes, it was important to determine the specific mass and density of the different wood materials to ensure that biogenic carbon is correctly accounted for in the LCA (see SM 1 Section S3.2.2 for details). Mass quantities for the most important material flows for the CLT and Concrete building are shown in Table 1.

Specific material quantities and ecoinvent unit processes used for modelling for the different building parts (e.g. roof, slab, external walls, etc.) are given in SM 2. The LCI in SM 2 for the two buildings has been divided into different building categories with subsections. This is a hierarchical division with Main groups at the top level, Building components at the next level and Constructions at the bottom level. Each Construction is modelled with different types of specific building materials.

2.2.2.2. Construction stage. The lifespan of each building was modelled as 100 years. The 100 years is set as a functional average lifespan on basis of the average lifetime for different types of buildings according Aagaard et al. (2013). CLT is a relatively new material, thus the lifespan of a CLT building has generally not yet been defined. However, a Swedish manufacture of CLT elements, Stora Enso, states that: “*With the right building physics construction methods, there is no limit to lifetime*” (Enso, 2013). Thereby, the lifespan of the CLT is defined as the same as for the Concrete building. The energy use for construction was not provided by Veidekke. Thus, energy use during construction was based on previous studies

Table 1
Quantities of the main materials used in the CLT and the Concrete building.

Most important materials	CLT building [tons]	Concrete building [tons]	CLT building [kg/m^2]	Concrete building [kg/m^2]
Wood	189.0	117.0	40.5	37.2
CLT	690.0	–	148.0	–
Concrete	2,910.0	4,320.0	624.0	1370.0
Steel	0.7	11.8	0.2	3.8
Gypsum board	467.0	51.8	100.0	16.4
Mineral wool	136.0	39.8	29.1	12.7

[7,40]. The energy used for construction was modelled as based on electricity. Table 2 indicate the energy use for construction of the CLT and Concrete building. Further details are provided in SM 1 Section S3.2.3

There will always be a waste of materials during construction and renovation of building. For instance, because materials are damaged during handling or because more material than what is actually needed is being delivered to the construction site. Thus, a waste share of the materials should be added to the quantity of the materials needed for the buildings. Material waste shares were estimated based on Petersen et al. [42]. Waste shares were not considered for prefabricated elements such as CLT elements and bathrooms as these are delivered as complete building modules. The applied waste shares for each building component is given in SM 2.

2.2.2.3. Use stage. During the use stage, material replacements and operational electricity and heat use are included in the LCA (see Fig. 1). According to DS/EN 15978:2012 [42], the operational energy includes all the building related energy consumption associated with integrated technical systems in the building. Veidekke provided information on the annual electricity and heat consumption for the two buildings, excluding the unheated basement. For electricity, the figure provided by Veidekke also include electricity use for household appliances and the like. Out of the total electricity consumption, we assigned 14% to the integrated technical systems based on the study by Rasmussen and Johannsen [44]. Table 3 show the estimated annual electricity and heat consumption per heated m^2 for the CLT and Concrete building. The electricity and heat consumption is supplied by the modelled Danish energy grid mix as presented in SM 1 Section S3.2.1.

Material replacements were modelled in the LCI based on the Estimated Service Lifetime (ESL) of building constructions and materials. The ESLs were based on estimations by the Danish Building Research Institute [39]. The ESLs are modelled according to the average functional service life [39]. The used ESLs for the different building constructions and materials can be found in SM 2. Reabsorption and uptake of CO_2 in the concrete as a result of the internal carbonation was modelled using the method described by Pade and Guimaraes [44]. Carbonation was modelled to occur during the building life-time. After building demolition, the concrete is assumed to be crushed into aggregate with the intention to replace natural gravel in new concrete production or as filling in other applications, such as road construction [10,44]. Based on Skullestad et al. [10], the aggregate are assumed to be exposed to air for four months before being used. Carbonation during the four month period is accounted and included as part of the EoL stage. For the aggregate, we assume a particle size of 10 mm and a surface area of 0.5 m^2/kg based on [45].

Table 2
Construction energy for the two buildings. The construction energy was calculated for structures in the external walls, internal walls and slab.

Component	CLT building	Concrete building
External walls	CLT elements: 3.4 MJ/m^2 wall	Steel columns: 4.5 MJ/m^2 wall
Internal walls	CLT elements: 3.4 MJ/m^2 wall	Cast in concrete walls: 17 MJ/m^2 wallSteel stud walls: 1 MJ/m^2 wall
Slab	CLT elements: 3.4 MJ/m^2 slab	Cast in concrete slab: 15 MJ/m^2 slab
Total per m^2 floor area	11.6 MJ/m^2	29.3 MJ/m^2

Table 3
Electricity and heat consumption for the two buildings.

	District heating [kWh/m^2/year]	Electricity [kWh/m^2/year]
Concrete building	63.9	4.9
CLT building	49.9	4.9

2.2.2.4. End of life stage. At the EoL stage, waste treatments for all the materials needs to be determined to select the right ecoinvent processes. The waste treatment share (i.e. recycling, incineration or landfilling) for all materials was based on Danish waste statistics for 2017 [46] except for expanded polystyrene (EPS) where treatment share was based on an EPD [47]. See SM 2 for an overview of the modelled waste treatment share and ecoinvent unit processes used for modeling the waste treatment of materials used in the two buildings.

2.2.3. Life cycle impact assessment

The LCIA methodology ReCiPe 2016 v1.1 Midpoint (H) with global normalization references from 2010 was used. In this study, two scenarios were modelled. A Base scenario was calculated using the standard ReCiPe 2016 LCIA methodology. A second Biogenic carbon scenario was defined where a GWP_{bio} factor was estimated to account for effects of temporary storage of biogenic carbon as timber in the buildings.

The GWP_{bio} factor was based on the method by Guest et al. [27]. The GWP_{bio} factor was estimated as a function of the storage period of the different wooden materials used in the two buildings, the rotation period of timber where the wooden materials are sourced from, and the time horizon over which GWP is assessed. By accounting for this, the GWP_{bio} takes into account that a net sequestration of carbon will occur if biogenic materials is both stored in the building and in new trees that are being planted (i.e. if storage period is long and rotation period is short). Thus, the carbon balance becomes net-negative and not zero. On the other hand if the storage period is short and the rotation period is long, then GWP_{bio} becomes positive, indicating an overall increase in carbon emissions [27]. The factors used for estimating the GWP_{bio} factor are described in SM 1 Section S2 Carbon sequestration and calculations are provided in SM 2. It should be noticed that the GWP_{bio} factor is only applicable to flows related to the building and should not be applied to biogenic carbon flows related to energy use during building operation. This is because the applied GWP_{bio} factor, is only valid for biogenic carbon that is stored over a longer period of time [27], as with the wood-based materials that is used as part of the building construction.

Previous studies have shown that CLT generally has a lower global warming impact compared to concrete [7,10]. However, a key question is then if the available forest area is sufficient for supplying a potentially increased use of CLT. This is especially relevant as the construction of new building floor area is expected to grow by more than 230 billion m^2 in 2060 [48]. If this area is to be constructed predominantly using CLT, then it is expected to create a large additional demand for timber. Therefore, using the LCI model described in Section 2.2.2, we estimate the m^2 transformation of forest needed for the CLT and the Concrete building per m^2 build. We further scale this to match the expected additional construction in 2060 (i.e. 230 billion m^2) and relate this to the global available forest area in 2020 which is estimated to be ca. 40 million km^2 [49]. This LCA only includes the structural system for the two mid-rise buildings. Thus other building components, such as the heating, ventilation, and air conditioning system and the interior design is not included. While these will induce further deforestation due to the production and maintenance, this is likely to be minor relative to the land area needed for production of the structural materials, most importantly the timber-based materials, and for the heat generation where an increasingly large share will be from bio-based materials.

3. Results

The normalized results at midpoint level are presented in Table 4 and show results per m^2 for the CLT and the Concrete building. The results are shown for the Base scenario. Results for global warming are also shown for the Biogenic carbon scenario, where the GWP_{bio} factor has been applied.

Table 4 shows that neither of the buildings has the lowest impact scores across all midpoint impact categories. The CLT building has a lower impact score in the majority of the impact categories with a lower score in 11 out of the 18 impact categories for both scenarios. The results for Global warming in the Biogenic carbon scenario show that potential impact for the Concrete building decrease by 1% while the impacts decrease by 36% for the CLT building when taking into account the GWP_{bio} factor. The relative difference between impact scores for the two buildings shows that the impact scores are generally similar for most impact categories. The main differences in impact scores are observed for Global warming, Fossil resource scarcity, Mineral resource scarcity, Water consumption and Marine eutrophication where the CLT building perform better. And for Ionizing radiation and Terrestrial acidification where the Concrete building perform better.

The contribution of the different life-cycle stages in the two buildings' life cycles are shown in Fig. 2. This shows that the operational energy is generally the main contributor to the total impact with some variation across impact scores. The production of building materials are also found to be important for the final impact, but generally less important than the energy use. Except for Mineral resource scarcity, Human carcinogenic toxicity, Water consumption, Global warming Base scenario and Fossil resource scarcity where impacts pertaining to the production of building materials exceed impacts related to generation of heat and electricity during building operation.

3.1. Global warming impact over building life-cycle

Fig. 3 shows the development of the characterized results for Global warming for the two buildings for the Base and the Biogenic carbon scenario during the LCA's study period of 100 years. The figure shows that the main differences in Global warming impact is due to embodied CO_2-eq pertaining to the building materials (incl. EoL treatment and carbonation) used for the two buildings. For the Concrete building, materials (incl. EoL treatment and carbonation) account for 62% and 58% in the Base and Biogenic carbon scenario, respectively. For the CLT building, materials account for 2% and −54% of the total impact on Global warming for the Base and Biogenic carbon scenario, respectively. The negative impact scores for CLT in the Biogenic carbon scenario is due to the inclusion of the GWP_{bio} factor, which increase the potential climate benefits from temporary sequestration of biogenic carbon in the CLT building. And also due to the consequential LCI-modelling approach where energy generation and recycling during EoL is credited by avoided production and, thus, avoided impacts.

Fig. 3 also show the development in the electricity and heat grid mix. The out-phasing of fossil energy sources and the transition towards more renewable energy sources is indicated by the reduction in annual Global warming impact during the 100 year period. Indeed, the Global warming impact from heat and electricity use per year reduces by ≈ 80% for both the CLT and the Concrete building over this period. The largest decrease in the impact is due to changes in the district heating grid mix. Where the use of hard coal, which accounts for 42% of the total impact in 2018, is completely phased out in 2035. The uptake of CO_2 in concrete via carbonation occurs during the entire building lifetime and after

Table 4
Normalized midpoint level impact scores for the CLT building and the Concrete building.

Impact category	Impact category abbreviation	CLT building	Concrete building	Relative difference (CLT/Concrete)
Fine particulate matter formation	PM	0.11	0.11	1.01
Fossil resource scarcity	Fos.rs	0.15	0.22	0.69
Freshwater ecotoxicity	FrW.ecotox	43.06	41.11	1.05
Freshwater eutrophication	FrW.eut	0.92	1.10	0.83
Global warming, Base scenario	GW base	5.69×10^{-2}	1.13×10^{-1}	0.50
Global warming, Biogenic carbon scenario	GW bio	3.61×10^{-2}	1.12×10^{-1}	0.32
Human carcinogenic toxicity	HTcarc	29.61	36.07	0.82
Human non-carcinogenic toxicity	HTncarc	11.73	12.36	0.95
Ionizing radiation	IR	2.17×10^{-2}	1.64×10^{-2}	1.32
Land use	LU	0.20	0.18	1.06
Marine ecotoxicity	Mar.ecotox	71.34	69.17	1.03
Marine eutrophication	Mar.eut	8.25×10^{-3}	1.06×10^{-2}	0.78
Mineral resource scarcity	Min.rs	-3.18×10^{-5}	9.62×10^{-5}	−0.33
Ozone formation, Human health	Ozone.HH	0.19	0.20	0.97
Ozone formation, Terrestrial ecosystems	Ozone.eco	0.22	0.23	0.96
Stratospheric ozone depletion	OD	5.78×10^{-2}	5.69×10^{-2}	1.02
Terrestrial acidification	Acid	0.38	0.34	1.13
Terrestrial ecotoxicity	Terr.ecotox	3.27	3.92	0.83
Water consumption	Water	2.96×10^{-2}	4.31×10^{-2}	0.69

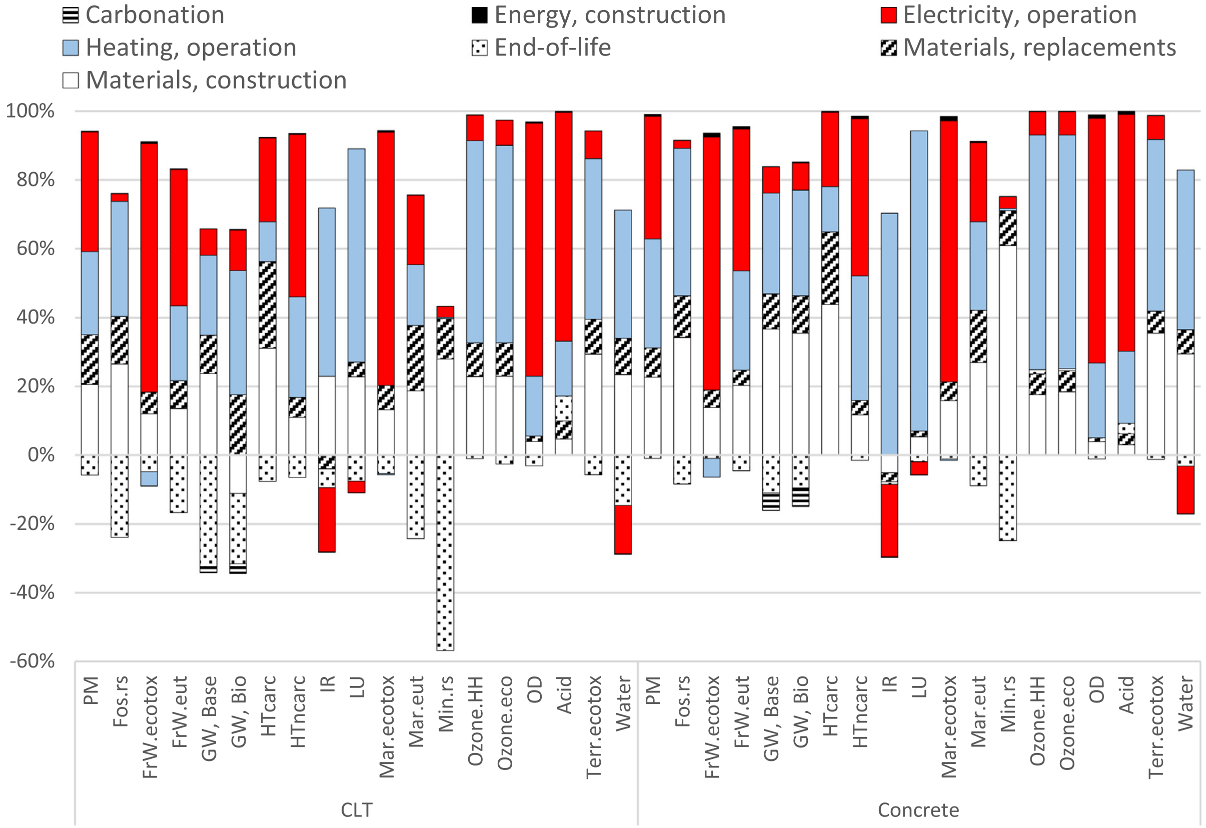

Fig. 2. Contribution analysis for the CLT and Concrete building, indicating the contribution of the major life-cycle stages to the total potential impact. Impact category abbreviations are presented in Table 4.

demolition. About 60 and 30 tonnes of CO_2 are taken up during the building lifetime for the Concrete and CLT building, respectively. An additional 155 and 94 tonnes of CO_2 for the Concrete and CLT building, respectively, are taken up during the EoL treatment of the concrete.

3.2. Forest transformation

Table 5 shows the comparison of the forest area needed for the CLT and the Concrete building based on the modelled LCI. Overall, the total forest area transformed across the full life-cycle of the two buildings differs by a factor 1.1, with CLT requiring transformation of the largest forest area with 47.5 m^2 per m^2 building area constructed. However, the majority of the forest transformation is a result of the energy use during building operation. Here, the factor variation is 0.8 with the Concrete building having a larger impact than the CLT building. The largest difference between the CLT and the Concrete building is observed for the materials where the CLT building's impact is a factor 7.1 larger than the Concrete building. This is due to the larger use of wooden materials in the CLT building. When comparing the estimated forest transformation of the two buildings with the global forest area in 2020 [49], fulfillment of future building construction area using CLT or Concrete will require about 3% or 2.8% of global forest area, respectively. However, only 0.8% and 0.1% stem from the building materials for the CLT and the Concrete building, respectively. Instead, the majority of the forest area needed pertain to the energy requirements, which is dependent on the heat and electricity grid mix, and independent of the building materials used in future construction.

4. Discussion

4.1. Environmental performance of case buildings

While the CLT building has a lower environmental impact than the Concrete building in the majority of impact categories, we cannot conclude if the CLT building has the best environmental performance. Because the impact categories where the Concrete building has the lowest impact scores might be the most important. From the results of the contribution analysis (see Fig. 2), it is illustrated that CLT as a material has a negative Global warming contribution for the Base scenario and for the Biogenic carbon scenario. Opposite, the structural materials of concrete and steel (reinforcement) in the Concrete building have a large contribution to the Global warming impact score. This indicates that, climate wise, CLT is preferable to concrete and steel as the structural building material. This is in line with previous studies (Žigart et al., 2018). These results, include the additional environmental impacts associated with the extra requirements for CLTs buildings, such as use of gypsum boards and concrete screed to ensure fire safety and reduce noise transportation, respectively. Additionally, as CLT is still a relatively new building material, it is likely that new technological solutions for fire protection and noise transportation will be developed, with a lower environmental impact. This will strengthen the environmental argument for choosing CLT as the structural material in midrise buildings.

For the assessment of additional forest transformation needed for CLT compared to concrete. We found that, while there is a larger forest need for production of wood-based materials such as CLT, the overall difference is relatively small as the main driver for forest transformation is the energy use during building operation. We tried to put the forest transformation into perspective

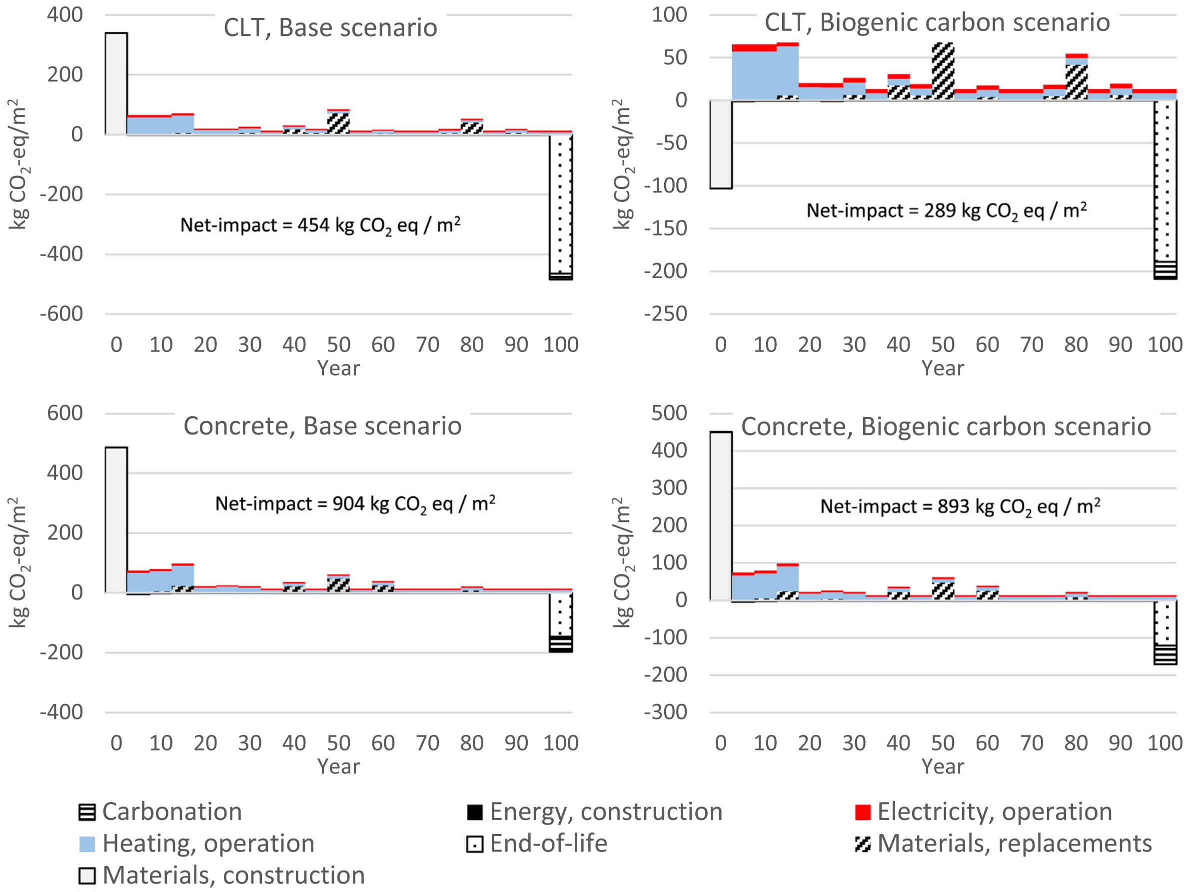

Fig. 3. Characterized results for Global warming at midpoint level expressed as kg CO$_2$-eq per m^2. Results are shown for both the CLT and the Concrete building and for the Base and the Biogenic carbon scenario. The figures show the timing of the CO$_2$-eq emissions during the buildings' life-cycle and the contribution of the major life-cycle stages to the total potential impact.

Table 5
Direct forest transformation for the Concrete and CLT building per m^2 building floor area and scaled to match the future building construction in 2060. The table also shows a comparison with the global forest area in 2020 and the share of global forest area needed for future building construction in 2060 based on the required forest transformation estimated for the CLT and the Concrete building.

	Forest transformation per m^2 building area [m^2/m^2]		Total Forest transformation for fulfilling future new build demand [km^2]		Factor variation (CLT/Concrete)	Percent share of available forest area (i.e. 4.06 × 10^7 km^2) needed for new buildings [%]	
	Concrete building	CLT building	Concrete building	CLT building		Concrete building	CLT building
Materials	1.7	11.9	4.37 × 10^4	3.10 × 10^5	7.1	0.1%	0.8%
Energy	42.2	35.6	1.10 × 10^6	9.26 × 10^5	0.8	2.7%	2.3%
Total	43.9	47.5	1.14 × 10^6	1.24 × 10^6	1.1	2.8%	3.0%

by relating to global forest area. We see that around 3% of global forest area is needed for construction of the future building floor area in 2060 if this is to be fulfilled by either the CLT or the Concrete building assessed in this study. Again, this is mainly driven by the energy use during operation, which is independent of the materials used for constructing the buildings. Nevertheless, a requirement of about 3 % of global forest area is a substantial share given that deforestation is a concern [49,50].

Hence, it is essential that new forest is planted and that forestry is sustainably managed in order to satisfy a large future demand for biomass for energy generation and/or building construction. Here, it should be noted, that this study and the LCA for the CLT and the Concrete building is modelled for Scandinavian conditions and for mid-rise buildings of 5–8 stories. Thus, simply upscaling to 230 billion m^2 will provide rather crude and uncertain results due to differences in climatic variations, selected building typology and technology as well as general uncertainty related to predicting the future. Still, the results provide a valid indication of the potential consequences related to future construction and it is clear that the increased use of wood-based materials for energy generation and building materials will be noteworthy and it is important to consider this now and start planning how to fulfill the future demand in a sustainable manner. Our results indicate that the main driver of deforestation is likely to be the increased use of bioenergy. Thus, we recommend placing a greater focus on modelling and forecasting this driver of deforestation and investigate options for reducing the extent and impact of future deforestation as a result of increased reliance on bioenergy.

4.2. Including effects of temporary biogenic carbon storage

Only by including and accounting for the biogenic carbon storage in the building via the GWP_{bio} factor, the performance of the CLT building compared to the Concrete building was improved by 34% in terms of impact score per m^2 for Global warming. This clearly shows that the inclusion of biogenic carbon and temporary carbon storage can substantially affect LCA results for buildings and potential decisions on the construction of buildings. Thus, it is important to consider the inclusion of biogenic carbon and how to model this.

The predominant approach to modelling biogenic carbon is to treat the biogenic carbon as neutral under the assumption that the biogenic carbon will follow a "short" carbon-cycle that, in the long-term, will not have a noteworthy effect on the climate. Thus, input of 1 kg biogenic carbon to the product system is assigned an impact of -1 kg CO_2-eq while the output of the biogenic carbon during EoL is assigned an impact of 1 kg CO_2-eq, thereby cancelling out the input. This is, for instance, done in the European Standard on environmental product declarations for evaluating sustainability of construction works [51].

However, the study by Guest et al. (2013) shows that the use of biogenic carbon is not necessarily neutral and the climate impact depends on the use of the biogenic carbon in the assessed product system as well as the management by the supplier of the materials containing biogenic carbon, such as forest plantations. Our results show a factor 1.7 difference between the Base scenario and the Biogenic carbon scenario for the total Global warming impact of the CLT building, where the only difference is how biogenic carbon is modelled. While the change would not lead to changed conclusions in this study, it is plausible that a factor 1.7 difference could lead to a difference in conclusions in other studies. Thus, while it is much simpler to apply a $-1/+1$ kg CO_2-eq for inputs and output of biogenic carbon, this does not take into account the potential positive or negative effects of the temporary storage of the biogenic carbon in the building stock. Indeed, our results show that it is important to use more complex methods for characterization of climate impacts from biogenic carbon if this is temporarily stored in e.g. buildings. Such as the approach by Guest et al. (2013), that take into account, time horizon, storage period, and rotation period should be applied to provide a more realistic representation of the global warming impact associated with the studied building.

4.3. Mitigating climate change by use of wood in buildings

The results of this study further underline the potential climate benefits of using wood-based materials, such as CLT, in buildings and as part of the structural system. While, we cannot unambiguously conclude that the CLT building performs environmentally better than the Concrete building, this is the case for Global warming. Thus, increased use of CLT in construction of new buildings appears to be a good solution for reducing the greenhouse gas emissions per constructed m^2. In particular in the short to medium term during the building's life-time where the sequestration of wood in the building contributes to removal of atmospheric CO_2, that will not be emitted before the wood material is incinerated (or otherwise decomposed) after the building is demolished. The temporary carbon storage in the building stock can contribute to reducing net carbon emissions to slow down climate change [52] to allow more time for creating a sustainable transformation of society that can realize long-term global commitments on climate change, such as the Paris agreement. However, it should be noted that there will be a lower carbon uptake from tree growth in the period from the first tree was cut down until a new tree of similar size has grown. This is because the growth rate of trees increase with age (or size) up to a certain point after which growth rate starts to decline again [53]. It is, therefore, important to consider these carbon dynamics in the short- to medium term in order to gain an overall climate benefit from the use of timber in construction of buildings.

4.4. Challenges for including biogenic carbon

The inclusion of biogenic carbon in LCA is important to better reflect the overall carbon balance of the evaluated systems as the potential removal and storage of carbon, independent of the emission source, might be important in the short term. Not least, in light of climate change where the need for action is urgent [54]. Our results indicate that if the storage period in the building is sufficiently long, then the use of biogenic carbon result in net-negative carbon emissions during the building life-time because biogenic carbon is stored in the building and additional carbon is being taken up during new forest growth. Thus, inclusion of biogenic carbon in the LCA provides decision-makers with new valuable information that might be important with regards to decisions on different solution alternatives. However, the inclusion of biogenic carbon in assessment, such as LCA, also introduce a number of challenges that must be addressed [26]. A key challenges is how to model and treat biogenic carbon? Different options for including biogenic carbon exists and different standards provide different recommendation on how to include and account for biogenic carbon [26,52]. There is a lack of harmonization on this among standards and often practitioners are left with deciding which approach to take on their own. The consequence is a lack of comparability across standards and studies on e.g. timber-based buildings. This undermines the trust in LCA results for timber-based buildings and LCA in general due to the perceived arbitrariness of the results depending on the standard or approach selected by the practitioner. A harmonization process involving the standardization organizations and key actors within development of methods for biogenic carbon accounting could be a way forward. Similar harmonization processes have been performed on e.g. chemical impact assessment where model developers went through a harmonization process to come up with a new consensus model for modelling chemical impacts on humans and ecosystems, which is now endorsed by the European Commission [55,56]. Here it is also important to consider coping and boundary setting in LCAs with biogenic carbon and how to model the recycling and potential allocation of impacts among product systems. This issue has already been highlighted by Garcia and colleagues [26], which evaluated different approaches for modelling the recycling of wood-based products and the allocation of carbon impacts among life-cycles in a cascading system of life-cycles. It was evident that different approaches provide vastly different results, but also that operationalization of some approaches was unlikely due to the increased need for information about forest management and e.g. building EoL.

This leads to another key challenge, which is about the need for additional information for modelling biogenic carbon in a building LCA and the inherent uncertainty. The level of LCI detail for different processes will depend on the scale of the LCA such as product level, components, building or sector level). On bio-based product or component level, it is relevant to require that e.g. producers obtain information about the forest management from their suppliers. However, the potential climate impact will also depend on the subsequent use of the bio-based material. For instance, how long time will it be stored in the building and how will it be treated during EoL? Such information about the lifetime of the material and the waste management system at the time of demolition is highly uncertain. Furthermore, the material or component producer does not necessarily know where, when and how their products will be used. This makes it very difficult for the producers to adequately account for biogenic carbon across the full product lifecycle. Similar issues are observed for assessment at building or sector scale. Here, information about the type of materials might be known but the raw material suppliers are located further upstream in the supply chain and are likely not known by the LCA practitioner for a building LCA. Thus, information about forestry management is likely to be based on assumptions and thereby increase uncertainty of the result. The uncertainty about building lifetime and EoL after building demolition is also an issue on this scale. In fact, the potential future ability to better recycle bio-based materials or introduction of carbon capture and storage on bioenergy production (BECCS) as part of wood incineration might mean that the biogenic carbon will not be released after the building is demolished. Instead, the biogenic carbon can be transferred to another life-cycle and this recirculation of the biogenic carbon can continue for a very long period of time. In such case, the question is whether the biogenic carbon will actually be emitted due to future recirculation options and then how large a fraction should be allocated to the original production system when the carbon is eventually emitted after cascading through multiple life-cycles. The uncertainty pertaining to forecasting the future, means that there are no simple answers to these challenges. However, more and more studies evaluating the effects of different modelling approaches and future scenarios with regards to use and temporary storage of biogenic carbon are emerging [26,52,57]. This is a necessary first step to understand the sensitivity of the result to these different value based choices. We recommend that the next step is to start a harmonization process with regards to the choices to which results are most sensitive and setup procedures for dealing with these choices in a standardized manner. Here, an increased use of scenario analysis for modelling e.g. future waste management treatment might be relevant to provide a range of possible results rather than providing a single result [52].

5. Conclusion

This study investigated the potential environmental consequences of selecting to construct a concrete building or a CLT building, with a special focus on Global warming and the handling of biogenic carbon. Thus, a comparative LCA was conducted to evaluate the environmental performance of the two buildings. It was found that the CLT building has a lower environmental impact score in 11 out of 18 the impact categories. For Global warming, the total characterized impact was found to be 903.7 kg CO_2-eq/m^2 and 454.2 CO_2-eq/m^2 in the Base scenario and 892.9 CO_2-eq/m^2 and 288.5 CO_2-eq/m^2 in the Biogenic carbon scenario for the Concrete building and the CLT building respectively. We evaluated the potential forest transformations required for fulfilling future projections for new building construction and found that about 3% of current global forest area would be required independent of the building material as the main driver for forest transformation was found to be the energy use during operation of the buildings. Therefore, while neither of the buildings performed best across all impact categories, the CLT building has the lowest impact scores in the majority of the impact categories. Moreover, the CLT building had a substantially lower impact for Global warming. This indicate that increased use of CLT in building construction, instead of commonly used materials, such as concrete, could help mitigate climate change.

6. Supplementary material

Further details on the two case buildings and the methods used are provided in Supplementary Material 1. A complete overview of the life cycle inventory for modelling the two buildings and calculation of GWP_{bio} and carbonation are given in Supplementary Material 2. Source data for figures used in the main manuscript are also provided in Supplementary Material 2.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.111604.

References

[1] GlobalABC. IEA and UNEP, 2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector, Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme, 2019

[2] UNFCCC, Decision 1/CP.21 Adoption of the Paris Agreement. FCCC/CP/2015/10/Add.1, (2015).

[3] G. Habert, M. Röck, K. Steininger, A. Lupísek, H. Birgisdottir, H. Desing, C. Chandrakumar, F. Pittau, A. Passer, R. Rovers, K. Slavkovic, A. Hollberg, E. Hoxha, T. Jusselme, E. Nault, K. Allacker, T. Lützkendorf, Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions, Build. Cities. 1 (2020) 429–452. doi:10.5334/bc.47

[4] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: A critical review, Renew. Sustain. Energy Rev. 67 (2017) 408–416, https://doi.org/10.1016/j.rser.2016.09.058.

[5] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, A. Thiel, Cross laminated timber (CLT): overview and development, Eur. J. Wood Wood Prod. 74 (3) (2016) 331–351, https://doi.org/10.1007/s00107-015-0999-5.

[6] Ambrose Dodoo, Leif Gustavsson, Roger Sathre, Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems, Energy Build. 82 (2014) 194–210, https://doi.org/10.1016/j.enbuild.2014.06.034.

[7] Ying Liu, Haibo Guo, Cheng Sun, Wen-Shao Chang, Assessing cross laminated timber (CLT) as an alternative material for mid-rise residential buildings in cold regions in China-A life-cycle assessment approach, Sustain. 8 (10) (2016) 1047, https://doi.org/10.3390/su8101047.

[8] Nicola Lolli, Selamawit Mamo Fufa, Marianne Kjendseth Wiik, An assessment of greenhouse gas emissions from CLT and glulam in two residential nearly zero energy buildings, Wood, Mater. Sci. Eng. 14 (5) (2019) 342–354, https://doi.org/10.1080/17480272.2019.1655792.

[9] Francesca Pierobon, Monica Huang, Kathrina Simonen, Indroneil Ganguly, Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest, J. Build. Eng. 26 (2019) 100862, https://doi.org/10.1016/j.jobe.2019.100862.

[10] Julie Lyslo Skullestad, Rolf André Bohne, Jardar Lohne, High-rise Timber Buildings as a Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives, Energy Procedia 96 (2016) 112–123, https://doi.org/10.1016/j.egypro.2016.09.112.

[11] Maja Žigart, Rebeka Kovačič Lukman, Miroslav Premrov, Vesna Žegarac Leskovar, Environmental impact assessment of building envelope components for low-rise buildings, Energy. 163 (2018) 501–512, https://doi.org/10.1016/j.energy.2018.08.149.

[12] D. Peñaloza, M. Erlandsson, A. Falk, Exploring the climate impact effects of increased use of bio-based materials in buildings, Constr. Build. Mater. 125 (2016) 219–226, https://doi.org/10.1016/j.conbuildmat.2016.08.041.

[13] I. Lukić, M. Premrov, Ž.V. Leskovar, A. Passer, Assessment of the environmental impact of timber and its potential to mitigate embodied GHG emissions, IOP Conf. Ser. Earth Environ. Sci. 588 (2020), https://doi.org/10.1088/1755-1315/588/2/022068 022068.

[14] Jim Hart, Bernardino D'Amico, Francesco Pomponi, Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures, J. Ind. Ecol. 25 (2) (2021) 403–418, https://doi.org/10.1111/jiec.v25.210.1111/jiec.13139.

[15] Alexis Laurent, Stig I. Olsen, Michael Z. Hauschild, Limitations of carbon footprint as indicator of environmental sustainability, Environ. Sci. Technol. 46 (7) (2012) 4100–4108, https://doi.org/10.1021/es204163f.

[16] Y. Lechón, C. de la Rúa, J.I. Lechón, Environmental footprint and life cycle costing of a family house built on CLT structure. Analysis of hotspots and improvement measures, J. Build. Eng. 39 (2021) 102239, https://doi.org/10.1016/j.jobe.2021.102239.

[17] Rizal Taufiq Fauzi, Patrick Lavoie, Audrey Tanguy, Ben Amor, Life cycle assessment and life cycle costing of multistorey building: Attributional and consequential perspectives, Build. Environ. 197 (2021) 107836, https://doi.org/10.1016/j.buildenv.2021.107836.

[18] E.J. Forster, J.R. Healey, C.C. Dymond, G. Newman, G. Davies, D. Styles, Linking construction timber carbon storage with land use and forestry management practices, IOP Conf. Ser. Earth Environ. Sci. 323 (2019), https://doi.org/10.1088/1755-1315/323/1/012142 012142.

[19] Massimo Pizzol, Marco Scotti, Identifying marginal supplying countries of wood products via trade network analysis, Int. J. Life Cycle Assess. 22 (7) (2017) 1146–1158, https://doi.org/10.1007/s11367-016-1222-6.

[20] Michele De Rosa, Massimo Pizzol, Jannick Schmidt, How methodological choices affect LCA climate impact results: the case of structural timber, Int. J. Life Cycle Assess. 23 (1) (2018) 147–158, https://doi.org/10.1007/s11367-017-1312-0.

[21] Prakash Nepal, Kenneth E. Skog, David B. McKeever, Richard D. Bergman, Karen L. Abt, Robert C. Abt, Carbon Mitigation Impacts of Increased Softwood Lumber and Structural Panel Use for Nonresidential Construction in the United States, For. Prod. J. 66 (1-2) (2016) 77–87, https://doi.org/10.13073/FPJ-D-15-00019.

[22] Gustav Sandin, Greg M. Peters, Magdalena Svanström, Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling, Int. J. Life Cycle Assess. 19 (4) (2014) 723–731, https://doi.org/10.1007/s11367-013-0686-x.

[23] S. Cordier, F. Robichaud, P. Blanchet, B. Amor, Enhancing consistency in consequential life cycle inventory through material flow analysis, IOP Conf. Ser. Earth Environ. Sci. 323 (2019), https://doi.org/10.1088/1755-1315/323/1/012056 012056.

[24] Ali Tighnavard Balasbaneh, Willy Sher, Comparative sustainability evaluation of two engineered wood-based construction materials: Life cycle analysis of CLT versus GLT, Build. Environ. 204 (2021) 108112, https://doi.org/10.1016/j.buildenv.2021.108112.

[25] Kai Lan, Stephen S Kelley, Prakash Nepal, Yuan Yao, Dynamic life cycle carbon and energy analysis for cross-laminated timber in the Southeastern United States, Environ. Res. Lett. 15 (12) (2020) 124036, https://doi.org/10.1088/1748-9326/abc5e6.

[26] Rita Garcia, Rodrigo A.F. Alvarenga, Sophie Huysveld, Jo Dewulf, Karen Allacker, Accounting for biogenic carbon and end-of-life allocation in life cycle assessment of multi-output wood cascade systems, J. Clean. Prod. 275 (2020) 122795, https://doi.org/10.1016/j.jclepro.2020.122795.

[27] Geoffrey Guest, Francesco Cherubini, Anders H. Strømman, Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life, J. Ind. Ecol. 17 (1) (2013) 20–30, https://doi.org/10.1111/jiec.2013.17.issue-110.1111/j.1530-9290.2012.00507.x.

[28] Marieke Head, Pierre Bernier, Annie Levasseur, Robert Beauregard, Manuele Margni, Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment, J. Clean. Prod. 213 (2019) 289–299, https://doi.org/10.1016/j.jclepro.2018.12.122.

[29] Annie Levasseur, Pascal Lesage, Manuele Margni, Réjean Samson, Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment, J. Ind. Ecol. 17 (1) (2013) 117–128, https://doi.org/10.1111/jiec.2013.17.issue-110.1111/j.1530-9290.2012.00503.x.

[30] M. Head, M. Magnan, W.A. Kurz, A. Levasseur, R. Beauregard, M. Margni, Temporally-differentiated biogenic carbon accounting of wood building product life cycles, SN Appl. Sci. 3 (2021) 62, https://doi.org/10.1007/s42452-020-03979-2.

[31] EC-JRC, General guide for life cycle assessment—detailed guidance. ILCD Handbook—International Reference Life Cycle Data System, European Commission - Joint Research Centre, Luxembourg, 2010

[32] A. Bjørn, A. Laurent, M. Owsianiak, S.I. Olsen, Goal Definition, in: M. Hauschild, R.K. Rosenbaum, S.I. Olsen (Eds.), Life Cycle Assess. - Theory Pract., Springer International Publishing, 2018. doi:978-3-319-56474-6

[33] European Standard, Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method. EN 15978:2011, EUROPEAN COMMITTEE FOR STANDARDIZATION, 2011

[34] Danish Energy Agency, Energiscenarier frem mod 2020, 2035 og 2050 (Energy scenarios towards 2020, 2035, and 2050), Copenhagen, 2014. https://ens.dk/sites/ens.dk/files/EnergiKlimapolitik/energiscenarier_-_analyse_2014_web.pdf

[35] Danish Energy Agency, Energistatistik 2018, Copenhagen, 2019. https://ens.dk/sites/ens.dk/files/Analyser/energistatistik_2018.pdf.

[36] B.P. Weidema, C. Bauer, R. Hischier, C. Mutel, T. Nemecek, J. Reinhard, C.O. Vadenbo, G. Wernet, Overview and methodology, Data quality guideline for the ecoinvent database version 3. Ecoinvent Report 1(v3), St. Gallen (2013), www.ecoinvent.org.

[37] Ecoinvent, Ecoinvent version 3, (2019). https://ecoinvent.org/

[38] PRé, SimaPro (2019). https://pre-sustainability.com/solutions/tools/simapro/.

[39] N.-J. Aagaard, E. Brandt, S. Aggerholm, K. Haugbølle, Levetider af bygningsdele ved vurdering af bæredygtighed og totaløkonomi, 2013. http://www.sbi.dk/byggeteknik/kvalitet/levetider-af-bygningsdele-ved-vurdering-af-baeredygtighed-og-totalokonomi-1/appendiks-f-sbi-2013-30.

[40] Raymond J Cole, Energy and greenhouse gas emissions associated with the construction of alternative structural systems, Build. Environ. 34 (3) (1998) 335–348, https://doi.org/10.1016/S0360-1323(98)00020-1.

[41] E.H. Petersen, J. Dinesen, H. Krogh, Miljødata for bygningsdele, Statens Byggeforskningsinstitut (SBi), By og Byg, Copenhagen, 2001.

[42] Dansk Standard, DS/EN 15978: Bæredygtighed inden for byggeri og anlæg – Vurdering af bygningers miljømæssige kvalitet – Beregningsmetode, 2012.

[43] M.K. Rasmussen, K.B. Johannsen, Kvotehuset. Midtvejsevaluering, 2016.

[44] Claus Pade, Maria Guimaraes, The CO2 uptake of concrete in a 100 year perspective, Cem. Concr. Res. 37 (9) (2007) 1348–1356, https://doi.org/10.1016/j.cemconres.2007.06.009.

[45] K. Sobolev, M. Ferrada Gutiérrez, How Nanotechnology Can Change the Concrete World, in: Prog. Nanotechnol., John Wiley & Sons, Inc., Hoboken, NJ, USA, 2014: pp. 113–116. doi:10.1002/9780470588260.ch16.

[46] Danish EPA, Waste statistics 2017, Copenhagen, 2019. https://www.ads.mst.dk/Forms/Reports/ReportsOverview.aspx.

[47] Plastindustrien, Environmental Production Declaration (EPD) of Expanded Polystyrene (EPS) insulation, 2017. www.epddanmark.dk/media/1038/md-plastindustrien-16005-en.pdf.

[48] UN Environment and International Energy Agency, Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017, 2017. https://www.worldgbc.org/sites/default/files/UNEP 188_GABC_en (web).pdf.

[49] FAO, Global Forest Resources Assessment 2020: Main report, Food and Agriculture Organization of the United Nations, Rome, 2020. doi:10.4060/ca9825en.

[50] W. Steffen, K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, S. Sorlin, Planetary boundaries: Guiding human development on a changing planet, Science (80-.). 347 (2015) 1217. doi:10.1126/science.1259855

[51] EN, EN 15804:2012+A2:2019 'Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products,' 2019.

[52] Miguel Brandão, Annie Levasseur, Miko U.F. Kirschbaum, Bo P. Weidema, Annette L. Cowie, Susanne Vedel Jørgensen, Michael Z. Hauschild, David W. Pennington, Kirana Chomkhamsri, Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting, Int. J. Life Cycle Assess. 18 (1) (2013) 230–240, https://doi.org/10.1007/s11367-012-0451-6.

[53] Michinari Matsushita, Katsuhiko Takata, Gaku Hitsuma, Tsutomu Yagihashi, Mahoko Noguchi, Mitsue Shibata, Takashi Masaki, Emma Sayer, A novel growth model evaluating age–size effect on long-term trends in tree growth, Funct. Ecol. 29 (10) (2015) 1250–1259, https://doi.org/10.1111/fec.2015.29.issue-1010.1111/1365-2435.12416.

[54] IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2021.

[55] Ralph K. Rosenbaum, Till M. Bachmann, Lois Swirsky Gold, Mark A.J. Huijbregts, Olivier Jolliet, Ronnie Juraske, Annette Koehler, Henrik F. Larsen, Matthew MacLeod, Manuele Margni, Thomas E. McKone, Jérôme Payet, Marta Schuhmacher, Dik van de Meent, Michael Z. Hauschild, USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, Int. J. Life Cycle Assess. 13 (7) (2008) 532–546, https://doi.org/10.1007/s11367-008-0038-4.

[56] M.Z. Hauschild, M. Huijbregts, O. Jolliet, M. MacLeod, M. Margni, D. van de Meent, R.K. Rosenbaum, T.E. McKone, Building a model based on scientific consensus for Life Cycle Impact Assessment of chemicals: the search for harmony and parsimony, Environ. Sci. Technol. 42 (2008) 7032–7037. https://pubs.acs.org/doi/10.1021/es703145t.

[57] M. Fouquet, A. Levasseur, M. Margni, A. Lebert, S. Lasvaux, B. Souyri, C. Buhé, M. Woloszyn, Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment, Build. Environ. 90 (2015) 51–59, https://doi.org/10.1016/j.buildenv.2015.03.022.