Assessment of the environmental impact of timber and its potential to mitigate embodied GHG emissions

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Abstract. Currently, the world is undergoing the biggest wave of urban growth in history. To accommodate this unprecedented growth, adding more than 230 billion m² of new floor area to the global building stock by 2060 is expected. As embodied emissions are responsible for 11% of annual greenhouse gas (GHG) emissions globally, an increase in embodied emissions from new construction will put tremendous additional pressure on the natural environment. To investigate the environmental impact of timber and potential of mitigating the increase in embodied GHG emissions from new residential constructions, a life cycle assessment (LCA) is performed for the production stage of three low-energy modular buildings. The results suggested that by substituting reinforced concrete (RC) and masonry (M) with cross-laminated timber (CLT) in the building structure, 14.62% and 12.94% of emissions could be avoided on a building level, respectively. However, the substitution leads to a significant increase in land use impact. In order to get a sense of mitigation potential on the larger scale, the mitigation potential of embodied GHG emissions is investigated for an expected residential building stock new floor area growth predictions depending on the regional residential building structural material choice in the world key regions for periods from 2017 to 2060. Under the assumptions made, the preliminary results suggest that by 2060 a certain amount of emissions could be avoided if conventional structural materials were substituted with CLT, however, emissions from new floor area additions are still substantial. Moreover, global GHG mitigation potential raises new concerns and questions that need to be further investigated. In addition, the importance of considering the land use impact in the LCA studies of bio-based construction materials is highlighted.

1. Introduction

With 39% of energy-related greenhouse gas (GHG) emissions, 28% due to building operations, and 11% due to construction materials [1], the important role of the buildings and construction sector in achieving the Paris Agreement (PA) as well as the United Nations Sustainable Development Goals (SDGs) is undeniable. The world is currently experiencing the biggest wave of urban growth in human history, with half of the world’s current population living in urban areas. It is predicted that by 2060, 2/3 of the anticipated world population of 10 billion people will take up residence in cities. To accommodate this
unprecedented growth, more than 230 billion m$^2$ of new floor area, or an area equivalent to the current global building stock, is expected to be added to the global building stock by 2060 [2]. Due to the enormous additional pressure from urbanization and population growth, sustainable development cannot be achieved within the set objectives of the PA without taking into account the way buildings and cities are designed, built, and operated.

So far, considerable efforts have been made, and legislative regulatory measures have been taken to effectively increase the energy efficiency of buildings, thereby reducing energy demand and related GHG emissions. By the end of 2020, all new buildings in the European Union (EU) should be nearly Zero-Energy Buildings [3]. It is indisputable that the reduction of GHG emissions originating from operational energy use in the operation of buildings is crucial. However, if the area equivalent to New York is added to the current global building stock every month for the next 40 years, there is cause for concern about the GHG emissions associated with the materials utilized for the construction of new buildings. The importance of embodied GHG emissions becomes even clearer when one considers that, according to the Intergovernmental Panel on Climate Change (IPCC), GHG emissions should peak in 2020 and then decline rapidly to reach a net-zero globally by 2050 if global warming is to be limited below the threshold of 1.5°C of global average temperature set by the PA [4]. Given that the ratio of embodied and operational GHG emissions for new, advanced energy-efficient buildings is 1:1 [5], half of the total GHG emissions from new buildings would be neglected if the embodied emissions were overlooked, which could lead to half of the equation not being taken into account. Acknowledging both operational and embodied impacts is essential for effective decarbonization of the built environment by 2050 and for the greater chance of achieving climate change objectives.

One of the strategies identified for the reduction of the embodied GHG in the built environment is the application of low carbon$^1$ materials [6]. Wood, as a construction material, i.e., timber, from sustainably managed forests, is considered a low-carbon material [7]. However, it should be noted that the latter is not sufficient to make generalized assumptions about the superiority of timber from an environmental performance point of view, as GHG emissions are only one of many environmental indicators [8]. The role of wood in mitigating the effects of climate change is addressed in several reports, such as that of the Fourth Assessment Report of IPCC [9]. In addition, the increased use of wood products is also recognized as a potential contribution to the EU efforts to mitigate climate change from the European Commission [10].

Increased recognition of the lower GHG emissions associated with wood as a construction material has increased interest in the construction of timber buildings and the development of engineered-wood products to support construction. The increased interest is evident in the global annual production of cross-laminated timber (CLT), an engineered-wood product initially developed in Austria in the mid-1990s through a joint industry/academia research program. The global production of CLT amounted to 600,000 m$^3$ in 2013, 1 million m$^3$ in 2015, and it is estimated that global production will reach 3 million m$^3$ by 2025 [11]. Moreover, the annual growth rate of the market share in the European construction sector of structural engineered-wood products is between 2.5 and 15% [12].

However, the increasing anthropogenic pressure on land resources associated with the intensification and expansion of human activities, for instance, harvesting wood for the production of timber and bio-based construction materials, appears to be leading to soil quality degradation [13]. Land and soil conservation is crucial both for the provision of ecosystem services (i.e., food and biomass production) as well as for environmental protection, as land maintains important environmental functions (i.e., soil functions and carbon storage) [14]. Furthermore, land plays an important role in achieving many of the SDGs. The impact of forestry and the production of timber and bio-based products on the impacts associated with land use are increasingly being identified as important aspects to be considered when conducting a life cycle assessment (LCA) [15]. However, the consideration of land use in relation to the life cycle of construction materials is largely neglected.

$^1$ The term carbon refers to the greenhouse gas (GHG) emissions expressed as a carbon dioxide equivalents – CO$_2$eq.
In the present context, this study aims at assessing the environmental impacts of timber as well as evaluating the environmental consequences of replacing conventional structural construction materials with timber in the building structure on a building and an expected global new residential building stock level. At the building level, both the embodied GHG emissions and the land use impact are examined, which offers a broader perspective when considering the environmental impacts of buildings. In addition, the mitigation potential of the projected embodied GHG emissions for the new residential floor area growth is investigated.

2. Method
The study workflow is shown in Figure 1. In the first part of the study, the LCA was carried out at the building level to assess the environmental impact and potential for reduction of embodied GHG emissions and the land use impact per m² of the previously defined base case building models when CLT replaced reinforced concrete (RC) and masonry (M) in the building structure. In order to get a sense of mitigation potential on the larger scale, the second part of the study examines the mitigation potential of embodied GHG emissions for an expected residential building stock new floor area growth predictions depending on the regional residential building structural material choice in the key regions of the world for the period from 2017 to 2060 if RC and M were substituted by CLT. A more detailed description of the study methodology and the assumptions made are given in the following subsections.

2.1. Life cycle assessment (LCA)
This LCA follows the standardized framework from the ISO 14040/14044 standards, which consists of four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. The goal and scope phase includes the definition of the study objectives, which has been given in the introduction of the paper. It also defines the system boundary and the functional unit (FU). The base case model was adopted from Žigart et al. [16] and represents a modular low-energy building with external module dimensions of 7.4 x 7.4 x 3.6 m, designed with three different structural systems: RC, M, and CLT. The thermal transmittance (U) of a building envelope is 0.10 W/m²K and is equal for all evaluated buildings. The majority of the LCA studies evaluate specific buildings, hindering general conclusions, and comparability of the study results. Therefore, a generic but representative modular residential building is chosen, which can be subjected to horizontal and vertical multiplication into larger building models as in Leskovar et al. [17]. The reference buildings, however, meet the requirements for the load-bearing capacity of a low residential building with a compact form. The medium-sized and high rise buildings have higher structural requirements compared

![Figure 1. Flowchart of the study workflow.](image-url)
to the low-rise buildings. Therefore more materials are used for their construction, which influences the results of the environmental impact assessment. However, they are out of the scope of the study.

The configuration and thicknesses of the wall and roof elements for the structural systems under consideration are shown in Figure 2. The FU is defined as 1 m² of the gross floor area of a low-energy reference building designed with different structural systems. Within the system boundary, the production stage of the building’s life cycle is considered, which includes modules A1-A3, according to EN 15978, that covers the extraction of raw materials, the transport of these materials to the manufacturer, and the manufacturing process. The average transport values of the product from the manufacturer to the supplier and the losses in trade and transport are as well included in the system boundary.

The inventory data in the LCI phase includes all input and output flow from the building’s life cycle. In LCI, it is common to differentiate between consequential and attributional system modeling [18]. Based on the study objectives, the attributional system model is adopted. The generic LCI database EcoInvent

| RC                | M                | CLT              |
|-------------------|------------------|------------------|
| 1. 0.3 cm gypsum filler | 1. 1 cm lime plaster | 1. 9.5 cm cross-laminated timber |
| 2. 16 cm reinforced concrete (1% reinforcement) | 2. 20 cm vertically perforated brick | |
| 3. 36 cm rock wool | 3. 52 cm rock wool | 2. 34 cm rock wool |
| 4. 0.19 cm silicate plaster | 4. 0.19 cm silicate plaster | 3. 0.19 cm silicate plaster |

Figure 2. Configuration of external walls and roof components for different structural systems of low-energy modular building model (structural material highlighted).
v3.5 and “allocation at the point of substitution- unit” system model was used for the assessment. The selected datasets from the database are global market datasets covering the consumption mixes of the average global production.

In the LCIA phase, environmental impacts are quantified by assigning the LCI results to the selected impact categories according to characterization factors. The adapted Environmental Footprint (EF) v1.0 mid-point LCIA method of Product Environmental Footprint (PEF) initiative was used for the assessment implemented in SimaPro v9.0 software tool. The implementation in SimaPro is based on EF method 2.0. The impact categories adopted for this study are Climate Change (CC) with the IPCC 2013 Global Warming Potential for the time horizon of 100 years as a baseline model, including the carbon feedbacks for different substances and Land Use (LU) based on LANCA v 2.2 as a baseline model. These environmental indicators were selected because LU impact is usually neglected in LCA studies of construction materials, as well because a significant proportion of global GHG emissions comes from the construction sector. The CC indicator comprises three different sub-indicators: fossil, biogenic, and land use and transformation. CC fossil accounts for GHG emissions originating from the oxidation and reduction of fossil fuels by means of its transformation or degradation (e.g., combustion, digestion, landfilling), biogenic accounts for GHG emissions to air originating from the oxidation and reduction of biomass by means of its transformation or degradation (e.g., combustion, digestion, landfilling), while land use and land transformation account for emissions through land management. It should be noted, however, that biogenic carbon uptake and emissions, as well as carbon flows that describe land use and land transformation, are not accounted for in the present study; if they have been taken into account, they must be inventoried separately for each elementary flow following the carbon modeling in the PEF approach. Credits related to temporary carbon sequestration or delayed emissions are also excluded, as emissions expected within three centuries are modeled in EF as if they were emitted now, but can be included as additional environmental information. For the CC impact category, in the adapted EF method in SimaPro, carbon dioxide (emission to air) is added with a factor of carbon dioxide-fossil, carbon dioxide-to soil, or biomass stock with factor -1. The LANCA model enables assessing the impacts of land use on four soil properties: biotic production, erosion resistance, groundwater regeneration, and mechanical filtration, synthesized in one aggregated index, and includes characterization factors for both occupation and transformation land use.

2.2. A prospective global perspective

New residential floor area additions to the global building stock by 2060, broken down by key regions, is shown in Figure 3. These additions will mainly take place in developing countries. It is expected that half of the global building additions will be completed by 2035, depending on the region.

![Figure 3. Residential floor area additions to 2060 by key regions with the share of additions built by 2035 (note: ASEAN stands for the Association of Southeast Asian Nations) [19].](image)
The choice of materials for residential construction varies greatly from region to region. Figure 4 shows the global share of residential construction materials in 2017 for the world key regions. It should be noted that the cement and steel intensity by regions, i.e., average cement and steel consumption for the construction of 1 m² of residential floor area in a different region, is not considered in the study. It is assumed that RC contains 1% of reinforcement on average, and the average cement content in concrete for all regions is 290 kg/m³. CLT is adopted as the construction technology for the timber buildings. For the prospective scenarios up to 2060, the same structural material share as in 2017 is assumed. Furthermore, the business-as-usual scenario is assumed for the production of the construction materials. It is expected that future technologies will have less impact compared to today’s technologies. Thus no development is assumed as it represents the worst-case scenario. Percentage of steel buildings in global residential building structure material distribution is less than 1% (exception is Europe with approximately 2%), thus due to low share steel buildings are not considered in the study. For the composite buildings that utilize several materials as structural elements, aggregated and averaged data from M, CLT, and RC building per m² of floor area is assumed.

![Global residential building structural material share, 2017](image)

**Figure 4.** Global residential building structural material share in 2017 for the key regions [19].

3. Results and discussion

3.1. Building level

Table 1 shows the CC and CC broken down by sub-indicators as well as the LU impact results per FU of a low-energy building constructed with different structural systems. The results indicate that the CLT building had the least impact when CC is considered compared to RC and M. A more detailed analysis of the CC results reveals that the vast majority of the GHG emissions of all buildings examined are due to the oxidation and reduction of fossil fuels. Looking at the emissions originating from the oxidation and reduction of biomass, it can be seen that the construction of M building results in a higher release of biogenic carbon emissions compared to RC and CLT. Furthermore, the construction of the CLT building will lead to an increased release of GHG emissions originating through land management. However, the released biogenic and land use and transformation carbon associated with the production of the material is negligible compared to the fossil fuel-related GHG emissions for all examined buildings.

When the LU impact is examined, the CLT building has a substantially higher material production LU impact compared to RC and M. This significant difference is mainly due to the occupation land use interventions related to intensive forestry for the production of lamellas from spruce used for the assembly of CLT panels. This significant difference is expected as the land transformation, and occupation activities associated with a conversion from primary forest to a managed forest and intensive forest management practices could lead to the increased pressure on land resources and the ecosystem quality.
mental performance of conventional and bio-

effects of substitution would increase by 4.82%

emissions could be avoided if RC and M are replaced by CLT, respectively. On the contrary, the LU
to material production through the substitution of RC and M by CLT at building level are shown in Table 3. When CC is considered 14.62% and 12.94% of embodied GHG emissions could be avoided if RC and M are replaced by CLT, respectively. On the contrary, the LU effects of substitution would increase by 4,826.93% and 1,886.62%, respectively. These results indicate that there is a significant difference in the environmental performance of conventional and bio-based materials when evaluating and comparing their environmental impacts, depending on the environmental indicator examined. As in this case, the utilization of CLT in the building structure releases less GHG emissions, on the other hand, its production also has a greater impact on the ecosystem quality.

Table 1. The results of CC and LU for examined buildings constructed with different structural systems

|      | CC [kgCO2eq/FU] | CC fossil [kgCO2eq/FU] | CC biogenic [kgCO2eq/FU] | CC land use and transform. [kgCO2eq/FU] | LU [Pt/FU] |
|------|----------------|------------------------|--------------------------|------------------------------------------|------------|
| RC   | 245.04         | 244.45                 | 0.51                     | 0.08                                     | 1,111.87   |
| M    | 240.31         | 237.08                 | 2.98                     | 0.26                                     | 2,757.51   |
| CLT  | 209.21         | 208.10                 | 0.68                     | 0.43                                     | 54,781.28  |

The results indicate that there is a significant difference in the environmental performance of conventional and bio-based materials when evaluating and comparing their environmental impacts, depending on the environmental indicator examined. As in this case, the utilization of CLT in the building structure releases less GHG emissions, on the other hand, its production also has a greater impact on the ecosystem quality.

Table 2. The impact of structural and building envelope components on the CC and LU

|      | CC [kgCO2eq/FU] | LU [Pt/FU] |
|------|----------------|------------|
|      | Structural components | Building envelope components | Structural components | Building envelope components |
| RC   | 123.83         | 121.21     | 586.75       | 525.13       |
| M    | 88.15          | 152.17     | 2,088.96     | 668.55       |
| CLT  | 96.72          | 112.49     | 151,983.33   | 501.52       |

Table 3. The effects of structural material substitution per FU on CC and LU where negative values present decrease and positive values increase in impacts

|      | CC [kgCO2eq] | [%] | Land use [Pt] | [%] |
|------|--------------|-----|--------------|-----|
| RC substituted with CLT | -35.83 | -14.62 | 53,669.41 | 4,826.93 |
| M substituted with CLT | -31.10 | -12.94 | 52,023.77 | 1,886.62 |
3.2. Expected global residential building stock new floor area level

The embodied GHG emissions from an expected residential building stock new floor area growth predictions depending on the regional residential building structural material choice in the world key regions for periods from 2017 to 2060 are shown in Figure 5. Under the assumptions made, the preliminary results indicate that the expected increase in new residential space would release an additional 67.20 GtCO$_2$eq when the load-bearing and non-load bearing components of the building envelope are considered. Furthermore, if the conventional building materials were substituted by CLT in the building structure, a total of 5.92 GtCO$_2$eq or 9.22% could be avoided globally, depending on the region and the proportion of building material in the building stock.

In order to get a sense of the magnitude of the avoided emissions, in 2016, global annual buildings-related GHG emissions were 9 GtCO$_2$eq, while emissions from building construction that also includes the production of the materials were 3.70 GtCO$_2$eq. In addition, GHG emissions from building construction are growing steadily, from 3.10 GtCO$_2$eq in 2010 to 3.70 GtCO$_2$eq in 2016 [2]. As shown in Figure 5, assuming that the same amount of emissions are released annually from 2017 to 2030 as in 2016 from building construction, 48.10 GtCO$_2$eq are projected to be released over that period. However, if we consider that in the IPCC model pathways with no or limited overshoot of 1.5°C, global net anthropogenic GHG emissions should decrease by approximately 45% by 2030 compared to 2010 levels and reach the net-zero target by 2050, it is clear that despite the solely use of CLT in building structure, a significant amount of embodied GHG emissions is still being emitted due to new floor area additions. These results revealed that if the expected global new floor area additions would be constructed as low-energy CLT buildings, a certain amount of embodied GHG emissions could be avoided. However, on this scale, the mitigation is minor when considered in the context of PA climate goals and limited carbon emission budgets for achieving net-zero targets globally.

![Figure 5](image-url)
Moreover, these preliminary results raise new concerns and questions that need to be further addressed. The main concern arises from the consideration that forests are limited natural supply systems with atmospheric carbon and solar energy as resources and trees as products. Thus, the amount of wood from trees that can be harvested in sustainably managed forests is not inexhaustible. The question, therefore, arises as to how much wood is available for harvesting and utilization for buildings and the construction sector. Another important concern arises from the consideration that at a global scale, the atmospheric carbon dioxide is captured and stored by forests, but also by other vegetation, soils, oceans, and products. The question arises as to how the increase in wood harvesting for the construction sector and buildings would affect the complex global carbon cycle and land use change. That also includes the question of the wood harvest cycle length and forest carbon pool balance. These complex issues and questions, among many others related to the use of timber in the construction sector as an alternative low-carbon construction material in the context of climate change mitigation, should be further investigated.

4. Conclusion
This paper examines the environmental impact and the potential to mitigate the increase in embodied GHG emissions from new residential buildings when conventional structural construction materials are substituted by timber at the building and the expected new residential building stock level. The results revealed that substituting RC and M by CLT in the building structure, a certain amount of mainly fossil fuel-related embodied GHG emissions, could be avoided at building level. However, it is important to highlight that the substitution leads to a significant increase in LU impact. It is therefore proposed to consider the environmental impact of the production of construction materials from several perspectives, in particular when bio-based construction materials such as timber are assessed, as their intensive production can put increased pressure on land resources and ecosystem quality.

Scaling up to the global level revealed that a certain amount of embodied GHG emissions from the expected new residential construction could be avoided by using CLT as a load-bearing material. However, the emissions from the expected new residential floor area additions are still substantial and should be considered if we are aiming towards a net-zero built environment aligned with the global climate targets set in PA. It should be emphasized that the latter exercise is being carried out as a preliminary study in order to get a sense of mitigation potential on a larger scale, rather than to project exact values. Further research is needed to investigate the availability of wood as a limited resource for harvest and use in the construction sector and, more importantly, how the global carbon cycle would be affected by increased production of CLT.

It should also be noted that the construction feasibility of CLT in different regions of the world in terms of structural and technical performance, such as building height or moisture content, was not considered in the study. This consideration is an important area for further research, as a large part of the new floor area additions will occur in urban areas, but also regions with a high level of humidity. Furthermore, the datasets adopted in the study were not regionalized due to the lack of representative data, yielding results with higher uncertainty. The impact of transport to the construction site, the construction process, the use of the building, deconstruction, and activities related to the end of the life of the materials were not considered thus, their inclusion would have led to different results. However, consideration of the full life cycle of construction materials is an important area that will be investigated in further research.

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