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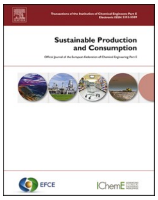

Environmental consequences of shifting to timber construction: The case of Denmark

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ABSTRACT

Many life cycle assessments (LCA) studies on wooden buildings show potential to decarbonise the building industry, though often neglecting to consider the systemic changes of such a shift at the building stock scale. This study applies a consequential LCA to evaluate the transition from conventional construction to increased wood-based construction in Denmark from 2022 to 2050. The assessment models a material flow analysis of the two construction scenarios, incorporating an area forecast and case buildings. By that, we assessed suppliers' capacity to likely meet the demand for wood, steel, and concrete, employed an input-output model to enhance completeness and country representativeness for other materials' markets, and considered the competition for land by indirect land use change. We implemented a dynamic IPCC-based assessment of GHG-emissions concurrently with a carbon forest model to anticipate the relationship between the delayed carbon storage resulting from using wood in buildings and forest regrowth management. The findings indicate wood construction is the most climate-friendly option for multifamily houses. In contrast, single-family houses (SFH) and office buildings (OB) exhibit the lowest climate impacts in the conventional scenario. The SFH result could be credible due to the sizable GWP impact gap between construction scenarios despite uncertainties related to the weight proportion of sedum roofs. The less conclusive OB findings relate to the substantial steel quantities in the wood case buildings, requiring further investigation. Generally, metals, cement-based- and biobased materials demonstrate the largest climate impact among the material categories. Across all three building typologies, the change to timber construction increased the impact on nature occupation (biodiversity). In conclusion, this study emphasises the need for further research on forest management model inputs, land use change approaches, potential steel suppliers' impact, and a broader array of case studies. It is because these are influential factors in facilitating informed decision-making of the increased implementation of wood in buildings. As the first study to integrate these modelling characteristics, it contributes to the research gap concerning geographical circumstances, forestry, and markets relevant to decision support for increased wood utilisation in Europe's building industry.

1. Introduction

The building industry is one of the largest contributors to global climate impacts (United Nations Environment Programme, 2022). The embodied carbon emissions and other environmental impacts of building materials are of interest because they often occur upfront and present the largest potential for improvements. According to IPCC (2023), it is crucial to significantly reduce these upfront greenhouse gas (GHG) emissions in the forthcoming years towards 2030 and 2050 to limit global temperature rise to 1.5–2 °C. Wood, as a building product, has emerged as one of many solutions to decarbonise the building sector due to its ability to sequester carbon by photosynthesis during growth (biogenic carbon), which then can be stored in buildings as long as the products remain in the buildings (Churkina et al., 2020; Pomponi et al., 2020).

In recent years, more studies have focused on the climate impact and

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benefits of using wood at the building level, applying the life cycle assessment (LCA) methodology. Many studies recommend wood to reduce the climate impacts of buildings. Nonetheless, these studies establish predominantly the recommendations on single case studies with a smaller building population and use the attributional LCA approach in 96 % of the scenarios (Andersen et al., 2021).

However, these studies do not examine what happens for a more large-scale change to wood construction technology in the built environment. It requires insights into the building stock development, the market for the concerned products, and the availability of resources. To address these aspects, we use the approach of consequential LCA for the analysis. In addition, the management practice of the relevant forestry that supplies the wood and the competition for land that follows also need consideration.

1.1. Consequential LCA and applications on buildings

The consequential LCA (CLCA) approach can address the aspects of markets, affected suppliers, and constrained suppliers. The method evaluates the suppliers expected to respond to a change in demand. It uses the four-step procedure: (1) identify the scale, (2) identify the time horizon, (3) assess market delimitation, (4) analyse the market trend and the suppliers that can increase or decrease their production (Weidema et al., 2009). Currently, the number of CLCA studies of buildings is limited and differs in quality, transparency of methodology documentation, and completeness of included conceptual and framework elements from the four-step CLCA procedure (Hansen et al., 2022b).

Recently, researchers have increasingly conducted studies using the CLCA approach for various strategic investigations. For example, investigations of decisions on green procurement and recycling for refurbishment projects (Ghose et al., 2017; Buyle et al., 2018a) or to understand the impact of circular interior wall alternatives (Buyle et al., 2019). Other studies investigated the relationship between energy and resources when renovating office buildings and how it contributes to climate targets (Ghose et al., 2019, 2020). Two other CLCA applications examined a modular active building (Roberts et al., 2022) and a wood-hybrid multistorey building (Fauzi et al., 2021). Some studies focused on marginal electricity mixes for building energy consumption (Roux et al., 2017; Frapin et al., 2022).

When it comes to increased wood in buildings, the literature includes a few CLCA studies initiated by Nepal et al. (2016), who assessed increased wood in low-rise non-residential buildings in three USA regions, applying two forest economic equilibrium models and a biological model for carbon estimation. Despite extensively assessing the forestry practices and economic effects on the forestry development of increased wood demand, the study does not evaluate the full life cycle nor the possible indirect land use changes (iLUC) related to the larger pressure on land from the increased wood demand in the building industry.

Likewise, Cordier et al. (2019) modelled increased wood in non-residential buildings in Quebec, Canada, using a prospective material flow analysis to inform the inventory modelling. This approach was evolved to understand a wider scope of environmental impacts of a larger variety of timber structures substituting steel and concrete structures (Cordier et al., 2021). The study embedded the dynamic timing of biogenic carbon fluxes from forest modelling in Cordier et al. (2022) and further examined end-of-life strategies, by which all were using a process-based LCA background database. However, the study did not consider residential building stock development (different structural archetypes than non-residential) and indirect land use changes.

In the UK, an investigation delved into how the net CO_2 balance over time would be affected by changing current grassland used for beef production to forestry for construction timber and bioenergy production (Forster et al., 2019). They consider forestry management and iLUC in their modelling; however, they focus on the climate consequences of transforming farmland to forest land for timber production. Hence, the objective is different than assessing the climate consequences of a change in demand for more wood in buildings while integrating the related forest modelling and land use change.

The previous studies of increased wood in buildings have not evaluated the simultaneous integration of detailed forest modelling and indirect land use change. In addition, the assessed building typologies were limited to considering non-residential buildings except for Forster et al. (2019), who studied houses without further distinctions to sub-typologies.

Based on the knowledge gap in the literature, this research applies CLCA to a wider scope of building typologies (single-family houses, multifamily houses, and office buildings), investigating the environmental impacts of a change from conventional construction to increased use of wood-based construction in the entire prospective building stock in Denmark towards 2050, and implements forest and iLUC modelling, while using an input-output background database. Using the IO database supports higher completeness in assessing the environmental impacts as it captures, in principle, all flows in the economy in its processes and the historical market share of product availability among the supplying sectors and countries (Lenzen, 2000; Rebitzer et al., 2002; Agez et al., 2020), which is particularly important for large scale CLCA. In addition, the IO database in this study includes iLUC assessment.

On this basis, the present study assesses the following research questions:

- What are the environmental consequences of a change from conventional construction to wood-based construction?
- What is the influence of the reference study period, affected suppliers, forest modelling, and iLUC on the environmental impacts of a change to wood-based construction?

2. Methodology

To address this study's research questions, we forecasted the demand for new buildings, then analysed three building typologies using three case buildings for each to continue the current conventional construction practice in Denmark as the base scenario and for a change to wood-based construction. The studied building typologies are single-family houses (SFH), multifamily houses (MFH), and office buildings (OB), and they accounted for around 60 % of the expected new building stock in Denmark according to Hoxha et al. (2024). The following three steps comprise the methodology of this study, as it is summarised in Fig. 1. First, based on three case buildings representing the building typologies, we predicted the future building areas based on historical development. Second, we scaled up a population sample of case buildings to make the material flow analyses. Third, we assessed the environmental consequences using consequential LCA, including a dynamic carbon forest and iLUC model.

2.1. Forecasting, material flow analysis, and scenarios for construction practices

We composed an average case building for each building typology from the material quantities of three actual case buildings. We randomly selected the case buildings in our available case sample of conventional (concrete-based) and wood-based constructions. The wooden case buildings are present in Andersen et al. (2023, 2024). Given that conventional and wood-based construction can have varying climate impact performance, the scope does not encompass the entire range of buildings in existence. Nor is the objective optimising and determining the lowest impacting timber building, but rather, it is to examine the impact of changing from conventional to wood-based construction and identify the factors that influence them. After making the average case buildings, we use forecasted information on the future gross building area of the three building typologies from Hoxha et al. (2024). The model uses historical area development from 1986 to 2021 to forecast the building area for 2022–2050.

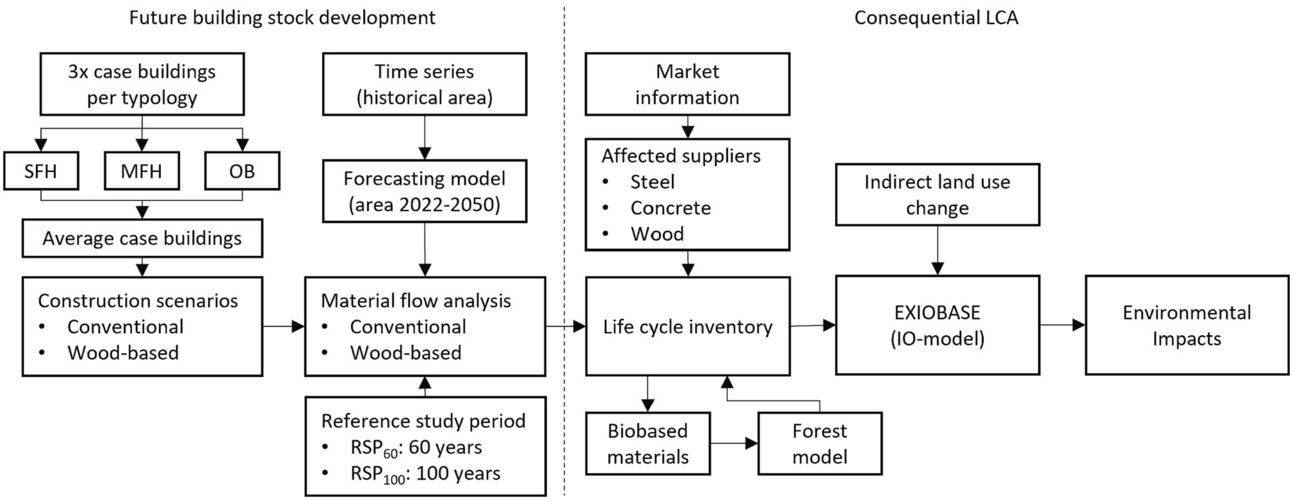

Fig. 1. The methodology used in this study. It encompasses the future building stock forecast and material flow for the conventional and wood-based construction technology scenarios. Then, the modelling overview and inputs to the consequential LCA for determining the environmental impacts. SFH = single-family houses, MFH = multifamily houses, OB = office buildings, RSP = reference study period.

Then, we combined the forecasted area of the building typologies and the average case buildings into a material flow analysis (MFA). It consists of upfront materials to construct the buildings equal to life cycle stages A1-A3 and the expected replacements, B4, during two reference study periods (RSP) of 60 (RSP_{60}) and 100 (RSP_{100}) years, in line with the EN 15978:2011 standard (EN 15978:2011, 2012). It resulted in a total number of 12 scenarios. The actual service life of SFHs is close to 60 years, and of MFHs and OBs, the service life is close to 100 years (Andersen and Negendahl, 2023), hence the reason behind the chosen RSPs.

The two RSPs also provide a sensitivity analysis of how they influence the environmental impacts regarding (i) more years to divide the total environmental impact into (ii) the total number of replacements from an increasing reference study period. Inspired by Heeren and Fishman (2019), Guven et al. (2022) and Soust-Verdaguer et al. (2023), we aggregated similar materials into material groups as follows: (1) Biobased. (2) Cement-based: Concrete, mortar, plaster. (3) Fired clay. (4) Metals: Steel, aluminium, copper, zinc. (5) Insulation. (6) Other: Aggregates, clay, bitumen, glass, natural stone, paint, plastic, textile.

2.2. LCA methodology

This study goes through the four steps for conducting an LCA: (1) goal and scope, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation of results, proposed by the ISO 14044 standard (DS/EN ISO 14044, 2008). A market-based approach is used to examine the changes in the economy when considering conventional and wood-based construction technology, respectively, to meet future forecasted building demand. This is the consequential LCA method and is particularly useful in understanding which suppliers, through market mechanisms, will be expected to be able to respond to an increase in demand. Further, the method accounts for the constrained suppliers who cannot contribute to meeting any additional demand and avoid allocation of co-products by using substitution, which the ISO 14044 standard (DS/EN ISO 14044, 2008) recommends.

2.2.1. Goal and scope of the LCA

The functional unit (FU) encompasses the material demand for a change from conventional to wood-based construction complying with the current Danish building code for the expected area development of the Danish building stock between 2022 and 2050 during two reference study periods of 60 and 100 years. The numerical values in the result will be presented as a reference flow of 1 m^2 gross floor area per year. This reference flow enables consideration of the average material consumption and environmental impact across various RSPs. The included life cycle stages within the system boundary of the study are presented in Fig. 2. Since the study wants to understand the impacts of material requirements for the two construction technologies, all other aspects are assumed equivalent. For example, the operational energy consumption is not considered because both construction technologies are expected to fulfil an equivalent thermal performance in accordance with the building code.

Further, the services related to the construction sector, such as consultancy, use of machinery and so forth, are not included. Due to this, the LCA addresses the changes in material flows; thus, it is not a complete LCA of all activities related to the building. For the included material processes, the background flows are of full completeness due to using an IO database but entail low detailing or representativeness for some materials (see elaboration in Sections 2.2.2 and 4.2).

2.2.2. Life cycle inventory

In the consequential LCI modelling applied in this study, the affected suppliers of products in the life cycle are identified (Weidema et al., 2009). It comprises the identification of the markets where the products trade, i.e., belongs to, and the identification of the market suppliers that are expected to respond to the Danish consumption of construction materials. Co-production is handled through system expansion, in which the co-products' function on the market is assessed and substitutes the marginal unconstrained suppliers of products with a similar function on the market. To define the market of a given product, we assessed whether the market is global or geographically delimited. In the latter case, only suppliers within the specific geographical delimitation can act as unconstrained suppliers to the Danish market. The unconstrained suppliers in the generally growing markets are identified as the suppliers who have seen the largest proportional increase in production over time (Buyle et al., 2018b; Consequential-LCA, 2020).

The EXIOBASE v.3.3.16b2 (Merciai and Schmidt, 2018) was applied as the background database in this study. EXIOBASE is a hybrid unit IO database containing information on the environmental impacts of different products and services. An IO database includes information on the global trade between countries and sectors measured in monetary units, which considers all imports and exports. The hybrid term refers to the sectors with physical goods and commodities, e.g., cement, represented in physical units instead of monetary. Using an IO database as EXIOBASE results in a top-down approach that considers the whole economy without omitted inputs. However, a limitation of IO databases

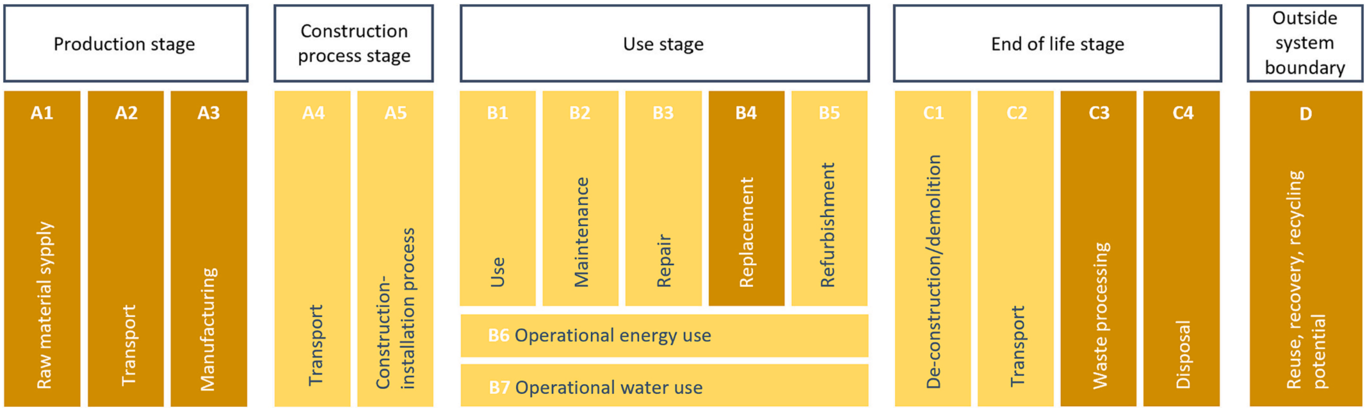

Fig. 2. The life cycle stages included in the LCA are the modules highlighted with darker colours.

is the high level of aggregation of industry sectors, so that the economy has fewer details than in process-based databases. EXIOBASE also uses substitution regarding co-products. Sections 3.2 and 3.3 in the SI provide information on the sectors used for the products and the end of life.

We want to highlight that the single-family houses may partly deviate from general wood buildings because two of them contain larger quantities of clay, another some eelgrass, and green roofs. The two latter were modelled as wood materials in EXIOBASE. In addition, two of the wood-based office buildings have steel in parts of the load-bearing structure besides wood, thus not being complete wood buildings. For further details on the material inventory see section 1.2 in the SI.

2.2.2.1. Identification of markets and affected suppliers. A separate analysis of affected supplying countries was conducted for the foreground system, including concrete (cement, sand, and gravel), steel, and wood. The remaining building materials relied on the markets in the background system. All analyses of the affected suppliers can be found in section 3 in the SI.

The market for steel is global with an increasing market trend, where China is currently the supplier which has globally increased its production since the year 2000, whereas the remaining countries and regions have had stable or declining production, according to the analysis of Buyle et al. (2018b); VisualCapitalist (2020).

Pizzol and Scotti (2016) previously identified the wood market as regional, wherein Denmark belongs to the North European market. FAOSTAT reveals that Denmark imports more than 90 % of its wood consumption. Sweden was analysed to have the steepest slope of trend in production within the north European market (FAO, 2020) (Fig. 10 in the SI). It is also apparent that Sweden has large areas of non-productive forest available, which indicates possibilities for an increase in production (FAO, 2020). The identification of Sweden as the affected supplier for wood demand in Denmark is previously corroborated by Pizzol and Scotti (2016) and Schmidt and Dalgaard (2016).

For the materials in concrete, i.e., cement, sand and gravel, the low value-to-weight ratio presumes those to belong to geographically limited markets, consistent with the theory in Weidema (2003). Sacchi (2017) supports the local market presumption for cement demand, and Buyle et al. (2018b) establish local or regional markets for sand and gravel. Danish cement production increased between 2016 and 2020. In addition, the trade data of the national cement producer Aalborg Portland shows that grey cement is primarily produced for national demand (Aalborg Portland, 2019) (see analysis in section 3.1 in the SI). Therefore, Denmark's future demand is expected to be covered by national production. However, Denmark is also an increasing importer of cement, and the national production has annual fluctuations. For this reason, cement is subject to a sensitivity analysis (see Section 4.2.1).

Denmark also appears to be the affected supplier regarding clay, based on the material accounts from Statistics Denmark. National production increased while imports and exports remained constant between 2014 and 2019 (Fig. 9 in the SI).

The demand for the foreground materials was then entered in EXIOBASE for the different sectors of the identified marginal supplying countries. For the building materials in the background system, i.e., others than steel, concrete, and wood, we used their average markets from EXIOBASE instead of making specific assessments of marginal suppliers by entering the demand for each material in their respective Denmark sector.

2.2.2.2. Biogenic carbon fluxes of wood products in LCA. Trees sequester carbon through photosynthesis, called biogenic carbon when growing in the forest. A tree used as a construction material temporarily stores the carbon for the period the timber remains in the building, which has implications for biogenic carbon modelling (Hoxha et al., 2020). Currently, biogenic carbon is generally considered in building LCAs either by the method 0/0, carbon neutral, or the method $-1/+1$, which considers carbon sequestration in the production stages (A1-A3) and emissions at the end-of-life stages (C3-C4), meaning the balance is neutral over the service life of the building (Andersen et al., 2021). Dynamic LCA of biogenic carbon in wood buildings has gained attention, though recently, a review stated that this forest modelling of dynamic timing of biogenic carbon still sees few applications in building LCA studies (Arehart et al., 2021). This study's approach to forest modelling is presented in the following section.

The reviewed studies by Arehart et al. (2021) primarily utilise dynamic methods developed by Levasseur et al. (2010, 2013) for the dynamic LCA of wood products. Levasseur et al. (2010, 2013) derive dynamic characterisation factors based on the Bern carbon cycle, which considers the instantaneous radiative forcing of a greenhouse gas (GHG) at arbitrarily chosen time horizons. Later, the GWP time horizons of 100 and 500 years are assessed for a wooden chair under various scenarios (Levasseur et al., 2013). Another dynamic method identified in Arehart et al. (2021) is the GWP_{bio} approach, initially introduced by Cherubini et al. (2011), which considers the decay rate of biogenic CO_2 in the atmosphere in relation to the time its emitted and the forest regrowth. Guest et al. (2013) expanded this method to long-lasting wooden products, incorporating GWP_{bio} factors that cover a range of rotation and storage periods for time horizons of 100 and 500 years.

The GWP_{bio} approach combines dynamic and biomass growth modelling to simplify application for LCA practitioners. However, the specific biomass growth inputs and end-of-life scenarios constrain the factors. The dynamic method allows for more flexibility in selecting time horizons and scenarios. Still, the LCA practitioner must incorporate a biomass growth model representative of the biomass origin, a forest model, into the analysis.

The dynamic studies discussed focus on the Bern Carbon cycle, indicating that the methodology of dynamic LCA might not be the most influential aspect of the GWP impact. The choice of GWP time horizon significantly affects the bioenergy and wooden products GWP impact (Levasseur et al., 2010; Cherubini et al., 2011; Guest et al., 2013; Peñaloza et al., 2016). Time horizon extension often reduces GWP impacts and can even change the product system from a biogenic carbon source to a sink. Especially when the reference study period approaches the time horizon, the biogenic carbon will experience significant benefits, following the principle of Levasseur et al. (2011). The GWP results need to consider whether the dynamic LCA model represents a harvested tree before construction or the regrowth of a replanted tree (Levasseur et al., 2013; Peñaloza et al., 2016; Hoxha et al., 2020), where the regrowth approach has the largest GWP impact, thus appearing as the more precautious option. Also, the forest modelling and anticipated anthropogenic storage time greatly impact the outcomes of dynamic LCA (Guest et al., 2013), and end-of-life scenarios because it influences whether the biogenic carbon is released or continues in other life cycles (Levasseur et al., 2013; Peñaloza et al., 2016; Pittau et al., 2018). This study's forest modelling approach is presented in the following section.

2.2.2.3. Forest modelling. The use of wood increases the demand for wood, influencing the choice to plant the next trees to supply the expected future market demands. Thus, a consequence of increasing the demand for wood is planting another tree, which begins to sequester carbon, assuming the principles of sustainable forest management are in place, conforming with CLCA studies using Swedish wood (Peñaloza et al., 2016; Schmidt and Dalgaard, 2016; De Rosa et al., 2018). A forest model captures in detail this relationship between the time of harvesting, growing of the replacement tree, and release of biogenic carbon due to the end of life of the wood component or the entire building. The forest model of De Rosa et al. (2016b) captures this relationship of timing biogenic carbon sequestration and emissions in the forest.

The first aspect is that foliage and branches of the harvested tree are presumed to have been left in the forest, which emits CO_2 over time as the woody debris decays. Meanwhile, the planted replacement tree absorbs atmospheric carbon over time, as presented in Fig. 3. Both aspects are included in the study, while the eventual harvest of the replacement tree belongs to the next product that uses this wood in the future. The Swedish spruce rotation period is 88 years (Schmidt and Dalgaard, 2016). Other inputs in the model come from the IPCC values for temperate forests (IPCC, 2006). Essentially, the forest model accounts for all CO_2 fluxes from sequestration and emissions occurring in the forest. These flows are then time-corrected with temporal characterisation factors from De Rosa et al. (2016b), which results in a temporal CO_2-equivalent (eq) value for the forest system that captures the biogenic carbon dynamics.

After harvest, the timber proceeds to a sawmill for production, where co-products, such as bark and sawdust, occur as a part of the processing of the timber. These co-products are handled by substitution. Wood co-products substitute pulpwood in the general market for biomass (Schmidt and Dalgaard, 2016; De Rosa et al., 2018). The Swedish forests produce both timber and pulpwood. So, an increase in the supply of bark and sawdust to the pulpwood market will reduce the need for pulpwood, which has a shorter rotation period at the time of biomass harvest in the forest (Schmidt and Dalgaard, 2016). This study assumes that pulpwood has half the rotation period of the wood used for timber (thereby changing from 88 to 44 years). The forest model is applied whenever wood product replacement occurs during the buildings' RSP. However, it is done by modelling the replanting in the year the replacement takes place to have the actual relationship with the GWP_{100} time horizon to time-correct the GHG emissions. For instance, this means a replacement of wood material in a building in year 15 is captured by a forest model starting in year 15. Here, 85 years remain of the 100-year time horizon, meaning that part of the 88-year rotation period will be outside the time horizon.

2.2.2.4. Indirect land use change (iLUC). In addition to forest modelling, there is evidence that deforestation occurs globally (IPCC, 2023), which, together with all land use changes, causes about 11 % of global climate impacts, though with great estimation uncertainty. The driver is the increasing global demand for land, often called indirect land use change (iLUC). However, there is no consensus on how the iLUC should be modelled for separate studies. Nevertheless, it may be important to include the iLUC assessment of wood buildings since the few previous CLCA studies that model iLUC of wood buildings come to the result that their climate impact increases between 10 and 60 % depending on the iLUC methodology and assumptions (Hansen et al., 2022a). Further elaboration and assessment of iLUC models are presented in De Rosa et al. (2016a).

The approach taken in this study takes into account that wood production for the building industry involves a demand for forest land, thus contributing to the current conversion of natural primary forest to managed forest on a global scale. This conversion of forests also has implications for biodiversity. The environmental impacts of iLUC are modelled and assessed by the method of Schmidt et al. (2015). The model assesses the temporary loss of carbon as a result of conversion from primary to managed forest in those countries where this conversion is taking place globally. The applied iLUC model is used in several LCA studies, and it is considered the most applicable among six LUC models (De Rosa et al., 2016b) and is integrated with the applied EXIOBASE version.

2.2.3. Life cycle impact assessment

This study includes several environmental impact categories, although it focuses on the impact on climate change with a more in-depth analysis. The impact categories include global warming potential, respiratory inorganic substances, aquatic and terrestrial ecotoxicity, nature occupation, acidification, aquatic and terrestrial eutrophication, respiratory organic substances, photochemical ozone formation

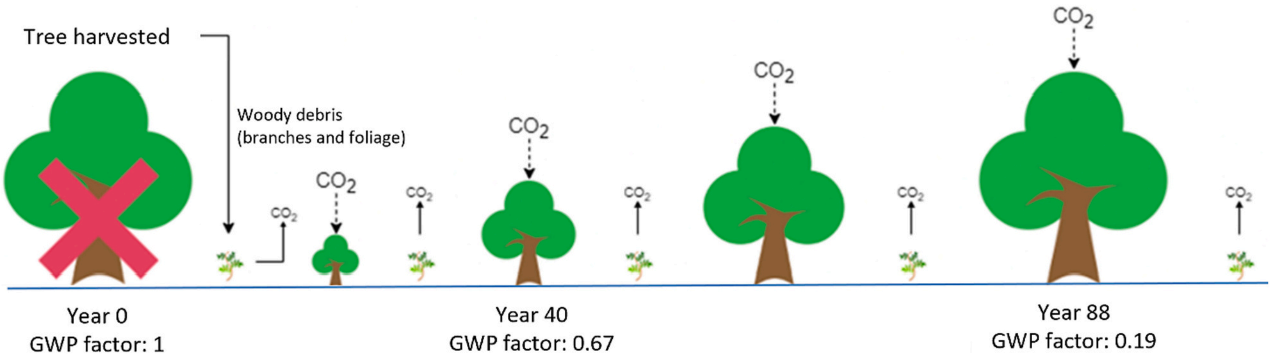

Fig. 3. The diagram shows the logic of the forest model after a tree harvest in year 0, whereafter a new tree is grown and sequesters carbon during the rotation period. Woody debris is considered left on the forest floor to emit CO_2, with temporal GWP factors decreasing over time (Schmidt and Brandao, 2013).

(vegetation), and non-renewable energy. The Stepwise2006 LCIA method converts emissions and other flows to the relevant impact categories above. The method uses the IPCC global warming potential with a 100-year time horizon (GWP_{100}) for assessing climate impacts. It is the most often used emission metric for climate impact, also in the EN 15804:2012 standard. The Stepwise2006 method is presented in Weidema et al. (2008) and Weidema (2009). The method is relevant because it includes characterisation factors for iLUC where the flow "Carbon dioxide, accelerated" represents the effect of accelerating 1 kg CO_2 one year earlier than otherwise the case. It is caused by natural land conversion forwarded one year because of the pressure on the global market for productive land. We omitted the following environmental impact categories because of their negligible zero impact: Ionising radiation and Ozone layer depletion. Human toxicity impact categories were omitted due to their great assessment uncertainty.

A dynamic discounting approach involves a time-correcting effect of the GHG emissions, which considers different effects of the GHG on the GWP_{100} depending on which year they are released during the 100-year time horizon. The dynamic discounting weighs current GHG emissions more important, thus an artificial way of modelling benefits of delaying GWP impacts (Brander and Broekhoff, 2023). The delay through timing of GHG emissions is relevant due to the global temperature rise has the steepest increase at present (IPCC, 2014). Further, various animal and plant species need time to adapt to changes in global temperatures and it gives time to develop carbon reducing technologies and nature-based solutions. Subsequently, the dynamic discounting entails that 1 kg CO_2 in year 0 will impact 1 kg CO_2-eq while the same emission in year 10 is weighted to only have an impact of 0.921 kg CO_2-eq (Schmidt and Brandao, 2013). All GHG emissions in the years 100 and later do not impact the climate in this approach due to the emissions occurring beyond the 100-year time horizon. The timing is explained further by Schmidt and Brandao (2013) and builds upon the IPCC Bern carbon cycle (IPCC, 2007).

3. Results

3.1. Material stock

The total material stock, kg normalised per m^2 gross floor area, of SFH for wood-based construction is slightly lower than for conventional with RSPs of 60 and 100 years, as presented in Table 1. The conventional scenario has only 5 % of the stock replaced for 60 years, increasing to 18 % with the 100-year RSP. The equivalent RSPs for the wood-based construction result in 35 % and 49 % being replaced, which are remarkedly larger replacement numbers than for the conventional SFH.

The material stock results for MFH for 60- and 100-year RSPs show that 721 and 770 kg/m^2 of material is needed for wood-based construction compared to the 1862 and 1941 kg/m^2 needed in conventional construction. Wood-based construction again has a larger share and absolute mass of the material stock from the replacements than conventional construction, with the mass being 91 and 155 kg/m^2, respectively. The absolute quantity replaced in the conventional construction amounts to 52 and 131 kg/m^2.

The OB have a lower material stock over the life cycle in the wood-based construction than the conventional scenario. The difference in share belonging to the stages of production and replacements between the two scenarios is small in distinction, particularly compared to the two other building typologies.

In the conventional scenario in general, concrete and fired clay are the most dominant materials in mass, followed by aggregates and steel. Turning to the wood-based scenario, concrete and biobased materials are the most employed materials, and with considerably less mass, they are followed by clay and plaster. (see section 2 in the SI for further details).

3.2. Environmental impact assessment

In this section, we will present the principal findings of the current investigation. The overall trend of the difference in climate impact and the other impact categories between construction scenarios is initially presented for the three building typologies. After, we unfold a deeper dive into climate impacts by showing results of the life stages and then for different material categories.

3.2.1. Trends in the difference of environmental impacts between construction scenarios

The results in Fig. 4 compare the environmental impacts of conventional and wood-based construction meeting the future building demand in Denmark. It does so by providing the percentage difference in impact between the conventional and wood-based construction scenario (wood-based minus conventional) across the assessed environmental impact categories. The results show an increased impact when switching to wood-based construction for SFH and OB for all impact categories. For the MFH, a switch to wood results in lower impacts for the climate impact category and most other environmental impact categories, except for nature occupation (RSP_{60} and RSP_{100}) and terrestrial ecotoxicity (RSP_{100}), which see an increased impact. The overall increase in impacts on nature occupation, representing biodiversity, for all three building typologies when shifting to wood-based construction arises because of the additional demand for land from the increased use of wood. The impact of nature occupation means taking up an area of land over a period (e.g., years). The potential disappeared fraction of endemic species during this period for a particular type of land area is represented by a damage number. That damage number indicates the potential for endemic species reduction compared to if the land area was not converted. However, besides the two mentioned impact categories for MFH, a closer inspection of Fig. 4 shows that the common trend of the remaining impact categories for each building typology is that they follow the trend of climate impact. Based on obtained results and previous studies (Lasvaux et al., 2016; Roesch et al., 2021; Cardoso et al., 2024), highlighting the correlation of global warming potential with other environmental indicators, the onward investigation of the results

Table 1

Material quantities in terms of weight divided into production stages and replacements for conventional and wood-based construction for 60- and 100-year RSPs for all building typologies. The weight is the share between life cycle stages and absolute weight as kg/m^2. SFH = single family houses, MFH = multi-family houses, OB = office buildings.

Typology		Production (A1-A3)				Replacements (B4)				Total	
		Conventional		Wood-based		Conventional		Wood-based		Conventional	Wood-based
		Share	kg/m^2	Share	kg/m^2	Share	kg/m^2	Share	kg/m^2	kg/m^2	kg/m^2
SFH	60 years	95 %	1260	65 %	735	5 %	70	35 %	389	1330	1129
	100 years	82 %	1260	51 %	735	18 %	283	49 %	706	1543	1441
MFH	60 years	97 %	1810	87 %	625	3 %	52	13 %	91	1862	721
	100 years	93 %	1810	80 %	625	7 %	131	20 %	155	1941	770
OB	60 years	97 %	1420	94 %	963	3 %	41	6 %	57	1461	1010
	100 years	95 %	1420	90 %	963	5 %	69	10 %	104	1489	1067

Fig. 4. The difference in impact between the conventional and wood-based scenarios (wood – conventional) for the considered impact categories for the three building typologies for RSP_{60} and RSP_{100}. The arrows show the GWP trend, and the red box highlights the impact categories that do not follow the GWP trend. Pay attention to the change in vertical axis values. SFH = single-family houses, MFH = multifamily houses, OB = office buildings. RSP_{60} = reference study period of 60 years, RSP_{100} = reference study period of 100 years, Photochem. ozone, veg. = photochemical ozone – vegetation, PM = particulate matter, TEG = triethylene glycol, PDF = potentially disappeared fractions of species, UES = unprotected eco-system, ppm = part per million, w = water, s = soil, $m^2 \cdot a$ = m^2 arable land.

hence concentrates on the climate impacts.

3.2.2. *Climate impact for the two construction scenarios*

The actual GWP impacts of the consequential LCA provided in Fig. 5 show that a shift to wood-based construction leads to an increased climate impact for SFH from 6.6 to 10.2 kg CO_2-eq/m^2/year for RSP_{60} and from 4.5 to 7 for RSP_{100}. When shifting to wood for MFH, the GWP impact decreases from 9.9 to 6.3 kg CO_2-eq/m^2/year for RSP_{60} and 7.5 to 4.6 for RSP_{100}. The GWP impact for OB also increases when shifting to wood-based construction, rising from 6.5 to 8.4 kg CO_2-eq/m^2/year for RSP_{60} and from 4.8 to 6.4 for RSP_{100}. From the data in Fig. 5, it is apparent that the absolute differences in climate impacts between conventional and wood-based construction are largest for RSP_{60} for all three building typologies, regardless of which construction scenario has the

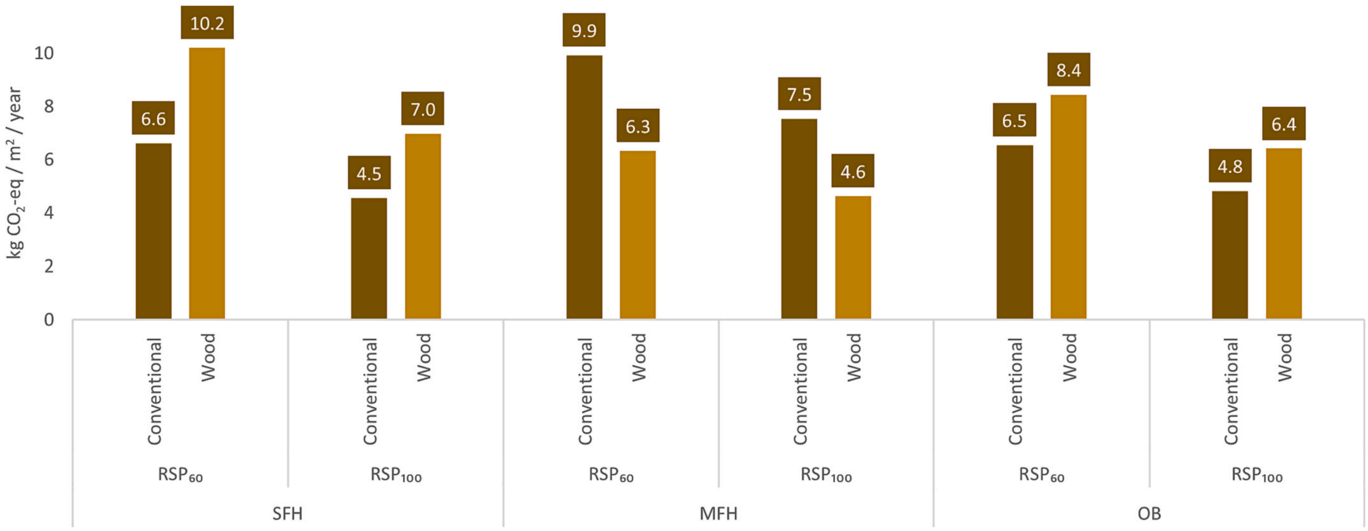

Fig. 5. The total climate impact of the construction scenarios. SFH = single-family houses, MFH = multifamily houses, OB = office buildings, RSP_{60} = reference study period of 60 years, RSP_{100} = reference study period of 100 years.

lowest climate impact. The differences in GWP impact highlighted in this section need further inspection of the life cycle stages to understand the factors affecting the impact.

3.2.3. Climate impact distributed on life cycle stages for the two construction scenarios

Fig. 6 compares the GWP impact of the life cycle stages A1-A3, B4, and C3-C4 + D for a change to wood-based construction for the three building typologies for RSP_{60} and RSP_{100}. Interestingly, the figure shows that a considerable part of the impact occurs in the production stage for all building typologies in both construction scenarios except for the wood-based SFH for RSP_{100}. In that situation, the replacement rate drives the larger impact of SFH in the wood-based scenario. In contrast, the production and end-of-life stages are closer to being similar for both construction scenarios.

Turning to the assessment of the life cycle stages of MFH, the production stage has the largest impact share for both construction scenarios. Still, its absolute impact is strikingly larger in the conventional scenario. Evidently, the end of life of the conventional scenario, particularly for RSP_{60}, has larger negative (avoided) GWP impacts than the wood-based scenario. The replacements' impact is slightly larger for the wood-based scenario but without a noticeable effect on the overall result.

The GWP impact for OB is similar to the results of the MFH just reversed. For this typology, the production stage has the largest share of GWP impact in both construction scenarios, and now, the wood-based construction exhibits the largest absolute impact. The larger negative (avoided) GWP impact of the wood-based scenario compared to the conventional at the end of life for RSP_{60} does not counterbalance the larger production stage impact. Again, the replacements in the wood-based scenario led to slightly larger GWP impacts but without effect on the overall result.

The negative numbers for GWP impacts at the end of life represent reductions in GWP impacts when the materials are recycled because they substitute other materials on the market with the same function, which then does not have to be produced. Therefore, it is not reductions in impacts of the buildings as such but expected reduced impacts of the avoided production. The wood materials also have negative numbers for GWP at the end of life since 90 % is assumed recycled, thus replacing virgin production of wood products. Further, modelling the timing of CO_2-eq emissions relative to the GWP_{100} time horizon means that biogenic carbon emissions have a smaller impact factor the closer to the 100 years the emission occurs.

3.2.4. Climate impact distributed on material categories for the two construction scenarios

Analysis of the material categories for SFH in Fig. 7 shows that mineral based materials, predominantly concrete, contribute mostly to the GWP impact in the conventional scenario with 2.3 kg CO_2-eq/m^2/year for RSP_{60} and 1.4 for RSP_{100}. Fired clay (bricks) and metals follow with a considerable impact, where metals increase their impact in RSP_{100} compared to $RSP_{60,}$ which is not the situation for fired clay. What stands out for the change to wood-based construction is that biobased materials are the largest and almost single contributor to the GWP impact, increasing by 6.4 kg CO_2-eq/m^2/year for RSP_{60} and by 4.1 for RSP_{100}. The result also indicates negative GWP impacts, i.e., reductions in impacts, from mineral based materials and fired clay because the first is less used and the second is not applied in the studied buildings in the wood-based scenario compared to the conventional.

The results provided in Fig. 8 of the GWP impact distributed on material categories for MFH reveal metals as the most impacting material group in the conventional scenario, with 4.7 kg CO_2-eq/m^2/year for RSP_{60} and 4.3 for RSP_{100}. Mineral based materials follow with 3.7 kg CO_2-eq/m^2/year and 2.3 for the respective RSPs. The remaining materials have a minor impact. Biobased materials lead to the largest change in GWP impact when changing to wood-based construction. However, it is a modest increase compared to the avoided GWP impacts from decreased use of metals and mineral based materials, which is why the wood-based MFHs accomplish reduced impact compared to conventional construction.

The extension from RSP_{60} to $RSP_{100,}$ i.e., more years to divide the impact into, for conventional construction reveals metals' GWP impact of 4.7 kg CO_2-eq/m^2/year in Fig. 8 to be almost counterbalanced by the need for replacements of 4.3 kg CO_2-eq/m^2/year. Opposingly, the mineral-based materials encounter notably diminished impact when extending the RSP, 3.7 reduced to 2.3 kg CO_2-eq/m^2/year. This condition also holds for the wood-based scenario where the avoided impact of mineral based materials in RSP_{100} is reduced relative to RSP_{60}. The biobased materials in the wood-based scenario appear to partly balance out the RSP extension by increased replacements.

Turning to OB in the conventional scenario in Fig. 9, mineral based materials and metals appear as the most prominent sources of GWP impact with 2.9 and 2.3 kg CO_2-eq/m^2/year for RSP_{60} and 1.8 and 2.2 for RSP_{100}. Metals are the material group with the largest increase in impact with the change to wood-based construction, with 1.5 kg CO_2-eq/m^2/year for RSP_{60} and 1.3 RSP_{100}. Biobased materials follow closely with an impact increase of 1.4 and 0.9 for RSP_{60} and $RSP_{100,}$

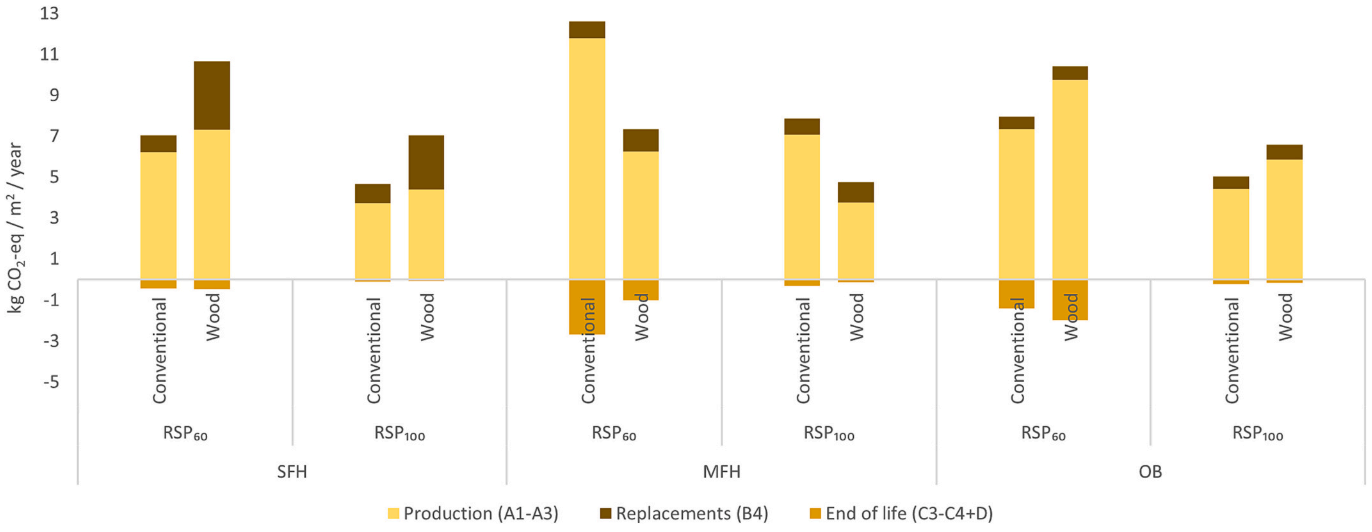

Fig. 6. Climate impact of the construction scenarios distributed onto life cycle stages. SFH = single-family houses, MFH = multifamily houses, OB = office buildings, RSP_{60} = reference study period of 60 years, RSP_{100} = reference study period of 100 years.

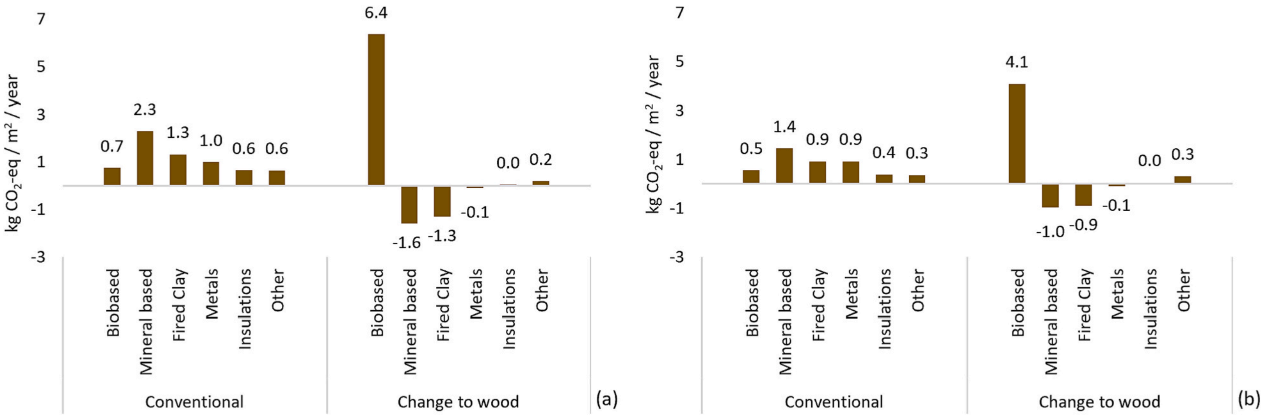

Fig. 7. The climate impact (kg CO_2-eq/m^2/year) for single-family houses of conventional construction and the change to wood distributed onto materials. The change to wood shows the difference in wood construction relative to conventional. (a) Shows the climate impact for an RSP of 60 years. (b) Shows the climate impact for an RSP of 100 years. RSP = reference study period.

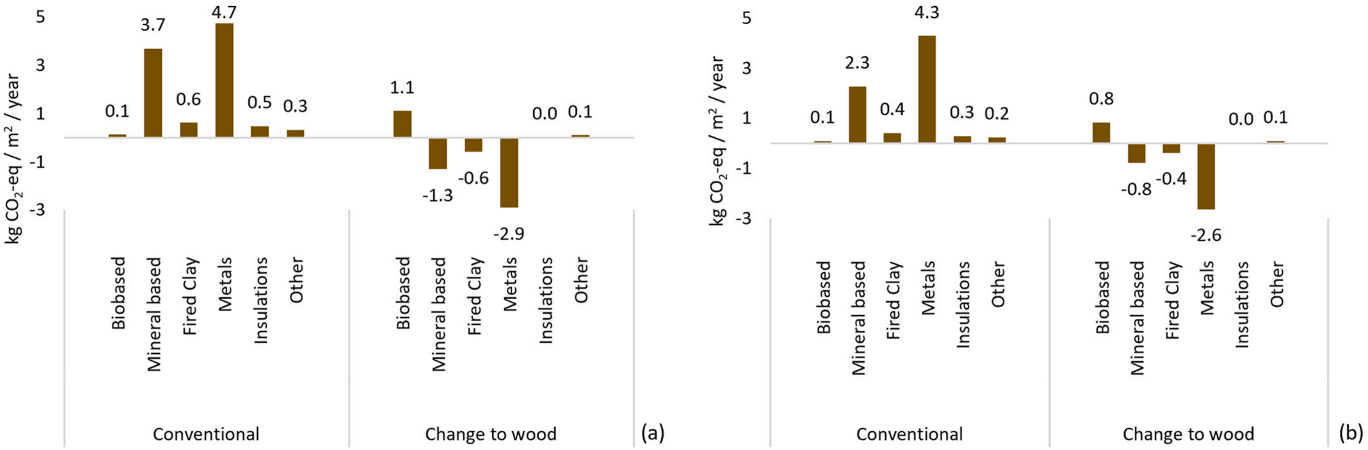

Fig. 8. The climate impact (kg CO_2-eq/m^2/year) for multifamily houses of conventional construction and the change to wood distributed onto materials. The change to wood shows the difference in wood construction relative to conventional. (a) Shows the climate impact for an RSP of 60 years. (b) Shows the climate impact for an RSP of 100 years. RSP = reference study period.

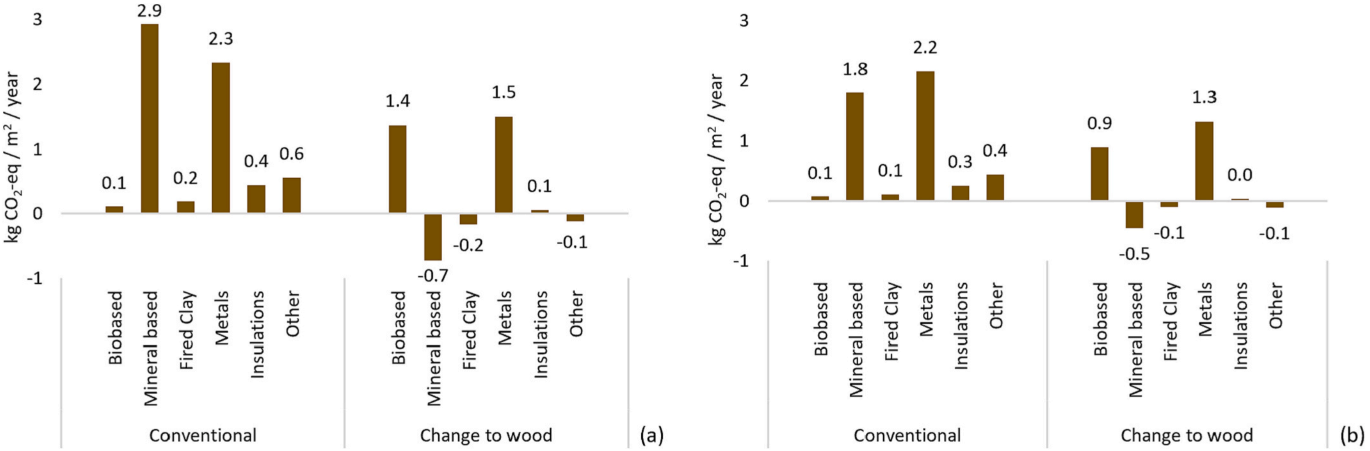

Fig. 9. The climate impact (kg CO_2-eq/m^2/year) for office buildings of conventional construction and a change to wood distributed into materials. The change to wood shows the difference in wood construction relative to conventional. (a) Shows the climate impact for an RSP of 60 years. (b) Shows the climate impact for an RSP of 100 years.

respectively. The impact reductions in wood-based construction primarily come from the avoided use of mineral-based materials.

Regarding the two analysed RSPs, we see that mineral-based materials and metals change order regarding which of those mostly contribute. As for the MFH, the extended RSP to 100 years leads to diminished GWP impact of mineral based materials for the OB, indicating that metals are expected to involve more replacements. The wood-based scenario shows that biobased materials for the OB also modestly diminish when extending the RSP from 60 to 100 years. It suggests that an expected increase in replacement does not counterbalance the extended RSP.

Together, these results provide insights into how the change from conventional to wood-based construction potentially differs for each building typology under study. It was also found that extending the RSP from 60 to 100 years reduces impact per year and is not counterbalanced by increased replacements. It emerged that mineral based materials, metals, and biobased materials predominantly influence the GWP impact depending on the considered construction scenario. These insights depend on the applied case study buildings, future building stock modelling, and method aspects related to forestry and consequential modelling, which are elaborated and discussed in the subsequent discussion chapter, including a sensitivity debate.

4. Discussion

Overall, the study provides insight into the expected main construction products and affected suppliers in a conventional construction scenario and when changing from conventional to wood-based construction. It is an early exploratory study investigating how results evolve regarding this change in demand when using consequential LCA and forestry modelling based on a forecast based on a confined building sample. Therefore, it is important to note that the results in this study must be handled and interpreted based on the choices and assumptions used in the study, including RSP, case studies, forest model, indirect land use change method, time-correction of GHG emissions, and the industry sector aggregation level in EXIOBASE. We explain these aspects further during this discussion of this study.

The study assessed the market effects based on the most competitive suppliers, using the trends in production data over time as a proxy to represent competitiveness. It is assumed the suppliers' ability to increase production over time indirectly reflects production constraints, e.g., in the form of resource availability, quotas, and policies. Nonetheless, these should ideally be assessed more explicitly. Further, an assessment was conducted of which affected suppliers and products have the largest influence on the climate impact of a shift from conventional to wood-based construction. This study also explains how results are influenced by the time-correction of GHG emissions and the dynamic timing of biogenic carbon fluxes, considering the temporary storage of biogenic carbon in wood materials and the uptake and release of biogenic carbon in forests at the stem level. The study's modelling and results should be seen in the context of the specific case buildings used. Although this study assesses the full spectrum of environmental indicators recommended in EN15804, 2011, the details and specifications are provided only on the GWP. This choice is justified through the previous literature of Lasvaux et al. (2016), Roesch et al. (2021), Cardoso et al. (2024), highlighting the strong correlation of the GWP with other environmental indicators, also identified through the results of this study, and the current urgency to solve the problem of climate change.

4.1. Case buildings

The results revealed that in some cases, it may be more climate-friendly to build more conventional construction, especially concrete, and that in other cases, it may be best to build with wood. The climate impacts illustrate how the characteristics of the specific cases and building typologies used in this study affect the general LCA-based decision support. This study uses a sample of three buildings per building typology for conventional and wood-based construction scenarios. The case studies were randomly chosen and then composed into an average building based on the three case studies for each building typology. The random choice also revealed that some of the chosen office buildings for the wood-alternative are bordering on hybrid structures, thus not being complete wooden constructions.

The one wooden single-family house contains a large amount of clay and eelgrass, with every biobased material modelled as wood, i.e., closer to typical wooden buildings. Likely, the results for the case building with eelgrass are slight overestimates, as wood is expected to have a larger climate impact than eelgrass. This is not expected to affect the overall conclusion of this study due to the relatively low material quantity of eelgrass in the specific case buildings, hence limiting its contribution to the climate impact. Another of the SFH case buildings has a green roof (sedum roof), which has a considerable mass and is categorised as biobased material, potentially influencing the result.

Concerning the wood-based office buildings, steel is part of some load-bearing structures in two case buildings. It appeared to significantly influence the climate impact, which may change with the inclusion of case studies where parts of the load-bearing structure do not include structural steel. On the other hand, it shows that some office buildings currently use steel. Since steel is a relative hotspot, it will be important to find construction methods that reduce its use in the load-bearing structures to decrease the climate impact of wood-based office buildings.

The relatively limited sample of case buildings should be expanded in future studies to comprehend better how the future wood building would look, particularly regarding single-family houses and office buildings. Therefore, the results are also likely to change using other case buildings. If metals' GWP impact in the wood-based OB decreases below the GWP of metals in the conventional OB, the conclusion of conventional OB having the least GWP impact likely changes. A similar GWP level of metals in both scenarios just does not alter that conclusion. The wood-based SFH requires larger reductions of biobased materials to change the conclusions for RSP_{60} from 8.7 to 5.1 kg CO_2-eq/m^2/year and RSP_{100} from 5.5 to 2. As the roofs' impact share of the biobased impact is about 40 % (SI Figs. 8 and 9), and it includes sedum green roofs, which is not made of wooden material, the reduction could possibly occur but necessitates more investigations. In the future, it may be beneficial to look at other countries with a greater tradition of wood construction to investigate how the characteristics of wood buildings may evolve.

4.1.1. The influence of the reference study periods and the end-of-life scenarios

The results show that a longer lifespan for the buildings leads to significant savings in climate impact per year for both construction scenarios despite the greater need for replacements. However, for a change to wood-based construction, the greater need for maintenance and new materials in connection with replacements during the buildings' service life results in significant climate impact. It should also be noted that the RSP influences the end-of-life biogenic carbon emission for wood. The 100-year RSP excludes biogenic carbon emissions at the end-of-life because their emissions occur beyond the GWP_{100} time horizon. These end-of-life avoided GWP impacts' lower-end share of the total impacts appear consistent with studies that do not account for GHG emissions beyond the GWP time horizon (Schmidt and Dalgaard, 2016; De Rosa et al., 2018). Conversely, longer time horizons yield interesting indications of the potential evolution of end-of-life emitted biogenic carbon and substitution effects (Cordier et al., 2022). Alternatively, it reduces the weight given to current emissions (De Rosa et al., 2018), which IPCC (2023) states to be crucial for urgently mitigating climate change. In addition, the recycling scenarios further influence the biogenic carbon at the end of life depending on the split between wood for recycling and incineration.

Another aspect with some uncertainty in the case studies is the material demand for replacements in both scenarios for all building typologies. First of all, it is uncertain to predict trends for long service life products such as buildings as many future factors besides technical durability can influence the service life, for instance, changed desires of functionalities, aesthetics, politics, etc. Secondly, the expected average service life of the individual materials is also linked with uncertainties from technical considerations and aesthetic and functional properties. Therefore, the material flows and environmental impacts of replacements require cautious interpretation. It should also be emphasised that production methods and waste treatment can be expected to change significantly over the long service life of the buildings, which adds further uncertainty to the results. For example, future changes in steel production that make production more climate-friendly may affect the results. The same applies to more general changes, such as changes in marginal electricity mixes, which generally influence all economic activities while having less influence on land use change.

With about a third larger GWP impact of the conventional MFH compared to wood-based, the outcome that wood-based is better appears quite robust because scenarios of lower impacting German steel and 10 years longer rotation unlikely change the large gap between the two construction technologies of this building typology. The sedum roof uncertainty primarily reduces the robustness of the SFH to perform best in the conventional scenario. Yet, considering the GWP impact disparity between construction scenarios, sensitivity to rotation period, marginal steel supply, and iLUC, it indicates that the conventional SFH, to some certainty, could perform better than the wood-based in most instances, albeit probably with a lower GWP impact gap. The OB outcome is uncertain because of the smaller GWP impact gap between construction scenarios and the steel quantity in wood-based construction, necessitating further investigation to reach conclusions. At the tail of this discussion on the contingent robustness of the results, the superior climate-friendly construction technology scenario does not stand out. The biodiversity impacts increase in all wood-based scenarios, which could render the potential climate benefits of wood ineffective, implying that investigations on levers to reduce biodiversity impacts need more attention.

4.2. *Methodological implications and limitations*

Time correction of GHG emissions is used in the study relative to a time horizon of 100 years in the GWP_{100} indicator. This means that emissions will have the largest impact in year zero and then decrease towards year 100, from where they do not have an impact. It therefore weighs current production stage (A1-A3) GHG emissions higher than emissions later in the life cycle. Although this approach is not aligned with the temperature changes, the values of GWP must not be compared with the limit values related to the carbon budget, but it represents the only way to artificially account for the benefits of temporary carbon storage (Brander and Broekhoff, 2023).

In general, the use of input-output data significantly influences the results (Castellani et al., 2019). As previously described, input-output data has the advantage of working with full completeness without arbitrary cut-offs in the database, meaning that the entire economy is included. Hence, the results will theoretically be closer to their actual impact compared to process data. Additionally, the process databases often also lack details on markets and geographical representativeness, which is well covered in the IO database, specifically for the Global North, and was thought relevant when assessing large-scale changes in CLCA. iLUC is also not assessed in process databases like Ecoinvent, which EXIOBASE conversely includes. The disadvantage is that input-output databases work with aggregated sector data, where many products can belong to the same sector, as the example of gypsum and cement below illustrates. Work is currently being done to address this limitation of input-output databases. One example is the Research Project: Getting the data right (2023), where the goal is a hybrid input-output database with much higher granularity than what currently exists. In the future, it will be possible to create improved LCAs that reduce these limitations of aggregation.

In EXIOBASE, gypsum belongs to the same sector as cement due to the relatively high aggregation in the current database. The reader needs to consider this for the climate impact of gypsum, which will typically be lower than cement. Since the results for a change to wood show a higher utilisation of gypsum, this uncertainty will cause the emissions from gypsum to be overestimated. However, as gypsum does not contribute significantly to the result in the mineral based material group, this is not considered to influence the study's overall conclusions.

4.2.1. *Sensitivity analysis*

The sensitivity analysis in Table 18 in the SI shows that the marginal steel from China has a significantly larger carbon footprint than the sensitivity scenario with European steel from Germany. Future changes in the steel market could make China no longer a marginal steel supplier. This could, for example, be the case in a scenario where countries like Denmark choose to pay a higher price for steel from Europe to create a business case for increasing German steel production.

In the sensitivity scenario with German cement, we only see a small difference in climate impact, which means that changes in the more localised market for cement do not have a large effect on the climate impact of construction.

It is shown in the sensitivity analysis that inputs in the form of the rotation time in the forest model have a significant role in the climate impact of wood-based construction. It is, therefore, important to emphasise that deviations in forestry from the current modelling can potentially greatly impact the results. This illustrates the complexity of modelling wood in LCA, where many factors can affect the outcome. It is worth noting that the data used to identify Sweden as an affected producer by increased demand for wood is only available up to 2017, reducing this assessment's timeliness.

The exclusion of the forest model has enough influence to change the overall conclusion that conventional construction has a lower GWP impact for SFH and OB than wood-based construction (see Table 9 in SI). However, the results without the forest model show modest savings of climate impact in the wood-based scenario, where we have to bear in mind that it potentially shifts the environmental impact to biodiversity due to changing to wood (see Fig. 4).

The results of excluding iLUC and forest modelling showed an even more significant reduction in climate impact when changing to wood-based construction. Although iLUC does not alter the ranking of the average m2 across the building typologies for wood-based construction, the resulting increase in the wooden GWP impact occurs similarly in other studies (De Rosa et al., 2018; Forster et al., 2019). It illustrates how these inclusions can lead to significant changes in the decision support of LCA results of construction practices. This emphasises the importance of future focus on such mechanisms and their models, as their influence on the results' subsequent conclusions is very apparent.

4.2.2. *LCA methodology*

As illustrated by the study, modelling wood in LCA is complex, with many factors influencing the result. Significant parts of the climate impact of wood are theoretically different from, e.g., emissions from fossil fuels or calcination in cement production because carbon emissions from higher demand for wood relate to the forest carbon cycle, notably deforestation as an effect of iLUC. Instead, calcination introduces additional carbon to the atmosphere outside of this cycle. However, it should be emphasised that since this study looks at the impact of human-induced activities, including changes in forestry and global land use impacts, there will be no distinction between these emissions. Here, the higher demand for wood and concrete, for example, will contribute to additional climate impact in different ways due to the different life cycles, as previously described. The pressure on the market for land will accelerate land use change on a global scale. An increased demand for wood will lead to additional production from land, leading to climate impact, although the land and wood relate primarily to natural carbon cycles. Again, remember that the carbon cycle is linked to when the carbon emissions occur during the 100-year horizon of GWP_{100}. The earlier the GHG emissions are released, the larger their impact using this method. For the other impact categories, the

Stepwise2006 method is not expected to cause a larger contextual difference for Denmark than other impact assessment methods because it was developed in Denmark while building upon the methods Impact 2002+ and EDIP2003 (Weidema et al., 2008; Weidema, 2009).

This study differs from similar studies in several ways. First, most LCAs of buildings hitherto performed are attributional. In contrast, this study uses consequential LCA, which answers questions about causality and the environmental impacts arising from a decision. As explained earlier, it means the focus is on the expected affected suppliers in the market, and co-products are modelled using substitution, where co-products displace alternative production when supplied to the market. For example, the wood processing in the sawmill creates co-products that substitute alternative biomass in the form of pulpwood. The attributional LCA typically handle co-products through allocation, where a specific allocation key is used to distribute the environmental impact to the co-produced products. This could, for example, be economic value or weight. Accordingly, the two LCA approaches fundamentally differ in system modelling and address different intended purposes.

4.2.3. *Forest modelling and iLUC*

As mentioned, this study uses a forestry model to model and time-correct the uptake and emission of CO_2 in the forest as the replacement tree grows. The advantage of using such a model is that an overall result for the forest's climate impact can be calculated in more detail. As illustrated in Table 19 in the SI, the GWP impact of the forest model changes significantly in the different replacement years. It revolves around whether the replacement tree in a particular year overall sequesters or emits carbon set in relation to the 100-year time horizon of the GWP_{100}. One of the assumptions in the forest model is that foliage and branches are left on the forest floor and release CO_2 over time. In some situations, these residues may be utilised for other commercial purposes in forest management not investigated in this study (Duncker et al., 2012). Similar applications exist of dynamic CLCA of wood buildings based on the Bern carbon cycle combined with forest modelling (De Rosa et al., 2018; Fauzi et al., 2021; Cordier et al., 2022), though using individual forest models with replanting relevant for their context, while Skullestad et al. (2016) uses the GWP_{bio} factors (Guest et al., 2013).

Since the co-products from the sawmill are modelled using substitution, the result for pulpwood greatly impacts the result for wood for construction. Table 20 in the SI shows that the climate impact of the forest model for pulpwood is considerably lower than that of construction wood. Since pulpwood in this study is modelled as the same Swedish forest as for the construction wood, with half the rotation time, the forest model is sensitive to these inputs. This was again demonstrated in the sensitivity scenario with an increased rotation time of 10 years. Therefore, a note of caution is due here since the forest model for pulpwood and the assessment of pulpwood as an avoided product significantly impact the climate impact of wood used in construction. Other studies also identified the substitution of pulp wood and its effect on increased wooden GWP impact (Schmidt and Dalgaard, 2016; De Rosa et al., 2018), whereas substituted natural gas decreases the wooden GWP impact but not as considerably as if excluding dynamic biogenic carbon (Skullestad et al., 2016). If the pulpwood is used for energy production, the carbon in the wood will be emitted as CO_2. Even assuming that the co-products from the sawmill will be used directly for energy purposes, the result will be the same as incinerating the pulpwood because the co-products would then displace this incineration of the pulpwood. Wood's reduced climate mitigation effect due to its co-products' substitution effect has also emerged in a few other studies that combine consequential LCA with time-dependent biogenic carbon uptake and emission when analysing wood-based construction (Hansen et al., 2022a).

In addition, the iLUC is considered in this study. This illustrates the effect of increasing the land area for productive purposes, such as managed forests. The demand for land applies pressure on the global market for land, which can potentially drive cultivated land into natural areas. This iLUC effect is difficult to quantify from an attributional perspective, which is why there is currently no consensus on its modelling when it is not analysed on a global scale. For the same reason, this effect is often omitted from LCAs despite the global climate impact related to land use, land use change, and forestry, which is known to cause about 11 % of global anthropogenic GHG emissions in 2019, though with large uncertainty on this estimate (IPCC, 2023).

It should be emphasised that the demonstrated high sensitivity of the climate impact on the forest and iLUC model must be considered when interpreting the results. The results of this study show that future work on LCA calculations of the potential for wood in construction should focus on the development of forest models and a more detailed understanding and modelling of the relevant forests and their forestry practices. Since the market for pulpwood is also affected through by-products, this focus is even more key, as this alternative production has a major influence on the resulting climate impact. It is clear that modelling of the displaced alternative biomass should be a focal point, as different data and assumptions may lead to different conclusions for decision support.

Due to the demonstrated high influence of forest modelling, it is crucial to increase the focus on impacted wood suppliers in the future. In a recently published report, Brownell et al. (2023) uncover the Danish market for wood. The report shows that Danish wood consumption is increasing in the energy and building sectors. This clearly underlines that the importance of modelling wood in LCA will increase as wood becomes more important in a Danish context. The report also shows Sweden as the primary relevant country for Danish wood consumption. A focus should be placed on these wood markets in the future, as it can have major implications for the environmental impact of wood.

5. Conclusion

The present research investigated the environmental consequences of a change from conventional to wood-based construction and how aspects in consequential LCA, forest modelling, and indirect land use change (iLUC) modelling influence the results for 60 and 100 years of reference study periods (RSP). Obtained results show that conventional construction to have lower global warming potential score than wood-based for building typologies of single-family houses and office buildings, respectively, by 35–36 % and 23–25 % for RSP_{60} and RSP_{100}. On the other hand, the multifamily houses presented 36–39 % lower impacts in the case of wood-based construction for RSP_{60} and RSP_{100}.

The assessment shows that the environmental impacts overall follow the trend of the global warming potential impact for the three building typologies except for nature occupation and partly ecotoxicity (dependent on the RSP). In addition, the more significant findings encountered that the climate impacts are notably sensitive to the rotation period in the forest model, forest modelling itself, iLUC, and the identified affected steel supplier.

The study has also found that conventional construction has more material mass linked to the production stage (A1-A3), and wood-based material mass is more linked to the replacements (B4). Shifting RSP from 60 to 100 years increases the replacement rate mostly for conventional construction due to some mineral-based materials, fired clay, and metals beginning to need replacements. The extension of the RSP to 100 years reduced the climate impact per m^2 per year for all three building typologies of single-family houses, multifamily houses, and office buildings in both the conventional and wood-based construction scenarios, despite the increased number of replacements. Although the extension of RSP has not shown to change the conclusion comparing conventional with biobased construction, the difference between GWP scores becomes smaller and slightly shifted in favour of wooden buildings. The main reasons behind the climate impact of the three building typologies were the biobased materials, mineral based materials (concrete), and metals (steel).

The study contributes to understanding which modelling approaches, and methodologies need further analysis when conducting an environmental assessment for decision support of changing to wood-based construction. Meanwhile, the small sample size of available case buildings, three case buildings for each building typology, did not allow for a complete assessment of what these would look like in the future. The aggregated sector data representing the materials in the input-output model further limited the study. A higher granularity would be useful to understand the impacts of different building materials. Changing the affected concrete supplier has minimal effect on the result, whereas changing the steel supplier considerably affects the GWP impact in favour of conventional construction. Including iLUC and forest modelling increases the GWP impact of wood-based construction relative to conventional. However, iLUC inclusion does not change construction scenario ranking, but excluding the forest model results in the wood construction having the lowest GWP impact overall. The rotation period in the forest model notably influences the GWP impact of wood-based construction. Thus, using a well-determined rotation period or considering a range of expected rotation periods can be useful because future climate change may affect forest production.

Despite its exploratory nature, this study offers insight into the improvements that will be needed on the design layout and archetypes of future buildings, particularly the wood buildings, on the forest model with data from relevant forestry practices, on the modelling and uncertainty of the iLUC, and finally on the identification of affected suppliers of steel and co-products from wood production. Further research could also usefully explore how different scenarios for the development of the future building stock can best mitigate climate impacts from the building industry, both with and without a change to wood-based construction.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used the Grammarly software in order to spell and grammar check the article. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors of this paper declare no known competing interest with regard to the research completed in this article.

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Appendix A. Supplementary data

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