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Implications for Design Incentives

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Temporal considerations in life cycle assessments of wooden buildings: Implications for design incentives

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ABSTRACT

The building and construction sector plays a vital role in mitigating climate change. Consequently, the use of wood and bio-based materials as a strategy for reducing the environmental impact of buildings is increasing. However, along with realising the potential environmental benefits of biomass, the focus on assessment methods and their inherent uncertainties increases. Typically, Life Cycle Assessment (LCA) is used for quantifying the environmental performance of buildings but is often criticised for not considering temporal factors related to emissions. Therefore, dynamic LCA approaches have been developed. To understand how dynamic LCA influences building design incentives, this study compares traditional LCA and dynamic LCA results on 45 cases of wooden buildings. The study finds that the overall ranking of the buildings' environmental performance is stable, irrespective of the method used. However, the dynamic biogenic carbon accounting methods significantly influence the results and shift burdens between upfront and future emissions. Therefore, methods for time-distributed biogenic carbon accounting crucially need addressing in LCAs of wood and bio-based products.

1. Introduction

1.1. Climate mitigation in the built environment

Climate change has become a pressing issue. Human-induced climate change has already triggered far-reaching damage, and the escalation in weather and climate extremes has resulted in irreversible impacts on both natural and human systems (IPCC, 2022). In 2015, realising the importance of climate mitigation led to the adoption of the Paris Agreement, in which 175 countries committed themselves to limiting global warming to well below 2 and preferably to 1.5 °C compared with pre-industrial levels (United Nations). The Paris Agreement highlighted countries' commitment to combating climate change, and since then, several countries have introduced national targets for greenhouse gas (GHG) reductions. An example is Denmark, which in 2020 made a national agreement to reach a 70% reduction of GHG emissions by 2030 compared to 1990 levels (The Government, 2019).

The built environment is critical in mitigating climate change. Together, buildings and construction account for 36% of global energy use and 39% of energy-related CO_2e emissions (International Energy Agency for Global Alliance for Buildings and Construction, 2019). Burning fossil fuels in buildings for energy, heating and cooling is a significant source of GHG emissions. The energy-intensive manufacturing processes for construction materials further contribute to GHG emissions (International Energy Agency for Global Alliance for Buildings and Construction, 2019). For many years, the primary focus has been optimizing buildings' energy efficiency to achieve GHG emission reductions. However, recent studies suggest that construction materials contribute approximately two-thirds of total GHG emissions from buildings and are crucial in reducing such emissions (Birgisdóttir and Madsen, 2017), (Zimmermann et al., 2021). Hence, new low-impact strategies have been introduced, such as retrofitting buildings for new purposes, reusing and recycling materials, and using more wood and bio-based materials (Fellner et al., 2017), (Pomponi and Moncaster, 2017), (Ghisellini et al., 2018), (Nuβholz et al., 2019), (Andersen et al. a).

Increasing the use of wood and bio-based materials is promoted as a low-impact strategy because of their inherent ability to sequester carbon (Jensen and Craig, 2019). In photosynthesis, trees absorb CO_2 from the atmosphere and sequester carbon within their fibers. The sequestered

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carbon is typically referred to as biogenic carbon in LCA, and, as opposed to non-biogenic carbon, biogenic carbon is considered nearly carbon-neutral over time (Prentice et al., 2001). If harvested sustainably, wood is a renewable resource that stores carbon throughout its lifespan. This potential may be further amplified if the wood is transferred and used in buildings, which will then act as long-term carbon storage until the end of life. Another environmental benefit of using wood and bio-based construction products is their low energy consumption during manufacturing and production. Compared to the energy-intensive manufacturing processes required for concrete and steel, producing wood and bio-based materials is typically less energy-intensive, resulting in lower GHG emissions (Rasmussen et al., 2021), (Gustavsson et al., 2006).

1.2. Biogenic carbon accounting in LCA

As the demand for low-impact construction materials grows, the environmental benefits of wood and bio-based materials are gaining attention. However, assessing the environmental impact of consuming wood and bio-based materials poses a challenge because of their carbon-sequestering capabilities. Life Cycle Assessment (LCA) is a standardized method of quantifying the environmental impact of products and services throughout their life cycle (Hauschild et al., 2018), (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). For buildings, LCA covers the impacts from raw material extraction, the manufacture of construction materials, construction processes, the use and operation of the building, and the disposal of the building materials at or by the end of life (CEN, 2012a), (CEN, 2012b). The biogenic carbon uptake in wood and bio-based materials is typically credited in the raw material extraction and released back by the end of life, disregarding any temporal considerations. This approach follows the −1/+1 rule to account for biogenic carbon in wood and bio-based products by the European standard EN16485:2014 (CEN, 2014a). The −1/+1 approach relies on the fundamental assumption that the biomass used in buildings comes from sustainably managed forests with continuous rotation and a constant level of carbon in the forest carbon pools so that it can be considered carbon-neutral. However, for wood and bio-based products, where carbon sequestration occurs gradually over time, this static approach may not accurately reflect the temporal dynamics of biogenic carbon sequestration in regrowing forests.

Along with the increasing focus on utilizing wood and bio-based materials in buildings, the emphasis on biogenic carbon accounting and related temporal uncertainties is gaining attention (Andersen et al. b). Several studies have investigated how to estimate the uptake and release of biogenic carbon in a temporal manner (Hoxha et al), (Levasseur et al., 2013), (Head et al., 2019), (Cherubini et al.), (Breton et al., 2018), (Tellnes et al., 2017). In (Hoxha et al), the biogenic carbon flow is represented dynamically through a biogenic carbon uptake in the forests before and after construction, resulting in significantly different impacts. However, there is no consensus on how to reflect and link the forest carbon flow with building LCAs, nor on which method is the most suitable and accurate.

1.3. Temporal emissions accounting in LCA

Besides the temporal concerns related to biogenic carbon accounting, traditional building LCAs often ignore temporality in emissions accounting. In traditional LCAs, all emissions are aggregated into one single pulse emission, irrespective of the time they occur, which implies that releasing instantaneously is the same as releasing over time (Hoxha et al), (Hellweg et al., 2003), (Ryberg et al., 2018). Thereby, this approach disregards the difference in releasing at different points in time, the accumulating effect of releasing emissions over a defined time horizon (TH), and the possibility that future emissions from long-lived products such as buildings may differ significantly from current emissions due to technological development. Altogether, this could cause time-related inconsistencies.

To account for the temporal effects, (Levasseur et al., 2010a) proposed a dynamic LCA framework. The dynamic LCA framework is commonly applied to account for temporal differences in releasing emissions, technological development and temporary carbon storage in the form of biomass. Besides including dynamic estimates of biogenic carbon uptake, as described in Section 1.2, the dynamic LCA framework also applies time-dependent characterization factors to represent the difference in releasing emissions over time, technological developments, and temporary carbon storage. This means that the applied characterization factor depends on when the emission occurs; current emissions get the full effect, whereas future emissions are discounted and thus have less effect in the atmosphere. It is crucial to be aware that the differences in characterization between the static and dynamic LCA methods are normative and merely a matter of distribution and interpretation, as releasing the same amount of CO_2 will have the same atmospheric effect, no matter which method is applied. Thereby, the dynamic characterization factors should be considered as temporal cut-off of emissions, which is not in line with IPCC guidelines for reporting long-term emissions (IPCC, 2022). The time-dependent characterization factors in (Levasseur et al., 2010a) rely on the Impulse Response Function of each GHG to estimate the cumulative radiative forcing when an emission is released. However, LCAs of buildings are often based on aggregated environmental data in, for example, Environmental Product Declarations (EPDs), where it is impossible to separate the different GHGs. Therefore, the Levasseur method is not applicable in such cases. To operationalize the approach, (Resch et al., 2021) developed an approximated approach, where emissions are simply multiplied by a discounting factor depending on the time they occur.

In addition to the dynamic methods proposed in (Resch et al., 2021), (Levasseur et al., 2010b), numerous others suggest dynamic frameworks for emissions accounting. One example is the method referred to as GWP_{bio} (Guest et al., 2013), (Cherubini et al., 2011), where an index, GWP_{bio}, is developed to estimate the climate impact of CO_2 emissions. The GWP_{bio} method focuses primarily on biogenic emissions, and thus, time-dependent characterization factors are applied for biogenic carbon flows (Guest et al., 2013), (Cherubini et al., 2011). (Breton et al., 2018) reviews dynamic methods in the existing literature concerning their approach to including temporal effects and suggests that GWP_{bio} is a simple method of accounting for biogenic carbon in LCAs. However, it only focuses on biogenic carbon flows, which may lead to inconsistencies.

1.4. Research aim

Despite the many studies trying to account for the temporal effects, there is currently no consensus on including time considerations and biogenic carbon in LCAs. Many studies focus on advancing existing dynamic methods to increase accuracy (Levasseur et al., 2013), (Guest et al., 2013), (Cherubini et al., 2011), (Shimako et al., 2018), (Negishi et al., 2018), (Faraca et al., 2019), (Head et al., 2020). Others evaluate different dynamic perspectives and consider how to apply these in LCA (Hoxha et al), (Breton et al., 2018), (Sohn et al.), (Collinge et al., 2013). Along with the growing interest in using wood in buildings and the urgency of climate mitigation, temporal emissions and biogenic carbon accounting have become more relevant and more debated within LCA communities. While there may be many scientific reasons for incorporating temporal factors into LCA, it is highly relevant to understand how the radically different approach to emissions accounting may affect building design incentives for practitioners, although this is an aspect that is rarely considered in the existing literature. Therefore, this study aims to add to this debate by investigating how including temporal factors in LCA affects building design incentives and, ultimately, real-life building designs. We do so by assessing 45 real cases of buildings using static LCA and dynamic LCA to answer the following questions.

Table 1
Main characteristics of building cases (details are described in (Andersen et al., 2024)).

Building typologies	#[a]	Year of construction	#[a]	Area	#[a]	Structural system	#[a]
Summerhouses	2	2005–2009	1	<1000 m^2	12	Wooden framing	8
Single-family houses	3	2010–2014	3	1000–10,000 m^2	22	Glued laminated timber	2
Terraced houses	9	2015–2019	11	>10,000 m^2	11	Prefabricated elements	7
Apartment buildings	11	2020-today	30			Prefabricated boxes	9
Other building typologies	20					CLT[b] or LVL[c]	9
						Hybrid[d]	10

[a] # represents the number of cases within each category.
[b] CLT: Cross Laminated Timber.
[c] LVL: Laminated Veneer Lumber.
[d] The hybrid structural system is a mixture of the other listed structural systems.

1. How does the choice of method affect the internal hierarchy of environmental performance rankings for wooden buildings?
2. How do temporal factors influence building design incentives when integrated into building LCAs?

2. Methods

2.1. Building cases

This study is based on 45 real-life cases of wooden buildings, which were also assessed in (Andersen et al., 2024), (Andersen et al., 2023a) where the buildings‘ inventories can be found. The building cases were singled out from a mapping of wooden buildings constructed or about to be built in Denmark and Norway from 2007 to 2023. The buildings were selected to represent a mixture of different building typologies, sizes, structural principles and visions. The building typologies include smaller buildings, such as summerhouses and single-family houses, as well as larger entities, such as terraced houses, apartment blocks and other building typologies. The "other building typologies" category includes offices, daycare centres, schools, sports facilities, community centres and shops. Additionally, the various structural principles include wooden framings, glued laminated timber systems, prefabricated elements such as wall elements, prefabricated boxes, for example, a one-storey apartment unit, cross-laminated timber elements or laminated veneer lumber and finally, a mix (hybrid). Table 1 outlines the main characteristics of the 45 cases.

To ensure consistency across the cases, we collected LCA inventory data based on a predefined list of building elements (Andersen et al., 2024). This includes the building elements: balconies, columns and beams, electrical installations, external walls, floor decks, foundations, ground floor slabs, internal walls, other roofs, stairs and ramps and windows, doors and glazing systems. The data were collected in collaboration with the architects, engineers, or contractors and included data on material quantities, compositions, and energy consumption. The data-collection process aimed at gathering exhaustive data on each case to ensure the completeness of the LCAs. However, in a few cases, it was difficult to obtain the required data. Hence, in these cases, we relied on estimates provided by the architects, engineers, or contractors. Technical installations were left out of the analysis due to a lack of data, and in thirteen cases, impacts from energy consumption were also excluded due to a lack of data.

2.2. LCA of building cases

As this study aims to investigate the practical implications of including temporal dynamics in environmental assessments of wooden buildings, this study applies both a static and a dynamic LCA approach. Even though static and dynamic LCA are fundamentally different in their LCA methodologies, the inventory modelling can be based on the same basic assumptions. Hence, this section describes assumptions and steps that apply to static and dynamic LCAs, whereas Sections 2.2.1 and 2.2.2 provide assumptions that are only applicable to one of the two methods.

All 45 building cases were modelled in the LCA software LCAbyg (Build). LCAbyg is based on the LCA methodology provided by European Standard EN15804 and divides the building life cycle into five life cycle stages (see Fig. 1). This study includes the life cycle modules of raw material supply (A1), transport (A2), manufacturing (A3), replacements (B4), operational energy use (B6), waste processing (C3) and disposal (C4) (marked in dark grey in Fig. 1). The life cycle stages included in the assessment follow the standard approach in Danish LCAs of buildings (Danish Authority of Social Services and Housing). Therefore, life cycle stages such as A4, A5, B2–B3, etc., were omitted from the assessment.

For the inventory modelling, we used the environmental data in the database gen_dk available in LCAbyg (BUILD). The gen_dk database is a generic database based on the German database Ökobau (Bundesinstitut für Bau, 2017), but as this study focuses specifically on wood products, we used EPD data for these material types to represent Danish conditions. To ensure a fair comparison, we also used EPD data for concrete products available on the Danish market (Andersen et al., 2024). The operational impact was estimated based on a projected scenario, with a continuously larger share of renewable energy in the grid mix. In the impact assessment, this study focuses only on the impact of Global Warming Potentials (GWP) as the dynamic approach applies only to this indicator. In (Andersen et al., 2024), we estimated the impact of the 45

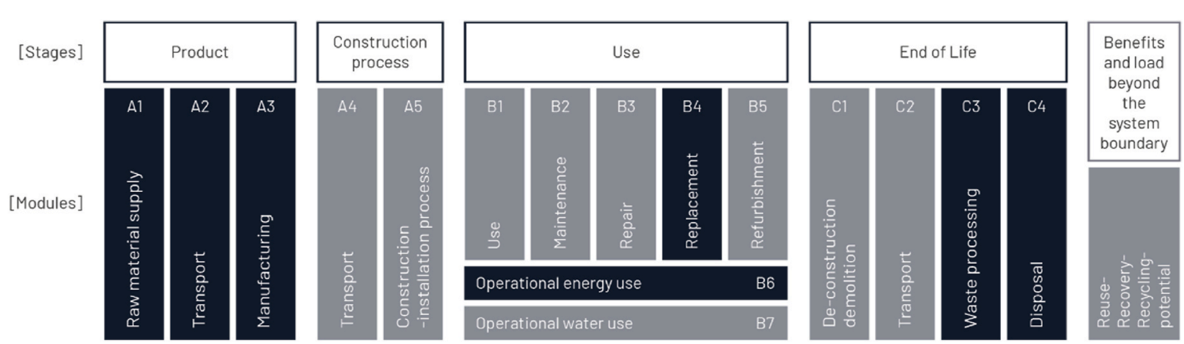

Fig. 1. Life cycle stages and modules in building LCA according to EN15978 (CEN, 2012a) and the life cycle modules included in this study, marked in dark grey.

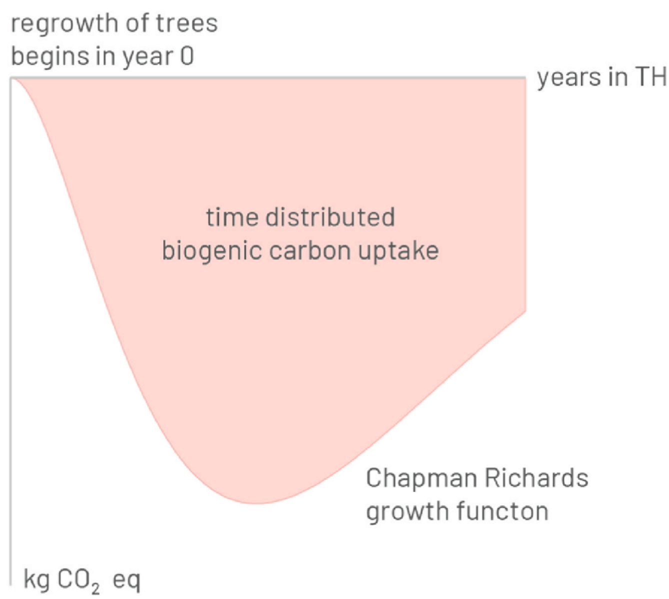

Fig. 2. Conceptual illustration of time-distributed biogenic carbon uptake of dry wood using the Chapman-Richards function.

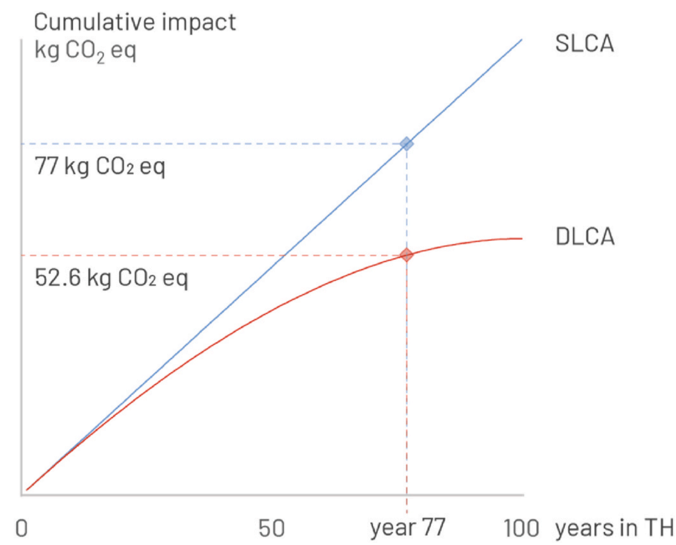

Fig. 3. Conceptual difference in releasing 1 kg CO_2 eq every year for 100 years using the static LCA and dynamic LCA approaches.

building cases on the remaining indicators following EN15804 (CEN, 2012b). The GWP is provided in the unit of kg CO_2 equivalents harmonized to the gross floor area and reference study period (RSP), depending on which scenario is considered (see Section 2.3).

From LCAbyg, we extracted all the data for the 45 building cases and adapted the data structure to allow dynamic calculations. We adapted the data in the Python programming language (Python Software Foundation), (JetBrains) and the details of the process are described in (Andersen et al., 2023b). Two fundamental adjustments were made to facilitate dynamic calculations. First, all inventory processes were mapped according to the year they occurred in the reference study period to include the temporal aspects. The second adjustment was the accounting of biogenic carbon. As the biogenic carbon content is rarely documented in the environmental data (Rasmussen et al., 2021), (Andersen et al.c), imputing the amount of biogenic carbon for construction products was necessary. To do so, we followed European Standard EN16449:2014 (CEN, 2014b) and used moisture and density data from the EPDs. For several materials, these data were also unavailable, and instead, we used data for similar materials. This gave us a list of the biogenic carbon content in all wood and bio-based materials that we used for further calculating the impact of biogenic carbon uptake and release according to the two methodologies (see Section 2.2.1 and 2.2.2) (list of biogenic carbon content of materials available in the Supplementary Material I).

2.2.1. Static LCA

The static LCAs follow the procedure described in Section 2.2. To ensure comparability between the static and dynamic LCAs, we estimated the impact of biogenic carbon based on each material's biogenic carbon content (see list in Supplementary Material I). To estimate the biogenic carbon uptake and release, the static LCA uses the $-1/+1$ rule following European standard EN16485:2014 (CEN, 2014a). Using the $-1/+1$ rule ensures that the biogenic carbon content is considered carbon-neutral throughout the whole life cycle. The $-1/+1$ rule states that the uptake of biogenic carbon should be accounted for as a negative impact (-1) in module A1 and balanced out when the biogenic carbon is released at the end of life with an equivalent positive impact in C3 ($+1$) (Hoxha et al), (Andersen et al.c), thereby providing an initial, temporary credit at the beginning of the building's life cycle.

2.2.2. Dynamic LCA

Inventory modelling in the dynamic LCAs is similar to that in the static LCAs (described in Section 2.2). However, to represent the temporal dynamics of the biogenic carbon uptake and release, we applied the Chapman Richards growth function to model the time-distributed biogenic carbon uptake after harvest (Resch et al., 2021). This approach is in line with the methodology by (Resch et al., 2021), however, alternatives, for example, Schnutes growth models, might provide similar results (Fengri et al., 1997). Applying the Chapman-Richards approach to biogenic carbon accounting assumes that harvesting trees for wood products frees up space in the forests and allows the growth of new trees. This is assumed to cause an increase in carbon sequestration in the forest, equivalent to the carbon content of the harvested wood. An example of estimating dry wood's time-distributed biogenic carbon uptake is presented in Fig. 2, using the dynamic biogenic carbon approach. It is calculated using Equations (1) and (2), where the parameters k and p represent the growth rate and catabolism of the trees and is, in this case, defined as $k = 0.023$ and $p = 3$. The content of biogenic CO_2 for each inventory product i is represented by $m_{CO_2,i}$ (Resch et al., 2021).

$$f_{CR}(y) = kpe^{-kp}\left(1 - e^{-kp}\right)^{p-1} \quad \text{(Eq. 1)}$$

$$f_{bio,i}(y) = m_{CO_2,i} \bullet f_{CR}(y) \Big/ \sum_{y=0}^{TH} f_{CR}(y) \quad \text{(Eq. 2)}$$

To investigate how temporal emissions accounting affect building design incentives, this study applies time-dependent discounting factors following the dynamic LCA approach developed by Resch et al. (2021). As described in Section 1.3, these discounting factors may be used to represent future technological improvements that cause reduced emissions or the possibility that future emissions might have less atmospheric effect than current emissions. The discounting factors are calculated using Equation (3) for each year, y, in the time horizon (TH). From Equation (1), the discounting factors are multiplied by the emission depending on when the emissions occur in the TH. For example, an emission released in year 1 is multiplied by the discounting factor for year 1, whereas an emission released in year 50 is multiplied by the respective discounting factor for year 50. In this study, we multiplied the static LCA results by the relevant discounting factors depending on when they occur in the TH; therefore, the inventory modelling assumptions for the static LCAs also apply to the dynamic LCAs (see Section 2.2). Fig. 3 provides an example of 1 kg CO_2 eq released every year for 100 years

Table 2
Scenarios considered in the study with combinations of different LCA methods, reference study periods (RSP) and time horizons (TH).

Scenario	LCA method	Reference study period	Time horizon	Biogenic carbon accounting	Temporal emissions accounting
$SLCA_{50,100}$	Static LCA	50 years	100 years	−1/+1	Static
$SLCA_{100,100}$	Static LCA	100 years	100 years	−1/+1	Static
$SLCA_{50,200}$	Static LCA	50 years	200 years	−1/+1	Static
$SLCA_{100,200}$	Static LCA	100 years	200 years	−1/+1	Static
$DLCA_{50,100}$	Dynamic LCA	50 years	100 years	Regrowth after harvest	Discounting future emissions
$DLCA_{100,100}$	Dynamic LCA	100 years	100 years	Regrowth after harvest	Discounting future emissions
$DLCA_{50,200}$	Dynamic LCA	50 years	200 years	Regrowth after harvest	Discounting future emissions
$DLCA_{100,200}$	Dynamic LCA	100 years	200 years	Regrowth after harvest	Discounting future emissions

using the static and dynamic LCA method over a 100-year period.

$$\textbf{\textit{Discounting factor}}_{TH}(y) = 2 - e^{\frac{\ln(2)}{TH}\,y} \qquad \text{(Eq. 3)}$$

2.3. Scenarios

This study considered eight different scenarios to capture the influence of the various temporal aspects. The eight scenarios combine reference study periods (RSP) and time horizons (TH) for the two methods, i.e. static LCA (SLCA) and dynamic LCA (DLCA). Danish building regulations define a standard RSP of 50 years, but to reflect the potential of a prolonged RSP, this study also includes scenarios with a 100-year RSP. Contrary to the RSP, the TH is not regulated by any authority. The TH represents the time horizon over which the radiative forcing is considered, and typically a TH of 100 years is chosen (as in GWP100). However, this choice is normative and is a matter of weighing current and future emissions (IPCC, 2022), (Resch et al., 2021). To reflect the effect of different THs, this study assesses a TH of both 100 years and 200 years. We considered eight scenarios that allow us to assess these temporal aspects in the assessments. Table 2 presents all scenarios and the respective LCA method, RSP and TH.

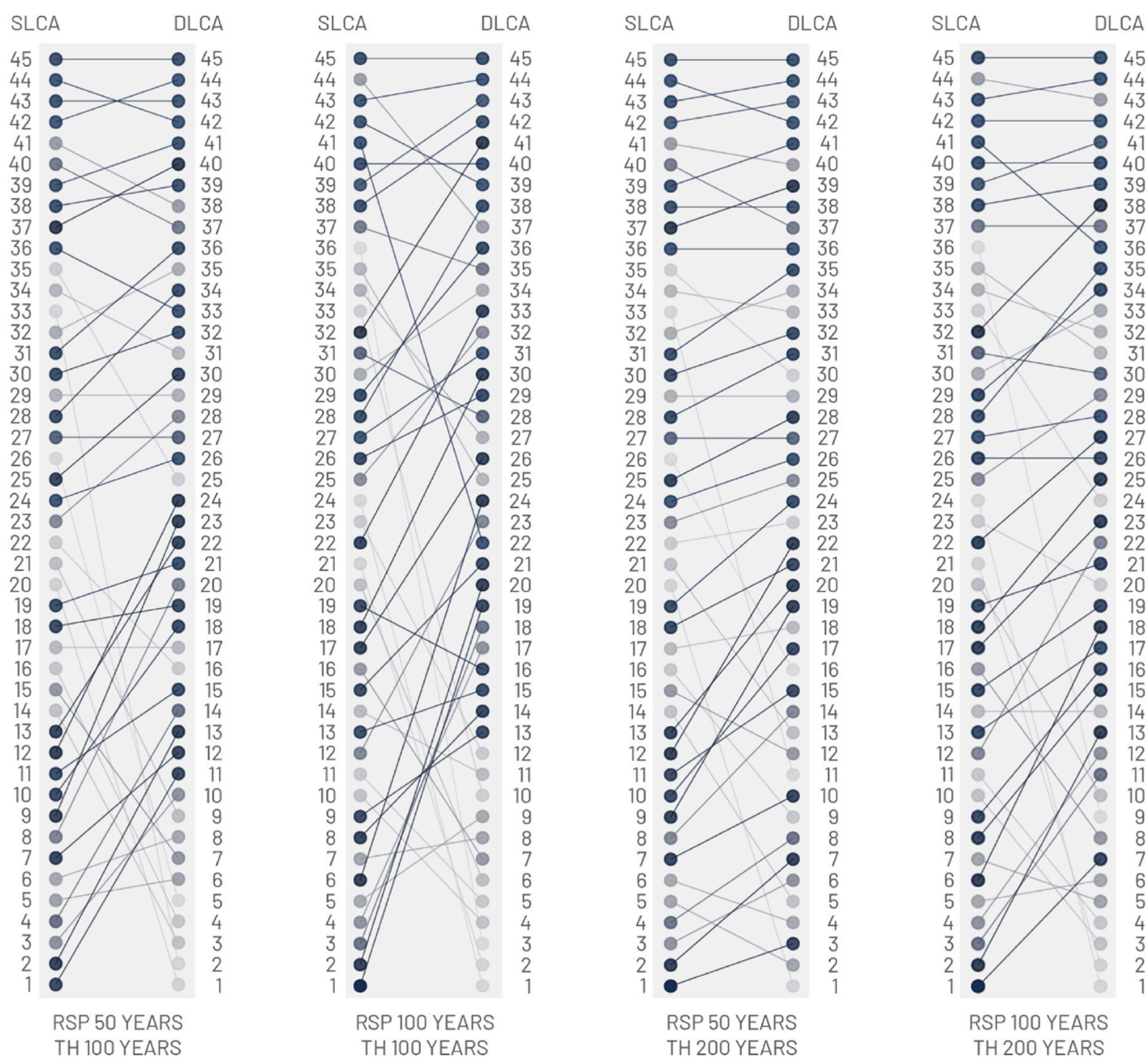

Fig. 4. Ranking of building cases when applying SLCA and DLCA, given an RSP of 50 and 100 years and a TH of 100 years and 200 years, respectively.

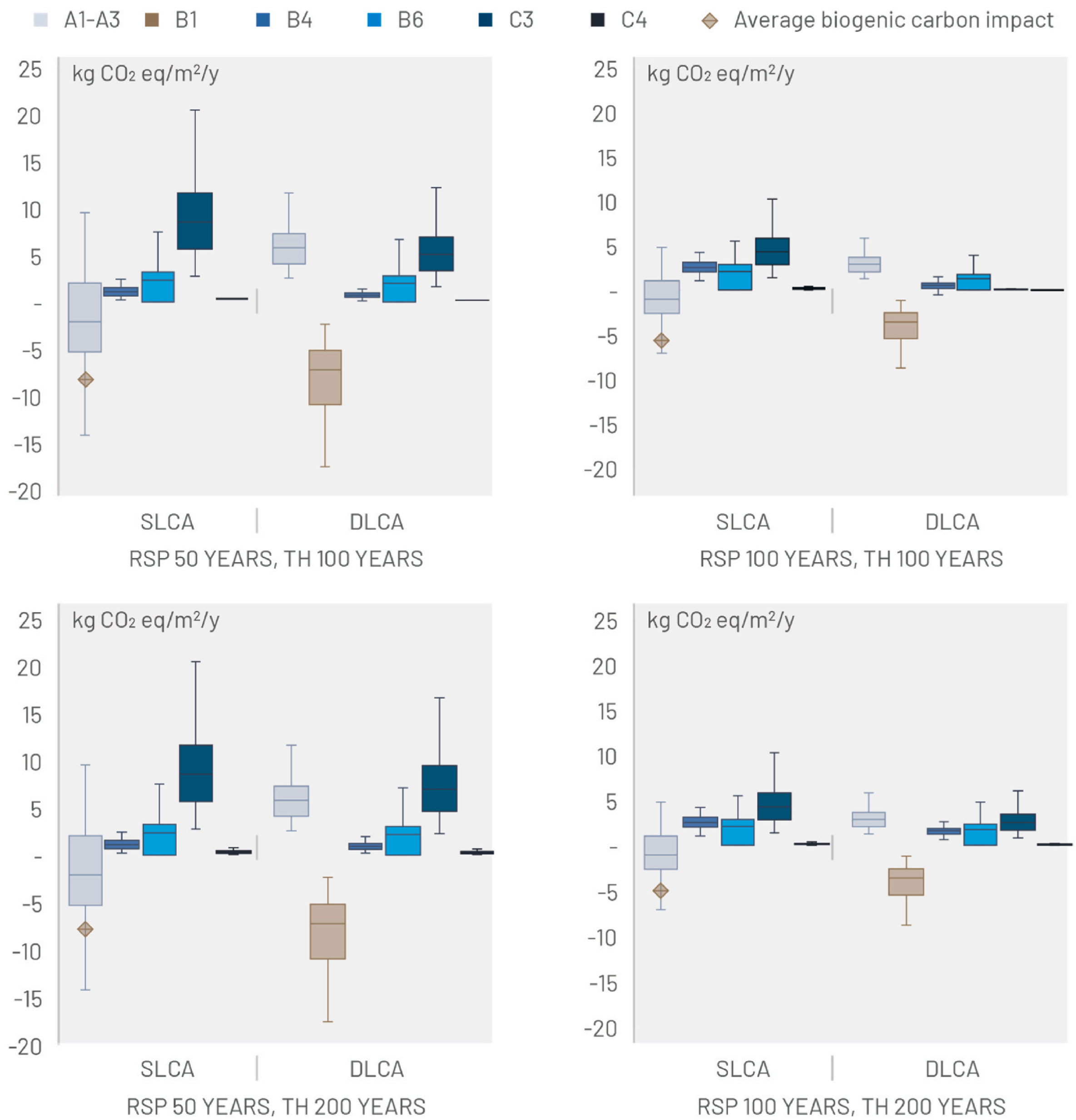

Fig. 5. -SLCA and DLCA results across life cycle modules for an RSP of 50 and 100 years and a TH of 100 and 200 years respectively. In DLCA, the biogenic carbon uptake is in life cycle module B1, as the uptake takes place throughout the RSP.

3. Results and discussion

3.1. Methods effect on building case incentives

We ranked the building cases within each scenario to investigate how including the temporal aspects in building LCAs affects building design. Rank one has the lowest GWP, whereas rank 45 represents the case with the highest GWP. Even though Fig. 4 shows different rankings for the building cases when using the two methods, we find that cases with a high ranking continuously have a high ranking, and the same for the cases with a low ranking. The cases with a high ranking, however, are much more stable than those with a low ranking. This is because the difference between the impact of the low-ranking cases is significantly lower and thus can easily be shifted when changing the method. The rankings are, in general, influenced by the choice of RSP and TH. Changing the RSP from 50 years to 100 years shifts the ranking significantly, where the cases assessed with SLCA are more stable in ranking than the cases assessed with the DLCA method. The same applies when going from a 100-year TH to a 200-year TH. Furthermore, we find that a few building cases experience a significant shift in their ranking when applying SLCA and DLCA; two to five building cases (depending on the scenario) decrease by more than 19 positions in ranking, going from SLCA to DLCA. This is because of the high amount of wood and wood-based products in the buildings, where, in DLCA, the biogenic carbon release is discounted at the end of life, thereby causing considerable benefits for the cases with a large biogenic carbon contribution. Altogether, we find that the ranking of the building cases remains consistent regardless of the method used. Therefore, the choice of method does not impact the comparisons of the overall performance of the buildings.

Although Fig. 4 shows that the ranking of the building cases is stable and that the best-performing building cases continue to be among the best-performing, irrespective of the method, it is relevant to investigate the influence of methods on building design incentives throughout the building's life cycle. Fig. 5 shows the impact of the building cases for each life cycle module in the eight scenarios. Note that for SLCA, the biogenic carbon uptake is placed in A1-A3, whereas for DLCA, the

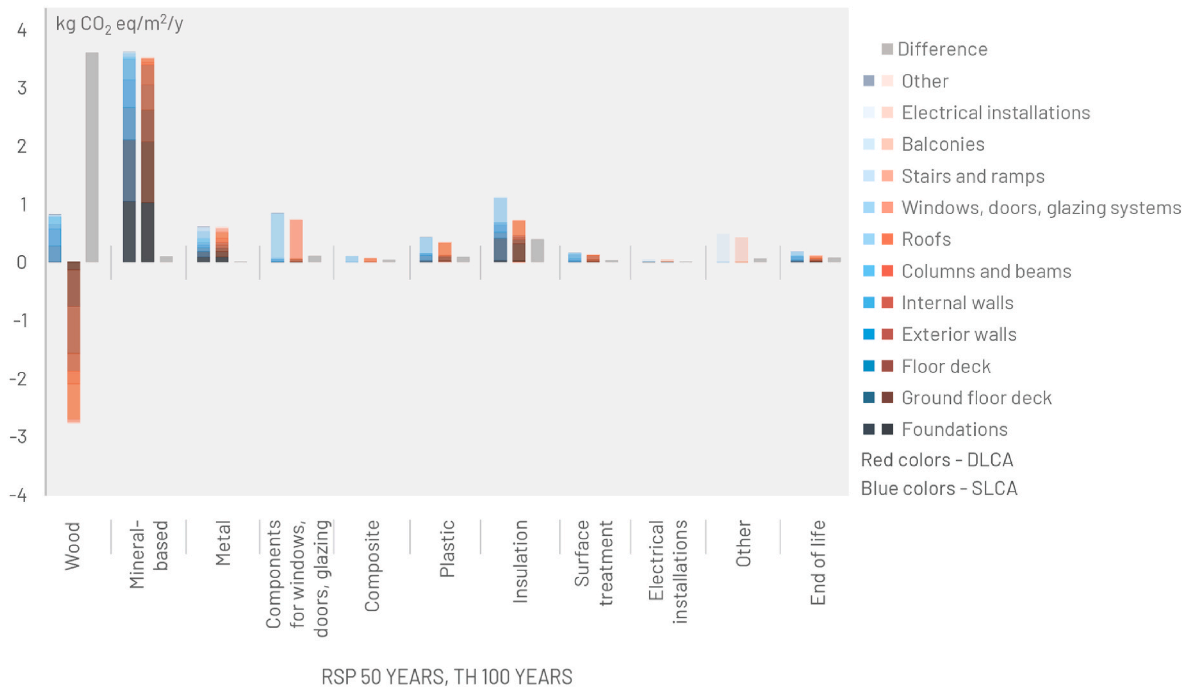

Fig. 6. Static LCA and dynamic LCA results for material types and building elements, as well as the absolute difference between static and dynamic results for a 50-year RSP and 100 years TH (the results for the remaining scenarios are presented in Supplementary Material II, Figs. 1–3).

biogenic carbon uptake is in B1, representing a time-dependent biogenic carbon uptake after harvest. In all scenarios, DLCA shifts the focus to stages early in the building life cycle due to the discounting principle in DLCA, where life cycle stages happening in the future (use and end of life stage) are less impactful and become less critical. The impact reduction in the future lifecycle stages ranges from 15% to 82% in B4, 6%–35% in B6, and 19%–99% in C3 and C4, where the smallest reductions are for the scenarios $SLCA_{50,200}$ to $DLCA_{50,200}$ and the largest reductions are for the $SLCA_{100,100}$ to $DLCA_{100,100}$ scenarios. The more considerable decrease between the $SLCA_{100,100}$ and $DLCA_{100,100}$ scenarios is because the RSP approaches the TH, resulting in the highest possible discounting of future emissions.

Altogether, applying DLCA increases the focus on the current life cycle stages. However, this approach poses a risk of reducing the importance of future emissions related to maintenance, energy consumption during use, and disposal. In doing so, it potentially decreases the relevance of low-impact strategies focusing on the use and end of life stage, such as design for disassembly, building for reuse and recycling, and maintenance-free buildings.

To understand further how the choice of method affects building design, we investigated the impact difference on the material type and building element levels. Fig. 6 shows the aggregated and averaged $SLCA_{50,100}$ and $DLCA_{50,100}$ results for each material type and building element and the absolute difference between the results using the two methods. The results for the remaining scenarios are similar to those of $SLCA_{50,100}$ and $DLCA_{50,100}$ and thus are presented in Supplementary Material II, Figs. 1–3. Overall, we find that wood products have the greatest difference when comparing SLCA and DLCA because of the different biogenic carbon accounting principles in SLCA and DLCA, respectively. In DLCA, the biogenic carbon uptake throughout the RSP is fully credited, while the biogenic carbon release by the end of life is discounted, resulting in a net benefit from biogenic carbon fluxes. This significantly differs from the SLCA method, where the $-1/+1$ rule dictates that biogenic carbon is considered carbon-neutral over the life cycle and thus provides no benefit of biogenic carbon uptake and storage.

The results show no significant difference between SLCA and DLCA for *mineral-based* and *metal* material categories, where the SLCA results are less than a factor 0.1 larger than the DLCA results. For the seven material categories *surface treatment, insulation, composite, components for windows and glazing systems, plastic, technical installations* and *others,* the difference between the two methods is minor for most building elements. However, compared to the *mineral-based* and *metal* material categories, the difference between SLCA and DLCA for these categories is larger, as they differ by a factor of 0.1–0.6. The more considerable difference between SLCA and DLCA results for the seven material categories is because they have a relatively short life span, and as future emissions have less impact in DLCA compared to SLCA, these material categories and building elements experience a more considerable change. However, for four material categories and building elements, we find a considerable difference between the SLCA and DLCA results: (i) *plastics, stairs* and *ramps,* (ii) *composite in roofs*, (iii) *insulation, columns* and *beams*, and (iv) *insulation* and *external walls*. This larger difference is because these material types have a high impact by the end of life. The material category *end of life* is greatly affected by the different methods for all building elements, as the dynamic method dictates that emissions by the end of life are discounted.

3.2. Timing of emissions

Section 3.1 shows that choosing a dynamic approach influences the impact results for wood products and products with many replacements but that the overall performance of a building is consistent, irrespective of the method applied. However, looking at the timing of when the emissions occur, the static and dynamic methods differ significantly. Fig. 7 (A-H) shows the average annual emissions across the 45 building cases for each scenario and is divided into biogenic and non-biogenic emissions. By 2030, the target year of the Danish climate agreement, the SLCA method reports approximately a four times lower impact than the DLCA method and about three times lower in 2050. Considering only non-biogenic GHG emissions in each scenario, we find that, although DLCA discounts emissions over time, the discounting effect seems insignificant until 2030 and 2050. Before 2030 and 2050, the most significant difference between the methods is the biogenic carbon

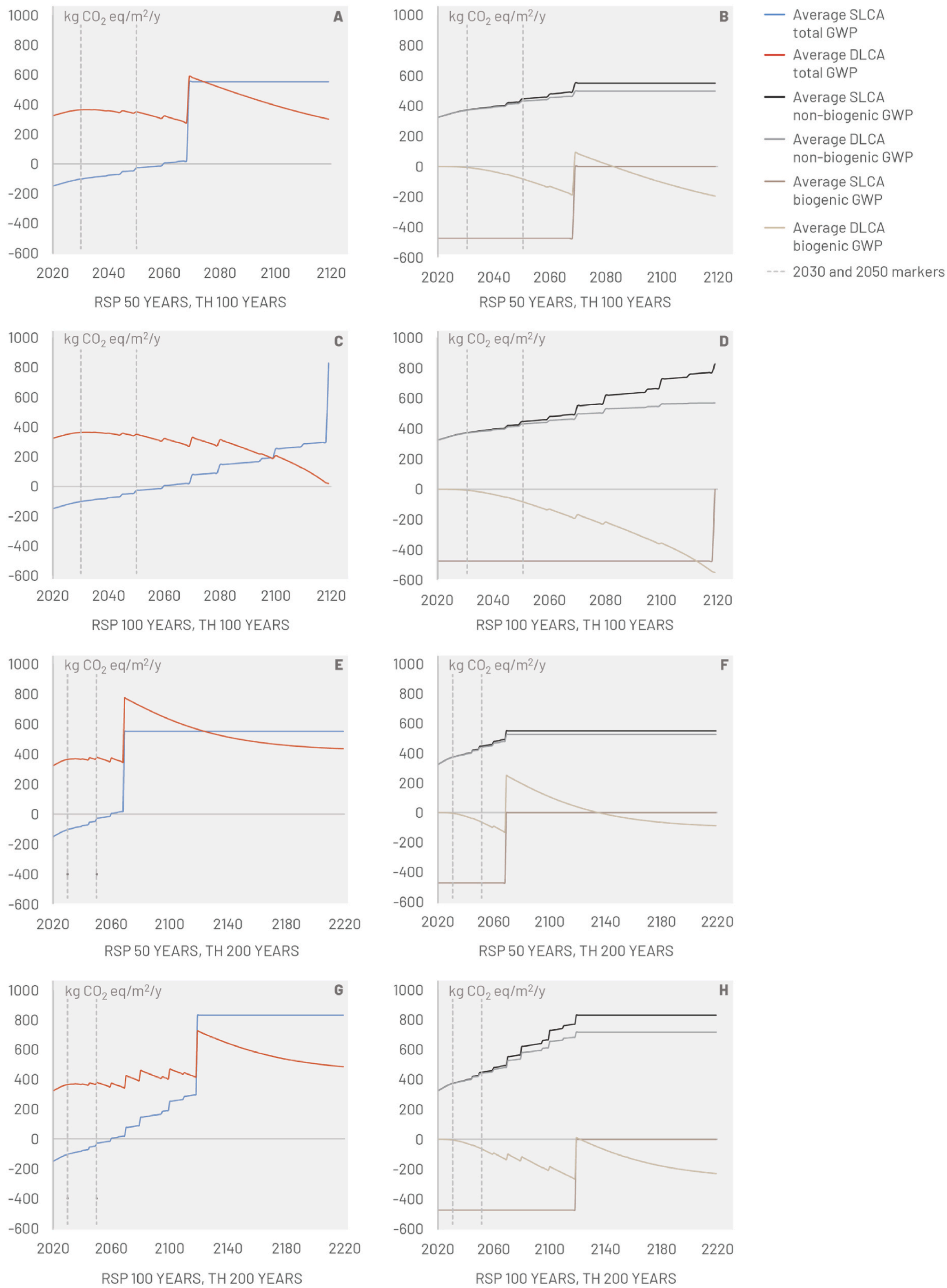

Fig. 7. Time-distributed emissions divided into total emissions, non-biogenic and biogenic emissions for the building cases and the eight scenarios.

accounting principles, highlighting the importance of these methods for estimating biogenic carbon uptake and release. Despite these significant differences in the results, it is essential to note that the physical emissions into the atmosphere will be equal regardless of the method applied. CO_2 released into the atmosphere stays for a long time; therefore, the long-term effects on the radiation forcing of an emission now or in the future are the same (Brander and Broekhoff, 2023). However, even though discounting future emissions does not reflect the actual effect of emissions, it will reflect how postponing emissions to the future may buy time for, for example, technological developments that will help mitigate the impact on global warming. Therefore, dynamic LCA approaches become a question of interpretation and reporting practices of the physical conditions.

Across all scenarios, we see large differences in the temporal distribution of emissions. The combination of RSP and TH is a sensitive aspect that greatly influences the reported results (Resch et al., 2021). Especially when the RSP approaches the TH in the dynamic method, future emissions are discounted with a very high discounting factor and, therefore, seem to have minimal impact (Fig. 7 C). Even though the choice of RSP and TH is normative, this is important to be aware of, especially when applying DLCA, as it may influence building design in practice. The large discounting of future emissions could increase the focus on the product stage while overlooking the importance of the end of life stage with a possible cost to future generations (Resch et al., 2021), (Polasky and Dampha, 2021).

Furthermore, the −1/+1 rule greatly influences the emissions over time. In year 0, the −1/+1 rule gives an upfront credit, which advantages the SLCA method by showing lower emissions until the end of life in Fig. 7 A, E, and G. The only exception is the scenarios of a 100-year RSP and 100-year TH (Fig. 7 C). Here, the credit of the upfront biogenic carbon uptake is outbalanced by the DLCA already in 2099 (before the end of life) because of a continuous increase in the dynamic biogenic carbon uptake, only possible when the RSP and TH are equal as the DLCA results then get the full biogenic carbon uptake before the end of life emissions occur. Another consequence of the RSP and TH being equal is that the DLCA results experience a considerable discounting effect of the end of life emissions. In practice, this large influence of the −1/+1 rule possibly increases incentives to focus on the end of life stage instead of reducing emissions at the product stage with an already very low impact. In addition, this also raises questions about the fairness of comparing two very different approaches to estimating biogenic carbon uptake, where there are large differences in *when* the benefit is credited. It might be that a 'harvest-before' scenario is a fairer comparison to the −1/+1 method, as in that case, the dynamic biogenic carbon uptake would be credited from year −100 to year 0 (Hoxha et al). Although biogenic carbon emissions contribute significantly to the total impact of the buildings, it is important to be aware of the fundamental difference between biogenic and non-biogenic emissions (Mackey et al., 2013). Biogenic emissions belong to the natural carbon cycle and will, therefore, occur irrespective of human activity to some extent. Conversely, fossil emissions only happen because of human activity and could be avoided entirely.

4. Conclusion

This study has investigated the effect of introducing temporal factors into building LCAs by assessing 45 cases of wooden buildings using traditional LCA, referred to as static LCA, and dynamic LCA. The study focuses on how the choice of method affects building design incentives in practice. From comparing the internal ranking of the wooden building LCAs, we find that the ranking is not significantly affected by the choice of method. Hence, cases with a low ranking continue to have a low ranking irrespective of whether the static or dynamic LCA method is applied, and the same is true for the cases with a high ranking. Although the overall building design is generally robust against the choice of method, the study shows that the environmental impact of wood and bio-based products is especially sensitive to which method, the static or dynamic method, is applied. Looking at the emissions over time, it becomes evident that the different biogenic carbon accounting principles are the main reason for the differences in the impact results when applying the static and dynamic LCA approaches, respectively. In comparison, the discounting of future emissions in dynamic LCA has considerably less influence on the total emission results, especially if the time horizon for the climate targets is taken into account.

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CRediT authorship contribution statement

Camilla Ernst Andersen: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Endrit Hoxha:** Conceptualization, Data curation, Supervision, Writing – review & editing. **Freja Nygaard Rasmussen:** Conceptualization, Data curation, Supervision, Writing – review & editing. **Christian Grau Sorensen:** Data curation, Software. **Harpa Birgisdottir:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

I, Camilla Ernst Andersen, state on behalf of all co-authors that the study does not relate to any sort of already published work. The study is supported financially by the Villum Foundation and Realdania, however the authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141260.

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