Quantifying the life cycle emissions of hybrid structures with advanced bio- and conventional materialization for low-embodied carbon urban densification of the Amsterdam Metropolitan Area

Migoni Alejandre, Elizabeth; Koskamp, Gilbert; van de Leur, Mick; Wandl, Alexander; van Timmeren, Arjan

DOI
10.1016/j.jclepro.2024.144273

Publication date
2024

Document Version
Final published version

Published in
Journal of Cleaner Production

Citation (APA)
Migoni Alejandre, E., Koskamp, G., van de Leur, M., Wandl, A., & van Timmeren, A. (2024). Quantifying the life cycle emissions of hybrid structures with advanced bio- and conventional materialization for low-embodied carbon urban densification of the Amsterdam Metropolitan Area. *Journal of Cleaner Production*, *483*, Article 144273. https://doi.org/10.1016/j.jclepro.2024.144273

Journal of Cleaner Production 483 (2024) 144273

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Quantifying the life cycle emissions of hybrid structures with advanced bio- and conventional materialization for low-embodied carbon urban densification of the Amsterdam Metropolitan Area

Elizabeth Migoni Alejandre[a,c,*], Gilbert Koskamp[b], Mick van de Leur[b], Alexander Wandl[a], Arjan van Timmeren[a]

[a] *Environmental Technology and Design Section, Urbanism Department, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628 BL, Delft, the Netherlands*
[b] *Architectural Technology Section, Department of Architectural Engineering + Technology, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628 BL, Delft, the Netherlands*
[c] *Wageningen Economic Research, Wageningen University & Research, the Netherlands*

ARTICLE INFO

Handling Editor: Yutao Wang

Keywords:
Life cycle assessment
Embodied carbon
Urban densification
Bio-based hybrid structures
Engineered timber
Multistorey buildings

ABSTRACT

More than 20% of global carbon emissions are linked with the production of construction materials used in the built environment. The use of bio-materials along with urban densification strategies that avoid demolition and reduce material demand, have been recommended to achieve urban sustainability goals. Addressing these measures, this study compares the life cycle embodied carbon emissions of seven hybrid top-up structural systems composed of concrete, steel and advanced engineered timber products made out of softwood and hardwood species. The life cycle carbon emissions (expressed in $kgCO_2$-eq) were estimated following a cradle-to-grave approach, with a functional unit equivalent to 1 m^2 of top-up structural system and focusing on The Netherlands and the city of Amsterdam as main geographical scope. A statistical analysis was included to account for the potential variation of emissions across each life cycle stage, using Monte Carlo simulations for random sampling. The results indicate that predominantly bio-based structures present a staggering 60% lower embodied carbon emissions compared with predominantly concrete, steel and modestly hybrid systems. Preserving the long-term carbon storage capacity of timber elements through high-quality reuse can offset 30–60% of the total positive emissions of the predominantly bio-based systems. Up to $6MtCO_2$-eq of the national carbon budget in The Netherlands can be saved from a radical uptake of bio-based structures in Amsterdam by 2050. Diversification of material diets with bio-based alternatives is recommended, along with established policy that can guarantee sustainable sourcing and prolonged lifespans through high-end reuse practices.

1. Introduction

The excessive use of non-renewable materials coupled with industrial activities that generate high amounts of greenhouse gas emissions (GHG's), such as carbon dioxide (CO_2), have exacerbated global threats to climate resilience and ecosystem quality(Costanza et al., 1998, 2017; Oberle et al., 2019). One of the largest contributors of GHG's is the construction sector, which accounts for approximately 37% of global emissions (Huang et al., 2018). From these, 10% are generated by the production of raw materials for conventional buildings and infrastructure, mainly cement, iron and steel (Chaturvedi and Ochsendorf, 2004; Flower and Sanjayan, 2007; Van Ruijven et al., 2016). It is estimated that a continuous use of conventional materials for future infrastructure will defeat the international climate agreements set during the United Nations Climate Change Conference in Paris (COP21, 2015; https://unfccc.int/), and could claim 35–60% of the remaining carbon budget associated with limiting the global temperature increase to below 2 °C (Mishra et al., 2022; Müller et al., 2013).

As buildings become more energy efficient during their operational phase, one of the targets for further decarbonization attempts of the urban sector is to look at embodied impacts. The term 'embodied' refers to the energy and emissions that are linked to the materials in a building. When assessing the life cycle embodied carbon impacts of a building, the emissions are accounted across life cycle stages of a building, from the

---

* Corresponding author. Prinses Beatrixlaan 582 - 528, 2595BM, Den Haag, The Netherlands.
E-mail address: elizabeth.migonialejandre@wur.nl (E. Migoni Alejandre).

https://doi.org/10.1016/j.jclepro.2024.144273
Received 23 April 2024; Received in revised form 29 August 2024; Accepted 20 November 2024

extraction and processing to the disposal or recovery of materials at their end-of-life (Fig. 1). Strategies to decrease embodied impacts from buildings include avoidance, size reduction and material substitution (Camarasa et al., 2022; Souaid et al., 2024). For the latter one, recent advances of bio-based materials in the form of engineered timber, have introduced in the market viable substitutes for the conventional concrete and steel used in infrastructures (Bahrami et al., 2021; Chen et al., 2022; Liang et al., 2020) (See material strength profiles in Supplementary Information A; SI1).

1.1. Engineered timber as a low-embodied carbon structural alternative

Engineered timber is a structural material made of layers of wood, or wood-based composite, laminated together. Well known examples are cross laminated timber (CLT), laminated veneer lumber (LVL), and glued laminated timber (Glulam). Considering that the load-bearing structure is the largest volumetric material flow in buildings, it can account for the majority of the embodied impacts of buildings. Thus, it provides opportunities to largely decrease embodied impact when materials are choosing wisely (Heeren et al., 2015). According to life cycle studies comparing functionally equivalent structures, substitution with timber was found to reduce between 20 and 40% of the embodied carbon emissions of multistorey buildings (Andersen et al., 2022; Hemmati et al., 2024; Younis and Dodoo, 2022) (See detailed literature review Supplementary Information A; SI2). The study by D'amico et al. (2021) quantified the potential global benefits of using CLT to replace concrete floor in steel structural systems. Their results indicate that the simple substitution proposed could lead to a decrease of 1.5% of the annual global GHG emissions of the construction sector (D'Amico et al., 2021). This highlights the need to further develop quantitative comparisons of hybrid structures, with the goal to provide a better understanding of realistic and feasible structure materialization and their associated environmental impacts.

Moreover, the largest emissions associated with timber buildings have been identified in the literature to occur post-construction, meaning that close attention to efficient design, procurement and end-of-life of a building is essential (Hart et al., 2021). On this regard, an added benefit of timber is the light-weight of the material (especially in comparison with mineral ones), which results in the use of less energy intensive machinery during production and transportation (Adhikari and Ozarska, 2018), facilitating disassemble and reuse practices, and increasing its potential applications for urban densification strategies. These benefits are of high relevance for countries such as The Netherlands, where ambitious national goals (as exemplified by the Green Deal (www.metropoolregioamsterdam.nl/houtbouw/)), have been set to significantly reduce greenhouse gas emissions.

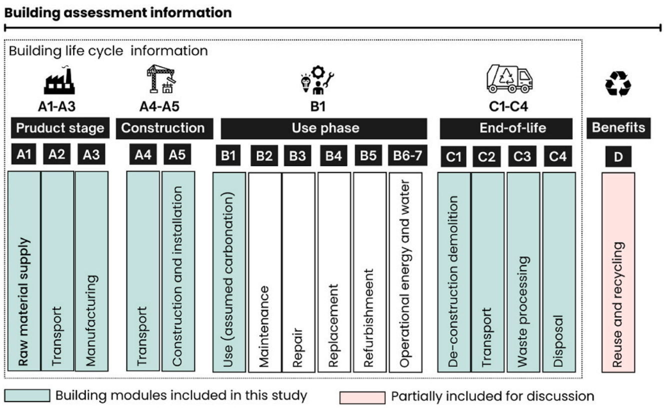


Fig. 1. Life cycle modules for buildings assessment (EN 15978).

1.2. Top-up structures to maximize urban densification and avoid demolition

As many countries in Europe, The Netherlands is grappling in the midst of a housing crisis (Boelhouwer, 2017, 2020). Increased migration from rural areas to cities, are leading to denser urban settings (Fang and Yu, 2017; Seto et al., 2011). The Amsterdam Metropolitan Area (AMA) alone has reported a 2% annual increase of their urban population (Gemeente Amsterdam, 2022). Considering the need to host an increasing urban setting while competing for land with multiple other uses, the challenge is to provide urban densification strategies that can align with sustainable development goals (Maes et al., 2016; Xu et al., 2022). While industrial and political interventions are supporting a transition to a circular bioeconomy by promoting the use bio-materials (Stark et al., 2022), circular strategies recommend to focus on a better distribution and renovation of the current building stock (Tukker et al., 2023). Addressing these points of concern, top-up structures have surged in popularity as a response to both, material substitution and urban densification needs (Camilo Gómez, 2023).

Top-up structures generally refer to an extension built on top of an existing building, this increases the available floor space without expanding the building's footprint, allowing to maximize the use of current urban stock while avoiding demolition, and thus decreasing material waste. The light-weight of engineered timber makes it particularly interesting for top-up applications, which can also incorporate early design choices to facilitate future adaptation and easy to disassemble practices. This highlights the need to further analyze the potential of engineered timber products for residential top-up structures, looking specifically at relevant combination of materials that can be used for light-weight designs, along with an in-depth analysis of the potential environmental implications and trade-offs between structural materials.

1.3. Objective of this study

Although several studies have compared the life cycle impacts of substituting concrete and steel with engineered timber in multi-story buildings (see Supplementary Information A; SI2), the comparisons have been limited to timber products made from softwood species (e.g., Spruce) (Dodoo et al., 2014; Ernst Andersen et al., 2023; Younis and Dodoo, 2022). Novel structural materials made from hardwood timber species (e.g., Beech) have recently entered the market, and present promising opportunities to further decrease embodied impacts while utilizing less cubic meters of material. Given the increasing housing demand in cities and the environmental urgency of decarbonizing the built environment, the goal of this study is to provide a comparative assessment of the embodied carbon emissions associated with residential top-up structural systems, focusing on a material comparison between predominantly mineral-based, bio-based and hybrid systems.

This study is the first one (to our knowledge) to differentiate between engineered timber made from hardwood (e.g. Beech) and softwood (e.g. Spruce), allowing to deepen the comparison between bio-based alternatives. Moreover, this study includes structures not only built with different rates of conventional materials, but it also accounts for scenarios in which the structural steel used is assumed to be made from 100% recycled content, for a comprehensive comparison of alternative structures. Our hypothesis is that a combination of predominantly bio-based structural materials and recycled steel will present lower embodied carbon emissions across its life cycle than structures made predominantly of conventional materials, potentially equivalent to structures made predominantly of bio-based elements. To test our hypothesis, this study presents a whole life embodied carbon assessment, following a cradle-to-grave approach (See Fig. 1) and focusing in The Netherlands as main geographical scope for the selection of relevant product data. The goals from the Amsterdam Metropolitan Area for projected new housing construction by 2050, are used to quantify cumulative GHG emissions at a regional scale, and to compare benchmarks in relation to the remaining national carbon budget estimated by 2050. This with the aim to illustrate the potential savings associated with a bio-based transition of structural systems, and identify the processes that require attention and further improvement within their life cycles. The quantitative contribution of this study is expected to provide valuable insights for consideration during decision-making and to encourage further research on the implications of bio-based materials in the transition towards a sustainable built environment.

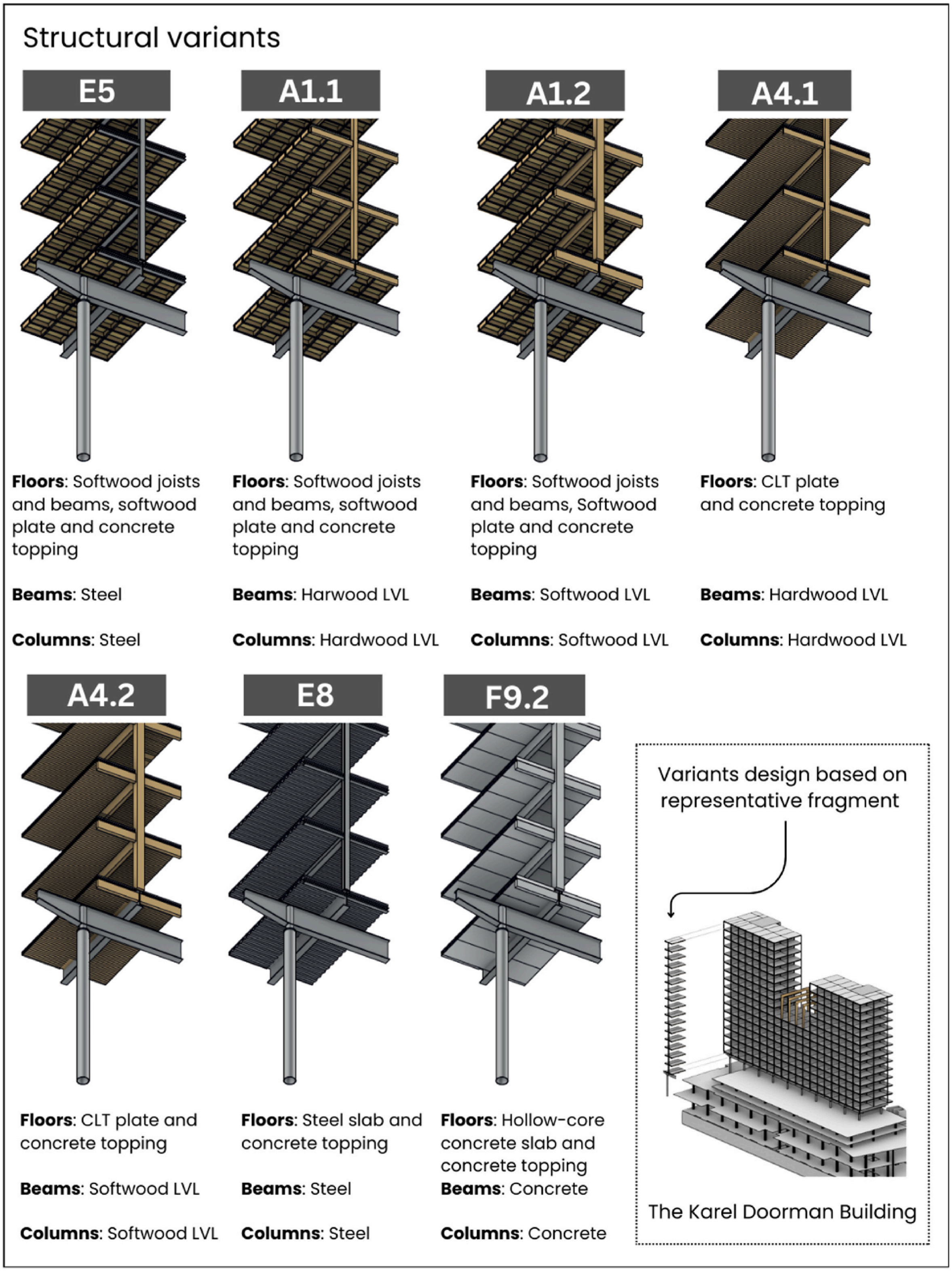


Fig. 2. Seven structural variants compared for alternative materialization systems (for high resolution of variants see Electronic Artwork 2–3).

2. Methods

2.1. Structural systems

This study builds on the work by van de Leur (2023) (van de Leur, 2023) comparing seven materialization scenarios for a residential top-up system (Fig. 2). The original variant names have been kept for the sake of consistency. Structural system E5, is based on original drawings provided by Ibelings van Tilburg architecten (www.ibelingsvantilburg.nl), for the Karel Doorman building, located in the Randstad area of The Netherlands. The rest of the structural alternatives (A.1, A.2, A4.1, A4.2, E8 and F9.2) were quantified in this study to provide comparative material scenarios (See material quantities in Table 1). The Karel Doorman was selected as a relevant case study due its innovative design for a multistorey light-weight residential top-up structure and homogeneous characteristics (See high resolution of top-up structure on Electronic Artwork 1). Moreover, its design and location context is representative of both, the Dutch building sector and the housing needs faced across metropolitan areas.

The building structure is homogenous (See Electronic Artwork 1), which means that a representative fragment was identified to derive the material quantifications for the entire top-up structure (Fig. 3). The purpose of the variants is to compare the influence of material selection in the whole life embodied carbon of a building, used both in hybrid structural systems and in systems comprised primarily a of a single material.

For this study, we compare seven variants that allow to distinguish between steel, concrete and timber structures, as well as between different types of timber (hard- and softwood), and hybrid combinations (See detailed configurations diagram in Electronic Artwork Fig. 4). The quantification of whole life embodied carbon accounts solely for the top-up structure, excluding the two concrete cores and ground foundation, which are the same across scenarios. The balconies are excluded from the LCA as they serve no structural purpose, but their weight is included in the structural calculation for the beams and columns. A floor concrete topping layer was included in all variants (except variant F9.2), for additional stability and noise reduction purposes. Additional design specifications are described in Supplementary Information A; SI3.

Table 1
Material intensities of each structural system.

Variant	Structural element	Material	Material intensity (in kg/m^2)
E5	Floor joists, beams and plate	Softwood LVL	32.78
	Floor topping	Concrete	146.04
	Beams and columns	Structural steel	39.85
A1.1	Floor joists, beams and plate	Softwood LVL	32.78
	Floor topping	Concrete	146.04
	Beams and columns	Hardwood LVL	17.22
A1.2	Floor joists, beams and plate	Softwood LVL	32.78
	Floor topping	Concrete	146.04
	Beams and columns	Softwood LVL	26.73
A4.1	Floor plate	CLT	57.09
	Floor topping	concrete	146.04
	Beams and columns	Hardwood LVL	23.47
A4.2	Floor plate	CLT	57.09
	Floor topping	concrete	146.04
	Beams and columns	Softwood LVL	26.83
E8	Floor	Steel deck	12.53
	Floor topping	Concrete	372.01
	Beams and columns	Structural steel	45.44
F9.2	Floor	Hollow core slabs	262.87
	Floor topping	Concrete	154.29
	Beams and columns	Concrete	190.08

2.2. Determination of total housing floor-area demand

Ambitions from the Amsterdam Metropolitan Area (AMA) were used as reference point to estimate the potential CO_2 emissions that would result from new housing construction by 2050 (See methodological framework in Fig. 4). First, we estimated the amount of average floor area (m^2) required to satisfy the increasing housing demand in the AMA. According to reports from the municipality, new construction is expected to reach a maximum of 7500 residential units per year ("WoningBouwplan 2022–2028"(Gemeente Amsterdam, 2022)), with current estimates reflecting a yearly average construction of 5000 homes. Moreover, we took into consideration the proportion of each housing type (as stipulated in the metropolitan strategy "Coalitieakkoord, 2022–2026"), which corresponds to 40% social, 40% medium-priced and 20% attributed to high-priced/private sector. Based on reports from the Dutch Statistical Center, the average floor area per housing type was considered to range between 40 and 60 m^2 (social), 40–90 m^2 (medium), and 70–150 m^2 (private). The total floor area demand by 2050 was obtained as the mean between of the aimed and current construction rates (the resulting m^2 are presented in Supplementary Information A; SI4).

2.3. Selection of embodied carbon coefficients (ECC's)

Following the European norms for buildings and building products assessment (EN 15978 and EN 15804:2012+A2:2019), the embodied carbon was calculated from cradle-to-grave, with benefits beyond system boundaries reported separately (Fig. 5). A selection of Embodied Carbon Coefficients (ECC's), expressed in kg CO_2-eq by kg of material assessed, was conducted for each material to identify the lowest and highest value coefficients available for each life cycle stage (See detailed description of ECC's selection in Supplementary Information A; SI5, and a table of the selected ECCs in Supplementary Information B; SIB1). To account for the variation of ECC's, we performed a Monte Carlo simulation to generate 1000 random samples $\left(\overrightarrow{ECC}\right)$ for each life cycle module of each structural material, assuming a uniform probability distribution between the lowest and highest ECC (See Supplementary Information B; SIB2).

2.4. Whole life embodied carbon emissions of each structural system

We calculated the whole life embodied carbon emissions of each structural system, accounting for a cradle-to-grave scope (See Figs. 1 and 5). According to the European norm EN15804+A2, the life cycle stages of buildings and construction products are grouped in process modules (See Fig. 1). This study includes modules A to C, accounting only for carbonation during use phase B, and assessing benefits of module D when specified. The functional unit corresponds to 1 m^2 of residential top-up structural system with a lifespan of approximately 70 years. The calculation for whole life embodied carbon emissions of 1 m^2 for a given structural system s is described in Equation (1):

$$WLEC_s = \frac{\sum m_{i,s} \bullet \overline{ECC}_{i,j}}{A} \tag{1}$$

Where:

$m_{i,s}$ = mass of material i in structural system s (in kg).
$\overline{ECC}_{i,j}$ = is the mean embodied carbon coefficient of material i for life cycle module j (expressed in $kgCO_2$-eq/kg of material i).
A = Gross floor area of the structural system, which corresponds to 10,500 m^2, and remains the same across all systems.

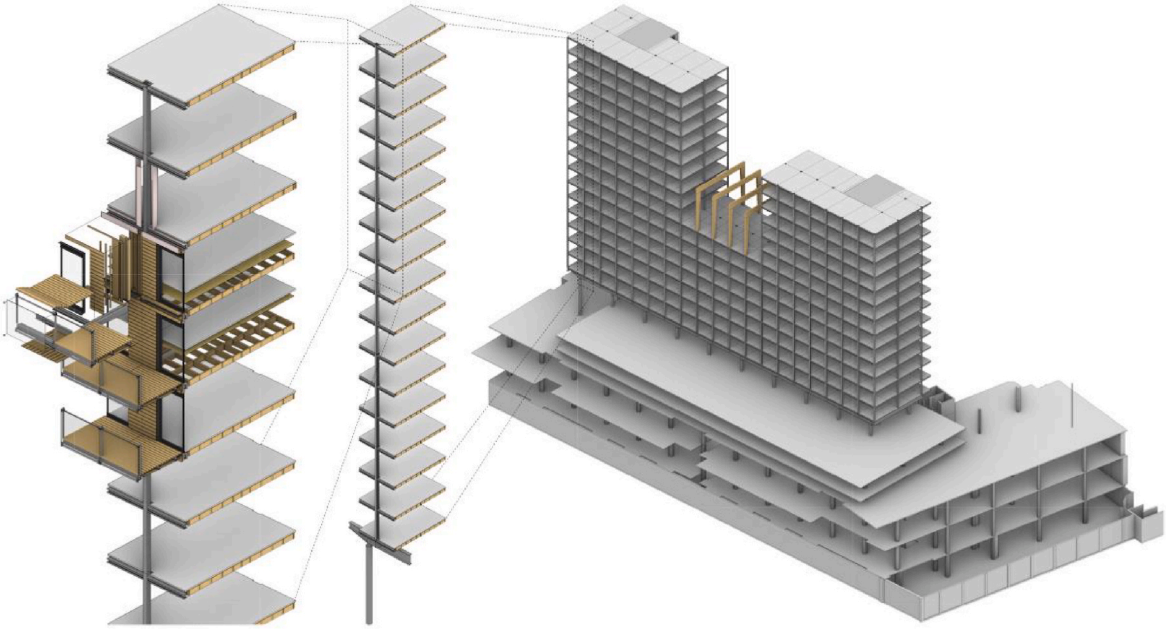


Fig. 3. Representative fragment identified to derive alternative materialization scenarios for homogenous top-up structure.

2.5. *Estimating cumulative GHG emissions of new construction by 2050*

To estimate impacts from the Amsterdam Metropolitan Area by 2050 and compare them with national goals, we estimated the cumulative GHG emissions of building the total housing demand with each structural system. To do this, we first multiplied the total m^2 demand (T) by the material intensities (I) of each structural system (See material intensities in Table 1), which are expressed in the units kg/m^2. Thus, the total demand of material i associated with structural system s is calculated as described in Equation (2):

$$M_{i,s} = T \bullet I_{i,a} \tag{2}$$

Where:

$M_{i,s}$ = Total demand of material i for structural system s by 2050 in the AMA (in kg)
T = Total demand for new housing in the Amsterdam Metropolitan Area by 2050 (in m^2)
A = Gross floor area of the structure (=10,500 m^2)
$I_{i,a} = m_{i,s}/A$ = mass of material i in structural system s, divided by the structure area A (expressed in kg/m^2)

The total material demand ($M_{i,s}$) is then multiplied by their corresponding ECC's and summed across life cycle modules. Where $\overrightarrow{ECC_{i,j}}$ represents the vector of randomly sampled embodied carbon emissions for material i in life cycle module j, and CCE_{2050}, the resulting cumulative carbon emissions associated with the construction of new housing by 2050 with structural system s, calculated as Equation (3):

$$CCE_{2050,s} = \sum \left(M_{i,s} \cdot \overrightarrow{ECC_{i,j}} \right) \tag{3}$$

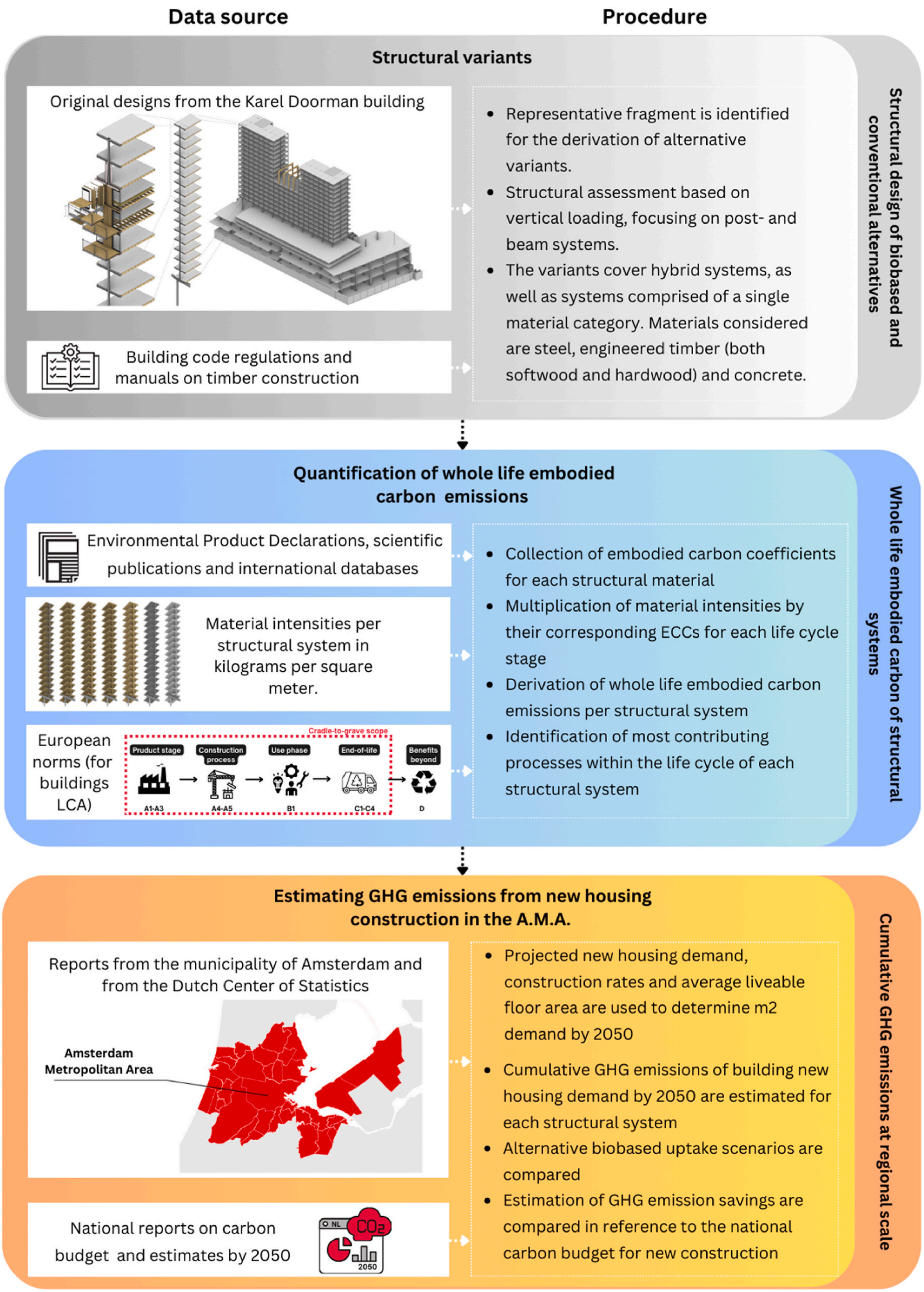
This results in distributions of cumulative carbon emissions for each structural system, expressed in $kgCO_2$-eq.

2.6. *Comparing emissions under different timber uptake scenarios by 2050*

To estimate the global warming mitigation potential from gradual substitution of predominantly mineral based structures versus bio-based structures, two scenarios are compared. First one describes a partial substitution (from 0%, 20%, 50%–90%) of conventional concrete (F9.2) and steel (E8) structures, with predominantly bio-based structures. For this, an average of the cumulative emissions by 2050 from structural systems A.1, A.2, A4.1 and A4.2 is used. We compare those potential savings up to 2050, with a second scenario in which only the “modest” hybrid system E5 is adopted (See detailed material quantities in Supplementary Information B; SIB3). The proportion of conventional structures assumed throughout the transition scenarios and calculation procedure is described in Supplementary Information A; SI6. These scenarios are relevant for The Netherlands, where agreements stablished by the ‘Green Deal Convenant Houtbouw’ (https://www.metropoolregioamsterdam.nl/houtbouw/) have set goals to increase timber construction by 20% in the Amsterdam Metropolitan Area, and for which a detailed quantification of life cycle emissions by 2050 could lead to better informed targets.

3. Results

Based on the design of a currently built top-up structure (denominated structural system E5), we designed six alternative structural systems (A1.1, A1.2, A4.1, A4.2, E8 and F9.2) (See Table 2 and Fig. 2) and evaluated the whole life embodied carbon of each structural system following the methodological framework as visualized in Fig. 4. All structural systems compared can be considered hybrid, with the exception of F9.2, which consists solely of concrete elements. The predominantly bio-based structures correspond to system A1.1, A1.2, A4.1 and A4.2, while structures E5 and E8 are predominantly steel. The whole life embodied carbon emissions of structures E8 and F9.2 resulted in an average value of 0.17 and 0.11 tons CO_2-eq for 1 m^2, respectively (Fig. 6), more than twice the average of the predominantly bio-based alternatives (=0.066 tons CO_2-eq/1 m^2)(See detailed values in Supplementary Information A; SI7). The best performing structure in terms of embodied carbon emissions corresponds to variant A4.1, where the footprint is estimated to be 0.061 tons of CO_2-eq excluding module D benefits (and = 0.005 tons of CO_2-eq when accounting for module D benefits from recycle and reuse after dismantling). The two structures with the lowest embodied carbon, A1.1 and A4.1, with 0.062 and 0.061 tons CO_2-eq respectively, were designed with hardwood LVL beams and columns, which uses approximately 400 tons less of timber than



- Representative fragment is identified for the derivation of alternative variants.
- Structural assessment based on vertical loading, focusing on post- and beam systems.
- The variants cover hybrid systems, as well as systems comprised of a single material category. Materials considered are steel, engineered timber (both softwood and hardwood) and concrete.

- Collection of embodied carbon coefficients for each structural material
- Multiplication of material intensities by their corresponding ECCs for each life cycle stage
- Derivation of whole life embodied carbon emissions per structural system
- Identification of most contributing processes within the life cycle of each structural system

- Projected new housing demand, construction rates and average liveable floor area are used to determine m2 demand by 2050
- Cumulative GHG emissions of building new housing demand by 2050 are estimated for each structural system
- Alternative biobased uptake scenarios are compared
- Estimation of GHG emission savings are compared in reference to the national carbon budget for new construction

Fig. 4. Methodological framework of this study.

structures A1.2 and A4.2, where the beams and columns are designed with softwood LVL. The main difference between structures A1.1 and A4.1 is the floor structure, with the first one designed with a spruce plate and spruce joists of system, and the latter with a CLT floor slab. It is also relevant to notice that while the spruce plate presents a slightly lower embodied carbon footprint, the CLT stores a higher amount of carbon and is rewarded a higher substitution benefit in module D.

In the case of predominantly mineral based variants, we compared

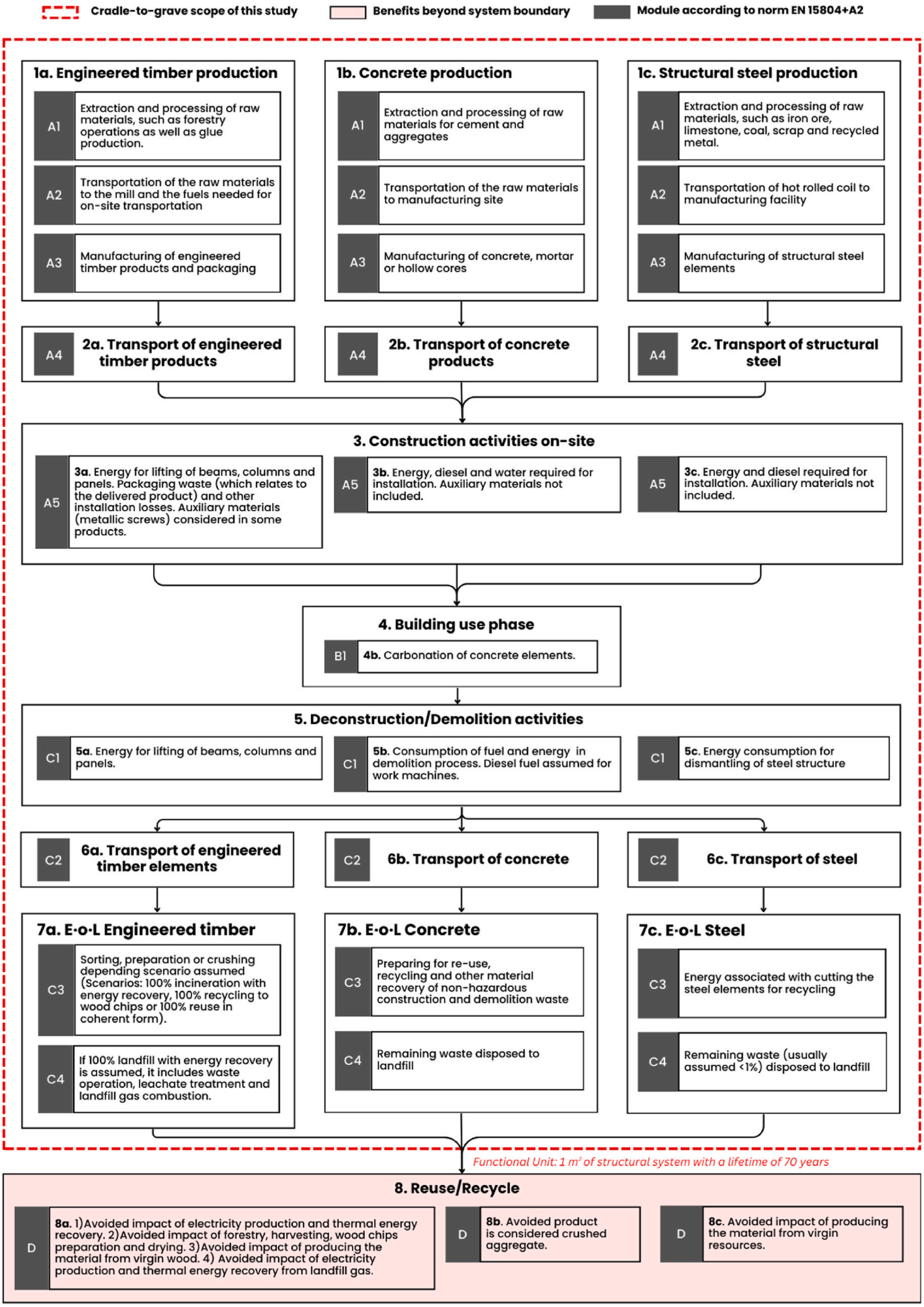


Fig. 5. Flow diagram of the life cycle scope and modules included in this study.

Table 2
Whole life cycle carbon emissions and weight estimated for 1 m^2 of structural system.

Variant	Life cycle emissions (in tons CO_2-eq)	SD	Min	Max	Structural Weight (tons)
E5	0.11	0.03	0.05	0.17	0.22
A.1.	0.06	0.01	0.04	0.08	0.20
A1.2	0.07	0.01	0.05	0.10	0.21
A4.1	0.06	0.00	0.05	0.07	0.23
A4.2	0.07	0.01	0.05	0.08	0.23
E8	0.17	0.03	0.10	0.24	0.43
F9.2	0.12	0.01	0.09	0.14	0.61

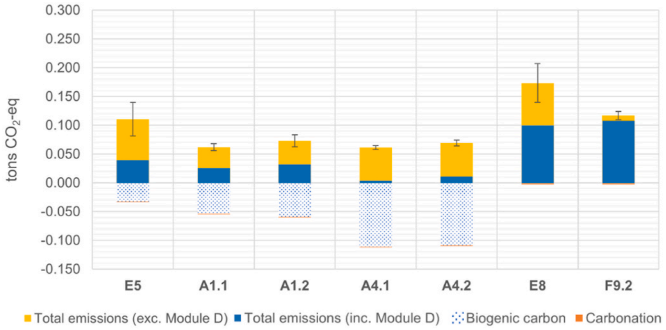


Fig. 6. Whole life cycle embodied carbon emissions (in tons CO_2-eq) for 1 m^2 of each structural systems. Error bars represent standard deviation.

three options: a predominantly steel structure (E8), a predominantly concrete structure (F9.2), and a hybrid steel structure with a modest amount of timber uptake (E5). The average life cycle emissions of these variants, excluding benefits of module D, ranged between 0.11 and 0.17 tons CO_2-eq for 1 m^2 (Fig. 6). The variant E5, is found to be competitive with the predominantly bio-based alternatives only when benefits of module D are accounted (which results in 0.04 tons CO_2-eq).

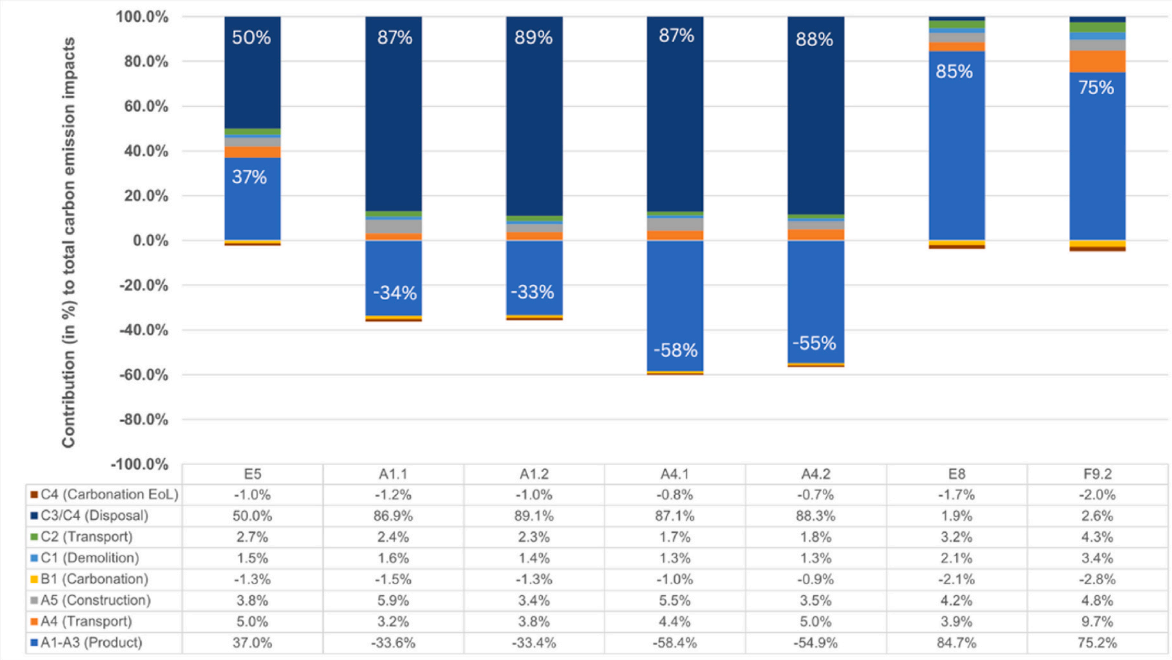
The amount of carbon stored in the construction materials was accounted for through measures of biogenic carbon for timber elements, and through estimates of carbonation for concrete (assumed during the use and disposal phase). The biogenic carbon, which corresponds partly to the amount of carbon stored in timber through the process of photosynthesis, is several orders of magnitude larger than the amount of carbon that is fixated to concrete materials due to atmospheric exposure through the carbonation process (Fig. 6). According to the results of the contribution analysis (Fig. 7), biogenic carbon can potentially offset between 30 and 60% of the total positive emissions associated with the life cycle of the predominantly bio-based alternatives (assuming incineration with energy recovery at end-of-life), whereas carbonation accounts for only 1–2% of the total positive emissions across systems.

The most contributing modules to the life cycle impacts of predominantly steel and concrete variants (E8 and F9.2), correspond to the production stages A1-A3. This implies that further decarbonization strategies for these variants would require alternative extraction and manufacturing processes for the material themselves. On the other hand, the rest of the variants (E5, A1.1, A.12, A4.1 and A4.2) present module C3/C4 (treatment and disposal at end-of-life) as the largest contributor to their environmental impacts. This presents multiple opportunities for further improvement of the carbon footprint, especially for predominantly bio-based structures, where the contribution of C3/C4 is up to 90% of the total positive emissions, and where several alternatives exist for end-of-life scenarios, such as reuse and recycle practices.

The emissions associated with transport to the construction site (module A4) and construction practices (A5) maintained a similar proportion across systems (~3–5% of total positive emissions), with the exception of variant F9.2, where transport at A4 represented almost 10% of the total positive emissions. Impacts of demolition and transport of demolition waste (module C1 and C2) ranged between 1 and 3% across most alternatives.

3.1. Cumulative GHG emissions of building residential superstructures by 2050

The impact of new housing construction required by 2050 in the Amsterdam Metropolitan Area (AMA), was estimated (as described in Methods) by multiplying the total material demand with the embodied carbon coefficients that were randomly sampled for each life cycle stage through Monte Carlo simulation. The results are presented in Table 3 and Fig. 8, where each boxplot represents the cumulative GHG emissions



	E5	A1.1	A1.2	A4.1	A4.2	E8	F9.2
C4 (Carbonation EoL)	-1.0%	-1.2%	-1.0%	-0.8%	-0.7%	-1.7%	-2.0%
C3/C4 (Disposal)	50.0%	86.9%	89.1%	87.1%	88.3%	1.9%	2.6%
C2 (Transport)	2.7%	2.4%	2.3%	1.7%	1.8%	3.2%	4.3%
C1 (Demolition)	1.5%	1.6%	1.4%	1.3%	1.3%	2.1%	3.4%
B1 (Carbonation)	-1.3%	-1.5%	-1.3%	-1.0%	-0.9%	-2.1%	-2.8%
A5 (Construction)	3.8%	5.9%	3.4%	5.5%	3.5%	4.2%	4.8%
A4 (Transport)	5.0%	3.2%	3.8%	4.4%	5.0%	3.9%	9.7%
A1-A3 (Product)	37.0%	-33.6%	-33.4%	-58.4%	-54.9%	84.7%	75.2%

Fig. 7. Contribution analysis of each structural system. It shows the relative contribution of each life cycle module to the total (positive) carbon emissions.

Table 3
Cumulative carbon emissions by 2050 of building total housing demand with each structural system.

Variant	Cumulative carbon emissions (tons CO_2-eq)	SD
E5	1.27E+06	3.36E+05
A.1.	7.17E+05	7.02E+04
A1.2	8.35E+05	1.17E+05
A4.1	7.16E+05	3.83E+04
A4.2	7.92E+05	5.96E+04
E8	2.00E+06	3.87E+05
F9.2	1.34E+06	8.23E+04

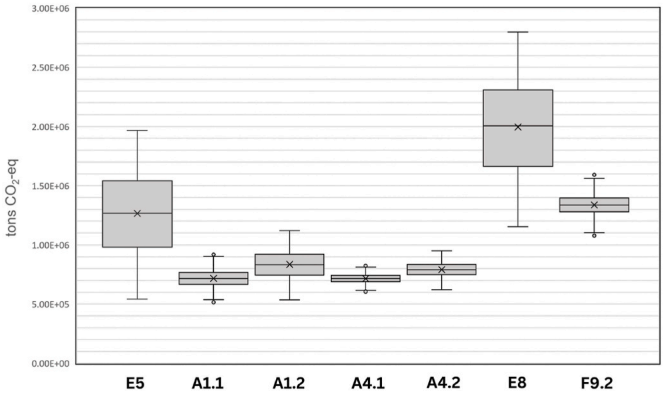


Fig. 8. Cumulative GHG emissions (in tons CO_2-eq) by 2050 of building total housing demand with each structural system in the Amsterdam Metropolitan Area.

that can be associated with building the total demand of new homes with each structural system. The values in Fig. 8 include accounting of biogenic carbon and exclude benefits of module D. Moreover, incineration with energy recovery is assumed as the end-of-life treatment of timber elements (this is the conventional assumption in The Netherlands, where landfill of timber elements is prohibited).

Based on our results, system E8 presents not only the highest average emissions, but also the largest data dispersion, followed by system E5. The large variance in those two systems is related to the large difference between low (0.047kgCO_2/kg) and high (2.590kgCO_2-eq/kg) embodied carbon coefficients that were used in module A1-A3 for structural steel, and the slightly high standard deviation in modules C3/C4. For the product stages A1-A3, the low ECC was retrieved from an Environmental Product Declaration of recycled structural steel (EMR, 2022). In which case, the extraction of raw material is avoided and only the impact of collecting and reshaping the steel is considered, leading to a considerable decrease on embodied emissions compared with the use of virgin material. The dispersion of the remaining systems was limited, with the tighter cluster of data observed for systems A1.1, A4.1, A4.2 and F9.3.

The predominantly bio-based alternatives presented emissions ranging between 6.67E+05 and 9.22E+05 tons of CO_2-eq within their 50% confidence interval. This is considerably lower than the emissions estimated for system F9.2, which range between 1.28E+06 and 1.40E+06 in its interquartile range. Structures A1.1, A1.2, A4.1 and A4.2, generate less than 9.22E+05 tons CO2-eq, within a 75% confidence range (Fig. 8).

3.2. Transition scenarios compared in relation to the Dutch national carbon budget

To compare the potential savings in GHG emissions of transitioning towards bio-based structural systems, we compared the potential savings of 1) a modest uptake of timber construction (represented with system E5, where timber represents 15% from the total tons of material used in the structure), versus 2) an uptake of predominantly bio-based structures (where the percentage of timber correspond to 25–37% from the total tons of material used in these structures). To represent the emissions of predominantly bio-based structures, we used the average footprint of structures A1.1, A1.2, A4.1 and A4.2. The assumptions made for each uptake scenario are described in Methods. The results indicate that an increase between 20 and 90% of predominantly bio-based alternatives, would lead to savings of up to 0.18 and 0.618 MtCO_2-eq, respectively (Fig. 9). In contrast, the uptake of variant E5 would reflect savings ranging only between 0.08 and 0.17MtCO_2-eq. In other words, the uptake of predominantly timber-based structures can save 2.25 times more GHG emissions throughout their life cycle, in comparison with a modest uptake where bio-based materials represent less than 20% of the material tons content in a structural system.

Considering that the national carbon budget for new residential construction in the Netherlands has been estimated at 7 Mt of CO_2-eq (when aiming for a 1.5 °C target) (Copper8 et al., 2023) by 2050, a 90% uptake of the modest variant E5 in the A.M.A would lead to a consumption of 1.27 MtCO_2-eq from the national budget, whereas a 90% uptake of predominantly bio-based structures would consume 0.822 MtCO2-eq. Thus, a radical uptake of predominantly bio-based structural systems could save up to 6 MtCO_2-eq from the national carbon budget by 2050 in comparison to conventional mineral systems.

4. Discussion

While the benefits of building with timber go well beyond the topic of carbon dynamics, their potential to avoid using carbon-intensive materials represents a substantial source for carbon emission savings (assuming the net consumption of carbon-intensive materials is actually decreased and not simply shifted to another sector). Our results show that predominantly bio-based structures can decrease up to 60% the embodied life cycle GHG emissions of residential buildings in comparison to steel and concrete structures. Moreover, the end-of-life considerations for the treatment, reuse and ultimate disposal of the engineered timber, were found to be the most contributing processes to the total life cycle footprint of the bio-based structures.

According to our contribution analysis, modules C1 to C4 can account for almost 90% of the total positive emissions associated with the predominantly bio-based structures. Incineration with energy recovery was assumed as the default treatment in the Netherlands for timber elements at their end-of-life, however, the total positive emissions can be further reduced through reuse and recycle practices (See sensitivity analysis in Supplementary Information A; SI8), and a considerably amount (up to a third) can be offset if we account for the benefits of avoided impacts (accounting for module D). Thus, mitigating embodied impacts is possible through the selection of construction materials and

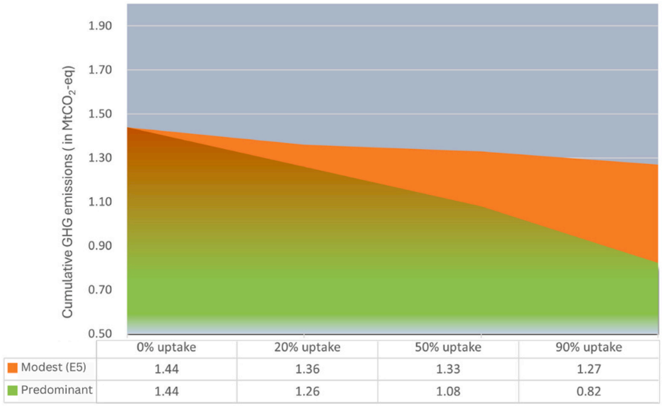


Fig. 9. GHG emissions of transition scenarios comparing uptake of moderate vs. predominantly bio-based structures in the Amsterdam Metropolitan Area.

the application of sustainable and circular strategies for reuse and recycling of building materials.

To facilitate circular practices, the structural systems were designed in a post-and-beams system, where dry connections and timber joists allow an easy dismantling of elements in the bio-based alternatives, while preserving a high structural integrity (Ghobadi and Sepasgozar, 2023; Rasmussen et al., 2019). According to product documentation from manufacturers of structural timber: "the products can theoretically be dismantled non-destructively, allowing 100% reuse" (KLH Massivholz GmbHK., 2023). This is further supported by the fact that in our design, the beams and columns are encapsulated in gypsum, which -aside fire protection aims-minimizes the risk and degree of degradation due to exposure.

Additionally, a novel feature of this study is the comparison between engineered timber made out of coniferous softwood (commonly Spruce) and from deciduous hardwood (European Beech). Engineered timber is predominantly made from softwood, though recent advances in the manufacturing of laminated veneer lumber have allowed a new category of structural hardwood to enter the market. To account for this cutting-edge material, we included in our study information from, currently, the only available manufacturer of hardwood LVL in Europe (Pollmeier, 2023). There are three relevant aspects to compare across alternatives: emissions, weight and material demand (See visualization in Supplementary Information A; SI9). Given the strength profile of hardwood, a lesser amount of wood is required to meet structural demands. Variants A1.1 and A4.1 (designed with Beech columns and beams) utilize approximately 400 m^3 less of timber than variants A1.2 and A4.2. In terms of weight, the bio-based variants (A1.1, A1.2, A4.1, A4.2) are the lightest structures in comparison to E5, E8 and F9.2. All bio-based variants present a comparably equivalent weight (despite using less material, variants A1.1 and A4.1 are not considerably lighter, this is due to the higher density of hardwood). Even though different structural materials will influence the thermal capacity of a building, studies such as the one by Heeren et al. (2015), support the findings that wooden variants present a consistent advantage throughout life cycle impact assessment (LCIA) scores when comparing between parametric designs, where: "the lower energy performance of wooden buildings (due to the reduced thermal inertia) is overcompensated by the lower environmental impact of the material." Design recommendations to improve energy performance in bio-based alternatives include alternative shading and ventilation strategies (e.g., heat recovery), and supplementing the thermal inertia with the use of phase change materials and hybrid systems (Heeren et al., 2015; Leskovar and Premrov, 2011; Strandberg-de Bruijn et al., 2019).

4.1. *Considerations for a sustainable bio-based future*

While the adoption of bio-based materials aligns with broader goals of achieving ecological balance and combating climate change, it is only one of the many interventions needed to foster a sustainable development of the construction sector. Along with material substitution, we highlight three important aspects to consider:

Reduce material demand. Stricter guidelines should be in place to help define when new construction is unavoidable, and when renovation and adaption strategies should be mandatorily prioritized. According to recent studies, adaptive reuse of buildings can show up to 70% reduction of environmental impacts in comparison to demolition and new construction (Hasik et al., 2019; Storck et al., 2023; Vilches et al., 2017).

Rethink design. As exemplified briefly through the structural systems compared in this study, different types of wood can be used in the design of timber buildings, each with their own strenght, performance and aesthetics profile. Wood is not one thing, is thousands of species entangled in multiple ecological configurations, with distinct physical properties and propensities. While foresters and designers tend to look at wood from seemingly opposite sides of the design spectrum, both are actively influencing the forest landscape in a globalized economy (Ibañez et al., 2019). Forests growth, is thus, constantly influenced by changing economic and cultural imperatives. In this regard, urban designers have the potential to impact both the product and the source, through their material selection and design considerations. This highlights the need for a stronger consideration of the relations between wood demand and forest dynamics in long-term strategies (Adhikari and Ozarska, 2018), and the potential of urban design to help shape the forest and wood producing landscapes across the globe (Klein et al., 2016).

Supply matters. A widely held assumption is that the demand for timber will exceed the supply available from forests on a sustainable basis (Churkina and Running, 2000). According to the Food and Agriculture Organization of the United Nations (FAO), wood needed for future timber constructions can come from increasing harvest from sustainably managed forest plantations, intermediate thinning of natural forests, redirecting existing wood uses, and increasing afforestation practices (FAO, 2022; Mishra et al., 2021). In 2020, naturally regenerated temperate and boreal forests provided about 44% of global industrial roundwood production(Mishra et al., 2022). Following historical trends, studies project an annual increase of regenerated temperate and boreal forest stocks, suggesting potential increase of the global supply of roundwood (Arets et al., 2011; Ceccherini et al., 2020; Fraser, 2019). Sourcing wood from sustainably managed and community-based forests is key to achieve long-term resilience, where highly productive plantations could alleviate harvest pressure from natural forests, while maintaining strict biodiversity, land protection and conservation policies (Chappin et al., 2015; Hua et al., 2022; Pirard et al., 2016). Addressing this key factor, the latest European norms for life cycle assessment of building and construction products, recommend to account for biogenic carbon stored in the timber elements as a negative value during product stages (module A1-A3), only when the timber is certified from sustainably managed sources.

4.2. *Limitations of the study*

On regards to the lifespan of the structures, this study assumed an average of 70 years. According to data from manufacturers, the construction elements assessed in this study present a lifespan beyond the one assumed for the top-up structure, with no material requirements accounted in the use phase for maintenance (B2), repair (B3), replacement (B4) and refurbishment (B5). However, it is recommended for future studies to include data regarding refurbishment and maintenance practices when available, to identify potential tradeoffs between materials and design. Moreover, our study compares the influence of material substitution on the carbon footprint of structural systems, focusing solely in the primary top-up structure, and excluding the concrete cores and foundation, which are assumed the same across all alternatives. Even though these cores were assumed identical for all systems, future studies could include the influence of material substitution on the core themselves, which could also be built with bio-based materials, and the potential implications for the foundation, since lighter structures would require less reinforcement of the foundation. Additional discussion on methodological considerations are included in Supplementary Information A; SI10.

5. Conclusion

Our results highlight the potential of engineered timber as a structural material that (with an appropriate wood sourcing and end-of-life treatment), it can be effectively used for both decarbonization and urban densification strategies. Predominant use of engineered timber in top-up structures, including beams, columns and floor systems, was found to decrease up to 60% the embodied carbon emissions of residential buildings compared with predominant and hybrid concrete and steel structures. To account for potential variations across the life cycle stages, a statistical analysis was conducted to include measures of data dispersion. Among the considerations taken for a comprehensive comparison between materials, we included potential variations that could arise from, for example, using 100% recycled steel instead of primary sourced materials, and alternative end-of-life scenarios. Our results demonstrate that predominant bio-based structures present consistently a significant advantage over mineral ones, with further possibilities to reduce emissions by guaranteeing a high-quality reuse of timber elements.

This study is placed within the geographical context of Amsterdam, in The Netherlands, providing a case study that is representative of the concerns faced by metropolitan areas across the world. Our findings suggest that an extensive uptake of engineered timber structures in the Amsterdam Metropolitan Area (~90% of projected new construction) can radically reduce the whole life embodied carbon emissions associated with new residential structures, and can save up to 6MtCO_2-eq from the national carbon budget allocated to new housing construction by 2050. From a policy standpoint, our results indicate that the current ambitions set by the municipality to increase the use of bio-materials in new construction is a step in the right direction. Based on our projected savings by 2050, the target is recommended to increase from 20% to at least 80%, specifically targeting residential structures, where the timber elements present a considerable long-term lifespan (>200years). We recommend as well for policy that can help stablish a system aimed at high-quality reuse of timber elements, supported by our results which indicate that predominant engineered timber top-up structures can store in average 0.083 tons CO_2-eq per m^2. Prolonging the lifespan of engineered timber is essential to maintain the carbon sequestered, helping in the long-run to offset the positive carbon emissions that result from new construction, and increasing the potential of cities to sustain long-term carbon sinks.

The information used for the engineered timber products assessed in this study pertains to manufacturers that comply with sustainably certified wood sources. This is essential to minimize risk of passing environmental burdens to other systems and undesired trade-offs, such as land degradation from intensive land use management and biodiversity loss. While future developments in the industry may allow the reuse of secondary wood for the production of engineered timber, this study emphasizes as well the importance of considering the different material properties that can be achieved when considering multiple wood species. In the midst of a changing climate and an increasing frequency of natural disasters, forests and other wood-producing landscapes are also subject to constant change. For this, diversification of material diets is recommended to increase urban resilience, where embracing the multifaceted nature of modern timber construction needs to go beyond simple material substitution, challenging us to think on buildings as part of complex systems that can contribute to both environmental resilience and social well-being.

CRediT authorship contribution statement

Elizabeth Migoni Alejandre: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Gilbert Koskamp:** Writing – review & editing, Supervision, Data curation. **Mick van de Leur:** Writing – review & editing, Investigation, Data curation. **Alexander Wandl:** Writing – review & editing, Supervision, Methodology. **Arjan van Timmeren:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Funding sources

This research was supported by the Amsterdam Institute for Advanced Metropolitan Solutions.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Elizabeth Migoni Alejandre reports financial support was provided by Amsterdam Institute for Advanced Metropolitan Solutions. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.144273.

Data availability

The data has been attached as Supplementary Information.

References

Adhikari, S., Ozarska, B., 2018. Minimizing environmental impacts of timber products through the production process "From Sawmill to Final Products.". Environ. Syst. Res. 7. https://doi.org/10.1186/s40068-018-0109-x.

Andersen, J.H., Rasmussen, N.L., Ryberg, M.W., 2022. Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon. Energy Build. 254, 111604. https://doi.org/10.1016/j.enbuild.2021.111604.

Arets, E., Van der Meer, P.J., Verwer, C.C., Hengeveld, G.M., Tolkamp, G.W., Nabuurs, G. J., Van Oorscho, M., 2011. Global Wood Production. Assessment of industrial round wood supply from forest management systems in different global regions. Alterra-Rapport 1808, 79.

Bahrami, A., Nexén, O., Jonsson, J., 2021. Comparing performance of cross-laminated timber and reinforced concrete walls. Int. J. Appl. Mech. Eng. 26, 28–43. https://doi.org/10.2478/ijame-2021-0033.

Boelhouwer, P., 2020. The housing market in The Netherlands as a driver for social inequalities: proposals for reform. Int. J. Hous. Pol. https://doi.org/10.1080/19491247.2019.1663056.

Boelhouwer, P., 2017. The role of government and financial institutions during a housing market crisis: a case study of The Netherlands. Int. J. Hous. Pol. https://doi.org/10.1080/19491247.2017.1357399.

Camarasa, C., Mata, É., Navarro, J.P.J., Reyna, J., Bezerra, P., Angelkorte, G.B., Feng, W., Filippidou, F., Forthuber, S., Harris, C., Sandberg, N.H., Ignatiadou, S., Kranzl, L., Langevin, J., Liu, X., Müller, A., Soria, R., Villamar, D., Dias, G.P., Wanemark, J., Yaramenka, K., 2022. A global comparison of building decarbonization scenarios by 2050 towards 1.5–2 °C targets. Nat. Commun. 13. https://doi.org/10.1038/s41467-022-29890-5.

Camilo Gómez, J., 2023. Timber Top-Ups on Reinforced Concrete Structures to Increase Dwellings Area.

Ceccherini, G., Duveiller, G., Grassi, G., Lemoine, G., Avitabile, V., Pilli, R., Cescatti, A., 2020. Abrupt increase in harvested forest area over Europe after 2015. Nature 583, 72–77. https://doi.org/10.1038/s41586-020-2438-y.

Chappin, M.M.H., Cambré, B., Vermeulen, P.A.M., Lozano, R., 2015. Internalizing sustainable practices: a configurational approach on sustainable forest management of the Dutch wood trade and timber industry. J. Clean. Prod. 107, 760–774. https://doi.org/10.1016/j.jclepro.2015.05.087.

Chaturvedi, S., Ochsendorf, J., 2004. Global environmental impacts due to cement and steel. Struct. Eng. Int.: J. Int. Assoc. Bridge Struct. Eng. (IABSE) 14, 198–200. https://doi.org/10.2749/101686604777963748.

Chen, C.X., Pierobon, F., Jones, S., Maples, I., Gong, Y., Ganguly, I., 2022. Comparative life cycle assessment of mass timber and concrete residential buildings: a case study in China. Sustainability 14. https://doi.org/10.3390/su14010144.

Churkina, G., Running, S., 2000. Investigating The Balance Between Timber Harvest And Productivity Of Global Coniferous Forests Under Global Change.

Copper8, Metabolic, nibe, Alba Concepts, 2023. Woningbouw Binnen Planetaire Grenzen.

Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1998. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

D'Amico, B., Pomponi, F., Hart, J., 2021. Global potential for material substitution in building construction: the case of cross laminated timber. J. Clean. Prod. 279, 123487. https://doi.org/10.1016/j.jclepro.2020.123487.

Dodoo, A., Gustavsson, L., Sathre, R., 2014. Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems. Energy Build. 82, 194–210. https://doi.org/10.1016/j.enbuild.2014.06.034.

EMR, 2022. Environmental Product Declaration - Reusable Steel.

Ernst Andersen, C., Garnow, A., Grau Sørensen, C., Wittchen, A., Kristensen Stranddorf, L., Hoxha, E., Nygaard Rasmussen, F., Birgisdottir, H., 2023. Whole Life Carbon Impact of: 45 Timber Buildings.

Fang, C., Yu, D., 2017. Urban agglomeration: an evolving concept of an emerging phenomenon. Landsc. Urban Plann. 162, 126–136. https://doi.org/10.1016/j.landurbplan.2017.02.014.

FAO, 2022. The State of the World's Forests, the State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome. https://doi.org/10.4060/cb9360en.

Flower, D.J.M., Sanjayan, J.G., 2007. Green house gas emissions due to concrete manufacture. Int. J. Life Cycle Assess. 12, 282–288. https://doi.org/10.1065/lca2007.05.327.

Fraser, A., 2019. Achieving the Sustainable Management of Forests.

Gemeente Amsterdam, 2022. Woningbouwplan 2022-2028.

Ghobadi, M., Sepasgozar, S.M.E., 2023. Circular economy strategies in modern timber construction as a potential response to climate change. J. Build. Eng. https://doi.org/10.1016/j.jobe.2023.107229.

Hart, J., D'Amico, B., Pomponi, F., 2021. Whole-life embodied carbon in multistory buildings: steel, concrete and timber structures. J. Ind. Ecol. 25, 403–418. https://doi.org/10.1111/jiec.13139.

Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B., Bilec, M.M., 2019. Comparative whole-building life cycle assessment of renovation and new construction. Build. Environ. 161. https://doi.org/10.1016/j.buildenv.2019.106218.

Heeren, N., Mutel, C.L., Steubing, B., Ostermeyer, Y., Wallbaum, H., Hellweg, S., 2015. Environmental impact of buildings - what matters? Environ. Sci. Technol. 49, 9832–9841. https://doi.org/10.1021/acs.est.5b01735.

Hemmati, Mahboobeh, Messadi, T., Gu, H., Seddelmeyer, J., Hemmati, Moein, 2024. Comparison of embodied carbon footprint of a mass timber building structure with a steel equivalent. Buildings 14. https://doi.org/10.3390/buildings14051276.

Hua, F., Adrian Bruijnzeel, L., Meli, P., Martin, P.A., Zhang, J., Nakagawa, S., Miao, X., Wang, W., McEvoy, C., Peña-Arancibia, J.L., Brancalion, P.H.S., Smith, P., Edwards, D.P., Balmford, A., 2022. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. Science 376, 839–844. https://doi.org/10.1126/science.abl4649, 1979.

Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., Zhang, X., 2018. Carbon emission of global construction sector. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.06.001.

Ibañez, D., Hutton, J.E., Moe, K., 2019. Wood Urbanism : from the Molecular to the Territorial. Actar Publishers, New York, NY.

Klein, D., Wolf, C., Schulz, C., Weber-Blaschke, G., 2016. Environmental impacts of various biomass supply chains for the provision of raw wood in Bavaria, Germany, with focus on climate change. Sci. Total Environ. 539, 45–60. https://doi.org/10.1016/j.scitotenv.2015.08.087.

KLH Massivholz GmbH, K., 2023. Environmental Product Declaration KLH®-CLT (Cross Laminated Timber).

Leskovar, V.Ž., Premrov, M., 2011. An approach in architectural design of energy-efficient timber buildings with a focus on the optimal glazing size in the south-oriented façade. Energy Build. 43, 3410–3418. https://doi.org/10.1016/j.enbuild.2011.09.003.

Liang, S., Gu, H., Bergman, R., Kelley, S.S., 2020. Comparative life-cycle assessment of a mass timber building and concrete alternative. Wood Fiber Sci. 52, 217–229. https://doi.org/10.22382/wfs-2020-019.

Maes, J., Zulian, G., Thijssen, M., Castell, C., Baró, F., Ferreira, A.M., Melo, J.C.P.G., David, N., Alzetta, C., Geneletti, D., Cortinovis, C., Zwierzchowska, I., Louro Alves, F., Souto Cruz, C., Blasi, C., Alós Ortí, M.M., Attorre, F., Azzella, M.J., 2016. Mapping and assessment of ecosystems and their services. Urban Ecosyst. https://doi.org/10.2779/625242.

Mishra, A., Humpenöder, F., Churkina, G., Reyer, C.P.O., Beier, F., Bodirsky, B.L., Schellnhuber, H.J., Lotze-Campen, H., Popp, A., 2022. Land use change and carbon emissions of a transformation to timber cities. Nat. Commun. 13. https://doi.org/10.1038/s41467-022-32244-w.

Mishra, A., Humpenöder, F., Dietrich, J.P., Bodirsky, B.L., Sohngen, B., Reyer, C.P.O., Lotze-Campen, H., Popp, A., 2021. Estimating global land system impacts of timber plantations using MAgPIE 4.3.5. Geosci. Model Dev. (GMD) 14, 6467–6494. https://doi.org/10.5194/gmd-14-6467-2021.

Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S., Brattebø, H., 2013. Carbon emissions of infrastructure development. Environ. Sci. Technol. 47, 11739–11746. https://doi.org/10.1021/es402618m.

Oberle, B., Bringezu, S., Hatfield-dodds, S., Hellweg, S., Schandl, H., Clement, J., Authors, C., Cabernard, L., Che, N., Chen, D., Droz, H., Ekins, P., Fischer-kowalski, M., Flörke, M., Frank, S., Froemelt, A., Geschke, A., Haupt, M., Havlik, P., Lenzen, M., Lieber, M., Liu, B., Lu, Y., Mehr, J., Miatto, A., Newth, D., Oberschelp, C., Obersteiner, M., Pfster, S., Piccoli, E., Schaldach, R., Sonderegger, T., Sudheshwar, A., Tanikawa, H., Voet, V. Der, Walker, C., West, J., Wang, Z., Zhu, B., Bifani, P., Convery, I., Cornell, S., Dellink, R., Eboli, F., Jouini, S.E., Ge, C., Groot, R. S. De, Kaviti, J., 2019. Global Resources Outlook Report, Summary for Policy Makers.

Pirard, R., Dal Secco, L., Warman, R., 2016. Do timber plantations contribute to forest conservation? Environ. Sci. Pol. 57, 122–130. https://doi.org/10.1016/j.envsci.2015.12.010.

Pollmeier, 2023. Environmental Product Declaration - BauBuche.

Rasmussen, F.N., Birkved, M., Birgisdóttir, H., 2019. Upcycling and Design for Disassembly - LCA of buildings employing circular design strategies. IOP Conf. Ser. Earth Environ. Sci. 225. https://doi.org/10.1088/1755-1315/225/1/012040.

Seto, K.C., Fragkias, M., Güneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. PLoS One 6. https://doi.org/10.1371/journal.pone.0023777.

Souaid, C., ten Caat, P.N., Meijer, A., Visscher, H., 2024. Downsizing and the use of timber as embodied carbon reduction strategies for new-build housing: a partial life cycle assessment. Build. Environ. 253. https://doi.org/10.1016/j.buildenv.2024.111285.

Stark, S., Biber-Freudenberger, L., Dietz, T., Escobar, N., Förster, J.J., Henderson, J., Laibach, N., Börner, J., 2022. Sustainability implications of transformation pathways for the bioeconomy. Sustain. Prod. Consum. 29, 215–227. https://doi.org/10.1016/j.spc.2021.10.011.

Storck, M., Slabik, S., Hafner, A., Herz, R., 2023. Towards assessing embodied emissions in existing buildings LCA—comparison of continuing use, energetic refurbishment versus demolition and new construction. Sustainability 15. https://doi.org/10.3390/su151813981.

Strandberg-de Bruijn, P., Donarelli, A., Balksten, K., 2019. Full-scale studies of improving energy performance by renovating historic Swedish timber buildings with hemp-lime. Appl. Sci. 9. https://doi.org/10.3390/app9122484.

Tukker, A., Behrens, P., Deetman, S., Hu, M., Alejandre, E.M., van der Meide, M., Zhong, X., Zhang, C., 2023. Circular construction: six key recommendations. One Earth. https://doi.org/10.1016/j.oneear.2023.10.021.

van de Leur, M., 2023. Reducing the Embodied Environmental Impact of Building Structures. Delft.

Van Ruijven, B.J., Van Vuuren, D.P., Boskaljon, W., Neelis, M.L., Saygin, D., Patel, M.K., 2016. Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. Resour. Conserv. Recycl. 112, 15–36. https://doi.org/10.1016/j.resconrec.2016.04.016.

Vilches, A., Garcia-Martinez, A., Sanchez-Montañes, B., 2017. Life cycle assessment (LCA) of building refurbishment: a literature review. Energy Build. https://doi.org/10.1016/j.enbuild.2016.11.042.

Xu, Z., Peng, J., Qiu, S., Liu, Y., Dong, J., Zhang, H., 2022. Responses of spatial relationships between ecosystem services and the Sustainable Development Goals to urbanization. Sci. Total Environ. 850, 157868. https://doi.org/10.1016/j.scitotenv.2022.157868.

Younis, A., Dodoo, A., 2022. Cross-laminated timber for building construction: a life-cycle-assessment overview. J. Build. Eng. 52, 104482. https://doi.org/10.1016/j.jobe.2022.104482.