Environmental Assessment of Increased Use of Wood in the Building Sector

Towards more Effective Life Cycle Assessment to Support Environmental Impact Mitigating Implementation of Biobased Materials

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DOI (link to publication from Publisher):
10.54337/aau715507534

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

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BY
RASMUS NØDDEGAARD HANSEN

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PhD Series:	Faculty of Engineering and Science, Aalborg University
Department:	Department of the Built Environment

ISSN: 2446-1636
ISBN: 978-87-94563-34-5

Published by:
Aalborg University Open Publishing
Kroghstræde 1-3
DK – 9220 Aalborg Øst
aauopen@aau.dk

Funding sources: Villum Fonden and Realdania Fonden

ENGLISH SUMMARY

Climate change is evident due to the CO_2 concentration reaching 419 parts per million (PPM), exceeding the 350 PPM upper boundary of the last 11000 years. It triggers increased severe weather events, causing adverse social harm, particularly for vulnerable communities. Consequently, the UN member states set out the Paris Agreement to limit temperature rise to 1.5 °C or below 2 °C. The building sector is a major contributor to global greenhouse gas (GHG) emissions by 37% while causing 35% waste generation and 50% resource extraction in the EU. Therefore, the building sector is imperative in combatting climate and environmental impacts.

In recent years, enhanced energy efficiency has improved operational climate impacts. However, the embodied impacts of materials have not seen similar progress during this time. To address this challenge, wood's ability to temporarily store biogenic carbon emerged as a potential solution for delaying buildings' embodied carbon emissions.

Life cycle assessment (LCA) is commonly used to analyse the environmental impact of buildings from cradle to grave. However, assessing the climate benefits and pitfalls of using more wood is complex due to biogenic carbon, forest modelling, land use, as well as LCA's degree of detailing, system interactions, and impact categories, and building design aspects. Consequently, this dissertation aims to enhance understanding of assessing increased timber use in construction by applying different LCA approaches and specific wood-related aspects for distinct decision contexts.

Because consequential LCA (CLCA) is not widely used on buildings, a systematic literature review examined its state-of-the-art. In the review, I also inspected the recommendations in the ILCD Handbook on attributional LCA (ALCA) and CLCA. To assess LCA in the early building design, I used a simplified design tool to model ten detailed wooden dwellings in a Danish context and compared their climate impact deviations. It used the -1/+1 biogenic carbon approach, entailing production stage uptake and end-of-life release. A CLCA evaluated the change from conventional to timber construction on the macro scale towards 2050. It incorporated a bottom-up material flow analysis (MFA), forest modelling of trees' regrowth, dynamic discounting of GHG emissions, and indirect land use change (iLUC), using an input-output model as the LCA database. Also, I analysed needed land and carbon storage for implementing fast-growing biobased materials in wood buildings towards 2050. The analysis evaluated straw, hemp, and grass materials to substitute insulation and non-loadbearing wood products.

Researchers have extensively debated the application of ALCA and CLCA without reaching a clear consensus. This study addressed inconsistencies between Chapters 5

and 6.5 in the ILCD Handbook and proposed a balanced interpretation that suggests ALCA for micro scale (building project) and CLCA for macro scale (building stock).

The literature review revealed intended applications of building CLCA for circularity, increased wood usage, energy supply changes, and material production improvements. The consequential inventory modelling involves identifying the market, market trends, and affected suppliers. It applies to building materials and substituted products from co-products or end-of-life recycling. The studies employ a range of modelling methods, from simple to sophisticated.

The dwellings' early design prediction of climate impact was underestimated by 12% on average. Biobased materials, insulations, and metals need accurate quantity estimations to progress these predictions. Future simplified design tools should consider floors' accuracy and include partition walls to address underestimations. The impact discrepancy between design stages is also affected by a few products or changes in environmental product declarations during the design process. For design configurations, footing foundations and paper wool showed promising results in reducing the climate impacts of wood dwellings. Lastly, turning away from wooden dwellings' fire safety surface requirements appears promising to decrease climate impacts by minimising added material and suggests further examination.

The forest model used an 88-year rotation period for Swedish forestry to evaluate the transition from conventional to timber construction. It showed negative climate impacts up to year fifteen of the reference study period, otherwise positive, when considered without system interactions. This is because the delay of biogenic carbon emission is weighed less important than the current over a 100-year time horizon of the global warming potential (GWP). It is paramount, given the urgent need to reduce GHG emissions. Combining substitution and forest modelling entailed wood co-products replacing pulp wood, making timber have a positive climate impact. The climate-mitigating effect of pulp wood is greater than that of wood co-products, which is avoided when substituted by timber residues.

Transitioning to timber buildings increased the impact on nature occupation (biodiversity) for all wooden buildings. Multifamily houses (MFH) emerged with lower climate impacts in the timber scenario, while it was conventional for single-family houses (SFH) and offices (OB). Wood, mineral-based materials, metals, and fired clay contributed mostly. Case studies and coarse material grouping assuredly influenced the outcome, coming through for wooden SFH with eel grass and sedum roof simplified as wood and wooden OB with a notable structural steel quantity. Further research should determine if the wooden case studies are representative and best practices and if the background database's material representation can be detailed. The results were sensitive to trees' rotation period, iLUC, affected steel supplier, and inclusion of the forest model.

To tackle the issue of wood buildings' impact on biodiversity and land use, the dissertation explored the mitigation potentials of fast-growing biobased materials. Utilizing straw, hemp, or grass reduced the need for wooded land by 50-61% in the production stages, with the most promising reductions in SFH and MFH and the least in OB. Danish production could supply a nearly 50% market penetration in 2050 in the pure straw scenario. With a combination of straw and grass, Danish supply could meet a 100% market demand. These scenarios reduce the total required land by 49-60% and shift the resource and land-policy authority to Denmark. The limitations include single case studies for each building typology, a lack of consideration of a full life cycle and other impact categories.

Synthesising this research, the climate-effective use of timber looms when it efficiently replaces carbon-intensive materials like steel and concrete. For other non-loadbearing applications, fast-growing biobased materials substituting wood products might be an optimal solution to mitigate the timber buildings' impact on land use impact, and likely biodiversity loss.

The dissertation showed the combination of the biogenic carbon approach and allocation procedure affects wood's climate impact. The LCA's decision context of analysing timber presents distinctively different challenges. The simplified standard LCA is useful for design-related decisions such as optimising implementation. Strategic decision support, e.g., on transitioning to wood, requires the LCA to assess system interactions and consider biobased resource aspects. ALCA with system modelling can provide useful insights for the micro-scale decision contexts, e.g., relevant for architectural enterprises or clients with smaller portfolios. It could be advanced by conducting a CLCA or a land use change analysis. Conducting a CLCA, ideally combined with forest modelling and iLUC (disclosed separately), is suggested for appropriate decision support on the macro scale. It seems relevant for clients with larger portfolios and policymakers.

DANSK RESUME

Klimaforandringerne er evidente, fordi CO_2-koncentrationen har nået 419 parts per million (ppm) og dermed overskredet de sidste 11.000 års øvre interval på 350 ppm. Det medfører allerede en forøgelse af voldsomme vejrhændelser med negative sociale effekter til følge, især for de mest sårbare samfund. Derfor indgik FN's medlemslande Paris-aftalen om at begrænse temperaturstigningen til 1,5 °C eller væsentligt under 2 °C. Bygningssektoren er en stor bidragyder til den globale udledning af drivhusgasser (GHG, eng: greenhouse gas) med 37%, mens den forårsager 35% affald og 50% ressourceforbrug i EU. Byggesektoren er derfor afgørende for at reducere klima- og miljøpåvirkninger.

I de senere år har øget energieffektivitet forbedret bygningers operationelle klimapåvirkning. Materialernes indlejrede påvirkning har imidlertid ikke oplevet samme fremskridt i denne periode. For at imødegå denne udfordring er træs evne til midlertidigt at lagre biogent kulstof dukket op som en potentiel løsning til at forsinke bygningers klimapåvirkning.

Livscyklusvurdering (LCA) anvendes ofte til at analysere bygningers miljøpåvirkning fra vugge til grav. Men det er komplekst at vurdere de klimamæssige fordele og faldgruber ved at bruge mere træ på grund af biogent kulstof, skovmodellering, arealanvendelse samt LCA's detaljeringsgrad, systeminteraktioner og påvirkningskategorier og bygningsdesignaspekter. Derfor har denne afhandling til formål at forbedre forståelsen af vurderingen af øget brug af træ i byggeriet ved at anvende forskellige LCA-tilgange og specifikke aspekter ved biogene ressourcer til forskellig beslutningsstøtte.

Da konsekvens-LCA (CLCA, eng: consequential CLA) ikke er særlig anvendt på bygninger, blev dets state-of-the-art undersøgt ved et systematisk litteratur review. I gennemgangen undersøgte jeg også anbefalingerne i ILCD Handbook vedrørende attributionel LCA (ALCA) og CLCA. For at vurdere LCA i den tidlige bygningsdesignfase brugte jeg et simplificeret designværktøj til at modellere ti detaljerede designfase træboliger i en dansk kontekst og sammenlignede deres klimapåvirkningsafvigelser. Der blev anvendt en -1/+1-tilgang til biogent kulstof, som omfatter kulstofoptagelse i produktionsfasen og frigivelse efter endt levetid. En CLCA evaluerede et skift fra konventionelt byggeri til træ på makroskala fem mod 2050. Det omfattede en bottom-up materialestrømsanalyse (MFA, eng: material flow analysis), skovmodellering af genplantede træers vækst, dynamisk diskontering af drivhusgasemissioner og indirekte ændringer i arealanvendelsen (iLUC, eng: indirect land use change), samt brug af en input-output model som LCA-database. Jeg analyserede også arealbehovet og kulstoflagring ved at implementere hurtigt voksende biobaserede materialer i træbygninger frem mod 2050. Analysen evaluerede

halm-, hamp- og græsmaterialer som erstatning for isolering og ikke-bærende træprodukter.

Forskere har diskuteret anvendelsen af ALCA og CLCA indgående uden at nå frem til en klar konsensus. Dette studie har behandlet uoverensstemmelser mellem kapitel 5 og 6.5 i ILCD Handbook og foreslog som indledning til afhandlingen en balanceret fortolkning, hvor ALCA foreslås til mikroskala (byggeprojekt) og CLCA til makroskala (bygningsmasse).

Litteratur-reviewet afslørede intenderede anvendelser af bygnings-CLCA for cirkularitet, øget træforbrug, ændret energikilde i forsyningen og ændringsalternativer i materialeproduktionen. Modellering af konsekvens-inventory involverer vurdering af markedet, markedstrenden og påvirkede leverandører. Det gælder både for byggematerialer og substituerede produkter fra biprodukter eller genanvendelse ved endt levetid. Den undersøgte litteratur anvender en række modelleringsmetoder, fra simple til sofistikerede.

Forudsigelse af boligernes klimapåvirkning i den tidlige designfase blev underestimeret med 12% i gennemsnit. Biobaserede materialer, isolering og metaller kræver præcise mængdeestimater for at forbedre disse forudsigelser. Fremtidige simplificerede designværktøjer bør tage højde for gulvenes præcision og inkludere skillevægge for at imødegå den generelle underestimering. Klimapåvirkningsafvigelsen mellem designfaserne kan også influeres af nogle få produkter eller ændring af miljøvaredeklarationer under designprocessen. Når det gælder designkonfigurationer, viste fundamenter og papiruld lovende resultater med hensyn til at reducere klimapåvirkningerne fra træboliger. Ligeledes virker det lovende at gå væk fra bygningsreglementets overfladekrav for brandsikkerhed i træboliger for at mindske klimapåvirkningen grundet minimering af ekstra materiale, hvilekt bør undersøges mere systematisk og fyldestgørende.

Skovmodellen brugte en 88-årig rotationsperiode for svensk skovbrug til at evaluere overgangen fra konventionelt byggeri til træ. Den viste negative klimapåvirkninger op til år 15 i referenceperioden, ellers positive, når systeminteraktioner ikke modelleres. Det skyldes, at forsinkelsen af den biogene kulstofudledning vægtes mindre end det nuværende globale opvarmningspotentiale (GWP) over en 100-årig tidshorisont. Dette valg kan væsentligt begrundes i betragtning af det presserende behov for at reducere udledningen af drivhusgasser. Kombinationen af substitution og skovmodellering betød, at træs biprodukter erstattede cellulosetræ, hvilket gav tømmer en positiv klimapåvirkning. Den klimareducerende effekt af cellulosetræ er større end den fra træs biprodukter, som undgås, når de erstattes af tømmerets restprodukter.

Ved en transition til træbyggeri øges påvirkningen af naturbeslaglæggelse (eng: nature occupation), altså biodiversiteten, fra alle træbygningstyper. Etageboliger (MFH, eng:

multifamily houses) viste sig at have lavest klimapåvirkning i træscenariet, mens det var konventionelt for enfamiliehuse (SFH, eng: single-family houses) og kontorer (OB, eng: office buildings). Træ, mineralbaserede materialer, metaller og mursten bidrog mest. Casestudier og simplificeret materialegruppering påvirkede med stor sandsynlighed resultatet, idet SFH i træ havde ålegræs og sedumtag forsimplet som træ og OB i træ havde en nævneværdig mængde konstruktionsstål. Yderligere forskning bør undersøge, om casestudierne i træ er repræsentative og bedste praksis, og om baggrundsdatabasens materialerepræsentation kan detaljeres yderligere. Resultaterne var følsomme over for træs rotationsperiode, iLUC, den påvirkede stålleverandør og inkludering af skovmodellen.

For at løse problemet med træbygningers påvirkning af biodiversitet og arealanvendelse undersøgte afhandlingen potentialet ved hurtigt voksende biobaserede materialer. Brug af halm, hamp eller græs reducerede behovet for skovareal med 50-61% i produktionsfaserne, med de mest lovende reduktioner for SFH og MFH og de mindste for OB. I det rene halmscenarie kan Dansk produktion næsten forsyne en 50% markedsimplementering. Med en kombination af halm og græs kan dansk udbud imødekomme en markedsefterspørgsel på 100 %. Disse scenarier reducerer det samlede arealbehov med 49-60% og flytter samtidig den ressource- og arealpolitiske kontrol til Danmark. Begrænsningerne omfatter et casestudie for hver bygningstypologi, manglende inkludering af hele livscyklussen og andre miljøpåvirkningskategorier.

En sammenfatning af forskningen går mod at en korrekt klimareducerende brug af træ er mulig, når det effektivt erstatter kulstofintensive materialer som stål og beton. Til andre ikke-bærende funktioner bør hurtigt voksende biobaserede materialer erstatte træprodukter, for at mindske træbygningers påvirkning af arealanvendelsen og sandsynligvis også biodiversiteten.

Afhandlingen viste, at kombinationen af den biogene kulstofmetode og allokeringsprocedure påvirker vurderingen af træs klimapåvirkning. LCA-beslutningskonteksten for analyse af træ giver forskellige udfordringer. Den simplificerede standard-LCA er nyttig til designrelaterede beslutningsstøtte såsom optimering af træimplementering. Strategisk beslutningsstøtte, f.eks. ved skift til træ, kræver, at den pågældende LCA vurderer systeminteraktioner og overvejer biobaserede ressourceaspekter. ALCA med systemmodellering kan give nyttig indsigt til beslutningsstøtte på mikroskala, f.eks. relevant for arkitektvirksomheder eller bygherrer med mindre porteføljer. Tilgangen kan avanceres ved at udføre en CLCA eller arealanvendelsesanalyse. Gennemførelse af en CLCA, ideelt kombineret med skovmodellering og iLUC (opgivet separat), foreslås som passende beslutningsstøtte på makroskala. Det er relevant for bygherrer med større porteføljer og politiske beslutningstagere.

ACKNOWLEDGEMENTS

Developing and composing my Ph.D. did not occur in full isolation. I came across many people from the research field during the period, bringing everything from good advice to interesting discussions, fun moments, and new inspirations. The first persons I would like to thank are certainly Harpa and also Freja for giving me the opportunity and position in the first place. Leonora deserves mention for setting up the contact and recommending me to the group before it all started.

It does not come as a surprise that the main support, guidance, and inspiration came from my supervisors, where Harpa constantly brings inspiring energy, humour, and the broader perspectives and always has time for support in critical situations. I will thank Freja and Endrit for their close collaboration with valuable guidance and feedback to develop the PhD and its papers on a more daily basis. In that regard, I am thankful for Morten's contribution to the PhD project, always bringing sharp methodological advice and critique and for our collaboration on master thesis supervision.

Among my article co-authors, I would like to thank my colleague Camilla for constructive input to the article's progress and for being a helpful discussion partner on our shared topic of LCA on wood in buildings. In addition, a great thanks to Jonas, Bo, and Jannick for their collaboration in developing my third article.

I conducted research for my last article at Politecnico di Milano. I really appreciated the supervision and cooperation with Francesco due to his solid knowledge, availability, guidance and introducing me to interesting people. But not least, our social get-along, spanning nice conversations, lunches, and swims in Lake Como. My temporary colleagues with whom I shared office or floor also made the stay enjoyable and cultural. In particularly for my social side, involving everything from the daily social interactions and fun to lunches, concerts and aperitivo time as well as conversations on political, societal, and professional topics.

I want to give a major thanks to my current and previous colleagues. The pleasant and supportive atmosphere makes every day work enjoyable. It stems from our room for humour, leisurely conversations, social hangouts, and also interesting academic discussions, collaboration, shared advises and frustrations with the other PhD students, and shared professional and social experiences at conferences and courses abroad.

I will thank family and friends for showing interest and support during the Ph.D. while, most importantly, providing the social foundation and life that is necessary to also perform in work-related activities.

To close, I would like to thank Nel and the team for developing the simplified design tool and learning I got in that context. I would also like to thank the Villum Foundation and Realdania for supporting the Ph.D. project.

Rasmus Nøddegaard Hansen

March, 2024

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PREFACE

This dissertation developed from original and independent work by the author Rasmus Nøddegaard Hansen, carried out from 2021-2024 at the Department of the Built Environment under the Faculty of Engineering and Science at Aalborg University. The dissertation builds on four core publications presented in Chapter 1. The publications' common focus centres on the life cycle assessment (LCA) of using wood in buildings and the application of its different approaches for various decision contexts. In addition to the four core publications, I authored or co-authored other publications relating to the topic. They are complementarily drawn into the dissertation for supplemental perspectives. The complementary publications encompass the following:

Topic: *Environmental assessment of wood in buildings*

Closing the Gap to Sufficiency-Based Absolute Climate Targets for Wood Buildings. *Hansen, R. N., Hoxha, E., Andersen, C. E., Rasmussen, F. N., Ryberg, M. W., Birgisdóttir, H.* In: Journal of Physics: Conference Series, vol. 2600, no. 18, 2023. DOI: https://doi.org/10.1088/1742-6596/2600/18/182002

Readjusting the Climate Change Hyperfocus: How Expanding the Scope of Impact Categories Will Affect the Evaluation of Wood Buildings. *Hansen, R. N., Hoxha, E., Andersen, C. E., Rasmussen, F. N., Ryberg, M. W., Birgisdóttir, H.* In: Journal of Physics: Conference Series, vol. 2600, no. 15, 2023. DOI: https://doi.org/10.1088/1742-6596/2600/15/152023

Environmental Product Declarations of Structural Wood: A Review of Impacts and Potential Pitfalls for Practice. *Rasmussen, F. N., Andersen, C. E., Wittchen, A., Hansen, R. N., Birgisdóttir, H.* In: Buildings, 2021. DOI: https://doi.org/10.3390/buildings11080362

Topic: *LCA approaches, and decision context focus related to buildings*

Wood as a Carbon Mitigating Building Material: A Review of Consequential LCA and Biogenic Carbon Characteristics. *Hansen, R. N., Rasmussen, F. N., Ryberg, M., Birgisdóttir, H.* In: IOP Conference Series: Earth and Environmental Science, vol. 1078, no. 1, 2022. DOI: https://doi.org/10.1088/1755-1315/1078/1/012066

GLOSSARY

ALCA	Attributional LCA
BIM	Building information model
CLCA	Consequential LCA
CLCI	Consequential LCI
CLT	Cross-laminated timber
CO_2-eq	CO_2-equivalents
DDS	Detailed design stage
dLUC	direct land use change
EN 15978	European standard: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method
EN 15804	Sustainability of construction works – Environmental product declarations – Core rules for the product
EPD	Environmental Product Declaration
FE	Functional equivalent
GHG	Greenhouse gas
GWP	Global warming potential
ILCD	International Reference Life Cyle Data System
iLUC	indirect land use change
IPCC	Intergovernmental Panel on Climate Change
ISO 14040	Environmental management - Life cycle assessment - Principles and framework
ISO 14044	Environmental management – Life cycle assessment – Requirements and guidelines
LCA	Life cycle assessment
LCI	Life cycle inventory
LULUCF	Land use, land use change and forestry
MFA	Material flow analysis
MFH	Multifamily house
OB	Office building
PB	Planetary boundary
PPM	Parts per million
RSP	Reference study period
SDS	Early design stage
SFH	Single-family house
SMACE	Small and medium sized architectural and construction enterprise

CHAPTER 1. INTRODUCTION

1.1. CONTRIBUTIONS

This dissertation aspires to contribute to the empirical knowledge on the environmental impacts of using wood and biobased resources in the building sector. Empirically, the research provides insights into relevant environmental impact categories for biobased resources, as well as important life cycle assessment (LCA) and building aspects important for the environmental impacts at the building project scale and building stock scale. With this, it engages with LCA modelling and results relevant for LCA practitioners in building design, planning, and the various policy-making levels in the building sector.

It provides the building designer with findings of which life cycle stages, materials, and building elements that are influential determinants of climate impacts in the early design prediction and the detailed design, as well as the best practice on reducing environmental burden-shifting through effective design and use of materials. The assessment of availability and supplying countries equip planners and policymakers with knowledge about the systemic effects of larger-scale changes to wood and biobased materials, including where the resources likely come from and the associated impacts.

Furthermore, the dissertation adds to the methodological conversation through insights into how methodological aspects influence the interpretation of environmental impacts. It does so by applying the attributional and consequential LCA approaches and two distinct conceptual modelling of biogenic carbon. One is the -1/+1 approach, which considers biogenic carbon uptake in the production stages and releases at the end of life, i.e., carbon neutrality over the life cycle. The other combined time-discounting the carbon emissions and sequestering in replanted trees through forest modelling.

Although this research geographically concentrates on a Danish context, it emphasises the likely necessity to consider the systemic effects of larger-scale changes in LCA. In addition, the different allocation procedures applied separately and with biogenic carbon modelling highlight that they have implications for climate impact assessment. Consequently, the dissertation provides new insights into the fundamentals important for augmenting the contingency of using wood and biobased resources in the building sector and for a more effective LCA on this topic.

1.2. CLIMATE CHANGE, PLANET EARTH, AND THE ROLE OF THE BUILDING SECTOR

The Holocene state is the period of the last about 11000 years and, until recently - a state where the global climate and nature remained substantially stable. The CO_2 concentration in the atmosphere during this period pendulated between 260 and 350 parts per million (ppm) (Waters et al., 2016), creating a period of history where human beings settled because the climate was foreseeable with little deviations, empowering the development of societies that made human beings not need to wander for food, shelter, and safe environments any longer. It is the foundation on which modern civilisation is built and thrives. Between 1999 and 2010, the world surpassed the 350 ppm upper boundary to 400 ppm (Waters et al., 2016) and today, levelling to about 417-419 ppm (Friedlingstein et al., 2023). With this surpass, the world entered more uncertain climate circumstances, making societies more vulnerable to the unknown, unforeseen encounters that may occur. Several IPCC (Intergovernmental Panel on Climate Change) reports attempt to address this new situation and the consequences it can have, latest by IPCC (2023).

The condition of the climate remains not the only emergency on our Earth. Six out of nine planetary boundaries are now transgressed, indicating cross-systemic challenges on several Earth functions. It is the result of increased habit destruction, pollution, and nature cycle disruption that add disability and reduce the robustness of the Earth's system to provide well-being for human beings and perhaps also for animals (Richardson et al., 2023).

The increased impact of climate change and other environmental impacts are caused by anthropogenic consumption and activities, resulting in significant attention in the last decade. Every IPCC report evaluates the climate's state to decline and the climate change-associated risks likely to levitate. The assessments suggest that not limiting global temperature increase to 1.5-2 °C will lead to adverse effects on the Earth system and increase the likelihood of triggering tipping points (IPCC, 2023). We need to address these challenges effectively and contribute to global efforts in combating the poly-emergency of climate change and the degradation of other Earth systems. The building and construction industry is not exempt from taking on the challenge.

Tackling the severe climate change issue, the building sector remains fundamental to transform. The building and construction sector significantly impacts the climate and environment. The building sector in Europe consumes 50% of extracted resources and generates 35% of the total waste (European Commission, 2024). It is responsible for a substantial amount of global greenhouse gas (GHG) emissions (37%) arising from raw material extraction, manufacturing, energy consumption from heating and cooling, and the increased number of appliances and equipment in buildings (United Nations Environment Programme, 2022). The production of building materials, the embodied carbon, contributes about 10% to the global climate impacts, while energy use emits about 27% (ibid).

The building sector might be the single industry with the largest impact on nature, whether that entails resource consumption, waste generation, or climate change, affecting the Earth's systems' capacities to cope with and assimilate these pressures. With continuous demand for new buildings globally, in Europe and Denmark, it is crucial to explore sustainable practices and construction technologies that can reduce the sector's carbon and environmental footprint of new buildings and the existing building stock through renovation and transformation.

1.2.1. PURSUING DECARBONISATION OF THE BUILDING SECTOR BY IMPLEMENTING WOOD AND BIOBASED MATERIALS

When diving into historical developments of reducing buildings' environmental burdens, the focus has centred on energy efficiency improvements for reducing operational energy carbon emissions (Hoxha et al., 2017; Skillington et al., 2022). This area of impact improvement has taken remarkable steps in the right direction. However, there is a growing recognition of the role of embodied carbon in the overall climate impacts of buildings (Hoxha et al., 2017; Röck et al., 2020; Skillington et al., 2022). Embodied carbon is emitted during the production stage's raw material extraction, manufacturing, and transportation of building materials. Still, conceptually, replacements and end-of-life stages also belong to the embodied definition. However, in the first place, we predominantly want to reduce embodied carbon in the production stage because the imminent GHG reductions are the most important, and the room of opportunity rapidly narrows (IPCC, 2023). Evidence indicates that the embodied carbon of European buildings needs more improvements than energy use (Birgisdóttir & Madsen, 2017; Chastas et al., 2016; Röck et al., 2020). It foremost brings attention to the materials used and the design configuration of buildings.

As researchers and practitioners in the industry grapple with the need to reduce embodied climate emissions of buildings, they are increasingly turning to wood materials. Wood attracts attention as a renewable material solution because it can assist in mitigating climate effects due to its regenerative nature, lower process emissions compared to traditional materials (Röck et al., 2020), and its potential as a carbon sink if the biogenic carbon in building materials resides long enough in the buildings (Arehart et al., 2021; Churkina et al., 2020).

To assess the climate impact and other environmental impacts of wood buildings, life cycle assessment (LCA) is often applied (Fnais et al., 2022; Nwodo & Anumba, 2019). It is a scientifically based method for assessing the climate and environmental impacts over the whole life cycle of a building. The many studies applying this method to wood buildings to address the climate impacts deduce a tendency that wood leads to a reduction of embodied GHG emissions of buildings compared to conventional materials (Camilla Ernst Andersen, Hoxha, Nygaard Rasmussen, et al., 2024; Duan et al., 2022; Greene et al., 2023; Novais Passarelli & Mouton, 2023; Younis & Dodoo, 2022).

The studies above also present large variations among the wood buildings' climate impacts, suggesting that some wood building designs perform environmentally better than others. The greatest freedom of developing the building design pertains to the early design stages of a project. However, the design decisions at the early stage come with minimal knowledge of the individual building project, often encompassed by strict time and budget constraints (Basbagill et al., 2013). Accordingly, more research plausibly focuses on integrating LCA and environmental information with material quantities from digital building information models (BIM) in the building design process before entering the detailed design stage (Cavalliere et al., 2019; Obrecht et al., 2020; Teng et al., 2022). Despite the efforts to raise knowledge and information levels in earlier design stages, already having a BIM model implies that the design development is past the (very) early design stage. A BIM model will not often be developed for small building projects because dimensions and cost may not break even.

A few attempts address the concerns of early design quantity estimation for use in LCA for renovation and industrial building projects through material quantity-generating tools (K. Kanafani et al., 2022; Reisinger et al., 2022). Similar tools are needed for the early design of wood buildings to elevate LCA for the design decision support and lack of knowledge of important aspects being influential to the environmental impacts in the early design.

1.2.2. PUZZLES OF ASSESSING THE ENVIRONMENTAL IMPACTS OF WOOD AND BIOBASED MATERIALS IN BUILDINGS

Returning to the regenerative nature of wood, trees, and the forest they compose, sequester carbon during growth until they reach a maturity state where carbon sequestering and release stabilise. Therefore, studies suggest that when trees reach maturity, they can be harvested and processed into building products to temporarily delay biogenic carbon emissions when remaining in the building (Churkina et al., 2020). It led researchers to embark on concepts and accounting methodologies for temporal modelling of the connection between the uptake and release of biogenic carbon in forests and storage time in buildings (Levasseur et al., 2010, 2013). The wood-building LCA studies in the previous section and most others do not account for temporal aspects of biogenic carbon and delayed emissions (C. E. Andersen et al., 2021). Other specialists suggest that wood sourced from sustainable forestry upholds carbon neutrality because the annual tree harvest does not exceed the annual increment in tree volume (Helin et al., 2013). It seems reasonable from the perspective of forest product supply. Still, for a fully utilised forest supply, any further demand might result in other consumers needing to change to alternative forests for supply, which might not necessarily be carbon neutral. The carbon neutrality perspective does not necessarily mean climate-neutral forestry, as Cherubini et al. (2011) pointed out. A few studies apply the temporal accounting of biogenic carbon and forestry (Camilla Ernst Andersen, Hoxha, Rasmussen, et al., 2024; Head et al., 2020; Peñaloza et al., 2016), nonetheless, only on the building project scale. It does not cover temporal biogenic carbon considerations on larger-scale building stock assessments on using wood in buildings.

The single-minded focus on environmental sustainability through the climate lens may involve looming burden shifts. Wood buildings previously emerged with a notable impact on land use (Allacker et al., 2014; Kayo et al., 2019; Lukić et al., 2020; Mouton et al., 2023; Peñaloza et al., 2019). Wood availability, effectively land use, appears affirmed in Europe to meet future building demand. However, it confines the product system to exterior walls and roofs, thus not including the full detailed material flows related to buildings. In the perspective of increased demand elsewhere, enough supply is also questioned (Pomponi et al., 2020).

The direct land use change considered in the previous studies does not undertake the indirect land use change assessment of implementing wood in buildings; the latter was found to have a larger climate impact (De Rosa et al., 2018). Also, IPCC (2022) assess land use, land use change and forestry (LULUCF), which include indirect land use changes, to contribute 11% of global GHG emissions. Though it comes with a large uncertainty range, it underlines its significance. Land use change impacts are further closely linked to biodiversity impacts, where both impact categories are among the transgressed planetary boundaries (Richardson et al., 2023). It evidently calls for assessing the environmental sustainability of wood and biobased materials in buildings by carefully integrating a wider scope of impact categories and understanding the impacts from direct and indirect land use changes, which needs progression from the current fragmented application in the research field.

1.3. THE DISTINCTION OF LCA APPROACHES AND THEIR APPLICATION TO WOOD IN THE BUILDING SECTOR

Two overarching LCA approaches are defined in the ILCD Handbook (JRC-IEA, 2010), a consensus document completed in 2010 involving leading people in the field of LCA. Forwardly, this dissertation will mainly refer to the document as the ILCD Handbook. Consequently, it remains relevant to draw in as a reference despite the 13 years since its completion. It signifies the two LCA approaches as attributional (ALCA) and consequential (CLCA). They are explained to inherit the capability to answer different questions, hence being applied for different intended applications (Gustavsson et al., 2015). When to use which LCA approach and at what scale of decision support show inconsistencies among chapters in the ILCD Handbook (Ekvall et al., 2016). Presently, 96% of studies assessing wood in buildings apply ALCA at the building project scale (C. E. Andersen et al., 2021).

The ILCD Handbook advises using attributional modelling for micro-scale decision support, which may be considered equivalent to the building project scale, and long-term marginal mixes (CLCA) for the macro scale decision support, which may be considered equivalent to the building stock scale. Therefore, despite the inconsistencies, the distinction is an appropriate initial guiding mark for conducting LCA on wood and biobased materials in buildings. Because LCA studies of wood in buildings underrepresent CLCA, it will be relevant to apply this approach. It is particularly important to understand the environmental impacts of larger-scale implementation of wood in the building sector, specifically with the guidance of the ILCD Handbook in mind.

1.4. RESEARCH PURPOSE, FOCUS AND QUESTIONS

The transition of the building sector towards climate targets through increased implementation of wood and biobased materials necessitates an effective LCA for appropriate decision support. This dissertation reflects the identified research gaps by investigating a palette of early design drivers, potential burden shifting, biogenic carbon modelling, and system modelling for larger-scale changes.

This dissertation intends to expand the basis of empirical-based knowledge on assessing the environmental impacts of wood and biobased materials in the building sector. This is foremost important to improve decision support on reducing pressure on the climate and environment by competently integrating wood and biobased resources in the building sector.

Therefore, the dissertation aims to:

1. Present the state-of-the-art methodologies of consequential LCA to buildings, particularly wood buildings and the coupled LCA goal and scope aspects.
2. Detect, for the building sector, the LCA and building aspects critical to the climate impact of wood buildings in the detailed design and the essential aspects to accurately predict in the early design.
3. Elevate understanding of the environmental consequences of a larger-scale change to wood-based construction.
4. Model the resource availability and effect on land use impact and carbon storage of a larger-scale implementation of fast-growing biobased materials in wood buildings.

The main research question (MRQ) of the PhD dissertation:

MRQ: How can the attributional and consequential LCA approaches and the assessed impact categories advance the understanding of an effective LCA for implementing wood and fast-growing biobased resources in the building sector?

The sub-research questions (SRQ) that feed into the main research question:

SRQ1**:** Which modelling methods and focuses are applied in consequential LCA related to buildings?

SRQ2: In what ways do LCA and building design aspects influence the environmental impacts of wood buildings in the early and detailed design stages?

SRQ3: How can consequential LCA and biomass-related modelling affect the environmental impact of a change to wood-based construction?

SRQ4: What is the effect on land use impact and carbon storage of implementing materials of fast-growing biobased resources in wood buildings?

1.5. READING GUIDE

This dissertation comprehends the main and sub-research questions through the academic work presented in the four publications below:

Publication 1: **A systematic review of consequential LCA on buildings: the perspectives and challenges of application and inventory modelling.** *Hansen, R. N.; Rasmussen, F. N., Ryberg, M., Birgisdóttir, H*. First Published In: The International Journal of Life Cycle Assessment 28, 131-145, 2023. Reproduced with the permission from Springer Nature. DOI: https://doi.org/10.1007/s11367-022-02126-w

Publication 2: **Enabling rapid prediction of quantities to accelerate LCA for decision support in the early building design**. *Hansen, R. N.; Hoxha, E.; Rasmussen, F. N., Ryberg, M. W., Andersen, C. E.; Birgisdóttir, H*. In: Journal of Building Engineering, 2023. DOI: https://doi.org/10.1016/j.jobe.2023.106974

Publication 3: **Environmental consequences of shifting to timber construction: the case of Denmark**. *Hansen, R. N.; Eliassen, J. L.; Schmidt, J.; Andersen, C. E.; Weidema, B. P.; Birgisdóttir, H.; Hoxha, E*. In: Sustainable Production and Consumption, 2024. DOI: https://doi.org/10.1016/j.spc.2024.02.014

Publication 4: **Reducing the land use impact of wood buildings with fast-growing biobased materials**. *Hansen, R. N.; Hoxha, E.; Birgisdóttir, H.; Pittau, F.* Draft, Expected Submitted To: Sustainable Cities and Societies, 2024.

The conducted research in this dissertation evaluates existing research on consequential LCA and empirically assesses the environmental impacts of wood buildings at the building project level and building stock level through different approaches to LCA. Figure 1-1 illustrates the link between the main publications, the SRQs, their answers to them, and how they feed into the MRQ.

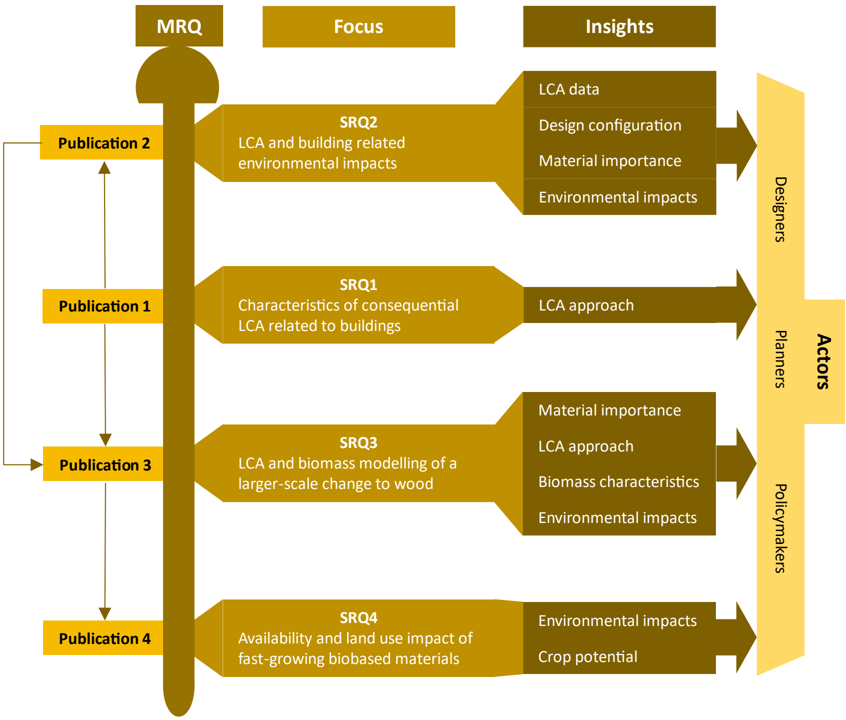

Figure 1-1 Structure of how the main publications are connected and the focus, insights, and actors they address.

Publication 1 uses a systematic literature review to summarise how consequential LCA is applied to buildings, including which research gaps exist regarding the topic focuses and life cycle inventory modelling. The suggestions from the ILCD Handbook is used to decide on the relevant LCA approach for each decision context scale. It entails ALCA for building micro scale, i.e., building projects, and ALCA with system interactions or CLCA for macro scale, i.e., building stock. Publication 2 assesses the LCA and building-related aspects influential to the climate impact of wood buildings in the early design stage prediction of material quantities and the quantities in the detailed design.

Publication 3 combines a building area forecast and case buildings into a material flow analysis for the future Danish building stock for a change to wood-based construction. It assesses the environmental impacts of this change using the consequential LCA approach. It combines it with forest modelling by relating the biogenic carbon uptake and release of the replacement tree to the storage time of wooden materials in the buildings.

Publication 4 addresses the challenge of increased biodiversity impact from timber buildings. It investigates how implementing fast-growing biobased materials in wood buildings affects land use impact and carbon storage. These materials substitute insulations and wooden non-loadbearing products at the building stock scale in Denmark. It further addresses the availability of the different biobased resources in Denmark and if they require imports from other countries.

Publications 2-4 are parallel studies, not chronological, considering the empirical assessment of wood and biobased resources in buildings. They focus on different decision context scales, from building project scale to building stock scale. An overview of the overarching methods used in the publications are preented in Table 1-1.

Table 1-1 The methodologies applied in the different publications to examine the research purpose, focus and questions.

Methodologies	**Publication**			
	1	2	3	4
Systematic literature review	X			
Case study		X	X	X
Simplified design tool		X		
Life cycle assessment, attributional		X		
Life cycle assessment, consequential			X	
Life cycle assessment, system approach				X
Material flow analysis			X	X

Table 1-1 The methodologies applied in the different publications.

CHAPTER 2. STATE-OF-THE-ART

This chapter comprises the state-of-the-art consequential LCA in the built environment from the review article (Publication 1), CLCA on wood buildings, and the state-of-the-art LCA approaches to wood and biogenic materials in the built environment. The chapter further specifies and provides insights into the relevant knowledge related to the research gaps and concepts that this dissertation engages with.

2.1. OVERARCHING LIFE CYCLE ASSESSMENT APPROACHES AND THEIR DISTINCTIONS

Life cycle assessment (LCA) is a scientific-based methodology to evaluate environmental impacts and resource consumption associated with a product system from raw material extraction, processing, and manufacturing to construction, use and end of life (Finnveden et al., 2009). The LCA frameworks and procedures comprise the international standards of ISO 14040 (DS/EN ISO 14040, 2008) and ISO 14044 (DS/EN ISO 14044, 2008). In addition, the ILCD Handbook defines the two overarching LCA approaches: attributional (ALCA) and consequential (CLCA).

Publication 1 engages with where and when to use the two approaches according to the ILCD Handbook, which essentially relates to the decision support context. The decision support context can be categorised as the micro or meso/macro scale (forwardly referred to as the macro scale). However, the ILCD Handbook presents inconsistencies between Chapter 5 on 'Goal Definition' and Chapter 6.5 on 'Life cycle inventory' modelling on when to use which LCA approach for a given decision context. Ekvall et al. (2016) also detected and discussed similar inconsistencies and ambiguity. Further, discussions on when to use which approach regarding the theoretical and practical relevancy prevail in other research-based conversations (Brander, 2019; Bo P. Weidema et al., 2019), and in the editorial issue of Anex and Lifset (2014).

At this stage, the dissertation will not discuss the theoretical and practical truthfulness or correctness of the two LCA approaches for general product systems. Meanwhile, it will engage with the two approaches in a practical way specific to the building sector while still aiming to ensure that the scale of the study and intended application harmonise. Therefore, the dissertation acknowledges the building sector as a distinct product system with special characteristics compared to most other product systems. The building sector's special characteristics involve the manifold practical risks such as fragmented supply chains, construction site logistics and management, numerous stakeholders, distributed data ownership, complex information management, unique building and people configurations for every project, and buildings long service life.

These risks influence the material quantities needed for the LCA during a building design process. Therefore, the dissertation perceives the LCA approaches as written in Publication 1, which were cited from the ILCD Handbook (2010):

(i) attributional LCA: “ALCA can answer questions related to a supply chain’s optimisation potential or evaluate a specified system’s impact”,

(ii) consequential LCA: “CLCA can answer questions regarding the impacts of imposing a change on a system or the effect of increasing the demand for a certain product or service”.

The ILCD Handbook definitions in Chapters 5 and 6.5 can add to these two explanations. However, it requires an interpretative balancing of the two chapters' definitions of when to use ALCA or CLCA. Chapter 5 tilts towards CLCA as relevant for the context of micro and macro-scale decision support. Conversely, Chapter 6.5 advises using attributional life cycle inventory modelling for the micro and macro scale, except for the foreground systems at the macro scale where long-term marginal mixes should be applied, i.e., consequential life cycle inventory modelling. Here, interpretative balancing might suggest using the attributional approach for the micro scale decision support and the consequential for the macro scale. It is not necessarily theoretically correct but could appear practically useful for using LCA in the building sector in light of the special characteristics concerning building projects. The discussion will engage with the usefulness of this interpretation and possible reconsiderations or reinterpretations of it.

In addition to selecting the LCA approach according to the scale of the decision support, the decision support context also needs to comprehend the intended application belonging to and explained in Chapter 5 on ‘Goal Definition’ in the ILCD Handbook. As mentioned, this chapter tilts toward CLCA involving that consequential modelling supports a decision to be made, for example, with the formulation “whether a decision is to be supported implies whether the study is interested in the potential consequences of this decision meaning that it involves a decision to be made” as stated in the ILCD Handbook (2010). Interpreting ‘decision’ on this basis with regard to the building sector can be understood to involve strategy or strategic decisions. Hence, intended applications focusing on strategy should at least involve CLCA. Strategy herein denotes a decision leading to repetitive conduct over a (confined) period beyond a single building project. Using CLCA for strategy could imply that building design configuration or optimisation involves ALCA instead. Accordingly, the ILCD handbook has now been interpreted considering a more harmonised relation of scale and intended application of the decision context.

2.2. LIFE CYCLE ASSESSMENT OF WOOD BUILDINGS

The building sector has its own standard for LCA in EN 15978 (EN 15978:2011, 2012), mainly adhering to the building project scale. It includes life cycle stages tailored to the built environment, such as the upfront stages of production stages A1-A3 and construction stages A4-A5, the use stages of B1-B6, the end-of-life stages C1-C4, and stage of benefits beyond the system boundary, the D stage. However, using LCA for wood and biobased materials in buildings further entails the complexity of how to model the biogenic carbon. Studies show that the building sector can harness the climate benefits of adopting wood and biobased materials when sourced from sustainably managed forests (Arehart et al., 2021; Churkina et al., 2020). Because trees sequester carbon through photosynthesis when growing in forests, they can store carbon temporarily in buildings when used as building products for the time the timber remains in the building. This relationship between sequestration and emissions has implications when modelling the potential to delay the biogenic carbon in LCA to make buildings a source or sink of carbon (Hoxha et al., 2020).

Currently, the building LCA standard EN 15978 (2012) considers biogenic carbon by the method 0/0, carbon neutral, or the method -1/+1. The latter considers all the embodied biogenic carbon negative (sequestration) in the production stages (A1-A3) and positive (emissions) in the end-of-life stages (C3-C4). It means the carbon balance is neutral over the whole building life cycle (ibid). The -1/+1 approach is used when a certain wood product originates from sustainable forestry. It entails the annual harvest biomass is less than the annual increment from forest growth. Hence, the carbon emission and sequestration remain constant or increase yearly on the landscape level of that forest (EN 16485:2014, 2014).

The -1/+1 biogenic carbon concept was the most widely applied for building LCAs (C. E. Andersen et al., 2021). Through this method, many studies indicate a climate mitigation effect of using wood in buildings (C. E. Andersen et al., 2021; Mouton et al., 2023; Ouellet-Plamondon et al., 2023), and others also evaluate wooden design solutions for the most climate-friendly configuration (Dodoo et al., 2022). Since the approach leads to carbon neutrality over the life cycle, the climate benefits compared to conventional construction mainly arise from lower production GHG emissions. What is more to these assessments is the few case buildings that individual studies apply, only 13 using the -1/+1 approach (C. E. Andersen et al., 2021), limiting the generality of outcomes and conclusions on building the most climate-friendly with wood and biobased materials.

2.3. DECISION SUPPORT IN THE EARLY DESIGN STAGES

A step towards better decision support for reducing the environmental impacts of wood buildings also corresponds to integrating LCA at the different levels of development (LOD) through which building projects progress. The earlier in the design stage that decisions take place, the more crucial it will affect the environmental impacts. However, the design freedom is also greater despite the generally constrained time and budget nature of building projects (Basbagill et al., 2013).

Research increasingly evolves around implementing LCA decisions in different LODs supported by digital and BIM-based tools (Teng et al., 2022), which particularly was elevated in studies of continuous LCA information by Cavaliere et al. (2019) and Palumbo et al. (2020). The main obstacles of BIM and digital building models centre on the formats and terminologies around data inputs, quality, and ownership hand-over for every LOD, alongside the need for enhanced automated processes (Safari & Azari Jafari, 2021; Teng et al., 2022). However, an automation process recently attempted to integrate a common LCA tool with BIM models (Najjar et al., 2022).

Although research progresses in integrating LCA in earlier design stage decisions, having a BIM model in a building project means that the LOD of that building project is possibly already between the basic and detailed design. It likely responds to LOD 300-400 in the definition of Gomes et al. (2019). Reasonably, using LCA in decision support should be improved in the (very) early building design, which is before projects have a BIM or digital model. It also becomes important for building projects that do not necessitate a digital model, typically smaller projects, such as single-family houses.

2.4. CONSEQUENTIAL LCA IN THE BUILDING SECTOR AND OF WOOD BUILDINGS

The covered body of research in the previous two sections hitherto applied the attributional LCA approach. Several literature review studies approve that the attributional approach generally applies to most building LCAs (Anand & Amor, 2017; Buyle et al., 2013; Fauzi et al., 2021; Khasreen et al., 2009; Nwodo & Anumba, 2019; Sauer & Calmon, 2020). In this context, Publication 1 unveils only 37 studies on consequential LCA in the built environment, and of that, eight focus partly or fully on wood in buildings, plus one being published after the publication.

Looking at the CLCA modelling of the empirical studies, most use the four-step framework of Weidema et al. (2009) or its predecessor work. Hence, it is the framework used to characterise the empirical CLCA studies, and it is suggested that it be adhered to when conducting CLCA in the built environment. The framework comprises defining the time horizon, market delimitation, and market trend and assessing affected suppliers and co-products; recycling and reuse are solved by substitution or system expansion.

Delving into the intended applications of the CLCA studies in Figure 2-1, 27 assess empirical consequences, while 13 also examine the influence on CLCA from LCA methodological choices and methods specific to consequential LCA modelling. CLCA method development was the focus of six studies, and four only analysed method aspects. Comparing ALCA and CLCA unfolds as the most examined method aspect, but otherwise, the method aspect analysis scatters on several aspects of both general LCA and specific consequential methods. It also applies to the studies focusing on wood in buildings. The variety of applied methods stretches from literature references and assumptions to statistics in iterative procedures, linear regression, and forecasts using material flow analysis (MFA) to the more advanced network analysis, economic equilibrium models and forest production models.

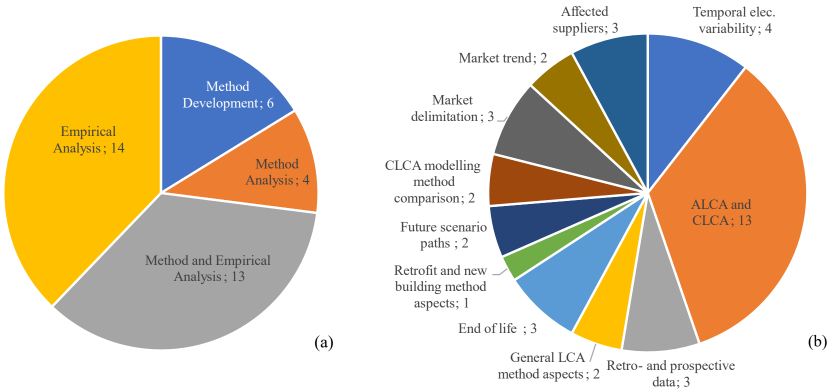

Figure 2-1 Purpose of the reviewed CLCA studies on buildings. (a) The focus of intended application. (b) Examined method aspects in the method analysis studies. From Publication 1 (Hansen, Rasmussen, et al., 2023)

The wood-focused CLCA studies in Publication 1 and in Hansen et al. (2022) lack completeness regarding the CLCA framework, so only the more comprehensive studies are elaborated on in the following. Nepal et al. (2016) studied increased wood in low-rise, non-residential buildings in North America using forest economic equilibrium models to assess the market responses to changes in demand and a biological model for estimating carbon fluxes. However, it misses out on quantifying the iLUC, conducting a full life cycle, and a broader spectrum of the building stock.

Another study on non-residential buildings in North America uses an MFA to forecast the inventory of increased wood implementation (S. Cordier et al., 2019). The inventory was applied to assess the environmental consequences of substituting steel and concrete structures with various types of wood structures (S. Cordier et al., 2021). Eventually, incorporating dynamic timing of biogenic carbon related to the forest practice and end-of-life scenarios advanced it, all of which were assessed using a process-based background database (Sylvain Cordier et al., 2022). iLUC and the inclusion of the residential building stock are absent in these assessments.

CO_2 fluxes of changing grassland for beef production to forest for timber production took the focus in an assessment applying different forestry scenarios and ILUC (Forster et al., 2019). The study views the change in demand from the land management perspective, not a change in demand for more wood from the building perspective, yielding more insights into the climate effects of different land management scenarios rather than the climate effects of change in demand in the building sector. Despite the advanced modelling, the studies lack a combined forest modelling and iLUC assessment for a broader range of the building stock. Further, assessing environmental consequences using input-output LCA is abdicated.

2.5. COMPLEXITIES OF BIOBASED RESOURCE ASSESSMENT

To evaluate wood and biobased resources in LCA, different advanced modelling has been developed to address the regenerative nature concerning biobased resources in temporal assessments. The 0/0 and -1/+1 approaches to biogenic carbon avoid considering the temporal aspects. Levasseur et al. (2010) created a methodology for considering the dynamic timing of GHG emissions. It addresses the effect of every GHG emission on the cumulative radiative forcing in relation to when a unit of GHG emission occurs and the selected time horizon based on the Bern carbon cycle (IPCC, 2007). The GHG emissions occurring after 100 years do not result in climate impact as it happens beyond the 100-year time horizon of GWP.

They later elaborated the approach in (Levasseur et al., 2013), where they consider biogenic carbon temporarily stored for different scenarios and the carbon sequestration in the forest, considering forest modelling of Quebec’s boreal forests. The carbon temporal scope largely influences the carbon balance, namely whether the temporal assessment considers the harvested tree’s or the replacement tree’s carbon sequestration (Hoxha et al., 2020; Levasseur et al., 2013). Guest et al. (2013) computed with a similar method factors of the wooden biogenic carbon impact on GWP based on the tree rotation period in the forest and storage period in the anthroposphere, e.g., as a building product, for GWP with time horizons of 100 and 500 years. The rotation period denotes a tree's time to grow to maturity and be ready for harvest. De Rosa et al. (2016) developed a model incorporating forestry management systems considering species type, rotation periods, slash and foliage approach, thinning frequency, and different carbon pools.

Recently, a review stated that the dynamic timing of biogenic carbon and forest modelling still sees few applications in building LCA studies (Arehart et al., 2021). Essentially, the forestry management and forestry systems affected by the increasing use of wood need further assessment. In that regard, one should be aware that the climate impact of timing biogenic carbon release and uptake in the forest modelling appears susceptible to the allocation procedure. The substitution effect of wood co-products leads to considerable climate impact whether the substituted product is pulp wood or natural gas (De Rosa et al., 2018; Skullestad et al., 2016), whereas the common building ALCA usually deals with wooden co-products by an allocation key, disregarding the climate impacts of biogenic carbon substitution effects (C. E. Andersen et al., 2021).

The use of wood also comprises the consideration of resource availability and the previously mentioned impact categories of land use and terrestrial biodiversity. The

European forest cover increased between 1990-2020 (Forest Europe, 2020) while global deforestation reached 420 million ha in the same period, i.e., 14 mill. ha on average per year, conceived as land use changes, but at a reducing rate of deforestation between 2015-2020, amounting to 10 mill. ha per year (FAO, 2022). The afforestation and forest expansion moderately counterbalanced it by 5 mill. ha per year in that period. Nonetheless, the original global forest cover has declined from 6 to 3.6 billion hectares (Krishnaswamy & Hanson, 1999). The transgression of the Planetary Boundaries of land-system change and biosphere integrity (biodiversity), more severely than climate change, supports these statistics very well (Richardson et al., 2023).

As wood can have carbon-mitigating benefits in the right circumstances, the availability needs to be considered due to the long rotation period, implying that it takes time to increase forestry. Wood supply was assessed as sufficient for the construction sector in Europe (Göswein et al., 2021). However, the study only includes demand for roofs and exterior walls, not the complete building. Contrarily, Pomponi et al. (2020) question the availability of supply in many areas of the world and most of Europe. A study in Germany supports this outcome as they found that its bioeconomy of roundwood likely exceeds their fair share of the global sustainable roundwood supply, conditional to the scenario (Egenolf et al., 2022). An interesting discovery by Göswein et al. (2021) comprises the availability of fast-growing biobased resources in Europe, particularly straw. It needs further assessment of the potential to reduce burden-shifting from climate change to land use by decreasing the land use impacts caused by the current construction practice of wood buildings.

2.6. SUMMARY OF STATE-OF-THE-ART

First, the recommendations of the ILCD Handbook regarding the use of life cycle assessment (LCA) approaches in decision support were discussed. It highlights inconsistencies between Chapter 5 'Goal Definition', and Chapter 6.5 'Life cycle inventory'. Balancing these guidelines suggests using attributional LCA (ALCA) for micro-scale decision support and consequential LCA (CLCA) for macro-scale decision support. The text also emphasizes the importance of considering the intended application of the decision support, which draws a wafer-thin line between when to shift from one LCA approach to another.

Currently, the building LCA standard (EN 15978) considers biogenic carbon using two methods: 0/0 or -1/+1. The latter is used for wood products from sustainable forestry and means a carbon-neutral balance during the building's life cycle. However, it shows the temporarily stored biogenic carbon in the buildings, which can benefit the climate. Building LCAs widely use the carbon-neutral approach, and wood often shows climate-mitigating effects due to lower production impacts. However, limited case studies use the -1/+1 approach, which limits drawing generalized conclusions.

The earlier decision support occurs in the design process, the greater its influence on environmental impact. However, information is often limited. Integrating LCA at different levels of development (LOD) is crucial for accurately assessing and minimizing the environmental impacts of wooden buildings. While research has focused on implementing LCA decisions in later LODs (e.g., 300-400) supported by digital and BIM-based tools, there is a need to improve decision support in the early design stages, especially for projects that don't require a digital model like single-family houses. Incorporating LCA in the early building design ensures that environmental considerations are prioritised from the beginning.

Many studies on CLCA of wood in construction lack completeness in adhering to the CLCA framework and exclude indirect land use change (iLUC). The main framework steps include time horizon, market delimitation, market trend, affected supplier identification, use of substitution or system expansion for co-products, recycling, and reuse. 27 articles are empirical, while 13 investigate consequential. A few studies comprehensively model the environmental consequences of increasing wood in the building stock scale, but only one in the European context. Despite their thoroughness, they lack a combined assessment of forest modelling, iLUC, a broader range of building typologies, and the use of an input-output database.

The European forest cover increased between 1990 and 2020, while global deforestation reached 420 million ha. Afforestation and forest expansion partially counterbalanced deforestation, with increasing rates in recent years. Wood has carbon-mitigating benefits, but its availability in relation to demand must consider the long rotation period of trees, thus affecting land use. Wood supply seems sufficient for the construction sector in Europe, but concerns exist about availability in many parts of the world. In addition, land-system change and biodiversity have transgressed their planetary boundaries and pose a significant problem alongside climate change. A German study supports this, suggesting their bioeconomy of Roundwood likely exceeds their fair share. Compellingly, a study found that fast-growing biobased resources like straw have the potential to reduce the land use impacts of current wood buildings, at least when considering roofs and exterior walls.

CHAPTER 3. METHODS

The following chapter explains the methods applied in the present dissertation by elaborating on the highlighted methods in the reading guide. The connection between the methods and the publications are illustrated in Figure 1-1 in Chapter 1. Publication 1 is only covered by Section 3.1.

3.1. SYSTEMATIC LITERATURE REVIEW

Composing a literature review serves different roles where one is clarifying the status of the research field relevant to the undertaken work wherein the most relevant concepts and methods are set in perspective to position the study and identify research gaps that it contributes to fill out (Kamler & Thomson, 2006). The other is the systematic literature review aiming at synthesising a comprehensive collection of literature where a search protocol and systematic analysis of identified articles ensure rigour in data extraction and evaluation (de Almeida Biolchini et al., 2007). The ontology presented in the latter was applied in Publication 1 and works as its foundation in attempting to cover most of the relevant studies on CLCA on buildings.

A thorough search protocol involved the keyword areas and synonyms related to it: consequences, environmental assessment, approach, and building-related. It was presumed to capture most literature relevant to the topic. Because CLCA on buildings were expected not to be covered by many studies, we included the rather broad inclusion criteria: (i) including a self-stated consequential LCA on a case study of either building, building element or building material, (ii) providing sufficient explanation on applied methodological aspects and choices. Scopus, Web of Science, and Google Scholar were used to retrieve articles. After that, the abstract and keywords were used to exclude irrelevant literature, and the eventual group of articles were read to ensure they lived up to the inclusion criteria. The final group of studies' bibliography was investigated for further relevant studies (Wohlin, 2014). The review yielded 37 articles between 2000 and September 2021, fulfilling the criteria. It comprised journal articles, conference articles, and grey literature.

The data collection included the goal, intended application and division of studies into the scales of micro and macro depending on whether the studies are used for decision support on policy or building design. Additionally, the information on modelling the consequential LCI in the studies was time horizon, market delimitation, market volume trend, affected suppliers, constraint supply, and approach to substitution for multifunctionality, based on the framework of Weidema et al. (2009). This information was used to group empirical, method and method development studies, where the empirical micro and macro scale studies were characterised in terms of the object of assessment and studied change. LCI modelling aspects were grouped and then recommended for which scale of assessment they most profoundly should be used for.

3.2. MATERIAL FLOW ANALYSIS

Material flow analysis (MFA) is a method to spatially and temporally track material stocks and flows within a defined system boundary, which can be of an existing stock or future flows arising from Anthropogenic demand (Laner & Rechberger, 2016). As the LCA of building stocks rely on the materials associated with the system, MFA can serve a supporting role in this context (ibid) and is already applied in building stock LCAs using various scenarios (Heeren & Hellweg, 2019). The resources needed to transition to timber construction (Publication 3) and increased use of fast-growing materials in wood buildings (Publication 4) require the expected future material demand for informing the LCA.

Various approaches to MFA used in LCA exist where Publications 3 and 4 use the bottom-up modelling (Göswein et al., 2019) of existing case studies combined with the area forecast of Hoxha et al. (2024). The latter forecasts the area of single-family houses, multifamily houses and offices based on historical time series developments mimicking a frozen-policy scenario between 2022-2050. Some distinctions exist in the MFA's conduction for the two publications. Publication 3 considers the replacements of materials during two reference study periods of 60 and 100 years and includes all materials in the inventory of the case studies. Publication 4 excludes the replacements of materials, considers only the biobased materials for the MFA, and uses case studies for the base case scenarios while applying building element archetypes for the alternative scenarios.

3.3. LIFE CYCLE ASSESSMENT

The LCA used in Publications 2, 3, and 4 differ in their goal, intended application, standards, and impact assessment. Commonly, all three studies go through goal and intended application steps, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results. The overall focus in the three publications follows. Publication 2 engages with the climate impacts of designing with wood at the building project scale relevant for architects and consulting engineers. Publication 3 involves a change to wood at the building stock scale of Denmark and the environmental impacts of the likely exchanges it induces in the economy. Publication 4 also studies the building stock scale, focusing on fast-growing biobased materials in wood buildings, their availability, and their impact on land use.

3.3.1. GOAL AND INTENDED APPLICATION

The two-fold goal of Publication 2 is first to assess the climate change impacts of ten detailed design Danish wood dwellings. Second, in comparing the climate impacts of the detailed design to the early design stage, the latter was modelled with a simplified design tool developed according to the Danish building code. The study intends to clarify the material categories and building elements important to predict in the early design of wood dwellings more precisely before creating digital models. Also, it is to discover the design approaches with lower GHG emissions. Studies on LCA and building information models (BIM) integration at various design stages increase (Cavalliere et al., 2019; Crippa et al., 2020; K. Kanafani et al., 2022; Obrecht et al., 2020; Safari & Azari Jafari, 2021; Teng et al., 2022; Zimmermann et al., 2021), mainly focusing on the level of developments (LOD) 300-400 (Gomes et al., 2019), Publication 2 provides new climate impact insights of the early design stages before the BIM models at LOD 100-200, making decision support for design more accessible for small and medium sized architectural and construction enterprises (SMACEs).

Shifting the intended application to the strategic decision of whether or when to build with wood in the Danish building sector requires an LCA approach that captures the effects in the economy, the CLCA. Publication 3 does that by evaluating the environmental consequences of constructing the future expected building stock by conventional construction technology and when shifting to increased wood-based construction instead. Further, another goal was assessing the methodological and building aspects that considerably influence the results. Few studies extend the scope beyond the building project scale to assess the consequences of implementing wood while concurrently including some sort of biogenic carbon or forest modelling as well as land use changes (S. Cordier et al., 2019; Sylvain Cordier et al., 2021, 2022; Forster et al., 2019; Nepal et al., 2016). Forster et al. (2019) is the only study in a European context, but it takes the perspective of the forest supply for wood buildings and not the perspective of demand from the building sector. Therefore, we need building stock scale studies in the European context of changes in the economy and forest management aspects arising from increased demand for wood in the building sector.

Publication 3 revealed that nature occupation, i.e., biodiversity, increased for all three building typologies in the wood scenario. Combined with the evidence of a transgressed PB for Biosphere Integrity (Richardson et al., 2023), even more than the climate change PB, the goal of Publication 4 is to assess whether implementing materials of fast-growing biobased resources in wood buildings can reduce their land use impact, thus potentially indirectly the biodiversity impact. The intention was to further analyse Denmark's national availability and what could be needed from importing from other producing countries. Göswein et al. (2021) uncovered the potential for availability in Europe. Still, they limited the study to roofs and exterior walls of dwellings, omitting a more complete consideration of building elements and typologies. Therefore, the study intends to contribute to the knowledge of reducing land use impact of wood buildings, and simultaneously bringing insights to Danish policymaking on the use of the land for resource production.

3.3.2. OBJECT OF ASSESSMENT

Common to Publications 2, 3, and 4 is that they all consider new buildings designed with wood minimum to some extent in the structural elements. In Denmark, the standards at the building project scale are for the reference study period (RSP) of 50 years. The reference unit is environmental impact per m^2 gross floor area per year. Publication 2 adheres to these two standardised measures, and to make the buildings comparable, the functional equivalent (FE) was defined as dwellings with a 1 m^2 gross floor area adhering, with the greatest extent, to the Danish building code of structural, fire safety, acoustics, and energy properties for a 50-year RSP. It only focusses on climate impact; thus the reference unit translates to global warming potential (GWP) per m^2 gross floor area per year, i.e., kg CO_2-eq/m^2/year.

Publication 3 assesses single-family houses (SFH), multifamily houses (MFH), and office buildings (OB) and applies other RSPs than Publication 2, 60 years (RSP_{60}) and 100 years (RSP_{100}), respectively. The RSP_{60} align more precisely with the service life of SFH and RSP_{100} with the service life of MFH and OB (R. Andersen & Negendahl, 2023). Additionally, they are included to understand the effects of the weighting that an RSP asserts on the environmental impacts concerning material replacement rates and time correction of GWP (see Section 3.3.5). Addressing the goals of Publication 3, the FE included the needed material demanded in the future expected building stock between 2022-2050 in a conventional construction scenario and a change to a wood-based construction scenario for RSP_{60} and RSP_{100}. The results were converted to a reference unit of environmental impact per m^2 gross floor area per year.

In Publication 4, the same building typologies apply as in Publication 3 to investigate the potential to reduce the nature occupation of wood buildings by substituting insulation and non-loadbearing wood products with fast-growing biobased materials of straw, hemp, and grass. The FE comprises the needed biobased materials in a wood construction scenario and three scenarios of increased fast-growing biobased material complying quantitatively with the U-value of the Danish building code and qualitatively with fire safety and acoustic regulations for the expected future area in Denmark between 2022-2050. The study only assesses the biobased materials needed to construct the buildings; hence, it does not consider any RSP. As the land use and biodiversity crisis is imminent, the largest current potential of reducing these impacts pertains to the materials used to construct the building, hence this consideration. Further, part of the study intends to design archetypes using fast-growing biobased materials complying with the building code in broad terms, which also contributes to the research on this topic.

3.3.3. SYSTEM BOUNDARIES

Generally, Publications 2, 3, and 4 base their life cycle stages according to EN 15978, i.e., life cycle modules, and use the service life of the individual products from

Aagaard et al. (2013), developed for the Danish context. The operational energy of module B6 is omitted in the three publications since the goals are to assess embodied environmental impacts of wood materials, and the FE considers an equivalent energy performance for all studied buildings because the obey the building code.

For Publication 2, the modules involve the production of materials (A1-A3), transport to the construction site (A4), the waste part in the construction module (A5), replacements of materials during the use phase (B4), and processing and disposal at the end-of-life (C3-C4). All the used EPDs are cradle-to-grave, equivalent to the full life cycle. Any benefits beyond the system boundaries, module D, equivalent to substitution benefits, is not modelled in Publication 2. It aligns with the practice of the Danish LCA at the building project scale. Excluding module D is the polluter pays principle. But it also ensures methodological consistency of the applied allocation procedure since it excludes substitution for co-products for the production stage; thus, substitution should also not be used for the end-of-life stage.

The LCA in Publication 3 considers the building stock scale, which here entails that the system boundary of the LCI comprises the affected suppliers that respond to a change in demand for construction products, thus not necessarily the direct supply chain, and avoid allocation by substitution as recommended by ISO 14044 (DS/EN ISO 14044, 2008). It is the consequential LCA approach, where the identification of affected suppliers follows the framework of Weidema et al. (2009). Publication 3 handles co-products by substitution, where the co-products displace marginal suppliers of products with equivalent functions on the market. The wood co-products like chips and sawdust were considered to substitute pulp wood on the market for biomass. The included life cycle modules adhere to EN 15978 terminology, including A1-A3, B4, and C3-C4+D. Wood, steel and concrete were assessed regarding their geographical market and affected suppliers for demand in Denmark in the two construction scenarios. Examining the environmental impact of increased use of wood for an entire sector makes it relevant to assess the suppliers that can meet the demand and to model the system exchanges related to co-products and end-of-life activities.

Influential for wood’s climate impact, particularly in long-lived products like buildings, is the relationship of biogenic carbon temporarily stored in the buildings and sequestration in the forest. Publication 3 reflects the biogenic carbon sequestration of a replanted tree at the stem level after harvest instead of the sequestration in the harvested tree, which is the more conservative approach (Hoxha et al. (2020), Peñaloza et al. (2016), Levasseur et al. (2013)). The biogenic carbon sequestration, storage time and release are time-corrected according to GWP with a 100-year time horizon (see more in the section below). Recognising the valuation inherent in the choice of GWP time horizon is important because it is a weighting of the time the GHG emissions occur (Levasseur et al., 2011). The GHG emissions beyond the time horizon are not accounted for, thus functioning as a benefit. The 100 years are the most often applied and also used by IPCC.

The life cycle modules in Publication 4 comprise only the upfront production of the materials (A1-A3) needed in the building construction. The analysis only includes the wood and biobased materials to examine their relative difference. The scenarios comprise a base case of existing detailed design wood buildings, S0, and three alternative fast-growing biobased buildings of straw (SC1), hemp (SC2), and grass (SC3). SC3 uses only the grass materials for insulation; the remaining materials are equivalent to SC1. Further, these four biobased scenarios are analysed for four market penetration rates increasing linearly to 2050 from the current 11% in 2022. The rates in 2050 are: (A) current market penetration rate (11%), (B) 25%, (C) 50%, (D) 100%. The linear increase towards 2050 reflects that implementing novel products is expected to take time and is also used to gain insights into resource availability at the different implementation rates.

3.3.4. BUILDING MODEL AND MATERIAL DESCRIPTION

Compiling the material quantities used in the case buildings required combining data from building information models, bill of quantity, project plans, and drawings to arrive at complete case studies for the LCA. However, different scopes of building elements were used in the publications, as shown below. In addition, the operational energy was not considered in any of the studies because the purpose is the embodied environmental impacts of building with wood, presuming that the same functional equivalent applies to the energy performance in the respective publications. Generally, the disaggregation of building elements and materials is inspired by Heeren and Fishman (2019), Guven et al. (2022) and Soust-Verdaguer et al. (2023).

In Publication 2, the considered building elements for the detailed and early design stages comprise foundations, slabs, exterior walls, interior walls, floors, roofs, windows, and staircases. In addition, the detailed design stage comprises default values of technical installations of pipes and ducts, including metal screws and fasteners, but excluding solar panels and powered equipment because it was not consistent in data across buildings. The simplified design tool used for the early design did not provide any quantities of screws and fasteners nor technical installations and non-loadbearing interior walls, interior finishings and special wet-room products. Stairs and elevators were included if they appeared in the detailed design of buildings.

The considered building elements in Publication 3 encompass foundations, slabs, exterior walls, interior walls, floors, roofs, windows, doors, staircases, technical installations such as ducts and pipes, and solar panels.

Publication 4 studied only the building elements applicable for fast-growing biobased materials implementation, comprising interior walls, exterior walls, floors, and roofs. It is because it is a relative assessment of land use, availability, and CO_2 storage between wooden base cases and equivalents with increased integration of fast-growing biobased resources. Therefore, only the quantities of biobased materials were extracted from the building elements.

3.3.5. ENVIRONMENTAL DATA AND IMPACT ASSESSMENT

In Publication 2, LCAbyg (Kai Kanafani et al., 2021) version 5 (Jørgensen et al., 2021) was applied as the LCA tool, a process LCA, which uses the Ökabaudat database for generic processes (Ökobaudat, 2020),. EPDs were included for the most prominent products, including main wood products (see more in Publication 2). The study considered the impact category GWP with the 100-year time horizon and measured by the declared unit CO_2-eq/m^2/year, where biogenic carbon was accounted for by the -1/+1 method according to EN 15804:2019 (2019). It follows the European and Danish standard of conducting LCA at the building project scale.

Publication 3 consequential approach means that the applied LCA tool was EXIOABSE v.3.3.16b2 (Merciai & Schmidt, 2018) as the background database. It is an input-output (IO) model with hybrid units, entailing that physical products are measured in physical units and services in monetary units. An IO database is a top-down model that captures the trade of products and services in the entire economy divided into sectors, equivalent to the unit processes known from process LCA. The IO model has higher completeness (Agez et al., 2020; Lenzen, 2000; Rebitzer et al., 2002), geographical representation at the country level, and better represents markets that will be affected by larger scale changes.

The foreground materials were entered in the sectors for the affected countries, China for steel, Sweden for wood, Denmark for concrete, and the remaining materials were entered in the relevant Denmark sectors. Stepwise2006 was the used impact assessment method (B.P. Weidema et al., 2008; Bo Pedersen Weidema, 2009) considering the impact categories GWP (time horizon of 100 years), respiratory inorganic substances, aquatic and terrestrial ecotoxicity, nature occupation, acidification, aquatic and terrestrial eutrophication, respiratory organic substances, photochemical ozone formation (vegetation), and non-renewable energy.

GHG emissions were discounted according to when they occur during the 100-year time horizon (Jannick Høirup Schmidt & Brandao, 2013) based on the Bern carbon cycle (IPCC, 2007), meaning GHG emissions beyond the 100 years are excluded. In the IO model, iLUC is accounted for wood due to the competition for land that demand for wood asserts, using the method of Schmidt et al. (2015). The temporary carbon loss occurs due to primary forest conversion to productive forest, which is modelled for the countries where the conversion occurs. The iLUC approach was identified as the best among six models (De Rosa, Knudsen, et al., 2016).

The system LCA approach in Publication 4 applies statistics of Danish and European recent historical yield of wood and fast-growing biobased resources. The statistical analysis includes the average time series of what is already used by other sectors and what is available, i.e., not utilised by any sector. It helped determine the biogenic resources immediately available for construction without competing or taking that resource from other sectors. The yield factors of the different resources depended on the country of production.

This system consideration in Publication 4 of availability in terms of geographical location and quantity is very useful for discovering which resources are of national control. But also, the potential for the share of the demand national land can supply to the building sector. Further, straw is a dependent by-product, which means the demand for cereals drives the quantity. However, when it is not a fully utilised by-product, the potential demand from the construction sector does not shift impacts across sectors when the utilisation remains within the available quantity.

3.3.6. SENSITIVITY

Sensitivity analysis is recommended to obtain more robust outcomes and interpretations of LCA (EN 15978:2011, 2012; Hauschild et al., 2018). It assesses the LCA output’s variation of changing an input parameter in the model, for instance, an EPD of a larger impacting material, GWP time horizon, reference study period, or allocation procedure. Sensitivity analyses highlight the aspects that might need more careful assessment because of the influence it asserts on the outcome (ibid).

Publication 2 could benefit from a sensitivity analysis of EPDs for the wood products to see how much the GWP impact can vary from the early to the detailed design and in the detailed design only. Publication 3 provides a sensitivity analysis of affected suppliers of steel and concrete, the rotation period of trees, and the exclusion of iLUC and forest modelling. That way, it gives insight into their importance. One of the suggested approaches to deal with the inherent uncertainty of the forward-looking aspect of CLCA is scenario development (Zamagni et al., 2012). It could be based on the sensitivity analysis results, yielding a range of likely outcomes. It applies to other types of future-oriented LCAs as well. Publication 4 applies a simple scenario consideration through four market penetration rates with a linear increase towards 2050 from the current 11%. The possibility of resource availability and likely transition of the sector becomes clearer.

3.4. CASE STUDIES

Case studies are useful for understanding how and why related research questions are particularly important, but they can also be useful for descriptive investigations (Yin, 2018), e.g., the climate impact of a certain building typology. Case studies emerge suitable for research when desiring to understand a phenomenon in relation to its real conditions and context (ibid). It is very relevant for studying the environmental impacts of the entity phenomenon wood buildings because of (i) the geographical location specifics related to regulatory clauses, financial and economic conditions, (ii) the technical behaviour of wood and biobased materials, (iii) building tradition along with client and user requirements. It is also a widely used practice in LCA research on buildings (Ruuska, 2018).

The publications in the dissertation implement a different number of case studies for quantitative assessments for a real context investigation of environmental impacts of wood buildings with both descriptive and exploratory purposes, i.e., the latter comprising the how and why examinations suggested by Yin (2018). The case studies originate in Denmark, as this is the geographical focus of the research.

Publication 2 analyses ten detailed designs of residential housing, which is perceived as a greater number of case studies than many LCA studies on buildings. The GWP impact of the detailed design was descriptively assessed to uncover where the impact arises in the life cycle stages, building elements, and material groups. Despite eight buildings being terraced housing, the varying layout and structural systems across the cases yield insights into the associated GWP impacts for each design approach.

However, the larger case study population in Publication 2 does not entail that the findings are statistically generalisable on a greater scale. Nonetheless, it provides useful knowledge to understand the role of wood buildings and not at least design and material levers for reducing climate impacts. Further, the case studies are current representations of the real-world context. It remains important to be apprehensive that the reality is not imperative for how that context could be, i.e., be aware of the verification bias (Flyvbjerg, 2011). It applies also to the case studies in Publications 3 and 4.

Publication 3 uses three case buildings for each building typology of single-family houses (SFH), multifamily houses (MFH), and office buildings (OB) for conventional and wood-based construction, respectively. The random selection of these case studies reduced the bias of selecting any buildings with special properties or serving certain agendas. Hence, the average case study of each building typology and construction technology helped explore the aspects influential to the environmental impacts of change from conventional construction to increased wood at the building stock scale.

The selection of the case buildings in Publication 4 followed the information-oriented approach (Flyvbjerg, 2011) to ensure structural materials were of wood to function as a base case to establish fast-growing biobased archetypes for the wood buildings. It was not fully possible for the SFH case study because all the available buildings contained straw to a certain extent. Therefore, a base case archetype for the exterior walls were established with paper wool instead of straw insulation.

CHAPTER 4. FINDINGS

This chapter presents findings from Publications 1, 2, 3 and 4 that are relevant to address these dissertations sub-research questions. Publication 1 presents the review of CLCA focuses and modelling methods used on buildings and wood buildings. The other three publications are empirical studies of using wood and fast-growing biobased materials, considering different intended applications, LCA and biogenic-related approaches.

4.1. WHICH MODELLING METHODS AND FOCUSES ARE APPLIED IN CONSEQUENTIAL LCA RELATED TO BUILDINGS?

The general findings of Publication 1 were already presented in the state-of-the-art, while the empirical studies are further elaborated in the following. Figure 4-1 illustrates the relationship between the goal and scope aspects of the empirical studies and the consequential life cycle inventory (CLCI) modelling aspects. Thirteen studies focus on the micro scale and fifteen on the macro scale, where the studies applying more than one CLCI modelling method appear more than once.

The micro scale studies assess materials and buildings almost equally, with the buildings mostly focusing on wood compared to conventional materials. The material and few element studies centralise on circularity assessments. A similar number of macro scale studies assessing buildings and materials exist. The micro scale studies focused on changes in energy supply, increased wood, and circularity. The material studies mainly examine increased wood and changes in material production energy and building material substitution.

The market delimitation and trend were not defined or identified in several studies and had a similar distribution on the micro and macro scale. Ecoinvent and the iterative procedure appear to be the most applied CLCI modelling on the micro scale market delimitation where statistics or linear regression are the main approaches for identifying the market trend. Literature and Ecoinvent apply most to the affected suppliers identification at the micro scale, but the iterative procedure also notably appears.

For the macro scale studies, literature, economic partial equilibrium models, and forest production models emerge as the most applied market delimitation approaches. The market trend is mostly analysed by linear regression literature, partial equilibrium and forest production models. Literature references stand out as the most common identification method of the affected suppliers, followed by partial equilibrium and forest production models.

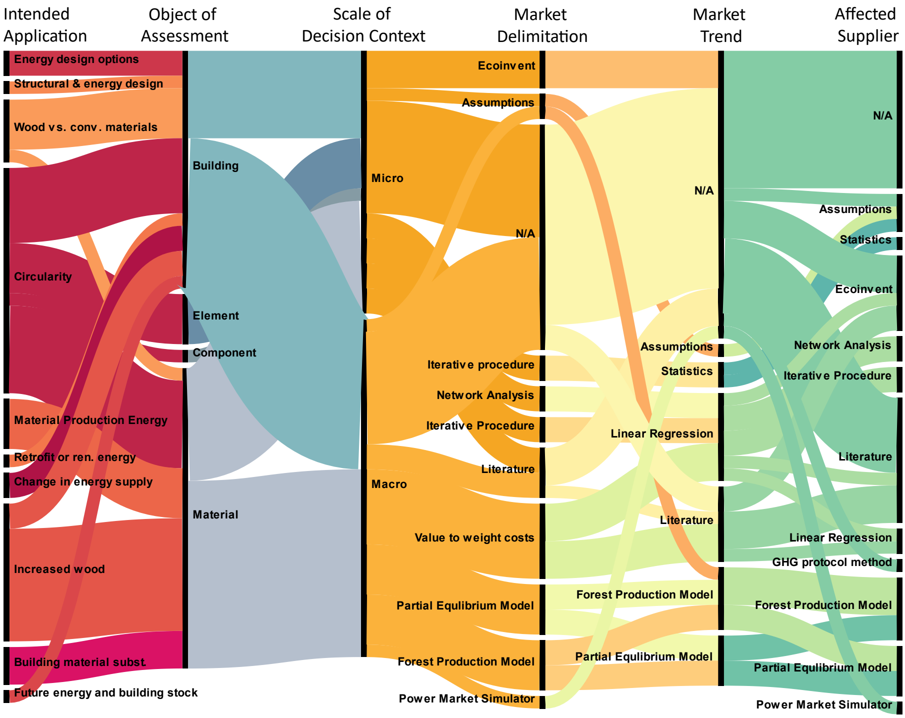

Figure 4-1 Relationship of the empirical studies' intended application, object of assessment and scale of decision context with CLCI modelling. Based on findings from Publication 1 (Hansen, Rasmussen, et al., 2023)

4.1.1. REVIEW OF CONSEQUENTIAL LCA ON WOOD IN BUILDINGS

Thirteen of the reviewed CLCA studies on buildings focus on wood as a material. The studies, which include the empirical, methodological and method development studies, are presented in Figure 4-2. It unfolds that all studies declaring a time horizon apply a long-term perspective, i.e., the default in the four-step framework. Five studies using substitution exclude or have generally lower documentation and consistency of modelling of the market, trend, and affected suppliers. The studies with higher documentation and consistency of CLCA aspects also tend to use more advanced modelling methods. However, the majority of these do not include biogenic carbon aspects. On the other hand, the studies with lower or excluded documentation and modelling consistency of CLCA tend to include biogenic carbon aspects with more advanced modelling.

Reference	Time Horizon	Market Delimitation	Market Trend	Affected Suppliers	Substitution	BC approach	Boundary	dLUC	iLUC
Buyle et al. (2019)	Long-term	Network analysis, iterative procedure	Linear regression	Network analysis, iterative procedure	Yes				
Buyle et al. (2019)	Long-term	Network analysis, iterative procedure	Linear regression	Network analysis, iterative procedure	Yes				
Buyle et al. (2018)	Long-term	Iterative procedure	Linear regression	Iterative procedure					
Nepal et al. (2016)	Long-term	PE and forest production model		PE and forest production model	Yes	Other dynamic	Aboveground, belowground, thinning	Yes	
Damvad Analytics (2016)	Long-term	Iterative procedure	Statistics	Statistics, assumptions	Yes	Dynamic time-dependent	Timber, thinning	Yes	Yes
Cordier et al. (2019)	Long-term	Assumptions	Material flow analysis	Statistics					
Pizzol et al. (2017)		Network analysis	Linear regression	Linear regression					
Forster et al. (2019)	Long-term	Assumptions	Forest production model	Forest production model	Yes	-1/+1	Timber, thinning	Yes	Yes
De Rosa et al. (2018)	Long-term	Literature, assumptions		Assumptions	Yes	Dynamic time-dependent	Aboveground, belowground, thinning	Yes	Yes
Fauzi et al. (2021)	Long-term		Literature	Literature, Ecoinvent	Yes				
Skullestad et al. (2016)	Long-term			Ecoinvent, assumptions	Yes	Dynamic time-dependent	Aboveground and belowground		
Dodoo et al. (2014)					Yes	-1/+1	Timber	Yes	
Sandin et al. (2014)					Yes				

Not included | Lower | Medium | Higher

CLCA aspects: Degree of documentation and modelling consistency
Biogenic carbon approach: Degree of modelling advancement

Figure 4-2 CLCA studies including wood as a part of the assessment. The left side covers the CLCA modelling aspects, and the right side covers the biogenic carbon aspects. Substitution, dLUC, and iLUC are denoted if included. The colours denote the degree of documentation and modelling consistency for CLCA aspects and the degree of modelling advancement of the biogenic carbon aspects. Based on findings from Publication 1 (Hansen, Rasmussen, et al., 2023)

4.2. IN WHAT WAYS DO LCA AND BUILDING DESIGN ASPECTS INFLUENCE THE ENVIRONMENTAL IMPACTS OF WOOD BUILDINGS IN THE EARLY AND DETAILED DESIGN STAGES?

4.2.1. CLIMATE IMPACT OF LIFE CYCLE STAGES

Publication 2 analysed climate impacts in the detailed design of 10 buildings from 2010-2021. The analysis only covered embodied impacts over the life cycle, hence omitting energy use during the use stages. For the buildings, excluding technical installations in the bill of quantity, experience data were added from other studies as an estimate. The biogenic carbon approach used the -1/+1 consideration, accounting for negative (reduction) in the production stages and positive (emission) at the end of life. All the GHG emissions were characterised with regard to the GWP_{100}, but the cumulative climate impact is time-independent, meaning that emissions count equally for every life cycle stage.

Figure 4-3 displays that the climate impact of wood buildings is largest at the end-of-life stages (C3+C4) while concurrently, some buildings have great reductive (negative) climate impacts at the production stages (A1-A3). The buildings with negative CO_2-eq emissions in the production stages show that these reductions are more than counterbalanced by emissions at the end of life. For the buildings with climate impact in the production stages, the impact arises fairly at a low magnitude except building M01 and R07. The construction stages (A4-A5) show very low climate impact, and replacements (B4) are larger than the production stage for several buildings. The biogenic carbon approach considers in this assessment the biogenic carbon to be negative in the production stage and positive at the end of life, hence explaining the reasons behind the outcomes above.

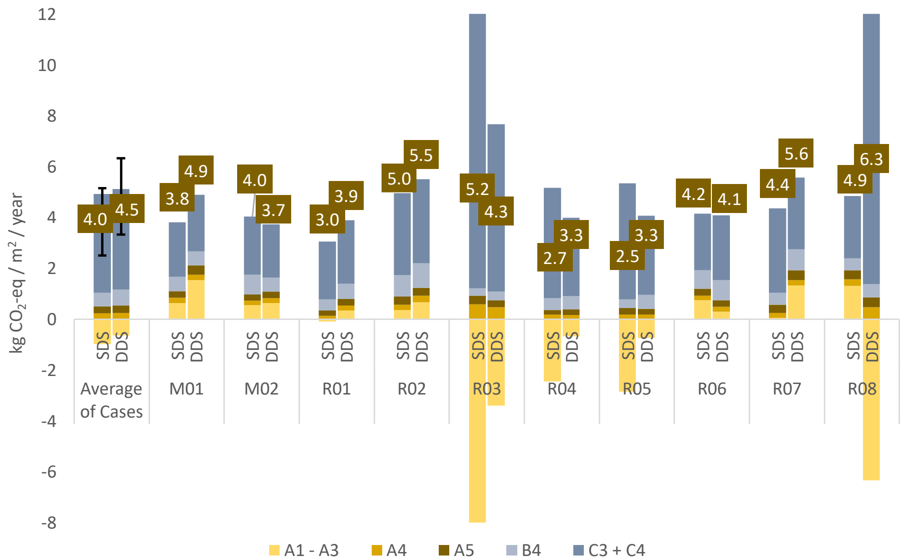

Figure 4-3 Life cycle stages' share of impacts of the detailed (DDS) and early design stage (SDS). M=multifamily houses, R=terraced houses. From Publication 2 (Hansen, Hoxha, Rasmussen, et al., 2023)

Based on the simplified design tool, the prediction in the early design stage reveals that it is remarkedly precise, although it predicts slightly greater negative CO_2-eq emissions in the production stages. The picture changes when studying the individual buildings. The simplified tool predicts the quantities, so the construction stages and replacements lead to quite similar climate impacts for almost every building. However, greater divergence occurs for the production and the end-of-life stages. The end-of-life stages appear comparable regarding the climate impact of the detailed and early design for the buildings, where the production stages result in positive CO_2-eq emissions in both design stages. In buildings, R03-R05 and R08, the production stages have a negative climate impact in one or both design stages, which results in less precise climate impact predictions for the end-of-life stages. Contrarily, the climate impact during the entire life cycle for these four buildings does not differ more considerably between design stages than the other buildings. The production stage associated with climate impact are commonly predicted with low precision, i.e., the biogenic carbon-related prediction. Still, it does not greatly influence the total life cycle climate impact.

4.2.2. CLIMATE IMPACT OF BUILDING ELEMENTS

As demonstrated in

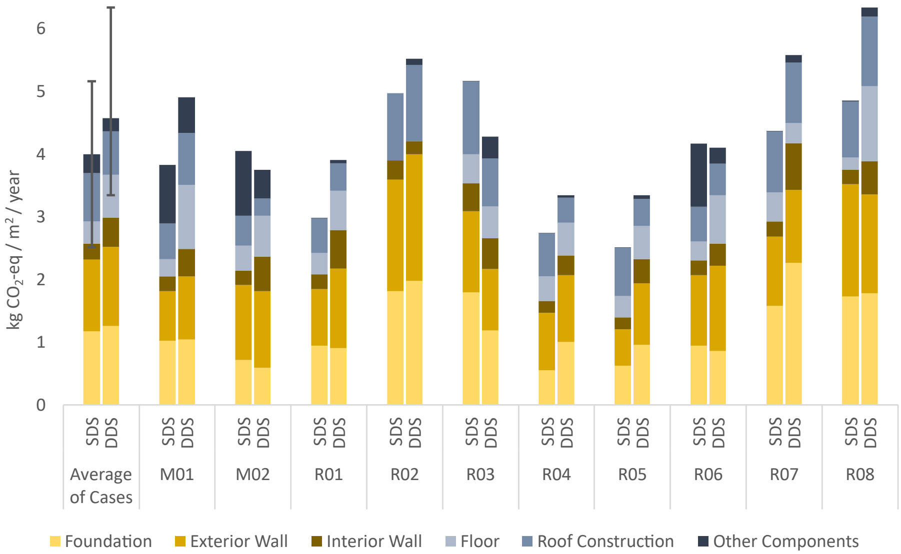

Figure *4-4*, the building elements of the foundation and exterior walls contribute mostly to the climate impact of wood buildings in the detailed design on average, followed by the floors and roofs, sharing similar contributions. The contribution from different building elements appears more motley when delving into the individual buildings.

The buildings M02 and R06 exhibit foundations with lower climate impact than exterior walls and floors because these buildings are the tallest among the case buildings by having 3-4 storeys. The buildings with 1-2 storeys, the lowest number of

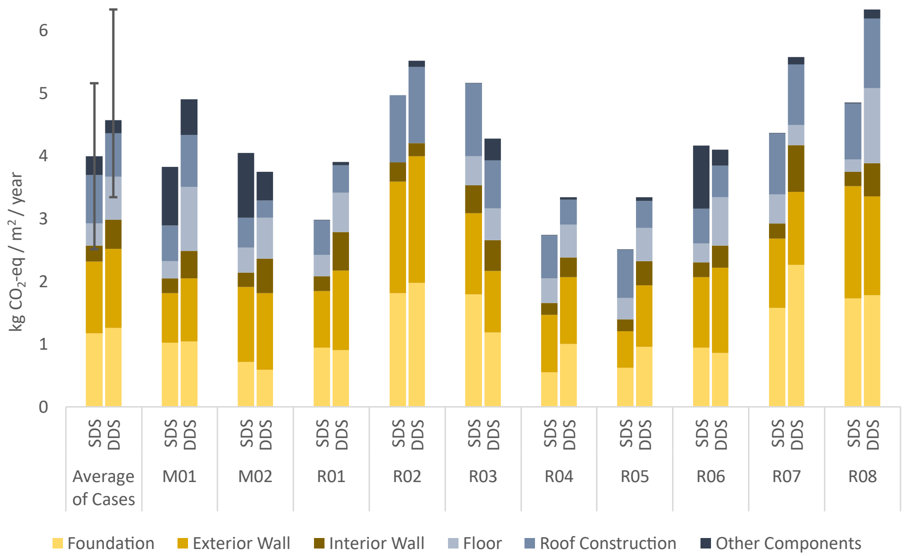

Figure 4-4 Building elements' climate impact in the detailed (DDS) and early design stage (SDS). M=multifamily houses, R=terraced houses. From Publication 2 (Hansen, Hoxha, Rasmussen, et al., 2023)

storeys, are R02-R05 and R07-R08, and they have the largest contribution from foundations when disregarding building R04-R05. Building R04-R05 are constructed with footing foundations. They show less contribution from foundations relative to their exterior walls and in absolute impact compared to most of the other buildings. The contribution from exterior walls seems more constant across the cases and is less susceptible to the number of storeys. Roof constructions have a greater overall contribution in the buildings with 1-2 storeys except in building R04-R05 despite these two having rafter structures like the other 1-2 storey buildings. Floors, in general, deviate between buildings and do not follow a trend that relates to structural typology neither number of storeys.

When we look at the average climate impacts in the early design, the predictions of foundations and exterior walls were very close to the detailed design. Floors and interior walls were predicted to have about half the climate impact in the early design. Still, they contribute, by absolute numbers, with less climate impact than foundations and exterior walls. The early design predicts roofs with a vaguely greater climate impact on average.

Taking a first sight at the foundations regarding the individual buildings, the climate impact is quite precisely predicted in the early design, but the two buildings with footing foundations are exempt due to impact underestimation. Building R03 gets a considerable overestimation of the climate impact. It is the only building of CLT structures. Exterior walls' climate impacts are precisely predicted in almost every building; the roofs' climate impact is quite precise in seven cases, but the floors' impacts are underestimated in half of the buildings. The climate impact of the interior walls was generally underestimated in all cases, which was expected because the simplified design tool only computes the loadbearing interior walls. The absolute climate impact of the interior walls has, despite that, a little share of the impact in the detailed design.

4.2.3. CLIMATE IMPACT OF MATERIALS

The average climate score in Figure 4-5 highlights insulations with the principal share of climate impact in the detailed design. Cement- and biobased materials follow with similar contributions, and then metals and plastics come afterwards. The other materials category also has a significant share but will not be covered further. For insulation materials, there are considerable variations between the buildings; for example, paper wool insulation in R04-R05 leads to a low impact of this material category.

The average climate impact of biobased materials is mainly driven by two buildings, R03 and R08, and is noticeably less in the other buildings. The former buildings are of CLT structure, leading to increased wood use in this case. At the same time, the latter has similar characteristics as many of the buildings. The main reason appears to be the amount of wood cladding employed due to its low service life. The cement-

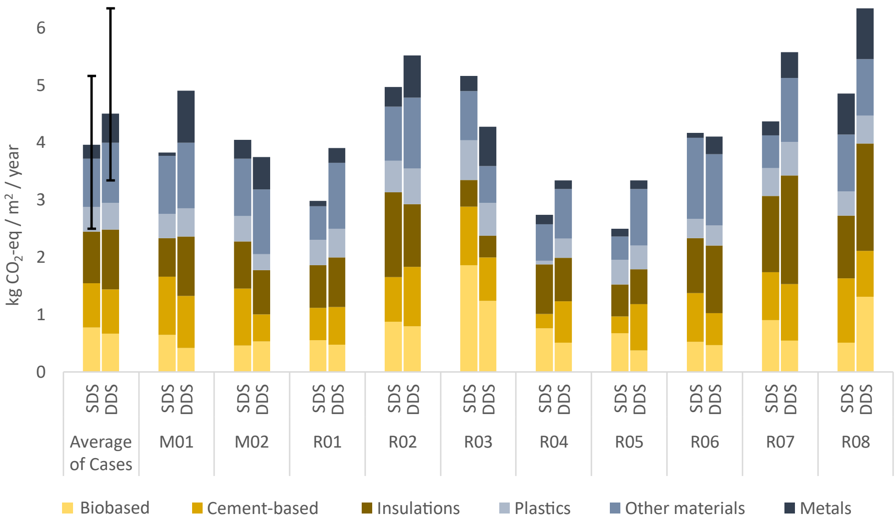

Figure 4-5 Material groups' climate impact in the detailed (DDS) and early design stage (SDS). M=multifamily houses, R=terraced houses. From Publication 2 (Hansen, Hoxha, Rasmussen, et al., 2023)

based materials have less variance in impact, but the two tallest buildings, M02 and R06, have the lowest share from this group, indicating a similar trend as the foundations. There are great variations between impact from metals, which might be because not all buildings include technical installations and joining products like screws and mounting brackets.

4.3. HOW CAN CONSEQUENTIAL LCA AND BIOMASS-RELATED MODELLING AFFECT THE ENVIRONMENTAL IMPACT OF A CHANGE TO WOOD-BASED CONSTRUCTION?

4.3.1. TOTAL AND LIFE CYCLE STAGES' CLIMATE IMPACT

Publication 3 evaluates the consequences of a change to wood-based construction by assessing the supplier (country) expected to meet the increased demand. The affected suppliers were Denmark for concrete, China for steel, and Sweden for wood. The study further dealt with co-products of these three materials using substitution where the expected marginal product supplying a similar product was displaced. Substitution was also the allocation procedure at the end of life. Finally, a model for the expected forest regrowth in Sweden were linked to the different wood products and the time they locked biogenic carbon in the building. The climate impact of all GHG emissions was based on their cumulative impact during the 100-year time horizon of GWP100, entailing that the later the emission occurs, the less cumulative impact.

When we delve into the climate impact from the different life cycle stages presented in Figure 4-6, the greatest climate impact occurs during the production stages for the conventional and change to wood-based construction. The replacement of materials follows, having the second greatest climate impact, while the end-of-life stages lead to negative climate impacts (reductions). Nonetheless, the three building typologies show differences in the magnitude of climate impact shared among the life cycle stages.

The SFH has slightly larger impacts from the production stages of the wood-based construction compared to the conventional. Still, the climate impact of replacement increases manifold for wood-based construction. The negative climate impact of the end-of-life stages is approximately equivalent to the two construction stages. The production stages of MFH exhibit a considerably smaller climate impact in the wood-based construction, but it also has a vaguely greater impact from replacement. The reductions seen for the end-of-life stages emerge quite lower for the wood-based construction. Turning now to the OB, the wood-based construction results in larger climate impacts from the production stages and vaguely larger from replacements. However, they also have the largest reductions at the end of life compared to the conventional construction for the RSP_{60} but not in the RSP_{100}.

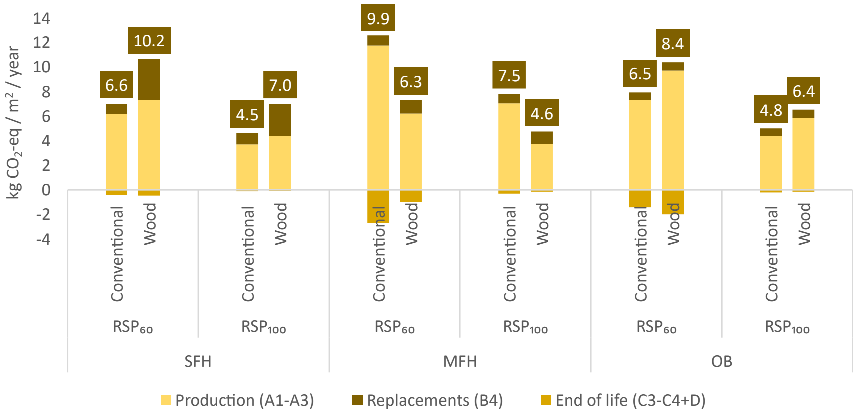

Figure 4-6 Climate impacts of life cycle stages for conventional and wood construction. The label denotes total climate impact, i.e., sum of positive and negative impacts). SFH=single-family houses, MFH=multifamily houses, OB=office buildings, RSP_{60}=60-year reference study period, RSP_{100}=100-year reference study period. From Publication 3 (Hansen, Eliassen, et al., 2024)

A comparison of the climate impacts share of life cycle stages of the two RSPs reveals that the extension leads to lower impact per m^2 gross floor area per year despite the imposed need for replacements. The climate impact from replacement in the wood-based construction decreases mostly for the SFH and slightly for MFH but increases faintly for the OB. A closer inspection of Figure 4-6 shows the climate impact reductions from the end-of-life stages remarkably decrease when extending the RSP from 60 to 100 years. The root cause behind this trend is that GHG emissions at the end-of-life stages occurring in year 100 are uncounted within the 100-year time horizon of GWP100.

4.3.2. CLIMATE IMPACT OF MATERIALS

The subsequent analysis examines the material categories contributing to the climate impact in Figure 4-7. It points out mineral based materials and metals as the most prominent emitter of GHGs for conventional construction. Surprisingly, biobased materials are the greatest climate contributor to wood-based construction. In addition, fired clay also contributed noteworthy to the climate impact of SFH in conventional construction, and metals do similarly for OB in wood-based construction. Of interest here is the reduced climate impact of mineral-based materials in wood-based construction for all three building typologies.

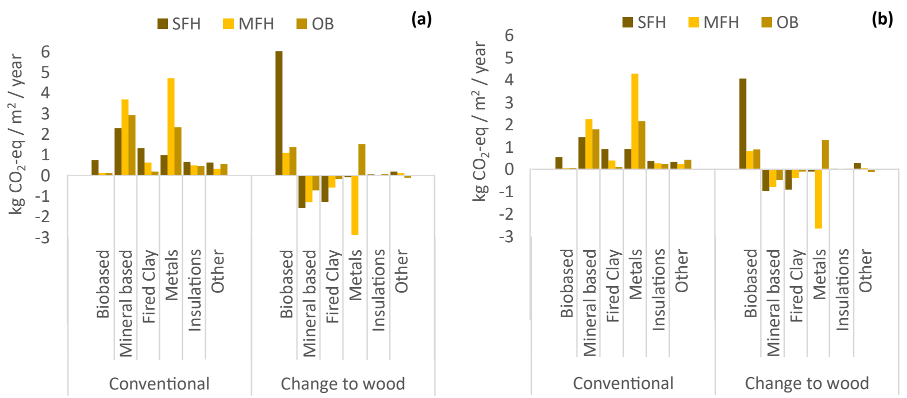

Figure 4-7 Climate impact of material groups. Change to wood shows the difference in the climate impact that the wood-based construction is larger (positive) or lesser (negative) than the conventional. (a) RSP=60 years. (b) RSP=100 years. SFH=single-family houses, MFH=multifamily houses, OB=office buildings, RSP=reference study period. Adapted from Publication 3 (Hansen, Eliassen, et al., 2024)

Further noticeable is the reduced impact from fired clay for the wood-based SFH. Altogether the climate impact reductions for SFH in the wood-based construction do not counterbalance the increased biobased impact. On the other hand, the wood-based MFH's avoided the climate impact of metals compared to the conventional construction, reducing it sufficiently to make wood the better option. The change to wood-based construction for OB reveals metals to have the largest climate impact, indicating a great quantity of metals employed compared to conventional construction. The remaining material categories have little contribution to the climate impact, hence making metals, biobased, and mineral based materials the significant GHG emission root causes and fired clay can also be included in this depiction for the SFH.

Further, the analysis in the figure reveals that the mineral based materials decrease in impact with an extension of the RSP from 60 to 100 years. Contrarily, metals only decrease slightly from an extended RSP, indicating replacements offset the more years to divide the impact. The biobased materials see a moderate decrease, less significant than the mineral based materials, but more considerable than the metals. In the SFH, the fired clay experiences, similar to the mineral based materials, a decrease in climate impact with an extension of the RSP. The remaining material categories do not change much in absolute numbers, and they seem trivial to encounter with their small contribution to the climate impact.

4.4. WHAT IS THE EFFECT ON LAND USE IMPACT AND CARBON STORAGE OF IMPLEMENTING MATERIALS OF FAST-GROWING BIOBASED RESOURCES IN WOOD BUILDINGS?

4.4.1. LAND USE-CO_2 STORAGE INDICATOR

Publication 4 explores the potential of substituting non-loadbearing wood and insulation products in wood buildings with fast-growing biobased materials of straw, hemp, and grass products. New archetypes of floors, exterior walls, interior walls, and roofs were developed for SFH, MFH, and OB. The biobased material scenarios were scaled up to the building stock of Denmark. The degree of implementation in the building stock was considered through four scenarios of market penetration rates. The first scenario accounts for the current market penetration rate at 11% in 2050. The other three scenarios examine a linear increase of 25%, 50%, and 100% market penetration towards 2050, starting at the current rate. They are named A, B, C, D.

On this basis, production stage land use and carbon storage were derived. It included how much of the production can be covered by land in Denmark and what is needed from imports. The land use of wood was calculated as the cumulative land needed from 2022-2050 because trees have longer rotation periods than this. The land use for the fast-growing biobased resources encompassed the year with the greatest demand since these resources' rotation period is one year or shorter.

Our analysis showed that straw stores the most biogenic CO_2 followed by the grass scenario, hemp, and finally, the wood scenario (the base case). Further analysis, as shown in Figure 4-8, signals that the land use needed for every kg CO_2 stored in the three building typologies decreased remarkably for implementing fast-growing biobased materials. The largest reduction in needed land emerges for the SFH by almost reaching the same low demand for land needed for the MFH. The OB will have the lowest reduction of land use per stored kg CO_2, but it is plausible since it also has the lowest substitution rate of implementing fast-growing biobased materials.

Despite straw appearing with the largest carbon storage potential, it does not lead to increased relative land use compared to the two other fast-growing biobased resource scenarios. The straw scenario remains with the lowest land needed per kg CO_2 storage for all three building typologies. The hemp scenario follows for the SFH and the grass scenario. The grass scenario for MFH and OB leads to less land needed than the hemp scenario.

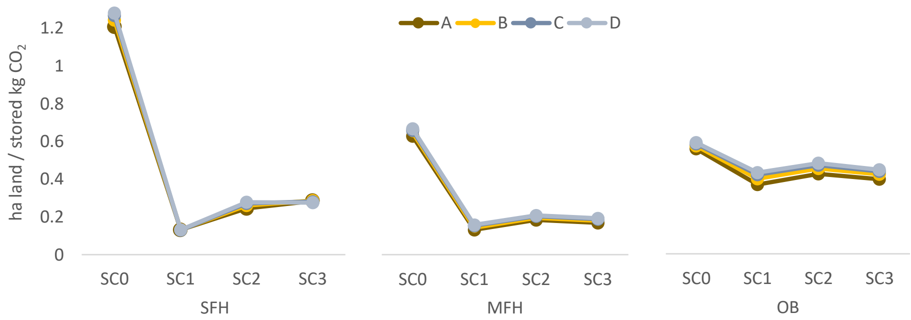

Figure 4-8 Land use per stored kg CO_2 for the three building typologies for each biobased material scenario. SFH=single-family house, MFH=multifamily house, OB=office building. SC0=wood, SC1=straw, SC2=hemp, SC3=grass. Market penetration rate in 2050: A=11%, B=25%, C=50%, D=100%. From Publication 4 (Hansen, Hoxha, et al., 2024)

4.4.2. LAND USE AND AVAILABILITY

Delving into the availability assessment, the land needed for the four biobased resources are compared in

Figure *4-9*. It uncovers larger differences among the resources. The needed wood cannot be covered by Danish national land in any of the scenarios, but it can be covered by the market for Denmark. However, the need for land abroad to supply wood drastically reduces in the fast-growing biobased scenarios. The situation changes when delving into the supply of straw, indicating that Denmark can cover the demand for all straw needed in SC3 for all market penetration rates. In SC1, the Denmark supply can cover the market penetration of the current and the 25% rate and almost also the 50% without interfering with other demand for straw. The national supply of straw can cover the 100% market penetration in theory, nonetheless, entailing that it competes with other sectors.

Figure *4-9*(c) illustrates hemp is not cultivated in Denmark, so using hemp in the buildings will require imports from European countries. The quantities of hemp used in SC1 and SC3 can be covered by the market for Denmark in the EU. The hemp needed in SC2 can be covered by the market for Denmark available for construction for the current market penetration rate without interfering with other sectors while the

100% scenario exceeds the market for Denmark by about 7000 ha. The grass is only considered in SC3, where the national supply available can cover the demand for all market penetration rates.

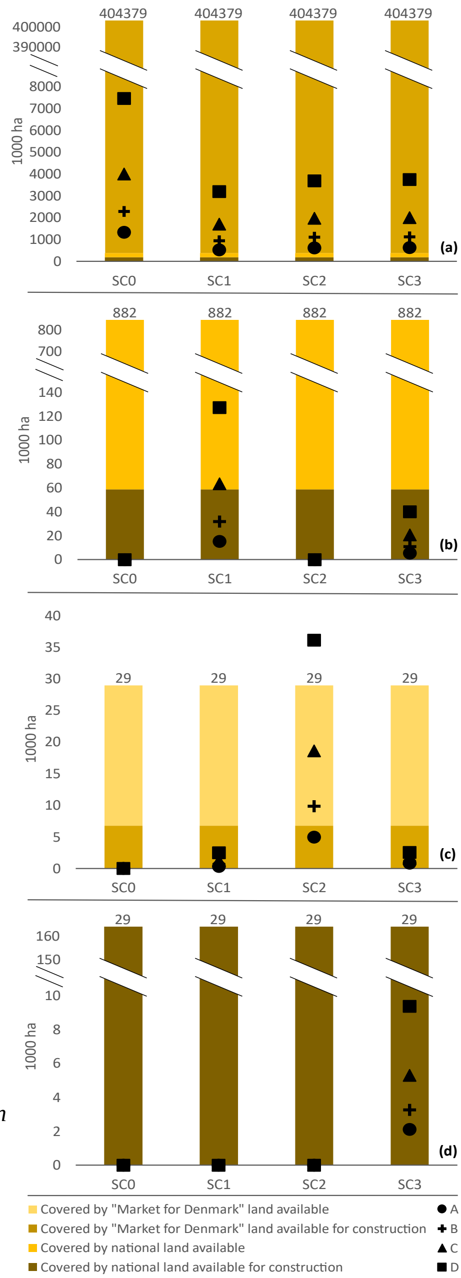

Figure 4-9 Land use needed (thousand ha) for the four biobased resources in the four market penetration scenarios. The coloured bars shows whether the needed land is in Denmark or in the Market for Denmark. (a) wood, (b) straw, (c) hemp, (d) grass. Market penetration in 2050: A= 11%, B= 25%, C=50%, D=100%. From Publication 4 (Hansen, Hoxha, et al., 2024)

4.5. SUMMARY OF FINDINGS

Publication 1 reviews and analyses current literature on CLCA. Publications 2, 3, and 4 are empirical studies using wood and biobased materials in buildings of various scales and LCA approaches.

Publication 1 analysed 37 articles on CLCA in buildings and discussed the difference between ALCA and CLCA in the ILCD Handbook. The study found 13 studies focusing on method analysis and 27 on empirical assessments, as mentioned in the state-of-the-art. Thirteen articles used CLCA for micro scale decision-making and fifteen focused on macro scale. Micro scale studies looked at material-level circularity and transitioning from conventional to wood at the building level. Macro scale studies focused on circularity, increased use of wood, and changes in energy supply, with some also considering material substitution or material production energy.

CLCI modelling encompasses a wide range of methods, extending from literature, Ecoinvent, and iterative procedure to linear regression analysis and economic models. It also applies to the studies on wood, where the more transparently documented and consistent CLCAs also use more advanced modelling. These studies tend to exclude biogenic carbon aspects, while the studies with reduced CLCA framework conformity focus more on biogenic carbon modelling.

Publication 2 compared the GWP impact of ten wooden dwellings in the early and detailed design stages. The simplified design tool used in the early stage showed an average 12% lower GWP impact than the detailed design. The life cycle stages A1-A3 and C3-C4 had fluctuations in impact between the two design stages, especially for buildings with higher biogenic carbon content.

Foundations, exterior walls, and floors significantly influence buildings’ GWP score, but the early design, in several cases, underestimates it for floors. Insulations, biobased materials, and cement-based materials are the main contributing material groups to the impact in both design stages. The early design should include metals to avoid underestimating wood buildings' total GWP impact. Additionally, using footing foundation and paper wool was found to reduce GWP impact, while using CLT for low-rise dwellings may increase the climate impact of biobased materials, thus also the total. However, this finding originates from only a single case study.

Publication 3 analysed the environmental effects of changing from conventional to wood-based construction in the Danish building stock. The study used CLCA, forest modelling, GHG emission discounting, and iLUC analysis. The wood-based scenario had the lowest GWP impact for MFH and conventional construction for SFH and OB. However, this conclusion was based on only three case studies for each building typology. The production stages A1-A3 had the greatest GWP impact across all building types and construction scenarios. Replacements (B4) also contributed significantly to the GWP impact in wood-based SFHs. Increasing the RSP from 60 to 100 years reduced the overall GWP impact in all scenarios.

Mineral-based materials and metals had the highest GWP impact in conventional construction for all building types, while biobased materials had the highest impact in the wood-based scenario. The impact of biobased materials was particularly significant in SFHs. Avoiding mineral-based materials, metals, and fired clay helped counterbalance the biobased impact in wood-based SFHs while avoiding mineral-based materials was predominant for wooden OBs. The reduced use of metals in MFHs made wood-based construction have the least impact, and avoiding mineral-based materials also helped reduce the impact.

Publication 4 evaluated the upfront land use and carbon storage of implementing more fast-growing biobased materials in wood buildings at four market penetration rates. The results showed the fast-growing biobased materials reduce the land use-CO_2 storage indicator by 78-90% for SFH, 68-76% for MFH, and 19-27% for OB. The straw scenario leads to the largest indicator reduction for three building typologies. The increased implementation of fast-growing biobased materials decreases the need for wooded land by 50-61%. The Danish supply can meet the demand in the pure straw scenario almost up to a 50% market penetration rate.

In contrast, it can cover the entire straw consumption in the grass scenario. Danish production can fully supply the grass for all market penetration scenarios. Hemp is not grown in Denmark and needs imports from abroad. The straw and grass implementation can reduce land use impact by 55-60% and 49-53%, respectively.

CHAPTER 5. DISCUSSION

5.1. INSIGHTS OF LCA ON WOOD IN THE BUILDING DESIGN

The early design climate impact predicted in the life cycle stages A1-A3 and C3-C4 fluctuated remarkably compared to the detailed design for most of the ten buildings. Conversely, the same results for the average across the buildings showed minor differences, which does not affect life cycle climate impacts. Communicating that a building in the early design may have low or negative emissions in the production stage due to negatively counted biogenic carbon can mislead designers, clients, and future occupants in individual building projects. The small difference, on average, suggests that it will not pertain across the building sector; paying attention to ten case buildings is a relatively small sample, though larger than most other LCA research on building case studies, e.g., averaging 4.4 case studies per article in Röck et al. (2020).

Based on the findings, designers should not advise on production-stage biogenic carbon reductions in the early design until investigating further the root causes behind the early and detailed design deviations. That investigation should involve whether the quantity distribution between material categories, the EPDs' biogenic carbon content, or both are the root causes of the fluctuations between the design stages. Additionally, it remains necessary to include both the production and end-of-life stages of biogenic materials when using the -1/+1 to avoid drawing incorrect conclusions.

The large impacts associated with foundations, exterior walls, and floors should be the focus for prediction in the early design decision-making process. Still, new materials and design innovations also call for exploration to reduce the impact of these building elements. Floors and interior walls have the largest average underestimations in the early design, and thus are important to predict accurately in the early design. The floors' lower average climate impact in the early design can partially be attributed to a plastic fibre membrane's share of the impact in one building is 49%, and polyurethane (PUR) used in a flooring underlay is 53% in another. More instances existed of single materials having a large share of a building element. In particularly for floors, which indicates that the choice of unit process or EPD representing a product can significantly influence the climate impacts of buildings and their elements. In Rasmussen et al. (2021), similar findings appeared for structural wood. Therefore, designers need to be aware that quantity prediction is not the only determinant for climate impacts, but EPDs appear likewise.

The detailed design uncovered footing foundation to impact the least among foundations. Building designers should aim to implement it for all low-rise buildings in the early design, although the applied simplified design tool underestimates the early design impacts of footing foundations.

The material contribution analysis revealed that insulation is the largest source of climate impacts; a great share of it stems from the exterior walls. So reducing the impact from insulation reduces the impact of the exterior walls. Buildings using paper wool insulation show lower climate impact, making biobased insulation a useful and beneficial climate solution to implement. The findings in Publication 4 indicate that using crop- or grass-based insulation products simultaneously reduces the burden-shift to land use impacts, which the wood-sourced paper wool potentially causes.

Furthermore, Figure 5-1 demonstrates insulation to be the material most climate impact responsive to changes in material quantity prediction in the early design. Investigating whether this also applies to the insulation of fast-growing biobased resources would be useful for building designers to know for more robust early design decision support. As cement-based materials are not very sensitive in impact response to larger material quantity deviations between design stages, reducing their total climate impact is more important. Of which the footing foundation is already a viable solution.

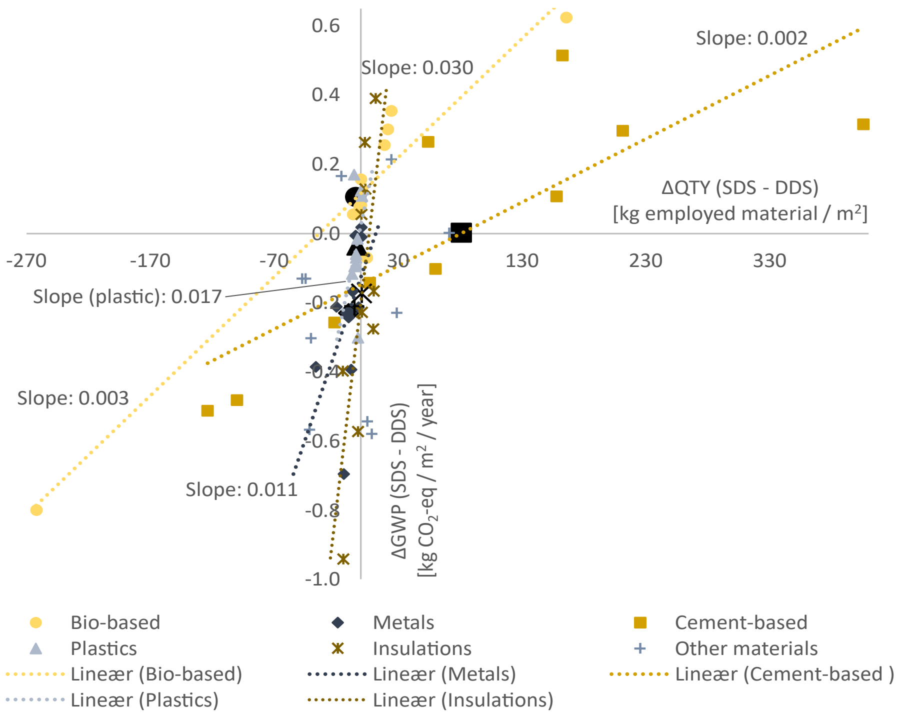

Figure 5-1 The difference of material quantities (ΔQTY) and impact (ΔGWP) when subtracting the detailed design from the early design. Black markers represent the average of cases, dotted lines are the linear relationship of ΔQTY and ΔGWP, DDS = detailed design stage, SDS = early design stage. From Publication 2 (Hansen, Hoxha, Rasmussen, et al., 2023).

The climate impact of biobased materials is also important to consider in the early design prediction due to the relatively considerable response to change in quantities. Two case buildings emerge with a large deviation in material quantity and impact between design stages. Excluding these two buildings would result in the biobased materials' slope in Figure 5-1 being even more inclined, indicating more responsiveness to changes in quantities. Nonetheless, the range of climate impact deviations reduces. Thus, not changing the overall conclusion that biobased materials are important to predict accurately. The two building outliers in the figure indicate that CLT is unsuitable for two-storey residential buildings, and wood cladding should be avoided because of replacement frequency. The other applications of wood have lower climate impact. However, basing these conclusions on single case buildings lacks robustness, suggesting further research on these findings.

Metals, such as technical installations and joint products, were mostly not included in the assessed simplified design tool. Although metals do not contribute as much to the climate impact as the above-discussed materials, they still need to be predicted in the early design because the underestimation is considerable enough to not leave out. The metals also exhibit high sensitivity to changes in material quantities, underlining their importance for the total climate impact. In some individual buildings, the near omission of metals leads to about 0.5-1 kg CO_2-eq/m^2/year underestimation of total embodied impacts.

Cement-based materials, metals, and insulations undeniably influence wood buildings. Other materials and new design solutions need implementation regarding these material groups, for instance, footing foundations and biobased insulation emerge as opportunities in this dissertation. Can reducing metal assembly quantities and the GWP impact be inspired through vernacular joinery technique, such as in some traditional Japanese low-rise housing, where the assembly functions without nails, screws and mountings? Further, may the increased comfort criteria met through increased technical installations be solved by passive strategies or simply reduced?

5.2. CONSEQUENTIAL AND SYSTEM PERSPECTIVES OF LARGER SCALE CHANGES TO BIOBASED CONSTRUCTION

The effectiveness of which biobased materials substitute cement-based materials, metals, and, to some extent, fired clay is important for the climate mitigation effect of changing to wood-based construction through the lens of combined consequential and forest modelling. Effectiveness entails that the wood needs to replace the right materials, the carbon-intensive materials, and requires efficient implementation. In the multifamily houses case studies, the combination of right and efficient results in reduced climate impacts using wood-based construction. The single-family houses case studies show inefficient use of wood products, leading to a larger climate impact of wood-based construction. These findings suggest that a break-even point where wood is better than conventional materials exists.

After the study conclusion, the type of case study and material grouping was found prominent in significantly influencing the outcome. Hence, the three buildings used for each building typology in Publication 3 need more case studies to make more robust conclusions on changing to timber construction. The same applies to Publication 4, where it only uses one case building for each building typology.

In Publication 3, the grouping of biobased materials, such as green roofs and eelgrass, and the high aggregation of materials in the background database EXIOBASE limits the ultimate conclusions of changing to timber construction. In extension, research should set up a more thorough concept of archetypes and material grouping for detailing the benefits and pitfalls. However, the assessment discloses the important aspects influencing a strategic change to wood-based construction, as presented in Table 5-1. It presents that the climate benefits of wood depend on several factors not usually accounted for in the attributional LCA at the building project scale.

Sensitivity Parameter	Average m^2 Conventional (baseline) RSP_{60} kg CO_2-eq/m^2/yr	Average m^2 Conventional (baseline) RSP_{100} kg CO_2-eq/m^2/yr	Average m^2 Change to wood RSP_{60} kg CO_2-eq/m^2/yr	Average m^2 Change to wood RSP_{100} kg CO_2-eq/m^2/yr
Cement from Denmark	7.66	5.58		
Cement from Germany	7.51	5.49		
Difference	*-0.15*	*-0.09*		
Steel from China	7.66	5.58	+0.81	+0.47
Steel from Germany	6.75	4.64	+1.19	+0.71
Difference	*-0.91*	*-0.94*	*+0.38*	*+0.24*
Rotation period 88 years	7.66	5.58	+0.81	+0.47
Rotation period, 98 years	7.72	5.63	+1.26	+0.90
Difference	*+0.06*	*+0.05*	*+0.45*	*+0.43*
Forestry model	7.66	5.58	+0.81	+0.47
No forestry model	7.57	5.47	-0.25	-0.49
Difference	*-0.09*	*-0.11*	*-1.06*	*-0.97*
Forestry model and iLUC	7.66	5.58	+0.81	+0.47
No forestry and no iLUC	7.53	5.43	-0.51	-0.76
Difference	*-0.13*	*-0.15*	*-1.30*	*-1.23*

Table 5-1 The sensitivity of climate impacts to CLCA and forest modelling aspects. The Average m^2 is the weighted m^2 across the three building typologies of single-family houses, multifamily houses and offices. RSP_{60}=60-year reference study period, RSP_{100}=100-year reference study period. From Publication 3 (Hansen, Eliassen, et al., 2024)

If the affected applier of steel shifts from China to Germany, the steel's climate impact decreases, which affects the two construction scenarios as it reduces the climate impact of conventional construction and increases the wood-based because the benefit of avoiding steel use is less notable. The rotation period in the forest model has an even larger influence on wood than the steel supplier. Thus, it is an important parameter to investigate more to ensure the most likely outcome of the forest model. Excluding the forest model considerably shifts the climate impact in favour of wood, and the same applies when excluding iLUC. The evidence of IPCC (2022) that land use, land use change, and forestry contribute 11% to the global climate impact, although with larger estimated uncertainties, advocates that an LCA should include it to enhance decision support.

In addition to the rotation period in the forest model, the identification of pulpwood as the avoided production from wood co-products significantly affects the climate impact of wood. It pertains because pulpwood was modelled with a 44-year rotation period, leading to larger carbon sequestration than timber wood, which results in a net climate impact of the substitution effect. Therefore, it is central to increase understanding of the forest model inputs of the pulpwood and consider whether other avoided production can likely occur from the wood co-products, e.g., substitution of other products or energy sources.

Assessing the impact of land use in Publication 4 of Denmark also emphasized the importance of considering system modelling, including how much is available and where, despite not being consequential as such. The reduced need for wood in the fast-growing biobased scenarios puts less pressure on the wood market for Denmark, and a long-term national strategy for increasing wood production could be more feasible.

The findings also discovered the availability of straw and grass for construction in Denmark. The former is a co-product but not fully utilised. However, the non-utilised quantities of straw and grass only meet the demand in some market penetration scenarios, which a building project scale assessment will not capture. The geographical origin of production remains important for the yield, i.e., the forest and agricultural management of the different biobased resources, as Publication 3 showed for wood.

To increase the robustness of Publication 4 it will be useful to expand the production stage assessment to a full LCA and consider more consequential aspects of substitution effects from co-products, iLUC and specific affected suppliers but also temporal aspects of biogenic carbon storage. However, the considerable reduction in direct land use impact of implementing fast-growing biobased resources will almost without doubt reduce the iLUC.

The findings in this section underline the significance of understanding relevant markets, the availability of wood and fast-growing biobased resources for increased demand, and the relevant forest management practices and interactions with other sectors. It specifically also applies to the Danish context as wood consumption is increasing in the construction and energy sectors (Brownell et al., 2023).

5.3. BIOMASS-RELATED CHARACTERISTICS AND LCA

The biomass-related aspects centre on the importance of the biogenic carbon approach, temporal aspects, and biomass cultivation management but also the trade-offs between impact categories of climate change, land use and biodiversity as Publication 3 presents. This biogenic carbon approach inherently interrelates with the allocation procedure and life cycle stages, which is why it is important for micro and macro scale decision support. For the macro scale, the temporal aspects and biomass cultivation management also have high importance for the decision support.

The temporal aspects in Publication 3 relate to buildings as carbon sinks, where longer temporal delays of biogenic carbon tilt the balance towards a sink instead of a source. It is the situation for wood used in years zero and fifteen. Beyond this, buildings are a biogenic carbon source in this dissertation (see Publication 3). The CLCA combined with temporal forest or biogenic carbon modelling also increases the climate impact in other CLCA studies compared to omitting the temporal biogenic carbon due to substitution effects (Hansen et al., 2022), although the avoided production differs between the studies.

In Publication 4, the land use impact also relates to temporal aspects since the rotation period of trees and crops resulted in different time paradigms of the needed land for resource supply during the period 2022-2050. The analysis did not comprise temporally modelling of the stored biogenic carbon by discounting, which could be one of the next steps since the shorter rotation time of fast-growing biobased resources might need less time to make buildings work as a sink compared to wood.

The attributional LCAs at the building project scale in Publication 2 do not consider temporal biogenic carbon aspects that influence the climate impact over the entire life cycle. However, it affects the impact arising from the individual life cycle stages of production and end of life. The -1/+1 approach used in these LCAs regards the supplying forests carbon neutral at the landscape level, i.e., sustainable forest management entailing that yearly fellings are not greater than the yearly growth increment, according to EN 16485 (2014).

The limitation of these LCAs is the exclusion of the impact categories land use (midpoint) or biodiversity (endpoint) in the LCAbyg tool, which Publication 3 highlights as inverse correlated with climate impact for the three studied building typologies. As the impact categories in this tool version adhere to EN 15804 (2012), it suggests including a land use impact category in the standard to uncover burden shifts if a greater focus on biobased materials materialises. Currently, the standard includes the resource indicator of the use of renewable primary energy total, which was found to increase in four wood dwellings compared to a concrete building in Hansen et al. (2023b). Still, it is not clearly perceptible to link it to land use.

When sourcing wood from sustainable forestry, the landscape-level approach risks that certified timber on occasions are fraudulent, less sustainable than non-certified timber, and might not reduce regional deforestation, as found by Norén et al (2016) and references therein. It applies to both forests in Europe and the Global South, so practitioners need to be aware of and check suppliers when purchasing certified wood. In addition, carbon neutrality at the landscape level concerns that it does not promote long-lived uses compared to short-lived uses, and that carbon flux neutrality does not result in climate neutrality (Cherubini et al., 2011).

A noteworthy reflection implies that the forest occupies land which cannot be used for food production. It shifts the use of agricultural production to other land (iLUC), which the landscape approach currently does not cover. The stem-level approach of forest modelling in Publication 3 is useful for alternative use scenarios of wood for short- and long-lived products and can be used within and across sectors. It provides insights into how biogenic carbon delay affects the cumulative climate impact through use in long-lived products.

5.4. LEARNINGS FOR EFFECTIVE LCA AS DECISION SUPPORT ON IMPLEMENTING BIOBASED MATERIALS IN BUILDINGS

The potential burden-shift of climate impacts to land use impacts and biodiversity is a significant observation for the building sector. Other studies support this finding (Kayo et al., 2019; Mishra et al., 2022; Mouton et al., 2023). Fast-growing biobased resources, as discovered in Publication 4, can help reduce the impact of wood buildings on land use. Despite room for advancements in the study, this finding suggests a promising strategy for reducing land use impacts, including those on iLUC and biodiversity. However, other factors like climate change, acidification, and ecotoxicity also impact biodiversity, e.g., the Damage to ecosystems in ReCiPe2016 impact assessment (Huijbregts et al., 2017).

Turning to the purposes and intended applications, the ALCA method in Publication 2 is useful for benchmarking and design optimization and configuration of buildings, i.e., answering how to implement wood and fast-growing biobased materials in buildings. It connects with the accounting context in the ILCD Handbook and resonates with the interpretive weighting of the ILCD Handbook in Publication 1 for building project scale LCA.

Nonetheless, based on the insights from the consequential LCA (Publication 3) and the system modelling (Publication 4), I will argue that the specific ALCA method in Publication 2 has limitations if used for more strategy-oriented intended applications of increased use of biobased resources. Strategy here connotes intended applications leading to repetitive conduct over time beyond a single building project, in principle, ranging from a micro scale decision made by an architectural studio to use more of a specific material like straw to a macro scale decision for policymaking of increasing the use of biobased materials. The limitations of using the ALCA for strategic applications pertain to the narrower system boundary applied to wood products governed by the current LCA standard. It involves that it allocates co-products without considering systemic interactions, market reactions, and availability, as well as omitting iLUC and forestry practices. Followingly, the generalisation of conclusions from the current standard of ALCA should be carefully and cautiously approached.

The limitations of the applied ALCA method principally impose the use of CLCA for strategy-focused intended applications or, at minimum, complement an ALCA. The energy sector more often uses CLCA for these applications (Luu et al., 2020). However, the scale of the decision context (micro or macro) may affect the benefits of balancing practicality and principality when considering the factors complicating the building product system mentioned in section 1.2.1.

Therefore, a pragmatic suggestion might be to use ALCA with system interactions for micro scale strategy decision support of biobased materials in the building sector. It involves analysing the availability of resources, whether they are co-products or not, and if they are fully utilized, using the principles of (Ekvall & Weidema, 2004). Additionally, iLUC assessment should be considered for biobased resources due to the notable impact of iLUC on global climate, although there is uncertainty in the estimates. Although iLUC is inherently consequential, a method was previously developed for use in ALCA (Jannick H. Schmidt et al., 2015).

The discussion above does not discuss how the biogenic carbon approach could apply. When disregarding co-product substitution effects, I would advocate that the forest modelling is useful for CLCA and the -1/+1 approach for ALCA at the building project scale, with or without the explained system interactions. Omitting forest modelling in the ALCA is a precautionary principle. This is because the dynamic assessment of biogenic carbon results in lower climate impact for wood buildings than the -1/+1 approach without modelling the effects of co-product substitution (C. E. Andersen et al., 2021). It potentially overestimates the climate benefits of wood by undue modelling of biogenic carbon in the LCA due to overlooking the biogenic carbon of co-products through allocation instead of substitution. It is an additional incautiousness to the already missing iLUC. To address this, the forest modelling or timing of biogenic carbon should be combined with co-product substitution effects, as in the CLCA, or the ALCA should incorporate substitution effects before applying forest modelling.

5.5. RESPONSIBILITY FOR ENVIRONMENTAL IMPACTS USING THE CONSEQUENTIAL AND ATTRIBUTIONAL APPROACH

Continuing the discussion about attributional and consequential LCA, I take it to a different topic, specifically, the taken environmental responsibility of using the two LCA approaches. It takes base in Ekvall (2020), to simplify that the environmental impact responsibility of the ALCA links to the direct value chain associated with the studied product system through physical flows and contractual obligations. The increase in EPDs to represent specific products and their production in the building sector makes this definition of ALCA responsibility relevant, inferring that EPD data are methodologically comparable and representative with little room for interpretation. It might not always be the situation in practice (Konradsen et al., 2023), but it is assumed in this discussion. Despite this, applying the attributional approach can be argued to be taking responsibility for the direct value chain's environmental impacts.

Conversely, the consequential approach assesses the affected value chain expected to respond to a change in demand induced by one or more buildings. One can term it a more indirect value chain, as it is used in this section. Indirect means that a change in demand induces changes in the economy with environmental impacts that are not necessarily directly linked to the studied product system's physical flows and contractual obligations. Applying the consequential approach encompasses taking responsibility for the environmental impacts of the indirect value chain due to market effects in the economy occurring from a change in demand.

Arguably, both approaches, hence responsibilities, are necessary because they address environmental impacts in two aspects of the economy: the direct value chain in the attributional approach, which is likely the constrained value chain, and the unconstrained affected indirect value chain in the consequential approach. A notable remark holds that the direct value chain can potentially also be the affected value chain in some cases. Only applying the consequential approach neglects the environmental burdens of the suppliers incapable of scaling their supply. On the other hand, only assessing the attributional impacts overlooks all emissions from the suppliers that scale up their production due to the increased demand that a building project induces.

Accordingly, the question of who should take what responsibility and in which situation logically arises. Ideally, the responsibility related to both value chains should materialise. Essentially, both the constrained and unconstrained value chains have environmental impacts and should be improved. First, it is suggested to consider whether the intended application is to benchmark or optimise and configure the design of a single building project or is a situation of decision support related to strategy. The strategic-related situation is anticipated to involve repetitive conduct, whereas the building project design is a unique situation that, in principle, will not occur again. The boundary between the two approaches' definition is certainly a wafer-thin line.

Overall, the consequential approach comes across as appropriate in strategic situations because it involves perpetual changes over a (bound) period. The attributional approach, i.e., direct value chain responsibility, appears suitable for the single building project. It is in a contingency where the data quality and management of material quantities in a general design process may have larger complications for the environmental impacts than extending the responsibility to the indirect (consequential) value chain. It does not entail that a building project avoids influencing the indirect value chain impacts but only holds that it disregards that responsibility.

Figure 5-2 conceptually suggests how the actors in the building sector should take the two types of responsibility and connect it to the scale of the decision context. It ties together with the discussion in Section 5.4, providing another perspective on the two LCA approaches, presuming that the LCA method and data have appropriate representativeness and completeness.

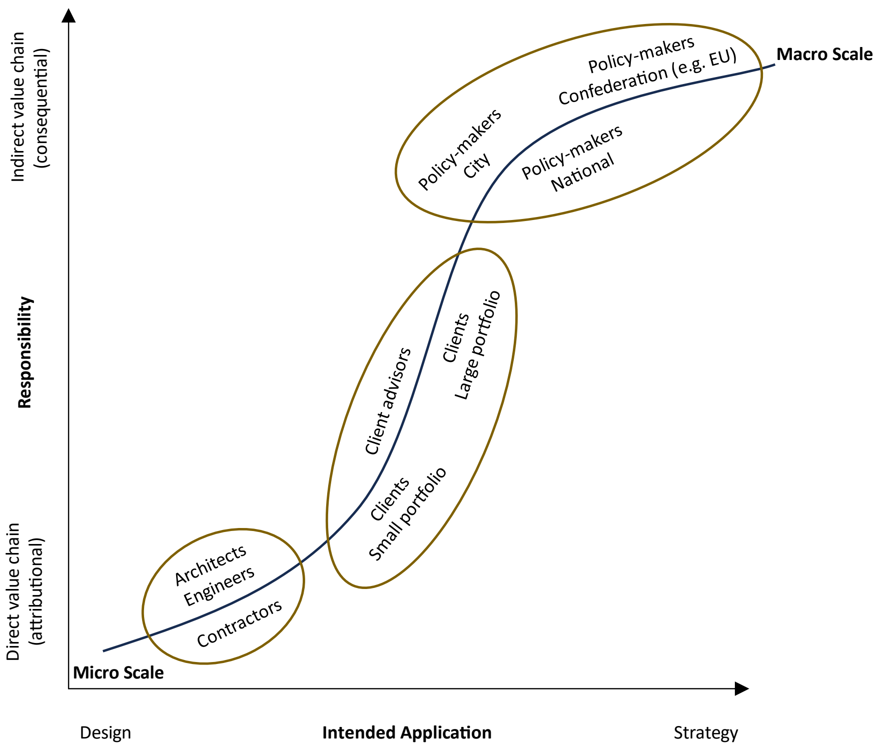

Figure 5-2 The responsibility suggested relevant for different actors associated with the building sector by connecting it to the intended application and the scale of the decision context. Micro can relate to the building project scale and macro to the building stock scale.

5.6. CONSUMPTION PERSPECTIVES OF ENVIRONMENTAL SUSTAINABILITY

Until this point, the dissertation reported outcomes and discussed implications of reducing relative environmental impacts when implementing wood and fast-growing biobased resources. In other words, it predominantly engaged with the supply side of the building sector system and less with the consumption side, as the environmental sustainability concept illustrates in Figure 5-3. The figure additionally shows that the deviation between an environmentally sustainable society and the current state of society is affected by both the supply and consumption side, including examples of leveraging factors. Environmentally improving the supply side, corresponding to efficiency improvements, without addressing consumption causes the improvements to be partially or fully counterbalanced by increased resource consumption. An effect known as the rebound effect and Jevons' paradox (Alcott, 2005, and references therein), the latter was already discovered in 1865 (Jevons, 1865).

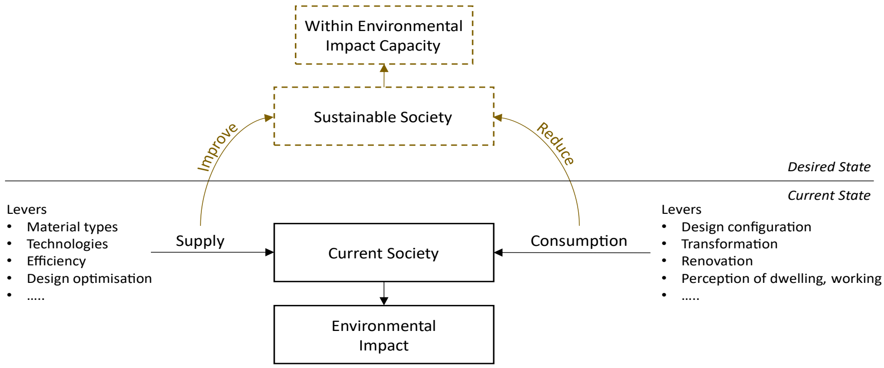

Figure 5-3 A simplified concept of environmental sustainability. Supply and consumption and their levers affect the deviation between the current and sustainable society.

To explain the rebound effect of efficiency gains on the supply side Alcott (2005) highlights the recognised *I=PAT* equation, impact *I* is a function of Population *P*, Affluence *A*, and Technology-factor *T*. Improvements of the technology factor is counterbalanced by population growth and increased affluence. Further, he emphasises that the right-side variables are interdependent. It entails that the efficiency gains of technology factor improvements affect the affluence and population, thus driving more consumption in a positive feedback loop with increasing environmental impacts. Alcott (2005) reviewed that the rebound effect is less than 1% to several hundred per cent. Undoubtedly, the transgression of six of the Planetary Boundaries supports this.

The operationalisation of the climate Planetary Boundary in Hansen et al. (2023a), through the absolute environmental sustainability assessment (AESA) concept, reveals that newly built wood dwellings in Denmark exceed their climate budget by 12.7 to 20.4. The climate budget of new dwellings emerged as 1.16 kg CO_2/m^2/year using the sufficiency distributive justice principle and compared to the project Reduction Roadmap yielding 0.4 kg CO_2/m^2/year, using the acquired rights principle. In the AESA concept, the budget distribution from global to national and to sector scale can be criticised as it involves deontological normative ethics for just distribution, and who is to decide what is fair?

However, the dwellings' excessive transgression of the climate budget, also supported by Andersen et al. (2020), suggests that even discussing fairness in AESA seems oblivious at the current building activity state. Therefore, reducing new building consumption appears viable and necessary in addition to supply side improvements. Essentially, reducing the annual newly built area will result in a larger budget per m^2 in the AESA because Hansen et al. (2023a) distribute the sector budget on the expected future areas based on the current construction patterns. To expand on the supply and consumption side, the next section synthesises LCA and environmental sustainability into the system thinking concept.

5.7. REFLECTIONS ON THE CONTRIBUTION TO SYSTEM LEVERAGE AND PERSPECTIVES ON INTERVENTIONS

A deeper understanding of the underlying mechanisms in a system to increase system change is lacking in sustainability science (Abson et al., 2017). To elevate the environmental sustainability transformation in the building sector, based on the empirical knowledge provided by this dissertation, it is imperative to understand and relate the findings to the systems with which it inevitably interacts (Fischer & Riechers, 2019). In that way, the dissertation engages with and contributes to the conversation on using environmental assessment by LCA in decision support using established sustainability science theory, specifically by comprehending which levers can be activated to increase system change.

I employ the 12 leverage points developed by Meadows (1999) as the guiding heuristic method. Briefly, she presents 12 points on how to intervene in a system, where 12 leads to the least leverage and 1 the greatest transformative change. The greater the leverage point, the more the inertia in the system against the intervention increases and vice versa. Consequently, addressing and intervening in the low leverage points is easier than the higher ones. Abson et al. (2017) grouped the leverage points into four system characteristics, as replicated below:

(i) System Intent (deep)
1. The power to transcend paradigms
2. The mindset/paradigm out of which the system arises
3. The goals of the system

(ii) System Design (deep)
4. The power to add, change or self-organise system structure
5. The rules of the system (e.g., incentives and constraints)
6. The structure of information flows (access to information)

(iii) System Feedbacks (shallow)
7. The gain around driving positive feedback loops

8. The strength of negative feedback loops
9. The length of delays, relative to the rate of system change

(iv) <u>System Parameters (shallow)</u>

10. The structure of material stocks and flows
11. The size of buffers and stocks, relative to their flows
12. Parameters (e.g., subsidies, taxes, standards)

The first two characterisations were termed deep leverage, and the last two were termed shallow leverage (ibid). Further, the leverage points are interchangeable with nearby points depending on the system and the considered interventions.

This section discusses how we can bring this dissertation's findings to different leverage points to increase systemic change and how other levers can support transformation. The discussion will first discuss general options for intervention, then it treats transformation at two system levels: the building design and the building sector. This is an attempt to make it more relevant practice and policymaking. First, I address the interventions and leverage points with common denominators for both system levels. Then, leverage points specific to each of the two system levels follows.

I begin with the common parameter in Publications 2-4 of impact per m^2 per year and denote it as impact intensity (point 12). It makes buildings comparable by working as a reference flow, and applicable as a limit value. If the building sector and its actors simply aim to material optimise against this parameter, the system leverage remains at the lowest point. If we do not attempt to understand and change the material use and building design more in-depth and refrain from addressing how to reduce the number of built square meters, we may only do slightly better than previously at best. It implies that the rebound effect can partially or fully halt the relative improvements. Impact intensity or a limit value might be a good starting point. Measuring material optimisation for small and medium enterprises, such as a five-person architectural studio with limited financial resources and sustainability knowledge, can turn out important, although it will still only have shallow leverage.

The impact intensity can increase leverage by using the insights of Publication 2 of applying a footing foundation and using biobased insulation instead of mineral based. Hence, it changes the structure of new buildings' material stocks (point 10). Adding the knowledge that wood reduces climate impact if it efficiently substitutes cement-based materials and metals (Publication 3), the leverage seems to advance to point nine. It is because it reduces system change rate of GHG emissions, which has lengthy delays of impact on climate change. Here, the increase in wood consumption should stay within the increment growth capacity of current forest stocks. It is the case because the unchangeable slow growth rate of forests entails delayed response to increased use of wood.

Further, the impact on land use and nature occupation increases with the use of wood compared to conventional materials (Publication 3). Building less is one lever to slow down the change rate of wood and reduce the impact on land use. Equally interesting, Publication 4 revealed that implementing fast-growing biobased materials as a substitute for non-loadbearing wood products can reduce wood consumption and the impact on land use. It slows down the change rate of wood and brings the leverage to a combination of points eight and seven. Limiting the square meter consumption and implementing fast-growing biobased materials support keeping the forest stock closer to its goal (point 8) by slowing demand, thus slowing the land use impact (point 7), yielding potential positive effects for biodiversity, and reducing the risk of forest degradation over time.

Now follows the discussion of the two system level considerations: The building design and building sector. The first supports designers with insights into building design system change, with the premise that a building has already decided to be built. The building sector system supports all the industry’s actors by insights of system change ranging from designers to policymakers. Though most relevant for more influential decision makers such as clients with larger portfolios and policymakers.

5.7.1. THE BUILDING DESIGN AS THE SYSTEM

Contingent transformative use of biogenic resources in a building design system congregates to using wood to efficiently replace structural metals and concrete. It also comprises implementing only fast-growing biobased materials for insulation and non-loadbearing products to reduce climate and land use impact. It raises the system leverage to the feedback level because it slows down climate and land use impact. Providing information for designers on how to use these products effectively, both generally and in product technical descriptions, increases information flow and access, potentially elevating the leverage of building design to point six.

To reach point four of self-reorganising the individual building design system, the resource-wise use of materials and building element types needs additional analysis of how to reduce square meter consumption. It can comprise providing the desired function(s) of buildings with the least possible area. The designer may obtain this through multifunctional rooms or sharing some parts of living or office spaces. Using reclaimed wood from other buildings and designing for deconstruction might further add to the buildings' ability to meet future demanded functions.

5.7.2. THE BUILDING SECTOR AS THE SYSTEM

When considering the building design as a system itself, interventions that appear as relatively deep leverages may not necessarily have the same transformative change when considering the building sector as a system. Returning to the limit value, this parameter can drive larger system change as a negative feedback loop at point 8 instead of point 12. It requires the building sector to establish an impact tax for internalising environmental impacts based on the impact intensity, e.g., CO_2-eq tax. The tax should be ambitious enough relative to the impact of current buildings to drive structural change, e.g., other considerations on housing in Section 82. Otherwise, leverage remains at point 12, the likely situation with the current Danish limit value.

Publication 2 showed the two lowest impacting cases emit about 3.5 kg CO_2/m^2/year. Hansen et al. (2023a) revealed that the climate impact targets of new Danish dwellings should be between 0.4-1.16 kg CO_2/m^2/year relative to the Planetary Boundary. It yields a target range for a limit value to aim at. If the building sector constructs less new area per year, then the impact per m^2 could be slightly larger. An ambitious climate tax could be a mitigating solution, but it will most likely meet high industry resistance. Starting with a reasonable climate tax and progressively increasing it would be beneficial to prepare the sector to adjust while easing resistance.

While an impact tax can shape behaviour, strong purchasing power may partially overcome it. Adding a gradually restrictive rule (point 5) on the number of newly built areas per year in the planning law and specifying rules for various building typologies move transformation into the deep leverage points. A systemic change that balances between system rules and self-organisation (points 5 and 4) would be a political regulation of not using more wood or fast-growing biobased materials than the annual production, for example, in Europe. Meanwhile, this rule does not cover the indirect land use change occurring between sectors. It compels a cross-sectorial re-organisation of the agricultural sector to a more plant-based production to free up land to increase resources for biogenic material supply to the building sector.

Stepping into even deeper transformation comprises the building sector's goals and mindset paradigms. For instance, environmental goals determine building design instead of construction, operational, and investment profits, where profits work as a means to stay in the market. Intending sufficiency-thinking to enter all decisions in the building sector could work as another goal or mindset change. Thereby, we only built what is necessary for people to have a decent life. In a similar arena, more radical paradigms involve post-growth principles involving rethinking well-being in the way that economic growth and expansion only provide well-being to a certain system state. After that, the steady state system promotes well-being in the direction of relational and care-based principles, a similar arena of sufficiency.

5.7.3. SUMMATIONS OF THE SYSTEM LEVERAGE POINTS AND INTERVENTIONS

It becomes clear that the greater the leverage points, the less it involves the findings from the LCAs. The LCAs relate the material use and building designs to environmental impacts (causality) to outline environmentally resource-wise integration of wood and fast-growing biobased materials, i.e., shallow leverage points.

The deep leverage points mostly concern the teleological end goals and purposes of a system, here the building design and building sector (Fischer & Riechers, 2019). The leverage points of a system's intent can shape the building sector's environmentally sustainable 'desired' purpose. In contrast, the environmentally resource-wise means to get there is the domain of LCA. Hence, the leverage points bridge causality and normativity, which often appear as contradictory perspectives, but both are certainly important in understanding and changing systems, as Fisher and Riechers (2019) advocate.

5.8. SUMMARY OF DISCUSSION

Accurately predicting material quantities and their GWP impact in the early design stages at the building project scale is important for biobased materials, insulations, and metals. The latter needs inclusion to avoid underestimating the total impacts by 0.5-1 kg CO_2-eq/m^2/year. However, the choice of specific products and their unit process or EPD can also substantially affect the predicted impact. Exploring new design solutions and passive strategies might help reduce the impact of cement-based materials and technical installations of metals.

In assessing a larger scale change from conventional to timber construction, the systemic effects related to wood residues, affected steel suppliers and iLUC appear important. The same emerges for the rotation period in the forest management modelling. It comprehends that immoderate use of wood is not a strategy, thus requiring effective use, implying efficiently displacing the carbon-intensive steel and concrete materials to be climate beneficial. Wood generally increases biodiversity impacts compared to conventional construction, but substituting parts with fast-growing biobased materials remarkably mitigates the land use impact and likely the biodiversity. The crop supply is also greater than wood within Denmark, bringing more political control over optimally using the national land and its resources.

The dissertation showed an inherent relationship between the biogenic carbon approach and the allocation procedure regarding wood's climate impact. CLCA's substitution, stem-level forest modelling and GHG discounting lead to larger climate impacts in the production stage. The -1/+1 landscape approach shows negative impacts in the production stage and reflects carbon neutrality for wood sourced from sustainable forests. However, the landscape level does not consider trade-offs among long- and short-lived wood products or the impact of increased demand for land. Meanwhile, it might be a useful pragmatic simplification for building design configurations and optimisations.

For strategic decision support of a repetitive nature, ALCA with system considerations, like substitution effects, is applicable for the micro scale context. In contrast, CLCA and forest modelling are suggested for the macro scale. Including iLUC and impact categories of land use and/or biodiversity is recommended for all strategic decisions. The attributional approach was also discussed regarding the responsibility taken for the direct value chain's environmental impact, while it is the affected (indirect) value chain for the consequential approach. These responsibilities seem suitable to follow the decision context suggestions above.

Currently, environmental sustainability mainly addresses supply side improvements. Still, the partial or full offsetting of the efficiency gains by rebound effects found in other research emphasises the need to consider the consumption side of society. The transgression of six PBs and the exceedance of climate budgets for Danish wood dwellings by a factor of 12.7 to 20.4 uncovered in the dissertation evidently supports it. Hence, reducing new building consumption as a complementary solution to supply side levers is imperative. In this context, understanding the role of LCA in elevating system leverage is crucial for improved environmental sustainability of the building design and sector. The system leverage point framework can usefully connect environmental effects derived by LCA and deontological paradigms of the larger system. For example, the material-wise building design or land use reducing governance for increased biobased building products uncovered by LCA while also addressing the purpose and goals of the sector.

CHAPTER 6. CONCLUSIONS

The following section responds to the four sub-research questions and the main research question. The main research question attempts to compile the findings from the sub-research questions.

6.1. RESEARCH QUESTION ANSWERS

SRQ1: Which modelling methods and focuses are applied in consequential LCA related to buildings?

A systematic literature review (SLR) explored the current state-of-the-art using consequential LCA (CLCA) on buildings. The review focused on 37 articles, almost evenly divided between assessing methodological and empirical aspects. The 13 empirical studies at the micro scale primarily assessed the circularity of materials and a shift towards timber construction for whole buildings. The 15 macro scale empirical studies had a wider palette of focuses. It primarily encompassed circularity, increased use of wood, and changes in building energy supply; however, it also included material production improvements of constituent substitution or energy source.

The framework of modelling the consequential inventory involves the steps of assessing the products' market, market trends, and affected suppliers. The SLR shoed that methods range from simple to sophisticated modelling. Notable approaches in the studies included literature references, Ecoinvent, iterative procedures, linear regression analysis of production data, and economic models. The degree of consequential modelling generally decreased when biogenic carbon modelling increased in wood-dedicated studies and vice versa.

Nonetheless, the lack of harmonisation in modelling may not be a significant challenge in the building CLCAs as long as they arenot used for benchmarking. The CLCAs were in the studies often found with purposes of changing a consudt which grapples with predicting future environmental consequences of a change. This forward-looking aspect is inherently uncertain. It entails that scenarios or sensitivity analysis are more important to incorporate in building CLCA than harmonisation in modelling. In addition, conforming to the CLCA framework and transparently documenting adherence are crucial because they are lacking in several reviewed articles. While consistent inventory modelling is preferable for consistency, relevant literature can cover certain steps in the framework if recent studies exist for the geographical context.

SRQ2: In what ways do LCA and building design aspects influence the environmental impacts of wood buildings in the early and detailed design stages?

Ten Danish detailed design wooden dwellings were assessed using the standard LCA approach EN 15978, using the biogenic carbon -1/+1 approach, and then modelled with a simplified design tool representing the early design. Results showed that the early design stage underestimated the average impact from GWP by 12%. The largest fluctuations came from the production (A1-A3) and end-of-life (C3-C4) stages, which were also the stages that contrubted most to the buildings' climate impact. Buildings with high biogenic carbon content showed largest inaccuracy of predicted GWP impact in these life cycle stages. Therefore, LCA practitioners should be cautious about communicating the predicted GWP impact in the production and end-of-life stages. However, it had a minor effect on the total impact prediction, which practitioners can communicate instead.

The foundations, walls, and floors had the biggest impact in both design stages. The first two elements were well-estimated, while the accuracy of floor predictions needs improvement in future simplified design tools for decision support. Biobased materials, insulations, and metals are highly responsive to small deviations in quantity predictions. Metals were often underestimated, resulting in a reduced total impact of 0.5-1 kg CO_2-eq/m^2/year for most cases. Hence, early design tools should include default values for metals. Besides material quantities, the choice of building products and their EPDs also significantly affect climate impact in the early and detailed design.

A valuable practical outcome is that footing or piled foundations materialise to mitigate the climate impact of wood dwellings. Resultingly, they should be preferred where soil conditions allow this sort of foundation. Building terraced houses without vertical residence separations moderates the acoustic requirements in floors and lessens their climate impact. Additionally, paper wool revealed impact-reducing properties for insulation, making biobased insulation worth further investigation.

SRQ3: How can consequential LCA and biomass-related modelling affect the environmental impact of a change to wood-based construction?

To address this question, a consequential LCA (CLCA) was conducted for a change from conventional to wood-based construction for the Danish building stock towards 2050. It included forest modelling at the stem level, dynamic GHG assessment and iLUC. It showed that wood is climate-beneficial for multi-family houses but not for single-family houses and office buildings. The substitution of wood residues for pulpwood combined with forest modelling negatively affected timber's GWP impact. This is due to the shorter rotation period of pulpwood, which has a greater carbon storage effect that is avoided when displaced by the wood residues. Further, iLUC and the forest model's rotation period notably influence the wood-based scenario's GWP impact.

For building design and practice, the study conveys that wood mainly works as a climate mitigating material when substituting concrete and steel efficiently. In this context, the applied case buildings and material grouping are key in such assessments. Steel and wood contributed similarly to the timber offices' GWP score. It means the case studies are either not representative or that timber design must considerably reduce steel use. Likewise, the single-family houses contained a notable quantity of biogenic materials like eel grass and sedum roofs, simplified as wood. Therefore, assessing more buildings is needed to clarify this outcome. A significant finding was that transitioning to wood construction increased the impact on nature occupation, i.e., biodiversity, for all buildings, regardless of their GWP impact trend. This environmental trade-off led to the development and investigation of SRQ4.

SRQ4: What is the effect on land use impact and carbon storage of implementing materials of fast-growing biobased resources in wood buildings?

Three wooden building typologies were compared to developed case studies where fast-growing biobased materials of straw, hemp, and grass substituted insulation and non-loadbearing wood products. Using four market penetration scenarios, the buildings were scaled to the Danish forecasted expected construction activity towards 2050. The study concentrated the analyses on the production stage (A1-A3) and the relative difference between the biobased materials. The assessment of biogenic carbon storage showed significant reductions in land needed per stored quantity: 78-90% for single-family houses, 68-76% for multifamily houses, and 19-27% for offices. Straw materials resulted in the largest decrease.

Another compelling finding is the significant decrease in the need for forest land, ranging from 50% to 61%, depending on the scenario and the fast-growing resource. However, the Danish wood supply cannot meet the demand fully in any scenario, necessitating imports. The advantage for Denmark lies in its national supply of straw available for construction, which can nearly cover a 50% market penetration. In a combined scenario with straw and grass, Danish land can supply all the demand even at a 100% market penetration rate. Those scenarios reduce the need for land by 55-60% and 49-53%, respectively. Since Denmark does not cultivate hemp, the use relies on imports. Nonetheless, its short rotation makes farming easily initiated. The fast-growing biobased materials can benefit Denmark by bringing the resources within national control. Through optimal land governance, this can lead to environmental and economic synergies between the agricultural and building sectors.

MRQ: How can the attributional and consequential LCA approaches and the assessed impact categories advance the understanding of an effective LCA for implementing wood and fast-growing biobased resources in the building sector?

This dissertation considers the more effective LCA for environmental mitigating implementation of wood and biobased materials through two interrelated perspectives. It encompasses the intended application with building design and strategy on either side and the decision context scale of building project scale (micro) and building stock scale (macro).

The attributional LCA (ALCA) version adhering to the EN 15978 standard was found relevant for building design optimisation and configuration. It applies because of the detailed information that unit processes and, essentially, EPDs deliver. Ideally, it pushes material producers to reduce impacts and make building designers and clients abandon high-impacting products, which should elevate system leverage in the long term. Further, the decision support on environmental impact in the early design faces uncertainty of material quantification, requesting the operational benefit of ALCA.

ALCA should effectively help mitigate GWP impacts when used for benchmarking and decisions on limit values that are ambitious enough to force architects and engineers to consider buildings in new uses and designs. Therefore, using the carbon neutral -1/+1 biogenic carbon approach for wood sourced from sustainable forestry is a useful simplification, as it discloses biogenic carbon flows. However, it is critical to convey that these ALCA types should preferably not be used for generalise claims that wood buildings are superior or inferior to other constructions. The core reason for this suggestion affiliates with the confined system modelling and simplified representation of biogenic carbon and cultivation. Also, these ALCAs should include more biobased-related impact categories such as land use and biodiversity. Therefore, these ALCAs intended application should focus on the implementation of wood and biobased materials in buildings.

Decision support on transitioning to timber construction instead of more conventional construction requires examining system interactions in the economy and considering an expanded system boundary of biogenic aspects, i.e., biogenic carbon fluxes, cultivation management, and relevant impact categories. It advances the environmental assessment but could increase the uncertainty and outcome spectrum. However, it should also be closer to reflecting the real-world complexities. Regardless, this dissertation showed that consequential LCA (CLCA) and forest modelling explicitise that wood is not indispensably the key solution for environmental mitigation if not implemented effectively. The increased biodiversity for shifting to timber buildings emphasises that expanding impact categories for biobased products remains imperative, specifically when associated with transgressed Planetary Boundaries.

This CLCA study on the *transition to timber* involves a strategic intended application because its decision will principally support repetitive conduct. The other approach to decision support for strategy was a system LCA, primarily attributional. Compared to the standard ALCA for building design, the system aspect corresponds to considering the geographical availability of resources for different market demands. In addition, the rotation of trees and crops was also distinguished. The straw analysis emerges as a consequential aspect by assessing whether it is a fully utilised co-product. In this case, the demand for cereals determines the supply of straw. Despite the system LCA not being either a full LCA or a complete consequential, it yields insights useful for strategic decision support. Ideally, the dissertation recommended applying a systemic approach to decision support for strategy regarding biobased materials, including relevant biogenic modelling for the building project scale and building stock scale. An ALCA with system considerations might be useful for the micro scale, whereas the macro scale should use or at least complement it with a CLCA.

6.2. FUTURE RESEARCH

It is imperative to increase the adoption of LCA for early design decision support for wood dwellings by providing tools for small and medium-sized architectural and engineering enterprises. Fundamentally, it is because they may often design residential buildings before a BIM model is even developed. Based on the simplified design tool assessed in this dissertation, this and future tools should develop default values for metal products per m^2 involving assembly fasteners and technical installations. Also, as for metals, partition walls and wet room products must be included so as not to underestimate the total impact, which a default value could improve. Further, biobased insulations should investigate whether they can help reduce insulations' impact responsiveness to quantity deviations between the early and detailed design impacts instead of the predominantly used mineral insulation in the case studies.

The studied simplified design tool included a few building elements challenging the current Danish building code, particularly regarding fire safety surface requirements. The elements emerged to reduce climate impacts compared to the detailed design stage equivalents, an aspect that future research should investigate more systematically. Similarly, using a sand honeycomb solution instead of concrete for acoustic purposes in floor separations unfolded promisingly but requires more consistent examination before making generalised conclusions. In conclusion, the LCA tools need to implement a land use impact category for a more holistic environmental assessment of implementing wood in buildings for practitioners.

The decision to transition to wood and fast-growing biobased materials, and for which buildings, requires future research and assessment of more case studies because the number of buildings in this dissertation was small. It should involve case studies representative of the current construction practice, a business-as-usual study, and a best-practice assessment for the effective pathway of increasing biobased material use.

In addition to building related future research, LCA and biobased related future research are inevitably critical. Progressing the study on change to timber buildings involves expanding scenarios of co-product substitution effects and of which and how many included affected suppliers. In extension, it implicates to specify the categorisation of wood products and their tree species, including disaggregating their unit processes or sectors in the background database. Forests supplying these wood products necessitate a more profound examination of the management used as inputs in the forest modelling, notably for the correct rotation period. After addressing the action points topics, assessing the effect of using different forest models and the influence of climate impact on forest management strategies and output would be useful for detailing the sensitivity to these aspects.

The future progress of the fast-growing biobased material assessment should undergo a full LCA and consequential modelling. In addition, it should incorporate biogenic carbon storage potential in relation to cultivation, rotation period and timing of emissions, likely involving discounting of GHG emissions.

The wood and fast-growing biobased materials should also be assessed for renovation and transformation to comprehend the potential for such applications. Future research should also investigate how effective implementation of biobased construction performs in an absolute environmental sustainability assessment. It entails including more impact categories than climate change and provides a valuable contribution to addressing the consumption side of the building sector. So far, the suggestions for future research focus on the building sector, however, biobased resources require land, a resource that reaches across sectors. Therefore, from an ambitious political perspective, a future research recommendation involves assessing policy instruments of cross-sectoral synergetic land use at the national and even confederation levels, e.g., the EU.

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APPENDICES

Appendix A. Publication 1

Publication 1: **A systematic review of consequential LCA on buildings: the perspectives and challenges of application and inventory modelling.** *Hansen, R. N.; Rasmussen, F. N., Ryberg, M., Birgisdóttir, H*. First Published In: The International Journal of Life Cycle Assessment 28, 131-145, 2023. Reproduced with the permission from Springer Nature. DOI: https://doi.org/10.1007/s11367-022-02126-w

The International Journal of Life Cycle Assessment (2023) 28:131–145
https://doi.org/10.1007/s11367-022-02126-w

BUILDING COMPONENTS AND BUILDINGS

A systematic review of consequential LCA on buildings: the perspectives and challenges of applications and inventory modelling

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Received: 10 June 2022 / Accepted: 6 December 2022 / Published online: 15 December 2022

Abstract

Purpose The built environment has demonstrated the limited nature of applications of consequential LCA (LCA), whereas attributional LCA (ALCA) is applied in most situations. Therefore, this study aims to clarify the contexts in which CLCA might be applied and the state of CLCA on buildings by examining the following research questions: (i) How are the goal, scope and methodological aspects and associated gaps of CLCA of buildings addressed in the literature? (ii) How can these insights guide the applications of CLCA on buildings?

Methods The study employed the Systematic Literature Review methodology, which yielded 37 relevant studies. The study examined the sample regarding intended applications, the contexts of micro or meso/macro decision-making support, and the consequential life-cycle inventory modelling (CLCI) of time horizons, market delimitations, market volume trends, affected suppliers, constrained supplies and substitution. Furthermore, the basis for choosing either an ALCA or a CLCA approach was evaluated based on the ILCD Handbook.

Results and discussion Many studies include an empirical assessment, yet with half of those combining it with an evaluation of selected methodological aspects, thus CLCA on buildings seems to still be in the earlier exploration phase. In general, the empirical CLCAs emphasize the decision-making aspect in the stated application of the study. Furthermore, CLCA studies show an almost equal distribution of focus between the micro and meso/macro levels of decision support. This entails that CLCA on buildings currently applies to both material- and building-level assessments and policy situations. The inclusion of CLCI modelling elements varies: e.g., nine studies only include substitution as the single CLCI element. Additionally, modelling methods are described at various levels of detail, and with critical differences in the transparency of documentation. This, therefore, suggests that the consistency of included CLCI elements is inadequate, as is how they should be modelled.

Conclusions and recommendations Building on the ILCD Handbook, this study presents a proposal for deciding when to select CLCA on buildings. This is a proposal for a simple and clear distinction threshold between the micro and meso/macro levels. Additionally, CLCA on buildings need a more harmonized approach to CLCI modelling to increase and improve, which the built environment community could achieve by settling on a standard for the inclusion of CLCI elements and associated modelling methods.

Keywords Consequential LCA · Consequential modelling · Decision support · Building · Built environment · Construction sector · Review

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1 Introduction

Buildings contribute extensively to global energy use, resource consumption and greenhouse gas (GHG) emissions causing global warming (United Nations Environment Programme 2021). Therefore, mitigation of GHG emissions has been a crucial focus in the broad ratification of the Paris Agreement, whose goal is to stay well below a temperature increase of 2° Celsius and preferably under 1.5° Celsius (United Nations 2015).

This goal stimulated the development of EU policies regarding the decarbonization of buildings. More recently, the Green Deal launched its goals towards 2050, and legislation on particularly energy use and renovation strategies has attracted notice (EU 2010; EED 2012; European Commission 2020). The major challenge of decarbonization of buildings has created a shift to targeting the embodied carbon of buildings as well because the reduction in embodied emissions is lacking behind the improvements for emission reductions in the operational phase (Hoxha et al. 2017; Röck et al. 2020). Furthermore, Denmark, the Netherlands and France have introduced requirements of national GHG emissions regulation for buildings in a life-cycle perspective, with more legislative initiatives in preparation internationally (Toth et al. 2021).

Often, assessments of environmental impacts and resource use associated with buildings include a life-cycle assessment (LCA). LCA quantifies the exchanges with the environments from raw material extraction and production to operations and end of life, and allows for identifying the impacts and burden-shifting between stages of the life-cycle (Finnveden et al. 2009). LCA has its own international standards (ISO 14040 and 14044), and a more detailed consensus guideline in the ILCD Handbook (JRC-IEA 2010). Additionally, there are specific standards for the application area of buildings (EN 15978 and EN 15804),

LCA has two overall approaches: attributional LCA (ALCA) and consequential LCA (CLCA), according to the ILCD Handbook (2010). They are often associated with the ability to answer different questions. Hence, the defined purpose and related questions determine the appropriate approach (Gustavsson et al. 2015). ALCA can answer questions related to a supply chain's optimisation potential or evaluate a specified system's impact. CLCA can answer questions regarding the impacts of imposing a change on a system or the effect of increasing the demand for a certain product or service.

Building LCAs mostly apply the attributional approach (Khasreen et al. 2009; Buyle et al. 2013; Anand and Amor 2017; Nwodo and Anumba 2019; Sauer and Calmon 2020; Fauzi et al. 2021), thus leaving application of building CLCA in its fairly early stages (Buyle et al. 2013; Röck et al. 2020; Saade et al. 2020). Consequently, attributional-based conclusions shape most environmental and climate policy decisions on buildings. The ALCA-based decision-making might overlook aspects identified by the consequential approach since the latter considers the processes in the system that are affected by a change induced in the economy. The attributional approach generally does not include these indirect dynamics. A study of a Belgian dwelling found that the impact from water during the use phase was 57% higher for CLCA than for ALCA because the unconstrained treatment technologies (modelled in CLCA) had a higher impact than the average market treatment technology (modelled in ALCA) (Buyle et al. 2018a). Also, it is debated whether CLCA can better inform certain policy decisions regarding GHG mitigation (Brandão et al. 2014; Plevin et al. 2014). Therefore, the CLCA of buildings needs more attention if it is to have a role in and provide perspectives for the sustainable transition of buildings.

1.1 LCA and consequential framework

This section explains ALCA and CLCA as described in the ILCD Handbook (2010), including acknowledgement of internal incoherencies, and a description of the frequently applied methodological framework for CLCA.

The ILCD Handbook (2010) describes ALCA as an "actual or forecasted specific or average supply-chain plus its use and end-of-life value chain", and CLCA as a "generic supply-chain as it is theoretically expected in consequence of the analysed decision". The chapters on the definition of goals and scope in the ILCD Handbook show when to apply which LCA approach. This is termed the decision context, which distinguishes whether the LCA will be used as support in decision-making or not. When the goal and scope of an LCA involve decision-making support, either Situation A (micro level) or Situation B (meso/macro level) is concerned, otherwise Situation C (accounting) is involved, according to Chapter 5, 'Goal definition', in the ILCD Handbook. The first two decision-making contexts or situations lean conceptually more towards CLCA with statements such as "the extent of changes that the decision implies in the background system and other systems and that are caused via market mechanisms". Moreover, "whether a decision is to be supported implies whether the study is interested in the potential consequences of this decision". The consequential direction follows for micro level studies i.e., "cases with only small-scale, non-structural consequences in the background system", and for meso/macro level studies "cases that have large-scale, structural effects".

When the ILCD Handbook advises on life-cycle inventory (LCI) in Chapter 6.5, it depicts attributional modelling as appropriate for micro level and accounting studies. However, the same applies to meso/macro level studies, with the modification that "processes that have been identified as being affected by 'big' large-scale changes as consequence of the analysed decision shall be modelled as the market mix of the long-term marginal processes". This implies some consequential LCI (CLCI) modelling. Overall, this evokes some ambiguity between the goal and scope chapters and the chapter on LCI modelling, also concluded by Ekvall et al. (2016). This article interprets Situations A and B as consequential because the ILCD Handbook leans towards consequential descriptions of these. Therefore, the goal and scope determine when it is a CLCA, while the scale (Situation A or B) influences the CLCI modelling. The remaining part of the CLCA approach is analysed against the framework of Weidema et al. (2009) due to the incoherence between goal and scope and the relevant LCI modelling in the ILCD Handbook.

The CLCA framework has evolved since the early 1990s (Weidema 1993, 2003; Weidema et al. 1999, 2009; Ekvall and Weidema 2004), complemented by, for instance, theories of multifunctionality and system expansion (Ekvall 2000;

Weidema 2001). The CLCA framework encompasses the market mechanisms of effects due to changes in demand, all other demands remaining constant, i.e., the ceteris paribus assumption (Zamagni et al. 2012). Despite the framework, CLCA lacks a harmonized CLCI modelling method both in general (Earles and Halog 2011; Zamagni et al. 2012) and for buildings (Almeida et al. 2020).

A few reviews exist on the application of CLCA in general, although none about the specific application area of construction. Zamagni et al. (2012) conduct a goal and scope review of general CLCA and of when to use CLCA, although a detailed analysis of CLCI modelling was beyond the scope of the study. Earles and Halog (2011) and Almeida et al. (2020) review economic models used in CLCI both in general and for buildings but refrain from studying all aspects of the CLCI according to the stepwise procedures (Weidema 2003; Weidema et al. 2009) and the goal and scope aspects of the reviewed studies. Therefore, knowledge is needed about where building CLCAs currently stand in the focus between developments in CLCI modelling development, method analysis and empirical studies, as well as the level of decision-making support they inform. This is followed by understanding the coverage and disclosure of CLCI aspects to grasp where harmonization is needed.

This study therefore aims at combined coverage of the goals and scope of CLCA on buildings and applied CLCI aspects in relation to the four-step procedure of Weidema et al. (2009) by conducting a systematic literature review. These insights will aid awareness of where the focus of building CLCAs lies between analytical and empirical studies, and the focus and level of decision support alongside the comprehensiveness of CLCI modelling. This should ultimately lead to holistic recommendations for CLCA practice in the built environment. Thus, this study investigates the following research questions:

- How is CLCA on buildings addressed in the literature, in terms of the goal, scope and methodological aspects?
- What are the prevailing gaps in CLCA approaches and methodology used for environmental assessments of buildings on the micro and meso/macro levels as defined by the ILCD Handbook?
- How can these insights guide the application of CLCA on buildings to increase implementation where it is appropriate?

2 Methodology

The methodology describes the systematic literature review process and the execution of data and information extraction from the identified studies based on the ILCD Handbook and Weidema et al. (2009).

2.1 Systematic collection of literature

This study used a systematic literature review to obtain a comprehensive collection of the relevant literature. The review followed the structure of a search protocol and a stepwise systematic approach to achieve transparency and documentation based on the systematic research ontology provided by de Almeida Biolchini et al. (2007). This approach to the literature review will cover most of the studies relevant for mapping and analysing CLCA studies on buildings.

We formed a search protocol of the relevant keywords and their synonyms to aid in searches in the chosen search databases. Keywords encompassed four main subjects associated with the research questions and were separated into four blocks: consequences, environmental assessment, approach, and building-related (see Table 1 in the Supplementary information). The inclusion criteria for studies were a publication date from January 2000 to 14th September 2021, both months included. We considered all English-language journal articles and conference articles, as well as grey literature in Danish, Swedish and Norwegian due to the authors' ability to read these languages. Two criteria were used as a filter in evaluating the literature, both having to be satisfied to ensure we collected the desired articles.

1. The study must include a consequential LCA case study of a building, a building component or a building material that is defined as consequential in the article itself.
2. The study must provide sufficient information on applied methodological choices e.g., inventory modelling, multifunctionality handling and studied consequences.

Table 1 Characterization of decision contexts for the grouping of empirical studies. Adapted from the ILCD Handbook

Decision context	*Criteria*	*Grouping focus*	*Focus description*
Micro level	Not mediating decision support for policy	Material comparison	Comparison of materials, material constituents, or material processes
		Design strategy	Strategies for energy, structural design, circularity, or material use
Meso/macro level	Mediating decision support for policy	Policy information	Comparison of options to reach a policy goal
		Policy development	Comprehend consequences that a particular policy choice imposes

Scopus, Web of Science and Google Scholar were chosen as relevant search databases. All retrieved studies were filtered by looking at the title, abstract and keywords to include only relevant articles. All selected studies were then read to confirm their relevance. This resulted in a total of 35 relevant studies. A bibliographic check of the reference list and citations of the 35 studies was performed (Wohlin 2014), which yielded two additional relevant studies (see Fig. 1).

2.2 Data extraction

The information about goal, intended application, and questions addressed was extracted from the descriptions in the reviewed studies. Intended applications and addressed questions cover each study's definition of their aim, purpose, goal, or objective, which can include one or more intended applications for each study.

Next, the reviewed studies were categorized into four, depending on their intended application. The categories were (1) method development and case testing, (2) method analysis, (3) method and empirical analysis, and (4) empirical analysis. 'Empirical' connotes that a study includes a case study examination. Studies were added to the category 1 of method development and case testing when the study proposed a new method to model one or more aspects of the CLCI, such as market delimitation, market trend and affected suppliers. The studies test their methodological developments of the part of the CLCI that their methods were developed for in a case study. However, they refrain from conducting a CLCA involving the definition of goal and scope, thus they are not included in the 28 studies that are categorized as empirical analysis. Category 2 of the methodological analysis consists of studies scrutinizing CLCA and the influence of general LCA methodological aspects on the CLCA outcome but where no empirical-based intended application was stated. Category 3 of the studies of methodology and empirical analysis covered methodological analysis and an empirical assessment. The methodological analysis comprises both CLCA and general LCA characteristics. Ultimately, category 4 of the empirical analysis was confined to studies examining cases whether the intended application was consequentially or non-consequentially formulated, but where the authors state they conducted a CLCA. For categories 1 to 3 involving method analysis, we derived a characterization of the focus of each study, which could involve one or more focuses per study, depending on the intended applications. The characterization of the method focus could be general LCA aspects, e.g., end of life, temporal aspects, ALCA and CLCA impact comparison, or consequentially focused, e.g., retro- and prospective data comparison, or the size of the delimited market.

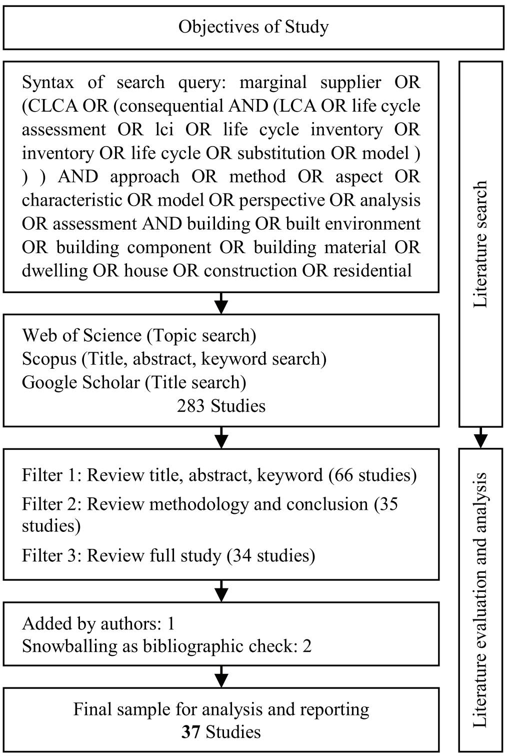

Fig. 1 Methodology of searching for and analysis of relevant studies including results of number of studies. The query was modified to suit rules of each of the three search databases

2.2.1 Characterization of decision context

The ILCD Handbook describes how an LCA for decision support belongs to the situations of either the micro or meso/macro levels, which defines the scale of the study. Even though the ILCD Handbook depicts attributional modelling for the micro level and more consequential modelling for the meso/macro level, the reviewed empirical studies of CLCA were still grouped into these two decision contexts because they did not necessarily base their choice on the ILCD Handbook. Studies of methodological development or of methodological aspects of (C)LCA were not considered relevant for the grouping of decision contexts. It is because they use case studies with the goal not of drawing conclusions about the consequences of change induced by the case study, but of understanding how the methodological aspects influence the CLCA outcome.

The criteria for grouping studies into the two decision contexts are presented in Table 1. Examples of meso/macro level grouping for purposes of policy information could be the choice of renewable energy expansion or increased insulation for climate impact reductions of buildings. For policy development it could be the consequences of increasing the demand for wood for residential buildings. Each study was assigned an object of study as either material, component or building. Studies analysing a building structure were also reported as a building object. Subsequently, the empirical studies were grouped by their decision support on either the meso/macro or micro levels.

2.2.2 CLCI modelling information

The collection of CLCI modelling information was based on the framework of Weidema et al. (2009). It included the time horizon, market delimitation, market volume trend, affected suppliers, constraints and multifunctionality handled by substitution. In the framework, the scale element was considered identical to the decision support level where small-scale equals micro level and large-scale equals meso/macro level. The time horizon was collected if the studies explicitly defined it as short-, medium-, or long-term, or had a defined reference period as in the ILCD Handbook. Here 0–5 years equal short-term, 5–10 years equal medium-term and more than 10 years equal long-term. Market delimitation, market volume trend, and affected suppliers were analysed, if disclosed, regarding the methods of modelling or identification used in each study. Furthermore, the level of specification i.e., the level of documented detail, of this CLCI modelling was evaluated for each study at three levels: low, medium, or high, provided the respective study included the CLCI aspect (for detailed information, see Table 4 in the Supplementary information). A low specification level specifies a CLCI aspect but omits the elaboration of modelling and choices, e.g., by applying an ecoinvent consequential database but overlooking considerations of processes and location effects (Prateep Na Talang et al. 2017). A high level is shown by describing and displaying the formulas, thresholds and considerations of identifying the market (Buyle et al. 2018b). The medium level is often a high-level specification of some aspects and a low level of the remaining.

3 Results

First, the results of the intended applications are aggregated into four focus areas where the intended applications, including the methodological aspects, are further disaggregated and arranged according to their focus. Subsequently, studies are organized around their decision support at the micro or meso/macro level, including a description of changes and of the object of assessment. The section finally analyses the applied time horizon and CLCI methodological aspects.

3.1 Intended applications of CLCA studies

The intended applications of an LCA study set the scene for one or more purposes of the study, which will define the LCA approach according to the ILCD Handbook. The intended applications and formulated questions lead to selections of whether a study focuses on methodological development and case testing, methodological analysis, empirical assessment, or a combination, and what is the aim of interpreting the results of the LCA conduction. For a study to be consequential, the intended applications should include at least one formulation with the principle of the consequence of a decision. See e.g., Table 2 in the Supplementary information for the division of the intended applications of each study into non-consequential and consequential.

The focus of the intended applications in Fig. 2(a) reveals that most studies, 27, aim at examining an empirical consequence. Half of these studies also analyse the general methodological aspects of LCA, such as the end of life, or ALCA and CLCA combined with the empirical assessment of the case study. In total, ten studies focus on the non-empirically consequential aspects. These studies can be consequential but understood as having the purpose of solely examining

Table 2 Method and empirical gaps in the building CLCA research literature and what those gaps consist of

Study focus	*Aspect*	*Focus gap*	*Reference examples addressing the gap*
Method	Market delimitation Market trend Affected suppliers	Examination of the effects of choices in modelling on the final impacts	(Pizzol and Scotti 2017; Sacchi 2017; Buyle et al. 2018b, 2019a, b)
Method	Electricity modelling	Combined marginal electricity development and global warming paths	(Roux et al. 2017)
Method	Renovation	Sensitivity to CLCI modelling choices	
Method	Biogenic carbon	Biogenic carbon modelling in CLCA of biogenic products	(De Rosa et al. 2018)
Empirical	Object of assessment	CLCA on building component level	
Empirical	Meso/macro level	Renovation policy and circular economy strategies	
Empirical	Micro and meso/macro level	Material strategies and optimal design of building typology and configuration	

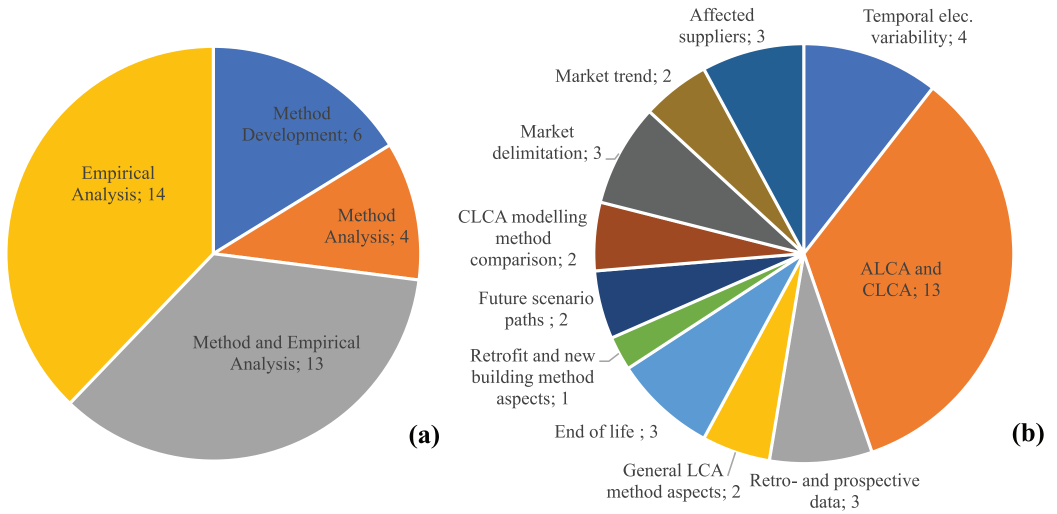

Fig. 2 **a** Reviewed studies separated into four aggregated focus areas of intended application and formulated questions i.e., method development and empirical test, method analysis, method and empirical analysis, and empirical analysis. **b** Show the methodological aspects represented as the number of times they are applied across the reviewed studies. Methodological aspects cover both CLCA and general LCA aspects that are examined in the studies regarding the impact on the CLCA. (The focus of the 28 studies with empirical assessment is elaborated in section 3.2)

CLCA method-related aspects. It could be comparing the ALCA and CLCA of a particular case, criteria for the inclusion of affected suppliers, or purely studies of methodological development for CLCI modelling.

In this review, empirically intended applications involving decisions converge mainly on (i) comparing options of materials, structural configuration, or production processes; (ii) increases of a certain material, component, or building type; (iii) breakthrough of a technology; (iv) substitution of one material for another; (v) choice of increased circular demand; and (vi) growth of retrofitting. The concept of studying a consequence of a decision, could in the intended application be explicitly written as “What are the environmental consequences of constructing more hybrid wood multi-storey buildings in 10 years?” (Fauzi et al. 2021). In several of the reviewed articles, this emerges more as an implied part of the intended application, such as “Compare the environmental impact of RC structures and timber structures” (Skullestad et al. 2016) or “What are the potential environmental impacts of an increase in resource demand associated with energy efficiency refurbishments?” (Ghose et al. 2017). The substance of these intended applications and questions is that they circle around a decision that changes the status quo. This shows that CLCA could be applied to studies that include those sets of purposes.

Representation of the methodological aspects across the studies displayed in Fig. 2(b) is widespread (Table 3 in the Supplementary information shows the representation for each study). Nonetheless, comparison of ALCA and CLCA appears to be the main methodological focus, examined in thirteen studies. Temporal electricity (elec.) variability, end of life, and retro- and prospective data comparison follow. Among the studies of methodological development most articles consider market delimitation and affected suppliers. The two studies comparing future scenarios analyse the influence of three trajectories of global warming in buildings’ energy consumption and the impact on future dwelling stock of two different electricity mixes.

3.2 Decision support level and the focus of studies

Choosing CLCA as the approach, whether the decision support is at the micro or meso/macro levels plays an essential role in the proceeding approach of the LCA modelling method, and in the interpretation of the outcome and conclusions.

3.2.1 Policy characteristics of meso/macro level decision-making support

Fifteen studies have meso/macro decision support. Two-thirds of the studies in Fig. 3 focus on policy development, and only a few on policy information. Studies of policy development address mainly the implications and effects of the environmental impacts of a decision to change the status

Table 3 CLCI modelling methods, aspects they cover, limitations, and recommendations for the relevant decision support level

CLCI method	*CLCI aspect*	*Limitations*	*Decision support*	*Reference examples*
Ecoinvent	Market delimitation Affected suppliers	Market aggregation or lack of representativeness	Micro level	(Prateep Na Talang et al. 2017; Fauzi et al. 2021)
Literature	Market delimitation Affected suppliers	The geographical location needs to be very similar	Micro level	(Buyle et al. 2018a; Pedinotti-Castelle et al. 2019)
Assumption	Market delimitation Affected suppliers	Inaccurate when market is not very local or well-known	Micro level	(Buyle et al. 2014)
Linear regression	Market trend Affected supplier	Development can follow an S-shaped curve, not linear Trade and production data often used only as a proxy for competitiveness	Micro level	(Buyle et al. 2018b, b)
Iterative procedure	Market delimitation Market trend Affected suppliers	Production data as only proxy for competitiveness Production and trade data are often aggregated at country level	Micro level	(Buyle et al. 2018b, b)
Network analysis (bottom-up)	Market delimitation market trend affected suppliers	Countries as affected suppliers; large countries may have considerable internal market variations	Micro level	(Sacchi 2017)
Network analysis (top-down)	Market delimitation Market trend Affected suppliers	Trade data as the only measure for countries belonging to a network (market) Complimented/validated with qualitative information regarding studied products Market trend and affected suppliers' identification is less advanced	Micro and meso/macro level	(Pizzol and Scotti 2017)
Electricity equilibrium models	Market delimitation Market trend Affected suppliers	Input data of weather data, installed renewable capacity, baseload, coal share of fossil fuels	Meso/macro level	(Roux et al. 2017; Collinge et al. 2018)
Economic equilibrium models	Market delimitation Market trend Affected suppliers	Choice or assumptions of input elasticities	Meso/macro level	(Nepal et al. 2016)
MFA	Market trend	Omit resource price and availability relationship Exclude demand from other sectors for the same resource	Meso/macro level	(Cordier et al. 2019)
Equilibrium and forest empirical model	Market delimitation Market trend Affected suppliers	Price elasticity assumptions from literature notably influence outcomes The base year of timber-use per unit and logging slash amount End of life options not considered	Meso/macro level	(Nepal et al. 2016)

quo through projected scenarios. One study examines the impact of increased hybrid wood multi-storey residential buildings, avoiding an emphasis on a particular policy, but analysing the consequences if policy would implement a perspective involving increased use of wood (Fauzi et al. 2021). Policy information studies compare various options for obtaining a policy goal. Pedinotti-Castelle et al. (2019) illustrate this by evaluating whether retrofitting the residential sector would improve the environmental and economic impacts more than installing new power plants to replace fossil-fuel energy sources.

All four policy information studies have buildings as their assessment target, while the policy development studies are distributed among eight material- and seven building-oriented studies. For policy information regarding buildings, the studied changes converge on circular material options, a choice of retrofitting or constructing new buildings, and changes in energy use for building design assumptions. One case of renovation explores the opportunity to reduce the impacts of increased demand for materials from a refurbishment by analysing strategies of circularity on site and the procurement of greener materials (Ghose et al. 2017). Building as an object in policy development focuses on the consequences of increased construction with wood, the development of energy supplies, and the relation between energy and building stock. The latter is a national-scale study that ascribes existing energy

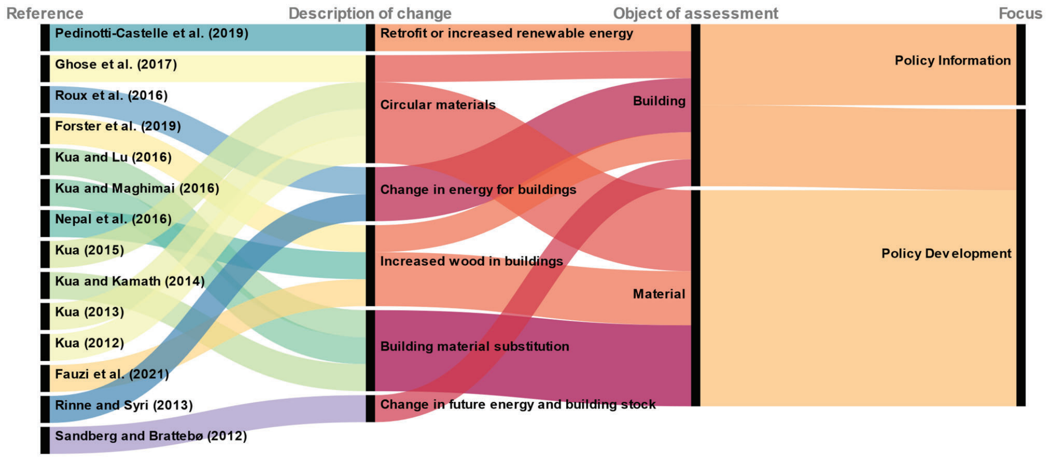

Fig. 3 Network of meso/macro level decision support studies' relation with their focus, object of assessment, and aggregated description of the change under study. It includes only studies that involve an empirical assessment. Policy information is comparison of alternatives to reach a policy goal. Policy development examines the effects of one policy proposal

policies and GHG targets. It examines the GHG impact of the energy demand of the future dwelling stock associated with an increased building area due to population growth, and how that demand governs the overall obligation to decarbonize (Sandberg and Brattebø 2012).

Studies with material as an assessment target focus exclusively on policy development. Six of the eight articles appraise various material strategies in Singapore related to changes in constituent or material substitution and recycling, e.g., concrete production, bricks displacing concrete, and the importance of perusing technology for its short-term processual aspects and long-term policy guidelines for concrete production and the integration of waste products (Kua 2012, 2015). The remaining two material studies draw consequences for increasing the number of wood products in the building industry. Here, the demand for wood in houses and low-rise non-residential buildings involved cases that explore the net climate-mitigation potential of displacing non-biogenic structural materials with structural wood. They recommend policy-making directed towards structural wood systems due to the reduction potential of climate impacts (Nepal et al. 2016; Forster et al. 2019).

3.2.2 Micro level decision-making support

The thirteen studies of micro level decision support focus on material comparison (8) or design strategy (5) (see Fig. 4). Of the material comparison studies, the majority target solely a material as their object of assessment. Two other studies compare materials, but in the function of a whole building, concentrating on wood displacing conventional structural materials. All the material comparison studies assess the consequences of circularity processes that primarily involve the comparison of waste or by-products, and to a lesser extent forms of energy.

Studies about building design strategies primarily look at the consequences of energy use under different circumstances, or the nexus between the structural and energy design of buildings. For instance, these studies are specifically energy optimization or renovation through energy improvements by means of increased insulation or heat pump installation under various energy-transition scenarios. The choice of structural configuration and energy consumption involves a decision whether energy design or structural design makes the largest contribution to a building's environmental impact. Dodoo et al. (2014) exemplified this in an analysis of three structurally different wood systems of cross-laminated timber, beam and column, and prefabricated modules designed as conventional and low-energy buildings respectively. The two studies of component design strategies appraise how choices between circular and conventional components affect the environmental impacts of various frequencies in building transformations.

3.3 CLCI methodological aspects

The analysis in Fig. 5 contains an overview of the CLCA aspects, if the reviewed studies include them, and the level of specification, i.e., how well it is described and documented. In an important notice, two of the studies focusing on method development avoid the aspects of time horizon and substitution (Vieira and Horvath 2008; Pizzol and Scotti 2017).

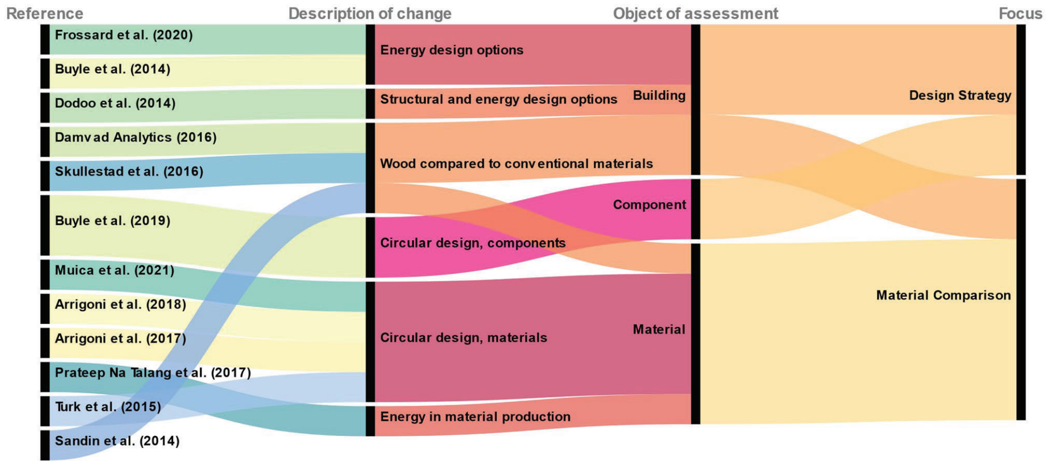

Fig. 4 Network of micro level decision support studies'relation with their focus, object of assessment, and aggregated description ofthe change under study. It includes only studies that involve an empirical assessment

This is because the purpose of these studies is to develop a method for one or more aspects of the CLCI modelling and to apply that method to that aspect of the CLCI, thus not conducting a full CLCA. Twenty-four studies include a time horizon, mainly practicing a long-term perspective, the default and often the case-study situation stated in Weidema et al. (2009). Two studies combine average and marginal data, and one study only applies average data, which is not included in the theoretical concept. Some analyses adopt short- and/or medium-term time horizons either separately or accompanied by long-term time horizons, which are still within the framework. Overall, the studies encompass three of the pillars of CLCI modelling i.e., market delimitation, 21, market volume trend, 14, and affected suppliers, 26. Yet, each of these has distinct numbers of appearances and a broad spectrum of identification methods (see Fig. 5).

Market volume trends are mostly identified by linear regressions, which align with the linear, steady-state description of Weidema et al. (2009). However, the references to the literature also feature frequently as a method of identification. This is also the case for market delimitation and affected suppliers, ranging from assumptions and ecoinvent as modelling methods to network analysis, iterative procedures, equilibrium models and other market-based models. Most studies include substitution, but the studies without substitution comprise (i) method development studies with only the CLCI modelling as the scope but with the possibility of using the developed method to identify substituted affected suppliers (Vieira and Horvath 2008; Pizzol and Scotti 2017; Buyle et al. 2018b; Cordier et al. 2019); and (ii) energy consumption studies with a pre-confined market where substituted suppliers might be inherent in the modelling (Sandberg and Brattebø 2012; Roux et al. 2016; Frossard et al. 2020).

The method development side comprises different forms of network analysis by identifying affected suppliers and market delimitation top-down from trade and production volumes (Pizzol and Scotti 2017) and by bottom-up market equilibrium based on retrospective trading volumes (Sacchi 2017). Otherwise, an electricity system model that captures higher temporal dynamic and marginal aspects of the hourly electricity consumption of a house has been developed (Roux et al. 2017; Collinge et al. 2018). Cordier et al. (2019) assess changes in the supply chains of wood products from increased demand derived from their development of material flow analysis (MFA) for CLCI modelling.

In general, the level of specification of market delimitation, market trend and affected suppliers diverge from low to high, not correlating with how advanced the CLCI modelling is. The inclusion of constraints in modelling or in the discussion section of the reviewed studies emerges as a shifting between high or low levels of specification. The nine studies that only employ substitution as their consequential aspect omit constraints. On the other hand, the studies that only contain substitution have on most occasions the modelling of substitution specified at a high level. (Table 4 in the Supplementary information presents the detailed modelling method and level of specification for each study.)

Eight studies consider both retrospective and prospective data, but with various combinations and purposes. One purpose is an examination of the retrospective and the prospective data of market trends and affected suppliers (Buyle

Fig. 5 CLCI aspects of time horizon, modelling methods of market delimitation, market volume trend and affected suppliers as how many times they are represented across reviewed studies. Finally, level of specification is presented for constraints and substitution documentation. Elec. equilib. = electricity equilibrium, PM = power market, PE = partial equilibrium, MFA = material flow analysis

et al. 2018b, 2019a, b). However, in situations with a lack of prospective data, they used retrospective data as proxy data. Another study used retrospective and prospective data as a sensitivity analysis for the electricity mix (Ghose et al. 2017). Moreover, it was examined whether retrospective data for short-term changes and prospective data for long-term changes would yield different conclusions regarding affected suppliers (Rinne and Syri 2013). An additional application used the retrospective data to extrapolate the prospective data (Sandberg and Brattebø 2012; Cordier et al. 2019). Finally, one study combines retrospective extrapolate data with prospective economic and biological modelling for increased wood demand (Nepal et al. 2016).

Table 4 Relevancy guide of when to use which LCA approach at which decision support level

Decision support level	*Approach*	*Relevancy*	*Comments*
Micro level	ALCA	Building level projects of new, renovation, transformation, and material producers of less market-dominant positions	Based on ILCD 'Chapter 6.5' One building project may have a limited influence on the overall economy.
Meso/macro level	CLCA	Policy-making, regulation, and building development in neighbourhood, city, national, or regional context	Based on ILCD 'Chapter 5'; cf. section 1.1 It will reflect the causal market aspects of changes in the economy

4 Discussion

4.1 Consequential approaches and prevailing gaps

The reviewed studies contain a diverse range of intended applications. Several studies engage with the methodological aspects of either method development, method analysis, or a combination of method and empirical analysis. Many of these studies emphasize the methodological analysis rather than the empirical. Table 2 presents the identified research gaps.

In this review, the meso/macro level decision support would be the focus when studies are projected or coupled to policy-making, since this leads to large-scale changes. When the output of a study remains case-specific without involving policy, it was characterized as micro level, which results in smaller scale changes, i.e., marginal changes, within the economy's existing capacity. One limitation is that this review does not consider whether studies involving meso/macro level decision support base their analysis on marginal changes, and hence if they exclude large-scale changes.

4.2 CLCI methodological aspects and limitations

There is a wide range of applied methods in CLCI modelling in the reviewed studies, from simple to sophisticated, while exhibiting different levels in the transparency of documentation. Table 3 lists the identified modelling methods, the covered CLCI aspects and limitations alongside the decision support level they are recommended for. Commonly, it is important to be conscious about removing constrained suppliers due to, e.g., policies, quotas, or resource availability. One limitation of the reviewed studies is the employment of retrospective data for defining constrained suppliers, which might not reflect resource shortages or policies in general.

Many studies rarely employ all CLCA aspects, nor is the modelling process clearly specified. This could be upgraded to enhance the general consequential level of the cause-effect relationship (Roos and Ahlgren 2018). Fauzi et al. (2021) studied various CLCA aspects with alternating specification levels. They discuss what affects a market in general, though the modelling of market delimitation is disregarded. They explain thoroughly what determines market trend and affected suppliers, while avoiding direct modelling by referring to the literature and ecoinvent, which can lead to internal inconsistency. The consequential ecoinvent database might lead to inconsistencies when used as the reference for the consequential changes in a foreground system in cases where the geographical aggregation is not representative of the given study. Further, they reason for and reference to constraints for one affected supplier but not for the remaining foreground processes. It is complemented by specifying the recycling rates of the substitution processes that nonetheless lack the detailed explanation behind their identification. The number of included CLCA aspects in the reviewed studies increased towards 2019 to an average of 5.4 of 6 CLCA aspects (see Fig. 1 in the Supplementary information). The range of CLCI modelling methods underlines the lack of consistency across studies and internally. Thus, the LCA community in the built environment could agree on a harmonized CLCI modelling method to increase the consistency of CLCAs. Adequate CLCA aspect applications should follow Table 5. A few studies include all CLCA aspects, explain determining parameters, and discuss the constraints of applying retrospective and prospective data (Nepal et al. 2016; Buyle et al. 2019b).

Substitution can appear as a market-based mechanism if it considers the substituted processes as the affected processes. Yet, the categorization might not be a purely consequential element due to the ILCD Handbook. DS/EN ISO 14040 (2008), and DS/EN ISO 14044 (2008) argue it can be used for attributional LCA and other types of LCA, respectively (attributional and consequential are not terms in the ISO standards). Several studies only include substitution alongside the time horizon, and disregard other market-based CLCI modelling. These nine studies are therefore semi-consequential, as defined by Zamagni et al. (2012). Turk et al. (2015) explain substitution in terms of which processes are avoided due to recycling using literature references, although not adequately specifying whether it involves the actual affected (marginal) processes, which makes the substitution aspect less causally market-based. The remaining

Table 5 Minimum aspects to include in building CLCAs as derived from the four-step procedure framework of Weidema et al. (2009). Then, recommendations of what to include as a part of the assessment and a minimum specified level of documentation with examples

Aspect	*Recommendation (optionally)*	*Specification level*
Time horizon	Long-term (medium-, short-term)	No. of considered years, or as long-, medium-, and/or short-term
Market delimitation	Modelled for foreground system	Explaining the parameters that determine the market, e.g., trade data and minimum threshold for being included in a certain market
Market trend	Modelled for foreground system	Explaining the parameters that determine market trends, e.g., increasing market computed based on linear regressions of trade data
Affected suppliers	Modelled for foreground system	Explaining parameters that determine affected suppliers e.g., trade data as a proxy for competitiveness and as a threshold for being in the affected supplier mix
Constrained supply	Exclude qualitatively before or after modelling (quantitatively)	Discuss if affected suppliers are plausible and include a comparison with other literature, policies, or expert involvement
Substitution of affected processes	Multifunctional processes, recycling/reuse	Explaining the parameters that determine avoided production, e.g., avoided chipboard production from increased timber use for CLT

LCI is not consequential as the modelling originates from the associated supply chain and not the affected supply chain in the market. Similarly, Sandin et al. (2013) performed a consequential LCA model, which neglected the identification of marginal suppliers except for including substitution to model avoided production by the unconstrained suppliers. Proceeding substitution onwards in CLCA of buildings, studies should model avoided processes to be the affected suppliers while also completing consequential modelling of the remaining foreground system to ensure a more useful CLCA study.

4.3 Application and guide of CLCA on buildings

The ILCD Handbook specifies to use ALCA for accounting and micro level decision support. For meso/macro level decision support, it specifies to combine the use of long-term marginal mixes for the large-scale changes and attributional modelling for the small-scale changes. However, it shows some ambiguity across chapters regarding when to apply attributional and consequential approaches, as elaborated in section 1.1. Despite the ambiguity, it is a consensus document we recommend as the basis for the decision of which LCA approach to use. To condense the interpretation for the built environment, Table 4 provides a proposed guide of when ALCA and CLCA are relevant. Supplementary to the guide proposals, the micro level of decision support would benefit of an added CLCA, but not suggested as a requirement.

However, a dilemma arises for micro level decision support if a trend for a certain building or product type increases or decreases "independently" in each commenced building project. These individual micro level trends may amount collectively to a macro level change. It is important for consultants to recognize this. But, completing the CLCA jointly with the ALCA to improve the conclusions of such trends is mainly recommended for the building authorities and researchers. To make it easier to differentiate between micro or meso/macro level decision support of an LCA, the built environment community could agree on and introduce a distinctive threshold. This could, for example, be built on the most appropriate of either total building area or total building project cost. We recommend initiative joint consensus work to establish clear criteria or recommendations for defining when a study is at the micro, meso or macro level.

After the choice to conduct a CLCA, instead of following the ILCD Handbook, it might act according to the four-step procedural framework of Weidema et al. (2009), where Table 5 presents the minimum level of the CLCA aspects we recommend for inclusion. The four-step framework provides an inherent homogeneous approach to CLCA, and of the 24 reviewed studies referring to a CLCA framework, 19 use the four-step framework or its predecessor's work and theories (Weidema et al. 1999; Weidema 2003; Ekvall and Weidema 2004).

Regarding data application, retrospective and prospective data considerably influence the environmental impacts of building CLCAs (Buyle et al. 2018b, 2019a, b). Therefore, considering retrospective and prospective data on market delimitation, market trend and affected suppliers in a sensitivity analysis could be a common element in future CLCA studies of buildings. This improves the robustness of outcomes since retrospective data are often more available. However, they are not necessarily representative of future trends, whereas prospective data are inherently uncertain but can consider future changes due to their projection aspect (Pizzol and Scotti 2017). Using scenario development to demonstrate various paths of future possibilities should reduce the inherent uncertainty of a prospective approach (Zamagni et al. 2012). Developing robust scenarios requires a structured methodological framework, as in Pesonen et al. (2000). For ALCA studies, various scenario applications exist (Lasvaux et al. 2017; Drouilles et al. 2019; Scherz et al. 2022).

5 Conclusion

This review has revealed how limited numbers of CLCA studies of buildings exist. The analysis shows a lack of methodological studies about the influence of CLCI modelling choices. Additional research gaps concern renovation approaches and the effects of future climate change pathways on CLCA outcomes. Micro level studies feature circular aspects and wood in buildings as their main subjects. The meso/macro level studies report on similar topics, though with geographically concentrated circular aspects, and accompanied by a focus on energy supply pathways. Ergo, wider circular strategies and renovation policies lack focus at the meso/macro level, while the premises of component design, material strategies and building configurations need stressing at both decision support levels. Although studies engage a broad spectrum of applications of both methodological and empirical aspects, the documentation and modelling methods of CLCI lack systematization and differ in consistency. Altogether, there is a need for further CLCA studies on buildings to provide a more comprehensive basis for concluding and generalizing outcomes. Studies also need to improve the level of CLCI to augment the quality of, and strengthen, the consequential approach and interpretations.

The choice of LCA approach was discussed with reference to the ILCD Handbook. It concluded that ALCA should be applied in micro level decision support, but that an additional CLCA may improve the insights into decision support because the ILCD Handbook suggests that the consequences of small-scale changes should be examined. This entails that building LCAs could continuously be conducted with the current standardized LCA for micro level studies. Building LCAs for meso/macro level decision support should as a minimum conduct it as a CLCA. The approach to conduct a CLCA may follow the four-step framework of Weidema et al. (2009) because it is homogeneous and the most frequently applied framework in the reviewed studies.

Meso/macro level decisions would primarily comprise policy-making, and building projects on a neighbourhood, city, national or regional scale involving policymakers, -advisors, and building development professionals. Micro level decisions would often be relevant for designers, advisors, and clients in individual building projects. It was proposed to agree on a threshold definition that simplifies the micro- and meso/macro level distinctions, for example, those characterized by the most appropriate measure of the size of the total building area or the total costs of the building project.

Appropriate CLCI modelling should be transparently documented and balance the decision support level, applicability and level of advancement while accommodating some element of the market approach. It ensures a more market mechanism-based assessment that captures constrained suppliers and creates the hypothetical affected supply chain. These are the principal elements from which CLCA deviates from ALCA. In any case, these CLCI aspects fluctuate in consistency and specification. Evolving consequential studies of buildings, we advocate the built environment agreeing on a CLCI modelling method to harmonize CLCA of buildings. Lastly, retrospective, or prospective data notably influence the environmental impacts of CLCA of buildings and should preferably be included as a sensitivity analysis.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-022-02126-w.

Funding The authors would like to acknowledge VILLUM Fonden for the financial support of the research as a part of grant no. 00029297 and 37169.

Declarations

Conflict of interest The authors declare no competing interests.

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Appendix B. Publication 2

Publication 2: **Enabling rapid prediction of quantities to accelerate LCA for decision support in the early building design**. *Hansen, R. N.; Hoxha, E.; Rasmussen, F. N., Ryberg, M. W., Andersen, C. E.; Birgisdóttir, H*. In: Journal of Building Engineering, 2023. DOI: https://doi.org/10.1016/j.jobe.2023.106974

Journal of Building Engineering 76 (2023) 106974

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Enabling rapid prediction of quantities to accelerate LCA for decision support in the early building design

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ARTICLE INFO

Keywords:
Life-cycle assessment
Environmental impact assessment
Wood buildings
Embodied greenhouse gas emissions
Parametric quantity generation
Bill of quantity (BoQ)

ABSTRACT

Buildings are a significant contributor to climate change. This is why life-cycle assessments (LCA) are becoming increasingly popular for documenting environmental impacts during the detailed design stages of building projects, level of development (LOD) 300–400. In that context, wood is gaining recognition as a material that can reduce the embodied impacts of buildings. However, of particular concern is the incapability of research and practice to generate quantities rapidly in the early design stage. It is an underlying key issue for enabling LCA as decision support in these early building designs. Therefore, this study's aim is two-fold: (i) introducing a simplified design tool for wood dwellings and assessing how the predicted early design climate impacts perform compared to detailed design case studies (ii) evaluating the root causes for predicting trustworthy climate impacts in the early design. The LCAbyg tool assessed the impacts of the life-cycle phases A1-A5, B4, B6, and C3–C4. The climate impacts of the simplified designs (LOD 100–200) were analysed against ten detailed design buildings with the impact disaggregated into life-cycle phases, component types and material categories. The simplified design tool shows it is reliable for comparing the various GHG emissions associated with different designs. Still, the total impact is underestimated by an average of 12% compared with the detailed modelling. It primarily arises from the lack of simplified design metals and that a single product in a component can constitute up to 53% of the climate impact. So, the LCA is sensitive to chosen generic processes, EPDs, and quantities estimations. This study points to the critical elements in material quantification and related climate impact between simplified and detailed building designs. The study also adds to the body of scientific literature on wooden building designs by presenting the quantities and GWP results for ten dwellings constructed between 2010 and 2021. Terraced houses with specific design elements, paper wool, and footing foundation show promising carbon reduction abilities here. In addition, the simplified tool has the potential to get small and medium-sized enterprises in the building industry on board with the sustainability agenda and lead to broader adoption of LCA in their practices.

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https://doi.org/10.1016/j.jobe.2023.106974
Received 29 March 2023; Received in revised form 18 May 2023; Accepted 30 May 2023
Available online 5 June 2023

1. Introduction

The increased attention on improving the environmental impacts of buildings has steered the focus towards using life-cycle assessment (LCA) in the built environment [1,2] and the adoption of national climate requirements for buildings [3]. These developments have been accompanied by a transition to incorporating embodied impact assessments because of its deficient progress, thus complementing the remarkably improved operational energy efficiency in building design [4,5]. In low- and near zero-energy buildings, research shows that the proportion of life-cycle-embodied energy can range from 26% to 100% [6]. Wood and bio-based materials can play a role in decarbonizing embodied impacts, given that they meet the conditions of sustainably managed production [7,8]. The effective and efficient design of an optimal structural CLT solution compared to a conventional CLT building has saved up to 43% of greenhouse gas (GHG) emissions [9].

1.1. Use of LCA at various levels of design development

Although the early design of a building project entails high design liberation under constrained time and budget resources, many decisions crucially affect the environmental impacts [10]. Therefore, along with the increased application of LCA, more research is directed at digitizing and implementing LCA-based decision support in the early and continuous design of buildings [11]. For instance, Cavalliere et al. [12] introduced a method for conducting LCA by the use of BIM as a project evolves through the levels of development (LOD), and they described it as continuous decision support.

However, manual data inputs and the lack of fully automated processes undermine the complete palette of advantages [13–15], particularly in the very early levels of development (LOD) [16], which usually arises due to the data configurations and terminologies hindering the integrated implementation of BIM and LCA [11]. A popular BIM software program integrated with a regular LCA tool was recently proposed as an automated workflow to assess whether a concrete or a steel structure would be the best building option [17]. In addition, Palumba et al. [18] developed a methodology to correct deviations of impacts occurring at different LODs when impact data progresses from generic unit processes in the early design stage to Environmental Product Declarations (EPDs) at higher LODs. Where most building LCAs are conducted in more detailed stages of the design (LOD 300–400), simplified procedures and tools may enable LCAs already at LOD 100 or 200 [19].

1.2. LCA as decision support in early building design

Quickly generating simplified quantities of buildings in the early design stage still appears as a void in research and practice because of the inadequacies of access to data and information [20]. However, a couple of attempts have been made to introduce parametric models for the renovation of reference buildings [21], as well as the structural and envelope pre-design of industrial buildings [22]. In parallel to this, BIM-informed LCA needs adoption in small and medium-sized architectural and construction enterprises (SMACE) since separately inspecting the implementation of BIM has its barriers. For Canadian SMACEs, BIM entails significant upfront costs and risks [23]. In the Netherlands, the barriers relate to knowledge gaps and the high levels of complexity of BIM practices, where SMACEs are typically already restricted by a lack of financial capacity [24]. This situation leaves opportunities for simplifying LCA decision support during the early design process in SMACEs. However, early design-stage tools must deliver LCA results that are sufficiently close to those of the detailed tools. This ensures that building designers can confidently proceed toward a more detailed design with the solutions tested in the early stages.

1.3. An early-stage quantity-tool for wood-based constructions

To elaborate on the previous paragraphs, research and practice accommodate a need for simplified quantities in the early design to support LCA decision support before BIM enters the process. Furthermore, improving the building design of wood has the potential to decarbonize embodied impacts, for which the early design knowledge should be enhanced. These two needs can be met based on parameterisation built upon predefined components that follow building code requirements. At the same time, making this parameterisation operable for SMACEs will be necessary if LCA as decision support in the building sector is to be widely adopted. To accommodate these needs, a freely available spreadsheet-based tool was developed in 2021 for the early stages of wood-based building design in Denmark (see Supplementary Information (SI) Appendix A). This is called a simplified design tool and requires only a few design inputs to calculate material quantities. The goal of the tool is to speed up LCA by predicting quantities at the early design stage, thus providing decision support more efficiently, already at LOD 100–200. As this has been developed in collaboration with SMACEs, the simplified tool represents this category of company approaches to design.

The developed tool can compute the material quantities of various wood-dwelling designs. The generated design quantities can afterwards be used in an LCA that represents an environmental assessment of the early stage. The quantities of the simplified model can be linked to a user's desired LCA tool. However, the accuracy of the simplified design when conducting LCA on the computed material quantities needs evaluating to understand its applicative reliance and usefulness. Thus, this study evaluates how the simplified design tool performs in the early design stage when assessing the climate impact of the material quantities compared to the results calculated at the detailed design stage. This leads to the following research questions about early-stage versus detailed design:

1. What are the differences and similarities in the material quantities and associated climate change impacts of detailed versus early design stages?
2. Which parameters, component types, and material categories are instrumental in the simplified design prediction, so that trustworthy GWP impacts are obtained compared to when the project reaches the detailed design?

In addition, the study adds to the body of scientific literature about wooden building designs by presenting the quantities and GWP results for ten residential buildings constructed between 2010 and 2021.

2. Methodology

The simplified design tool, representing the early design stage, is evaluated against the detailed design case studies to investigate the accuracy of predicting the detailed design impacts of buildings. Fig. 1 outlines the conceptual approach to arriving at a life-cycle inventory (LCI) for the simplified design tool (simplified LCI) and the detailed design case studies (detailed LCI). In both cases, the inventories are then modelled using the LCAbyg tool [25], a freely available LCA tool developed for the Danish construction industry and described in further detail below.

2.1. LCA

In the case of both the detailed and the simplified design, the climate impacts were evaluated using the LCA methodology following the EN 15978 norm [26]. The goal of the LCA is two-fold: (i) to compare the embodied GHG emissions of ten detailed design wooded buildings; and (ii) to identify the differences in embodied GHG emissions between the detailed and simplified designs. The functional unit (FU) is 1 m^2 of gross living area that complies with the Danish building code regarding the structure, fire safety, energy efficiency of insulation and acoustics (as far as possible) at the time of design for a 50-year reference study period (the building examples date from 2010 to 2021). The EN 15978 norm life-cycle phases considered for the LCA are the production of building products (A1-A3), transport to the construction site (A4), partly A5 limited to the waste at the construction site, replacement of components during the use phase (B4), and end-of-life waste-processing and disposal (C3–C4). The service life of products is acquired from generic Danish data from Aagaard et al. [27]. The LCA tool for modelling the detailed and simplified design of the different cases so as to conduct the impact assessment is LCAbyg [28] version 5 [29]. LCAbyg uses generic unit processes from the Ökobaudat database [30] and environmental product declarations (EPDs) (see SI Appendix B, table B7-B8 for the EPDs used and information on A4-A5). The applicable environmental impact category is the global warming potential (GWP) with a time horizon of 100 years. The declared unit kg CO_2-eq/m^2/year(yr) enables the impact comparison across the different building cases and the detailed and simplified design. The modelling of biogenic carbon in bio-based products adheres to the −1/+1 accounting approach recommended in the EN15804:2019 norm [31].

2.2. The selected case buildings

The sample of buildings comprises two multi-storey buildings (M01-M02) and eight terraced houses (R01-R08) (see SI Appendix B table B1-B6 for metadata on the selected cases). All the projects consist of more than one building block at the site. In the detailed design, the modular prefabricated (prefab) building constructions are classified as volumetric for a block module and panelized for a component module. A block module consists of one whole storey, including exterior walls, interior walls, and floor, all assembled at a factory. Component modules are exterior walls, interior walls and floors separately fabricated at a factory and assembled into a block

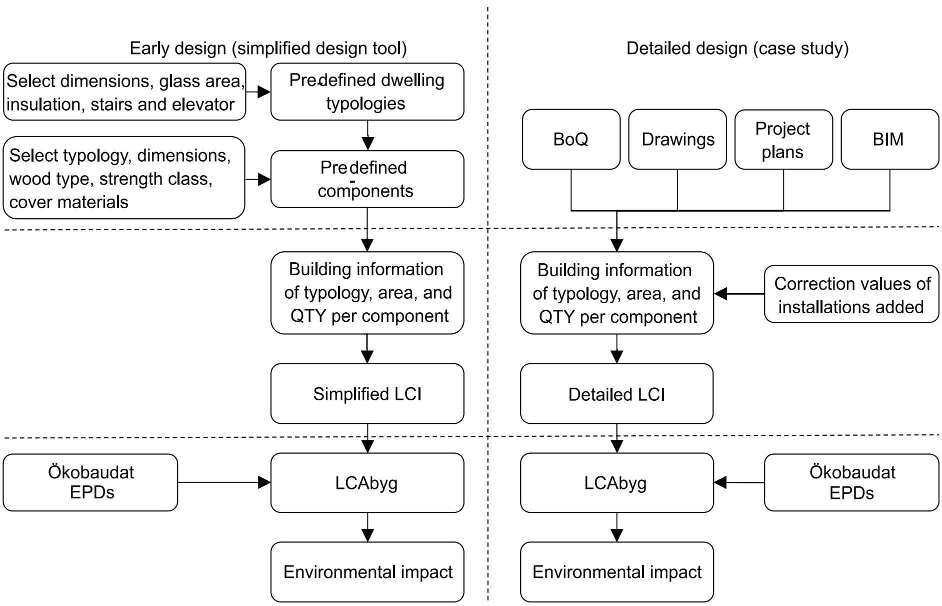

Fig. 1. The workflow of the simplified and detailed design from inputs of information to output as LCI to impact assessment. The inputs and outputs leading to the LCI differ between the two design stages.

on site. Another construction characteristic is cross-laminated timber (CLT). This study excluded common buildings, sheds and other detached constructions associated with the selected sites. The cases were divided into the component groups of foundation, including slab, exterior walls, including doors and windows, interior walls, floors, roof construction and other components, e.g., stairs and elevators. Table 1 gives an overview of the case studies alongside the simplified design.

2.2.1. The simplified design tool model

The simplified design tool can model one building block at a time and contains predefined component typologies which the user can select. The predefined dwelling options comprise single-family houses, two-storey terraced houses, and multi-storey apartment buildings with three to six storeys. One building block in the simplified design tool represents several blocks in the detailed design.

Moreover, the predefined component typologies will sometimes differ from the detailed design, the most representative being selected. The tool cannot model prefab components, so these cases buildings were modelled as timber-frame buildings, mainly affecting the floor component (see Table 2 for specifics on the detailed and simplified component differences).

Terraced houses R01 and R06 were modelled as three-storey dwellings to represent the detailed design most appropriately because the simplified design tool only provides options for terraced houses with two storeys. This approach is considered conservative given the stricter building code for multi-storey residential buildings.

Generally, the tool disregards interior finishings such as paintings, additional products for wet rooms, metal products such as reinforcing steel, assembly fasteners and technical installations in the form of ducts, pipes, boilers, ventilation aggregate and gutters. It includes elevators and stairs if selected.

The simplified design tool computes the components of floors, exterior walls and roof constructions based on structural, insulation (U-value) and fire safety calculations with the minimum necessary capacity to comply with the building code. Interior walls for residential separation rely on a similar computation, though the tool excludes non-loadbearing partition walls. Foundations base their quantities on a factor per area where only the density of insulation type and the number of load-bearing interior walls are changed in size. The simplified design tool can only consider one type of cladding at once. In cases where the detailed design applied two cladding types, the choice of cladding in the simplified design was based on which claddings had the most significant volume. Roof terraces and irregular roof shapes are not available in the tool, affecting the impact comparison of roof components. Fig. 1 displays the workflow of the simplified design tool and the variations to the case studies.

3. Results

The following sections compare theembodied GWP results obtained from the detailed and simplified design building model, i.e., from life-cycle modules A1-A5, B4 and C3–C4. The focus of the results gradually disaggregates the overall impact of the building cases into impact from life-cycle phases, component types and material categories of the selected buildings. Finally, it analyses the detailed and simplified design models' relationships between the mass intensity and the impact difference.

3.1. Overall impact analysis

Fig. 2 shows the GWP from the simplified and detailed design of all ten building cases. The average embodied GWP score for the detailed wooden buildings is equal to 4.5 kg $CO_2e/m^2/yr$, and those from the simplified model to 4 kg $CO_2e/m^2/yr$, with a relative difference of 12%. The impact from the detailed design models varies from 3.3 to 6.3 kg CO_2-eq/m^2/yr. A shift of view to the early design sets the impact ranges to between 2.5 and 5.2 kg $CO_2e/m^2/yr$, hence there is a comparable range between cases in the simplified and the detailed modelling.

Individual cases reveal more significant variations where the impacts of the early design generally exhibit 10–23% lower values. In contrast, in the case of buildings M02, R03, and R06 the impacts of the detailed design are 2–17% lower. To better understand the critical parameters of the variations between the detailed and simplified models, further analyses of the impacts of the different building life-cycle stages follows.

3.2. Impacts distributed among building life-cycle phases

Fig. 3 shows how impact of the production phase (A1-A3) is negative or relatively low. The average of the detailed design models is −0.6 kg $CO_2e/m^2/yr$, whereas it is −1 kg $CO_2e/m^2/yr$ for the simplified designs. Although the impacts between the detailed and simplified models have a 40% difference regarding phases A1-A3, this can be considered less significant in absolute values. The detailed designs extend between −6.3 and 1.5 kg $CO_2e/m^2/yr$, and the simplified designs encompass −8 to 1.3 kg CO_2-eq/m^2/yr. It is worth highlighting that the simplified design reveals a minor impact on the production stage apart from cases R06 and R08.

The life-cycle phases A4, A5 and B4 generally provide limited contributions to the overall impact, as the biggest share of the impact comes at the end-of-life phases (C3–C4). For the detailed design, the end-of-life impacts range between 2.1 and 11.3, close to the range

Table 1
Summary of variations to the detailed and simplified designs. DDS = detailed design stage, SDS = early design stage.

	Dwelling Typology	Structural Typology	Metals	Other
DDS	3 multi-storey, 8 terraced houses	8 volumetric prefab, 1 panelized prefab, 1 CLT.	Including metal assembly fasteners and installations such as screws, pipes, ducts.	Excluding installed powered equipment and solar panels.
SDS	3 multi-storey, 8 terraced houses	9 timber frames, 1 CLT.	Excluding metal fasteners and installations.	Excluding non-loadbearing partition walls.

Table 2
Difference in the design configurations of the detailed and simplified designs for the four relevant components. A "no" before a difference means that it is not present at that design stage, and it is present when "no" is absent. DDS = detailed design stage, SDS = early design stage, blank spaces = no structural or configurational differences.

Case	Exterior wall	Interior wall	Floor	Roof construction
M01 M02	DDS: wood + slate cladding SDS: fibre cement cladding	DDS: paint	DDS: bitumen between storeys	DDS: roof terraces, and no loadbearing materials included
R01	DDS: wood + slate cladding SDS: fibre cement cladding	DDS: paint		DDS: roof terraces
R02		DDS: paint	DDS: no floor component available SDS: only legal for internal storey separation	
R03			DDS: concrete SDS: honeycomb-sand	DDS: irregular shape
R04		DDS: paint	SDS: only permitted for internal storey separation, and no surface cover obeying fire protection regulation	
R05		DDS: paint	DDS: bitumen between storeys SDS: internal separation and no surface cover for fire protection	
R06	DDS: wood + brick tile cladding SDS: brick tile cladding	DDS: paint	DDS: bitumen between storeys	DDS: roof terraces
R07	DDS: wood + slate cladding SDS: wood cladding	DDS: concrete, and paint	DDS: bitumen between storeys	
R08	DDS: steel sheets + wood cladding SDS: steel sheets cladding	DDS: paint	DDS: bitumen between storeys	
General	DDS: treatment or paint of wood cladding and wet room products within the building	DDS: wet room products	DDS: wet room products SDS: prefab components are not available	

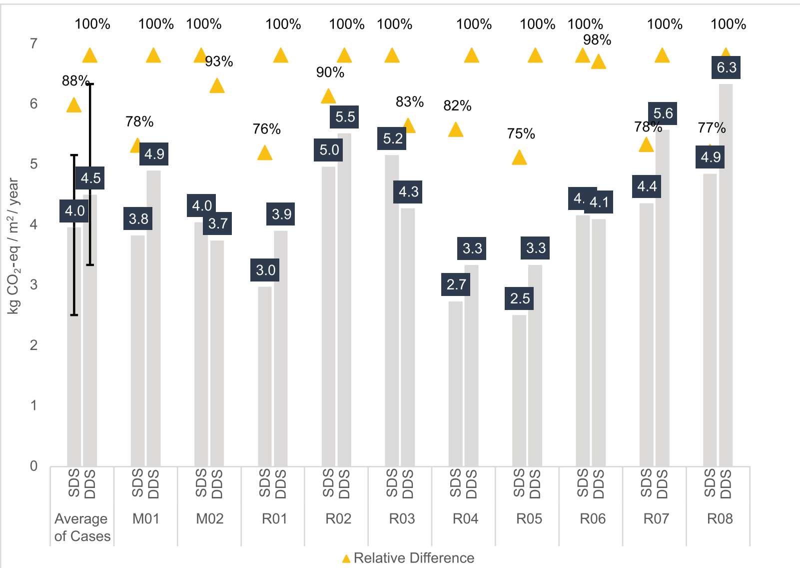

Fig. 2. Total GWP impact in kg CO_2-eq/m^2/yr for the ten sample buildings (including life-cycle modules A1-A5, B4, C3–C4) for the detailed and simplified design and the average across cases, including variance bars showing the buildings with the highest and lowest impacts. The dark blue boxes show the total GWP impact. The design stage with the greatest impact of that specific case has a triangle showing 100%. Triangles below 100% show the proportion that the least impacting design stage constitutes of the highest impacting stage for the building in question (lowest impacting stage/highest impacting stage). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of 2.2–11.9 for the simplified design. The average impacts of both the detailed and simplified design models are approximately 3.9 kg CO_2e/m^2/yr at the end of life, the impact of which can in reality occur long after the selected reference study period of 50 years.

Cases that provide impact reductions (negative emissions) in the production phases emerge with the highest impact at the end-of-life phases for both the detailed and simplified designs. The most considerable discrepancies between the impacts of production and

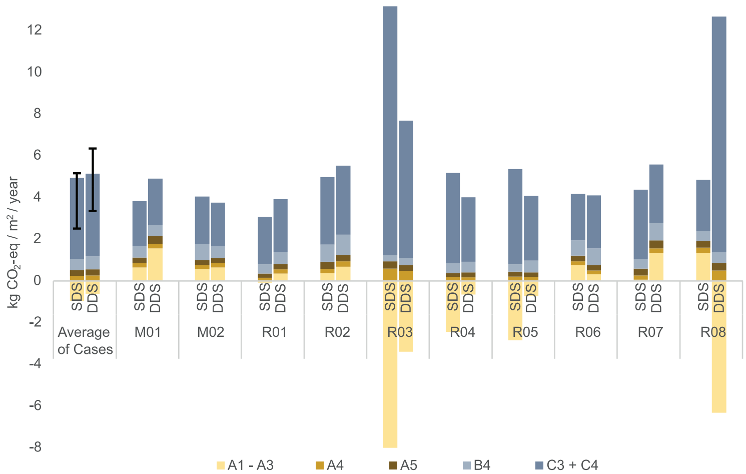

Fig. 3. Total GWP impact (including life-cycle modules A1-A5, B4, C3–C4) distributed on life-cycle phases for each building's detailed and simplified design, and the average across cases, including variance bars showing the highest and lowest impacts.

the end-of-life phases are primarily arising from the approach to calculate the biogenic carbon. The −1/+1 approach supported by EN 15804:2019 norm allocates the uptake of biogenic carbon for bio-based materials at the production phase (−1) and the release of it back to the atmosphere at the end-of-life phase (+1). Nonetheless, the root causes behind the larger release of greenhouse gases in the detailed design rather than the simplified design, viewed broadly, still need localizing by looking at the impact of the components, as shown in Fig. 4.

3.3. *Impacts distributed among component types*

Fig. 4 shows how the foundations, exterior walls and roof constructions contribute most to the total average impact across cases for the detailed design by 1.26 (28%), 1.26 (28%), and 0.70 (15%) kg CO2-eq/m^2/yr. Almost identically, the equivalent figures for the simplified design are 1.17 (29%), 1.15 (29%) and 0.77 (19%). Thus, the proportions of these three components in the total impact are respectively 71% and 77%. The discrepancy in these impact figures appears wider when viewed from the individual cases, where the detailed design demonstrates that the foundations range from 0.6 to 2.3 kg CO2-eq/m^2/yr, or 0.6 to 1.8 for the simplified design. The variations mainly arise from the buildings with footing foundations, which the simplified designs significantly underestimate, while the CLT case, conversely, exaggerates it.

The exterior walls range on average from 1 to 2 kg CO2-eq/m^2/yr in the detailed design and extend slightly lower in the simplified

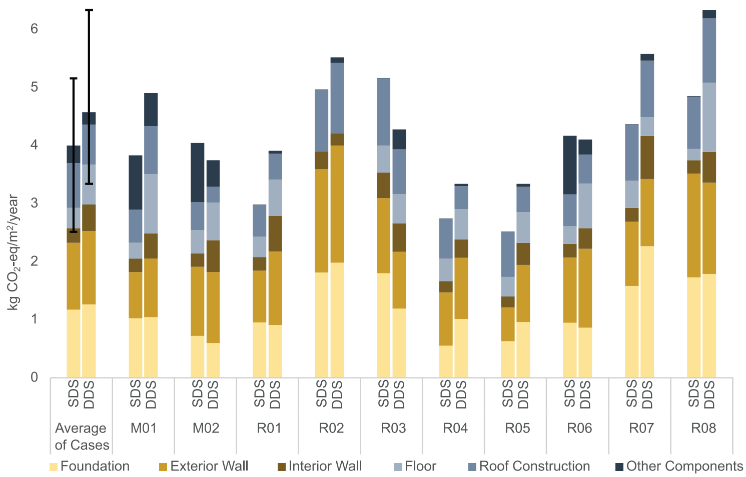

Fig. 4. Total GWP impact (including life-cycle modules A1-A5, B4, C3–C4) distributed among building component types for each building in the case of both the detailed and simplified designs. The average across cases including variance bars shows the cases with the highest and lowest impacts.

design from 0.6 to 1.8. In cases with the most significant discrepancies and with the highest impacts in the detailed design, the differences ascribed to cement-bonded chipboard, paint and assembly fasteners are not included in the simplified design, nor are windows and moisture-barrier impact variations.

The detailed design has an average span for the roof constructions of 0.3–1.2 kg CO2-eq/m^2/yr and for the simplified design of 0.5–1.2. The latter is primarily more impactful regarding roofs, as it includes products related to the ceiling on the top storeys, while the detailed design only sometimes does so, assigning them instead to the floors.

The simplified designs consistently and significantly underrate the impact of the interior walls since they only consider load-bearing, residence-separating walls. The floors also generally have a lower impact in the simplified design. This anomaly stems mainly from five cases in particular, M01-M02, R01, R06 and R08. The omission of wet rooms in the simplified design is one reason for this because tiles, mortar concrete, and other related products are excluded. In parallel, seven of the nine prefabs require bitumen between each storey in the detailed design, constituting 3–10% of the floors' impact.

Generally, a few products have a significant impact share of the floors comprising cement-bonded chipboard of 18–39%, gypsum of 18%, plastic-fibre membrane of 49% and PUR used in flooring underlay of 53%. This suggests the need for a deeper analysis of categories of applied materials in these cases of buildings and of what this means for predicting impacts in the simplified design.

3.4. *Impacts distributed among material categories*

For the detailed design stage, the three material categories with the largest average impacts are insulations 1.05 (23%), cement-based 0.77 (17%) and bio-based 0.67 (15%) kg CO_2-e/m^2/yr, as shown in Fig. 5. Likewise, the sequence for the simplified design is insulations 0.90 (23%), cement-based 0.78 (19%) and bio-based 0.76 (20%), although the detailed design has a slightly greater impact for insulation and vice versa for the bio-based materials. It is worth noting that the differences in absolute numbers could be considerably greater. Insulation contributes most to the impact on average for the actual cases, but two of the three buildings with the lowest impacts attributed to insulation (R04, R05) use paper wool instead of mineral wool.

The impact of bio-based materials is less for the detailed design, both in absolute numbers and in the share of the total, apart from building R08. The impact intensity (impact per kg of employed material) of bio-based materials is also less in the detailed design for all other cases other than R06 and R08. Hence the trend towards the simplified design tool in generating bio-based materials that have higher impact per FU and a higher impact intensity.

In the context of wooden dwellings, the cases of detailed design still show a notable average impact from metals of 0.51 (11%) kg CO_2-e/m^2/yr. This results from the assembly fasteners, gutters, installations (not electrical or otherwise powered installations) and other products that are necessary for wood buildings. This circumstance is widely omitted from the simplified design, on which metals impact at 0.24 (6%). Only building R08 shows a similar impact from metals in both design stages. When adding the average detailed design impact of metals to the simplified design, the total impact would be 4.27 kg CO2-eq/m^2/yr. That is just 5% lower than the detailed design stage (See SI Fig. B9 and B13 for more information on material categories.).

The biogenic carbon temporarily stored in the bio-based materials in the buildings have negative or low impacts on the production phases (A1-A3) in the detailed design (as shown in Fig. 3). All bio-based materials result in the storage of biogenic carbon. However, in the cases with net emissions, namely A1-A3, the impact of the non-bio-based materials is more significant than the reduction. The stored emissions are, on the contrary, shifted to the end-of-life phases (C3–C4), which is a theoretical burden shift when using the −1/+1 method. This method maintains a carbon-neutral perspective over the life-cycle of the building but attributes the savings in the production phases and the burden at the end-of-life phase.

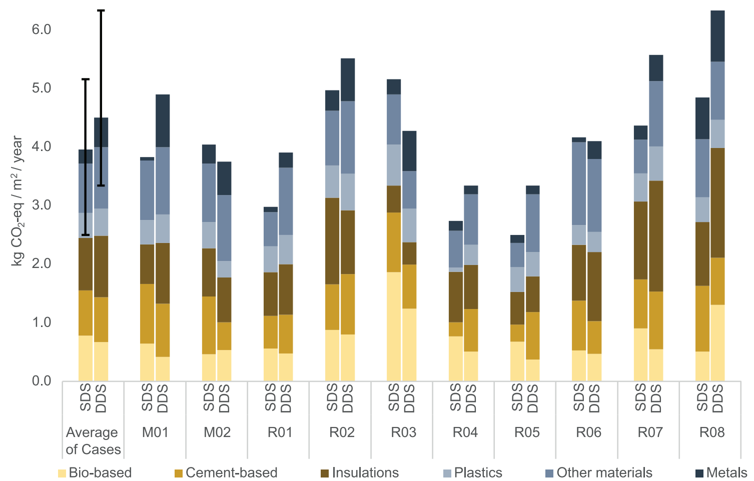

Fig. 5. Total GWP impact (including life-cycle modules A1-A5, B4, C3–C4) distributed among material categories for each building in both the detailed and simplified designs. The average across cases including variance bars shows the cases with the highest and lowest impacts.

3.4.1. Relationship of quantities and impact difference between detailed and simplified design

Fig. 6 presents the differences in quantities (ΔQTY) and impacts (ΔGWP) of subtracting the simplified design by the detailed design for the material categories. This reveals that many cases and their averages (black markers) concentrate around the origin. More substantial differences occur meanwhile among the individual cases and materials. As for the impact of the metals, the quantity is likewise underestimated in the simplified design by 10 kg/m^2 on average.

The figure provides the valuable insight that the materials with the steepest linear regression slope will show the most significant difference in impact by minor alterations to the weight. Nonetheless, the essential materials that require accurate computation of quantities for reliable prediction of impacts are the materials with the coupling of a steep linear slope and considerable ΔGWP scores. See Fig. 7 for a focused presentation of the ΔGWP scores. Therefore, the concerned material categories are insulations, metals, and bio-based materials. Hence, it is important to compute these material categories accurately between a simplified and a detailed quantity take-off. Despite plastics' steep slope and concretes considerable ΔGWP, they are not regarded among the most essential materials since they show less extensive ΔGWP and less steep slope, respectively.

The data markers in the second and fourth quadrants of Fig. 6 imply a disproportionate correlation between the difference in the material quantity and the GWP score. Therefore, materials will have a high impact-to-weight ratio for the detailed design if placed in the fourth quadrant, and similar for the simplified design if placed in the second quadrant. For the former, the anomaly features a cement-based material case, and is slightly the same for two cases of insulation. The detailed design has four cases of bio-based materials (M01, R01, R02, and R06). R01 has circa ten times the quantities of chipboard and laminated veneer lumber in the simplified design and features high emission factors compared to the other wood products. Despite there being more construction wood in the detailed design of case R06, the quantity and emissions factor of the wooden floor cover (twice the quantity) and the laminated veneer lumber in the simplified design result in a higher impact.

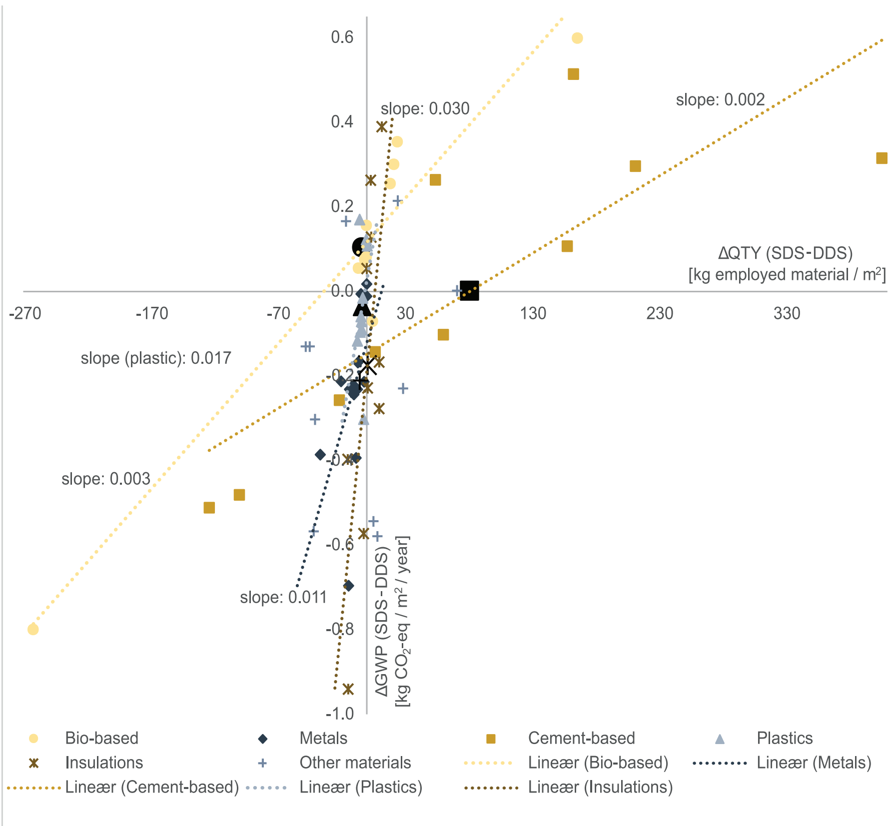

Fig. 6. The figure shows the differences between the material categories when subtracting the detailed design from the simplified design of the quantity (ΔQTY) and impact (ΔGWP) (incl. life-cycle modules A1-A5, B4, C3–C4) of the ten cases. The ΔQTY (kg employed material/m^2) is on the horizontal axis, the ΔGWP score (kg CO_2-eq/m^2/year) is on the vertical axis. The blacked markers show the average of the cases and the materials' linear regression with slope is represented by the dotted lines. DDS = detailed design stage, SDS = early design stage.

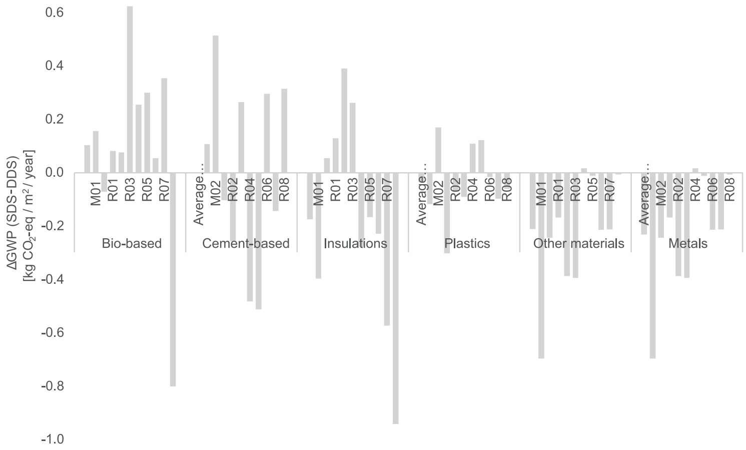

Fig. 7. The differences between the material categories when subtracting the detailed design from the simplified design of the impact (ΔGWP) (incl. life-cycle modules A1-A5, B4, C3–C4) of the ten cases.

4. Discussion

4.1. Characterization of buildings and their impact

The least impactful cases of design are two-storey and one-to two-storey buildings in both design stages, with volumetric modules of a wooden frame and designed with footing foundations. Aside from case R03, nine cases are of modular prefab buildings; eight are volumetric modules, and one is a panelized module. Six of these buildings have greater impacts in the detailed design case. The detailed design of prefab buildings contains additional bitumen in the floors between the storeys for protection. That explains the generally higher impact, as well as some detailed design cases that include upper-storey ceilings and ground-level flooring as a part of the floor components, unlike the simplified tool. The simplified design tool should thus be modified to include suitable modular prefab building components for floors.

4.2. Components: improvements needed for simplified modelling

Table 3 presents the main conclusions and improvement aspects for the different components. For the simplified wooden-frame exterior walls, the limitation is ascribed to the absence of metal assembly fasteners.

The roof construction needs consistency regarding which design stages under- or overestimate the impact. This is primarily because of the incongruity of the components to which the roof ceiling products belong. In addition, consideration of roof terraces, or moving from continuous flat or gabled roof shapes in the detailed design, may result in impact discrepancies, even though this is not apparent in this study.

The inaccuracy of the interior walls confirms that partition walls and wet-room products need representation in a simplified design

Table 3
Main conclusions and improvement aspects of the simplified design for the different component types and their structural typology.

Component type	Typology	Main conclusions and improvement aspects
Foundation	Raft	The one case of CLT structure needs to be more accurate. More cases are needed to evaluate whether it can be validated for the CLT structure.
	Footing	Inaccurate. Needs computation improvement in the simplified design tool.
Exterior wall	Wood frame	Aside from two cases, the simplified design consistently makes a slight underestimation of impact. Two-material cladding cases have a less accurate impact than single-material cladding. A designer should be aware of this when designing with more than one cladding material.
Interior wall	CLT	Quite accurate but needs further assessments of cases for validation.
	Wood frame	Inaccurate i.e., it is important to consider partition walls and wet-room products in the simplified design tool for this typology.
Floor	CLT	Quite accurate but needs further assessments of cases for validation.
	Beam system	Inaccuracies are difficult to validate: first, due to unharmonized data configurations, where some foundation and roof products in the detailed design are registered as floors. Second, prefab components need to be represented in the simplified design leading to the absence of bitumen between storeys, as in the detailed design. Prefab floor components should therefore be added to the simplified design tool.
Roof construction	Rafter construction	The roof shape of the detailed design is not very generic in all cases, which can lead to an inaccurate simplified design. The designer should be aware of this aspect. The ceiling products with the detailed design are often, unlike the simplified design, configured as belonging to the floors. It will keep the overall impact the same but muddle the analysis at the component level.

Table 4
Main conclusions and improvement aspects of the simplified design for the different material categories, excluding the "other materials" category.

Material category	Main conclusions and improvements
Bio-based	The simplified design consistently provides larger relative and absolute impacts and mass per FU.
	Construction practices could improve bio-based material applications based on the simplified design, as its quantities evolve from building code requirements for structure, fire safety and insulation capacity.
Metals	The simplified design needs an empirically based default factor per gross living area for components for metal assembly fasteners.
	The simplified design needs an empirically based default factor per building area for installations, e.g., ducts, pipes and water tanks, and for technical installations, e.g., ventilation aggregates and boilers.
	The impact is responsive to small differences in material quantities.
Cement-based	Slight underestimate in the simplified design, but no further improvement is needed.
Plastics	Small contribution in the detailed and simplified design (6–7%), but no further improvement is needed.
Insulations	The impact is responsive to small differences in material quantities, but no further improvement is needed.

model. The CLT interior wall needs an added default factor for the wooden frame underpinning the insulation because the non-loadbearing partition walls are not of CLT in practice. The simplified footing foundation needs improvement since the impacts emerge significantly lower in the early design. The footing foundations, meanwhile, show the lowest impact of the foundation components for both design stages. One suggestion is to focus on implementing this type of foundation where possible or to construct wooden buildings on sites where this type of foundation is feasible.

The raft foundations are modelled by a default quantity factor per area, still unfolding quite accurately in seven of the nine buildings with wooden frames. Adopting structural calculations for the raft foundation in the simplified tool might be relevant because this component generally has the largest share of the impacts. Another technicality is that the foundations rely on the local site's ground conditions. This aspect can affect the accuracy of the simplified designs of raft foundations.

4.3. Materials: improvements needed for simplified modelling

Table 4 provides an overview of the conclusions and improvements needed concerning the materials embedded in the components. Metals are the main material category requiring modification. Disregarding metals from the average impact of buildings of both detailed and simplified design, the difference in absolute impacts will be 0.2 kg $CO_2e/m^2/yr$ instead of 0.5. Theoretically adding the average impact of metals in the detailed design to the simplified design reveals a difference of only 5%. Integrating a default factor per area for technical installations, such as ventilation aggregates and boilers, and for installations, such as ducts, pipes, water tanks and assembly fasteners, could advance the tool further. Further, generating precise quantities of the metals, insulations and, in part, bio-based materials is more critical than cement-based materials because impact adjustments are relatively responsive to small changes in mass.

4.4. Lessons, inspiration, and recommendations for practice

Overall, the simplified design tool adds a dimension to early-stage environmental assessments by quickly generating quantities of a desired design. Access to the tool's background sheets facilitates the possibility of updating it for any national deviations in building codes and making it applicable in many European countries. The tool also addresses the increased attention being paid to building in wood where the climate-mitigation potential of low-rise residential buildings is most evident, as elaborated in section 1. Hence, it can support designers in making more effective design choices.

Cases R04-R05 mutually exhibit the least impact in this study in both the detailed and simplified design stages. This suggests that two-storey terraced houses of (prefab) wooden frame structure, in conjunction with footing foundations, results in the least impact. This confirms that using footing foundations to obtain the least impactful dwellings means that wooden buildings should be prioritised in areas where soil and ground conditions make this option applicable.

The tool also aimed to thoroughly compute the floor, exterior wall and roof components based on the Danish building code. As a result, some simplified components could be relevant for a deeper assessment to inspire construction practice towards lower component impacts, as discussed below. The outcome of another study confirms that dwellings currently seem to optimize according to labour and other costs rather than materials [32].

The average impact of floors in the case of the simplified design tool is 0.35 kg $CO_2e/m^2/yr$, with the four lowest impacts being from R08 (0.20), M01 (0.28), R06 (0.30) and R05 (0.34). The first and last cases are two-storey terraced houses, while the two in the middle were modelled as three-storey apartment blocks. As a result, the number of storeys does not influence the best-performing simplified floors. Table 5 explains the applicability, properties, and lessons for a further overview. A remark on floor F2 (SI Fig. B4): the structure is scaled up to obey the fire-resistance period and the remaining fire safety regulations, but not the fire safety surface cover requirement. A test to understand if the omitted surface cover reduced the impact interestingly resulted in the component having a low impact.

4.5. Limitations to the study and future research opportunities

The detailed design projects assessed in this study encompass several separate building blocks as a group of buildings, often with a variable number of storeys. In this regard, the simplified design tool's drawback is that it can only model a single building block. Correspondingly, this study does not compare one-to-one building blocks with respect to their dimensions. Instead, the simplified

Table 5
Designated components that show low impact in the simplified design with a description of how it is or can be applied (applicability), its properties and its lessons for practice.

Component	Applicability and properties	Lessons for practice
Floor (F2): beam system with a high-density layer of sand-honeycomb (equivalent to a concrete layer)	Internal horizontal storey separation only. Does not observe fire safety surface regulations.	Valuable to assess practical use potential from a climate mitigation perspective compared to a wooden beam-concrete system.
Floor (F4): beam system	Internal storey separation only. The requirement of the surface cover thickness (gypsum) increases from 2 to 3 storeys.	Increased gypsum thickness should not elicit a higher impact of this component.
Exterior wall (EW1): wooden frame	Two two-storey cases of paper wool insulation and wooden cladding. Two three-storey cases of mineral wool insulation and fibre cement cladding.	Paper wool reduces the impacts of two-storey terraced houses using the −1/+1 method. Wooden frame walls increase efficiency from 2 to 3 storeys.
Roof construction (RC3)	Three three-storey cases of rafter roof with bitumen. One four-storey case of rafter roof with steel sheets.	A low impact intensity also results in low functional unit impact. The roof components need an extended assessment.

design model used a representative building block from each case. Comparison per FU (per area) was still possible. However, this implies some uncertainty regarding the material intensity of the different building cases, which could shift in favour of either design stage, conditional on the project.

The tool's subsequent development is integration with LCAbyg and other LCA tools [28], a feature that can accelerate the LCA outcome to benefit from the added value of the quick quantity generation. The integration could preferably have predefined libraries of the components in the tool by using the generic processes of Ökobaudat or sector EPDs. Ultimately, public availability for industry designers and consultants could progress the LCA of wooden dwellings in practice.

Ultimately, this study assesses climate impacts exclusively by GWP, hence vacating a gap for assessing the tool's accuracy for other impact categories. Analysing a broader range of impact categories would be valuable in comprehensively estimating environmental sustainability.

5. Conclusion

In the effort to improve climate mitigation decision-making in the early stage of building design by LCA, this study has presented a comparison between simplified and detailed design quantities with references to ten actual wooden dwellings. The decision-making in the early building design implies restricted money and time alongside limited experience and knowledge. This a problem the simplified design tool addresses by cutting the time of quantity generation and the subsequent LCA. The conclusions to be drawn from comparing the detailed and simplified design of wood dwellings follow below:

- Dissimilar estimates of bio-based materials between design stages can shift the magnitude and proportion of impact in phases A1-A3 and C3–C4. However, this will not necessarily change the total impact significantly over the entire life-cycle.
- The GWP impact of bio-based materials, metals and insulation materials is responsive to slight quantity differences between the detailed and early design stages. These materials consequently require more accurate quantity predictions in the simplified design than, for instance, cement-based materials in the construction.
- In addition, simplified quantities in the early design stage (LOD 100–200) need added default values per gross living area of metals, such as assembly fasteners, installations, and technical installations, for a more complete impact estimate.
- A single product can have up to 53% of a component's impact. Hence, the accuracy of a simplified design compared to a detailed design may merely rely on the choice of the LCA generic unit process or the EPD representing that product than the prediction of quantities itself.

Based on the ten actual cases of buildings, some additional recommendations for the design of wooden buildings can be made:

- Concrete rafter foundations compose a significant share of a wooden dwelling's GWP impact, whereas a footing foundation, by contrast, results in the lowest total GWP impact in both the simplified and detailed designs. Thus, wooden dwellings could have a priority in areas with soil conditions that can take footing foundations.
- Building terraced houses with horizontal storeys that are not separating different apartments will reduce the impact of the floor components due to fewer requirements for acoustics. In addition, floor components that challenge the building code regarding fire safety surface requirements have a lower impact than those obeying the code. This circumstance provides a basis for further research.
- Using paper wool instead of mineral wool reduces the GWP impact of insulation, which on average is the largest contributory material category for the wooden buildings we studied. Therefore, examining bio-based insulation could be viable, including by studying the potential of insulation made from fast-growing bio-based materials.

The simplified design tool is useful for decision support in the early design phase when dealing with the components of the foundations, exterior walls, and floors. The simplified roof components of rafter constructions might estimate quantities and impact appropriately, but more cases with similar data configurations between the detailed and simplified design are required. Relative comparisons of design proposals are often sincerely used by designers. In contrast, pending further improvements, the total impact of the simplified design should be treated as underestimated compared to a detailed final design by an average of 12%.

Author contributions

Rasmus Nøddegaard Hansen: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – Original Draft, Visualisation. Endrit Hoxha: Conceptualization, Methodology, Validation, Writing – Review & Editing, Supervision. Freja Nygaard Rasmussen: Validation, Resources, Writing – Review & Editing, Funding acquisition. Morten Walbech Ryberg: Validation, Writing – Review & Editing. Camilla Ernst Andersen: Review, Data curation. Harpa Birgisdóttir: Validation, Resources, Writing – Review & Editing, Supervision, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to correct spelling and grammatic. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Funding

The authors would like to acknowledge VILLUM Fonden for financial support of the research as a part of grant no. 00029297 and 37169. The authors would also like to thank Real Dania for financial support in the collection of case studies as a part of grant no. PRGJ-2020-00273. The funding sources had no role in conducting the research in this article.

Declaration of competing interest

The authors declare no competing interest.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors wish to thank Jan Kauschen for his collaboration and for leading the development of the simplified design tool for this research project as well as the individual contributions to the team by Michael Granby-Larsen, Liv Ridder-Storgaard, Kasper VItten, Kasper Lau Køppen, William, and Bo Mortensen.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2023.106974.

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Appendix C. Publication 3

Publication 3: **Environmental consequences of shifting to timber construction: the case of Denmark**. *Hansen, R. N.; Eliassen, J. L.; Schmidt, J.; Andersen, C. E.; Weidema, B. P.; Birgisdóttir, H.; Hoxha, E.* In: Sustainable Production and Consumption, 2024. DOI: https://doi.org/10.1016/j.spc.2024.02.014

Sustainable Production and Consumption 46 (2024) 54–67

Contents lists available at ScienceDirect

Sustainable Production and Consumption

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

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

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A R T I C L E I N F O

Editor: Dr Diogo Aparecido Lopes Silva

Keywords:
Consequential life cycle assessment
Dynamic LCA
Indirect land use change
Forest modelling
Material flow analysis
System thinking

A B S T R A C T

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

1. Introduction

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

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

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https://doi.org/10.1016/j.spc.2024.02.014
Received 10 November 2023; Received in revised form 9 February 2024; Accepted 10 February 2024
Available online 15 February 2024

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

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

1.1. Consequential LCA and applications on buildings

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

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

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

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

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

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

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

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

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

2. Methodology

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

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

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

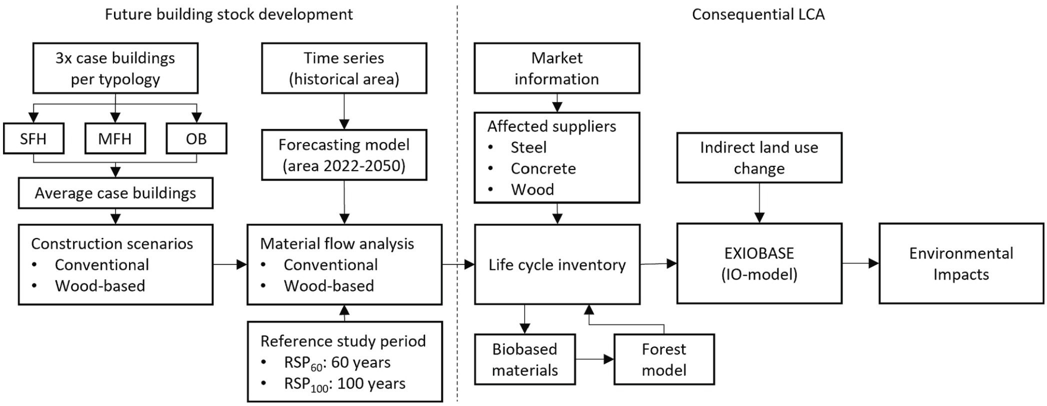

Fig. 1. The methodology used in this study. It encompasses the future building stock forecast and material flow for the conventional and wood-based construction technology scenarios. Then, the modelling overview and inputs to the consequential LCA for determining the environmental impacts. SFH = single-family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

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

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

2.2. LCA methodology

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

2.2.1. Goal and scope of the LCA

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

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

2.2.2. Life cycle inventory

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

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

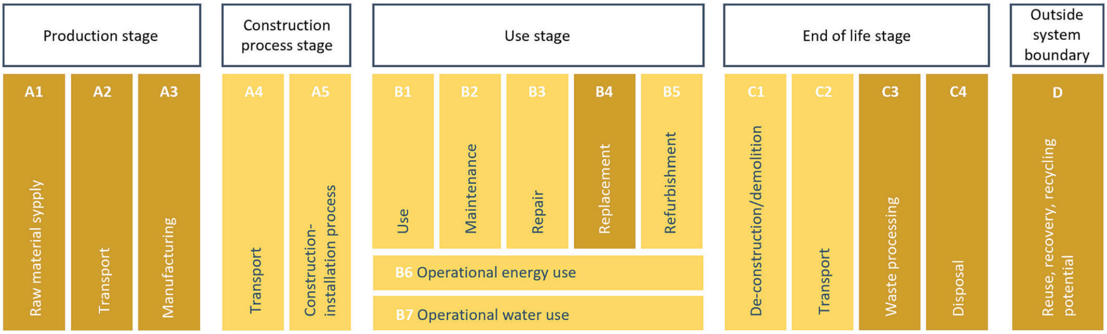

Fig. 2. The life cycle stages included in the LCA are the modules highlighted with darker colours.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.2.3. Life cycle impact assessment

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

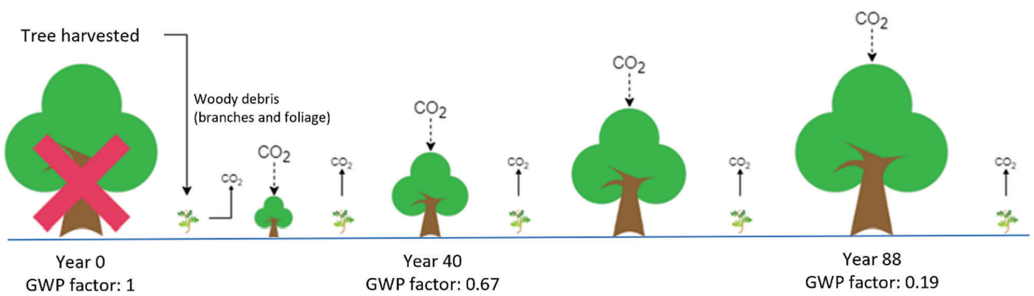

Fig. 3. The diagram shows the logic of the forest model after a tree harvest in year 0, whereafter a new tree is grown and sequesters carbon during the rotation period. Woody debris is considered left on the forest floor to emit CO_2, with temporal GWP factors decreasing over time (Schmidt and Brandao,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

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

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

3. Results

3.1. Material stock

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

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

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

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

3.2. Environmental impact assessment

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

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

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

Table 1
Material quantities in terms of weight divided into production stages and replacements for conventional and wood-based construction for 60- and 100-year RSPs for all building typologies. The weight is the share between life cycle stages and absolute weight as kg/m^2. SFH = single family houses, MFH = multi-family houses, OB = office buildings.

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

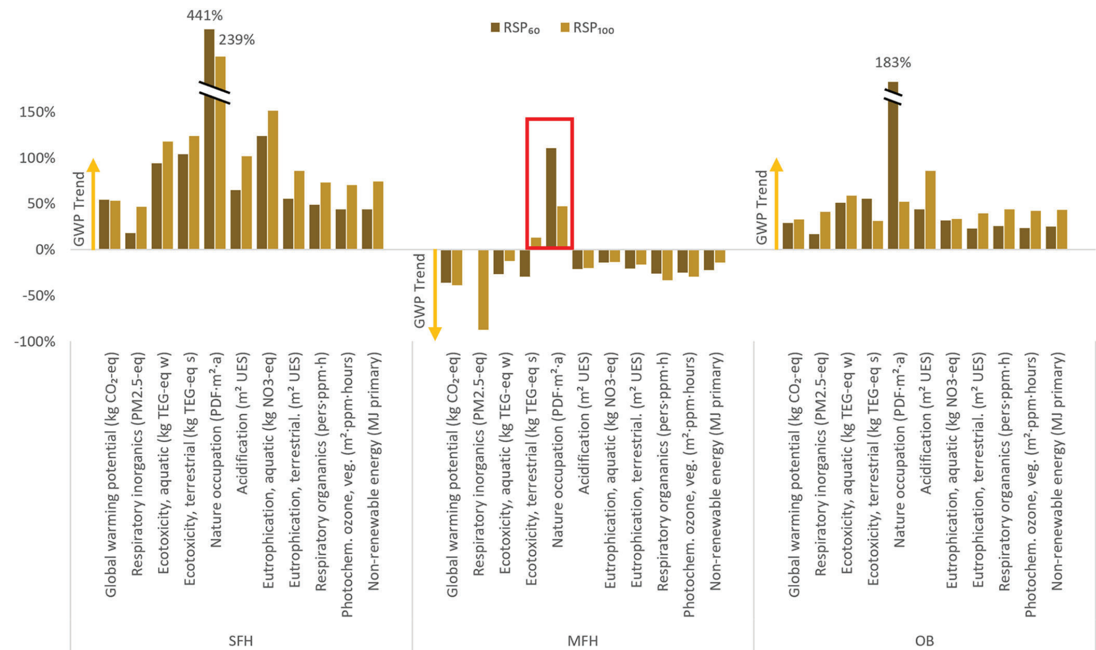

Fig. 4. The difference in impact between the conventional and wood-based scenarios (wood – conventional) for the considered impact categories for the three building typologies for RSP_{60} and RSP_{100}. The arrows show the GWP trend, and the red box highlights the impact categories that do not follow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

hence concentrates on the climate impacts.

3.2.2. Climate impact for the two construction scenarios

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

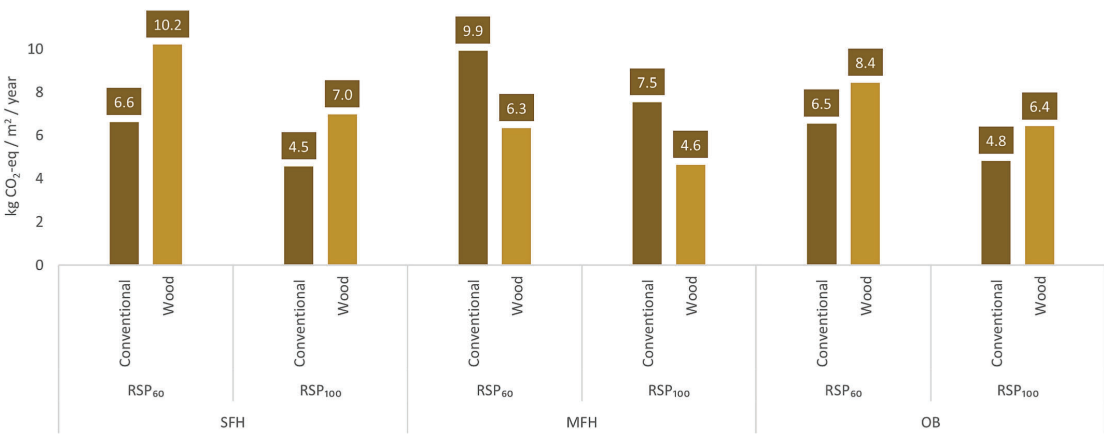

Fig. 5. The total climate impact of the construction scenarios. SFH = single-family houses, MFH = multifamily houses, OB = office buildings, RSP_{60} = reference study period of 60 years, RSP_{100} = reference study period of 100 years.

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

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

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

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

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

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

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

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

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

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

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

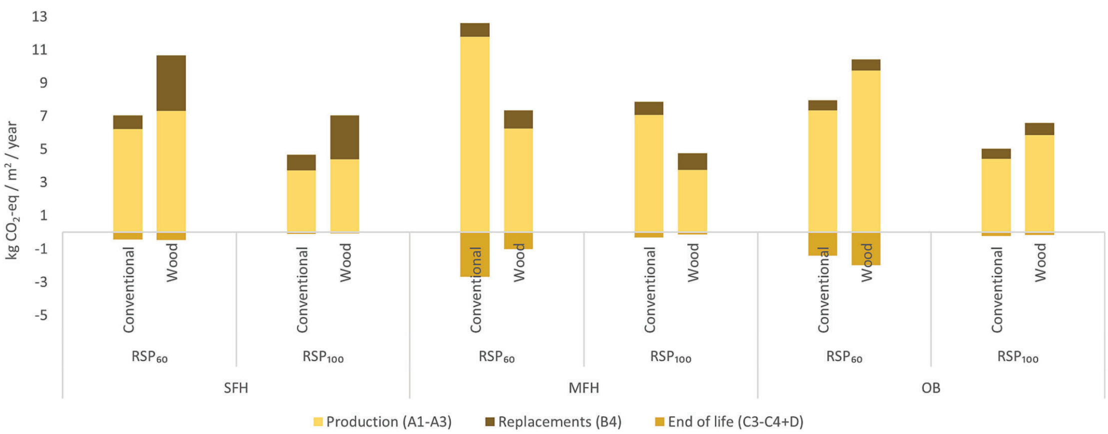

Fig. 6. Climate impact of the construction scenarios distributed onto life cycle stages. SFH = single-family houses, MFH = multifamily houses, OB = office buildings, RSP_{60} = reference study period of 60 years, RSP_{100} = reference study period of 100 years.

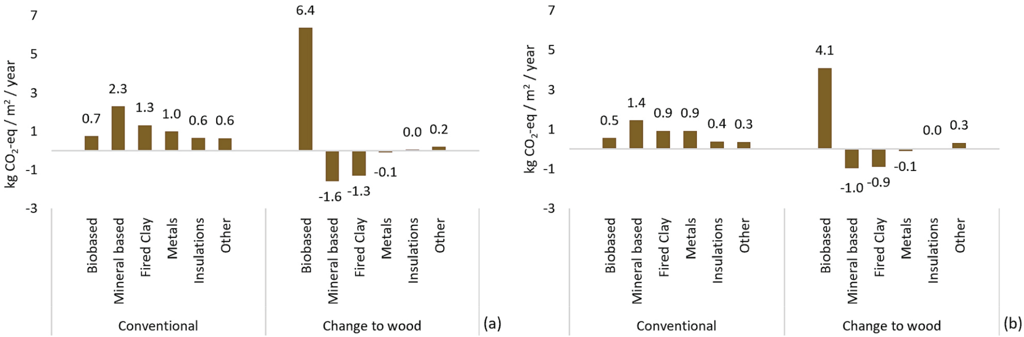

Fig. 7. The climate impact (kg CO_2-eq/m^2/year) for single-family houses of conventional construction and the change to wood distributed onto materials. The change to wood shows the difference in wood construction relative to conventional. (a) Shows the climate impact for an RSP of 60 years. (b) Shows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

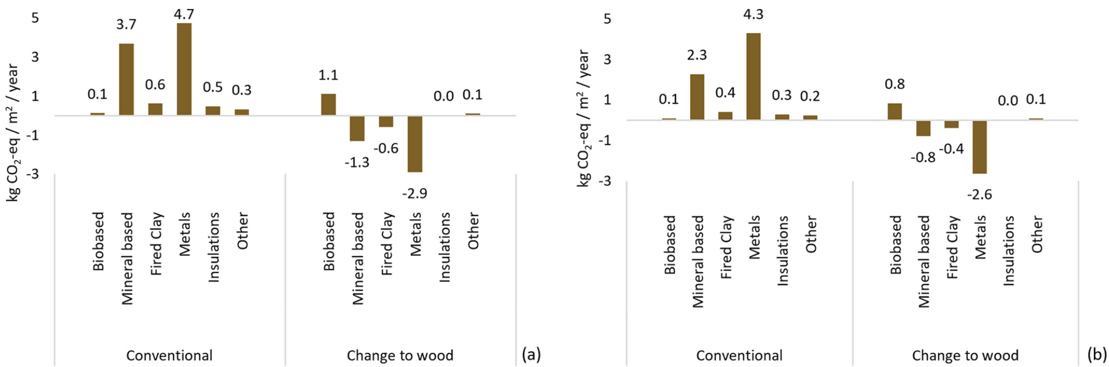

Fig. 8. The climate impact (kg CO_2-eq/m^2/year) for multifamily houses of conventional construction and the change to wood distributed onto materials. The change to wood shows the difference in wood construction relative to conventional. (a) Shows the climate impact for an RSP of 60 years. (b) Shows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

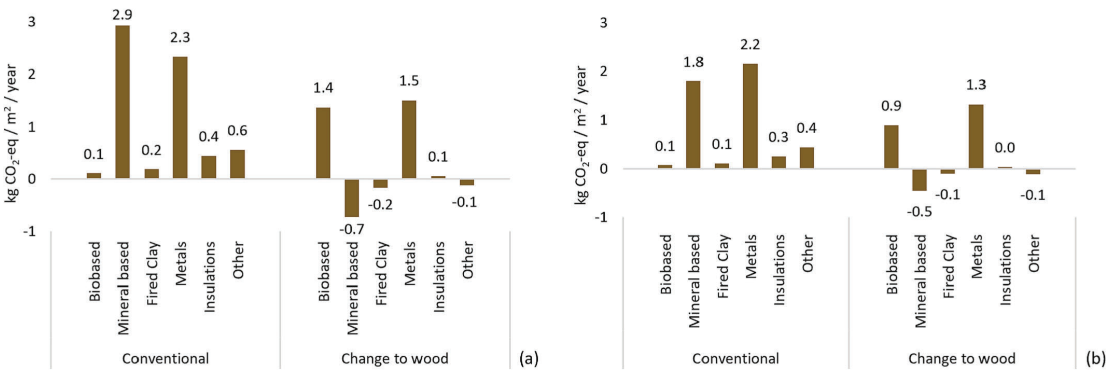

Fig. 9. The climate impact (kg CO_2-eq/m^2/year) for office buildings of conventional construction and a change to wood distributed into materials. The change to wood shows the difference in wood construction relative to conventional. (a) Shows the climate impact for an RSP of 60 years. (b) Shows the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

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

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

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

4. Discussion

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

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

4.1. Case buildings

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

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

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

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

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

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

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

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

4.2. Methodological implications and limitations

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

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

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

4.2.1. Sensitivity analysis

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

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

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

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

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

4.2.2. LCA methodology

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

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

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

4.2.3. Forest modelling and iLUC

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

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

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

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

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

5. Conclusion

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

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

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

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

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

Declaration of generative AI in scientific writing

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

Funding

The authors would like to acknowledge VILLUM Fonden for financial support of the research as a part of grant no. 00029297 and 37169. The authors would also like to thank Realdania for financial support in the collection of case studies as a part of grant no. PRGJ-2020-00273. The funding sources had no role in conducting the research in this article.

Declaration of competing interest

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

Acknowledgements

The authors wish to thank Simon Vemmelund, 2.-0 LCA consultants, for valuable feedback on the article's final draft regarding subject-specific content and formulations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.02.014.

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Appendix D. Publication 4

Publication 4: **Reducing the land use impact of wood buildings with fast-growing biobased materials**. *Hansen, R. N.; Hoxha, E.; Birgisdóttir, H.; Pittau, F.* Draft, Expected Submitted To: Sustainable Cities and Societies, 2024.