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Wood as a carbon mitigating building material: A review of consequential LCA and biogenic carbon characteristics

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Abstract. Buildings can potentially be carbon sinks by use of wood under correct circumstances because wood sequesters CO_2 i.e., biogenic carbon, from the atmosphere by photosynthesis during growth. Consequential life cycle assessment (CLCA) works as a decision support tool to assess consequences from a change in demand by including only the processes that are affected by this demand through market-based modelling. This study aims to review current research about CLCA on wood in buildings. First, by examining methodological approaches linked to CLCA modelling and biogenic carbon accounting of wood in buildings. Second, to evaluate conclusions of studies using CLCA on wood in buildings. We conducted a literature review of 13 articles that fulfilled the criteria of stating to conduct a CLCA concerning either buildings, components, or materials where wood is one of the materials.
The application of the reviewed studies include: method development, reuse, testing end of life aspects, CLCA inventory modelling, and comparison of ACLA and CLCA. The CLCA inventory of small-scale studies comprise a wide spectrum of methods ranging from simplistic to advanced methods, often retrospective. All large-scale studies integrate sophisticated modelling of prospective analysis. Dynamic time-dependent biogenic carbon accounting and indirect land use change (iLUC) are rarely represented. Although, both aspects have an impact on whether wood buildings respectively work as carbon sinks or provide net GHG emissions. Wood multi-storey buildings generally perform environmentally better than concrete and steel buildings due to wood displaces these materials and residues substitute fossil energy. End of life scenarios, choice of substituted production, retro- and prospective data, and the share of recycled steel further influence carbon mitigating potential of wood in buildings.
Research of CLCA on wood in buildings are many-fold. Some studies partially evade inclusion of some CLCA aspects i.e., market delimitation, market trend, affected suppliers, and substitution. A simultaneously high integration of both CLCA, time-dependent biogenic carbon accounting, and iLUC in the same study is almost absent. Consequently, more empirical and methodological CLCA studies are needed while including dynamic time-dependent biogenic carbon accounting to improve understanding of implications of policy decisions in transitions towards increased use of wood in buildings.

Keywords: Buildings, Consequential, Life Cycle Assessment, Wood, Biogenic Carbon.

1. Introduction

There is increased focus on embodied impacts of materials used in buildings because it is important to reduce the immediate accumulated greenhouse gas (GHG) emissions in the atmosphere [1]. On this basis, biogenic materials, particularly wood, attract enhanced attention because of its ability to store carbon under the right circumstances.

Life cycle assessment (LCA) is the methodology to model and measure environmental impacts across the life cycle of a product [2]. The LCA methodology distinguish between attributional (ALCA) and consequential (CLCA) [2]. ALCA account the environmental impacts of a product system where the system under study is assigned a mix of specific processes that is a part of the product value chain. The ALCA applies to previous, current, and future selected points in time of a system. Further, multifunctional processes can be solved by either substitution (system expansion) or allocation [2]. CLCA centers on the principle of consequences of a decision by attempting to define a product system by the processes affected by the consequences that the decision induces to the overall economic system [2,3]. Similar to ALCA, the CLCA approach can be applied at any point in time. CLCA models the processes expected to change from a decision instead of modelling value chain associated directly with the product as in ALCA. Unlike the ALCA approach CLCA can only solve multifunctionality by substitution.

1.1. Consequential LCA framework

The framework for CLCA has evolved over time and is described by the four-step procedure [4], which this study aims to follow. The first step of the four-step procedure is defining scale and time horizon. Scale entails whether a change in demand for a product will induce small- or large-scale changes in the economy. The difference of small- and large-scale change in demand is whether it alters the determining parameters of the existing market i.e., whether the change can be met within existing production capacity or if production capacity needs to be increased or decreased faster than planned e.g., installing more capital goods. Time-horizon involves whether the change in demand is considered to have consequences in either the short-, medium- or long-term. Time-horizon is not necessarily the equivalent to the service life of the building under study.

Second, a market delimitation must be conducted to encapsulate the supplying markets of a given product that experience a change in demand. Third, the market volume trend follows to determine the trend of the given product in the identified market. The trend influences whether the most or least competitive suppliers should be considered as inventory processes. An increasing, stable, or slowly decreasing market leads to the most competitive suppliers being the affected suppliers. A fast-decreasing market requires the least competitive suppliers to be included. Fourth, the unconstrained suppliers must be identified among these affected suppliers, frequently termed marginal suppliers. The four-step procedure would also be the practice to identify avoided affected suppliers of which production is substituted in case of multifunctional processes (see [4]).

1.2. Biogenic carbon methods

LCA of wood products encompasses a necessity for biogenic carbon considerations. Trees sequester atmospheric carbon by photosynthesis during growth, which is termed biogenic carbon. A harvested tree used as a construction material would have the sequestered carbon stored in the material until it reaches its end of life (EoL). At the EoL the material will typically be incinerated or landfilled with release of all the biogenic carbon to the atmosphere [5]. Currently, LCAs sometimes consider wood materials as carbon neutral i.e., the 0/0 method. A simplification that might underestimate the GHG reduction benefits of storing the biogenic carbon in long lasting products such as a building material and overestimate these benefits when using the wood for e.g., energy production [6,7]. Another method is the -1/+1 approach that account the sequestered carbon in wood materials as a negative impact during construction and consider it fully released at the EoL [5]. At times, the EoL is left out of Environmental

Product Declarations of wooden building materials [8], consequently the release is not accounted in the -1/+1 approach and the wooden building material emerge as more climate friendly than it might be.

The previous approaches consider the real carbon flows too simplistically in LCA, thus, underestimate the potential for storage in long lasting product as building materials. It requires a time-dependent approach, [6,9], which is termed dynamic in this study. The storage potential of wooden materials depends on the relation of the GWP time horizon (often 100 years), material service life, and the rotation period of the tree. Rotation period is the time it takes a new planted tree to sequester same amount of carbon as the harvested tree [10]. Before the carbon storage can reduce accumulated GHGs in the atmosphere and transform buildings to carbon sinks replanting is required. Another biogenic product aspect is land-use changes (LUC) from the change in use of wood, which can be considered as direct LUC (dLUC) and indirect LUC (iLUC) [10].

With larger attention directed at wood in buildings, the decisions to increase use of wood create changes and consequences to the underlying supply chains and production of materials. Hence, this review aims to evaluate the status of CLCA on buildings that include wood materials, and to what extent they adopt biogenic carbon and LUC aspects. That leads to the following research questions:

- What are the intended applications and scale of built environment CLCAs where wood materials are included?
- To what extend are biogenic carbon mechanisms captured in the CLCAs, what consequential modelling methods do the studies employ and what are their strengths and limitations?
- Which conclusions and learnings do the studies present when assessing environmental impacts of wood in buildings using CLCA?

2. Methods

2.1. Review process

Studies were searched via Google Scholar, Scopus, and Web of Science. Search words comprised three main categories of synonyms: (i) consequential LCA, CLCA, consequential life cycle assessment; consequential life cycle inventory; (ii) approach, methodology, characteristics, modelling, perspective; (iii) building, building component, building material, dwelling, construction. Included studies had to be published between January 1st 2000 and 14th of September 2021. Studies without wood as minimum one of the materials were excluded. The authors of this review also added known grey literature, which yielded 13 studies in total. Eight studies were published in journals with impact factor between 3.53-9.56, four studies were conference proceedings with impact factor between 0.41-1.89, and one study was grey literature.

2.2. Information extraction

During the review process data were extracted regarding goal, consequential aspects, and biogenic carbon aspects as presented in Table 1. Studies were divided into three overarching groups based on the stated intended applications e.g., as purpose, aim, goal, and assigned an object of study. The object of study covered whether a study considered material, component, building, or building stock and was also used as a simplified method to divide the studies into small- or large-scale of change. Studies with building stock as object in Table 2 were considered large-scale and the remaining considered small-scale. Time horizon was deducted by whether the study explicitly stated short-, medium- or long-term or included a reference period that were considered as follows: short-term is 0-5 years; medium-term is 6-10 years; long-term is more than ten years. The four-step procedure founded basis for extracting consequential life cycle inventory (CLCI) information i.e., market delimitation, market volume trend, affected suppliers, and substitution. These four aspects were evaluated and then divided into three specification levels of low, medium, or high.

With focus on wood in buildings, biogenic carbon stock plays an important role regarding climate impact assessment. Hence, information on biogenic carbon flow and how this was considered were analyzed. Further, included LUC aspects and the considered carbon stock were gathered from the studies.

Table 1. Extracted information and grouping of goal, consequential aspects, and biogenic carbon aspects

Goal Analysis		Consequential Aspects		Biogenic Carbon Aspects	
Intended application	Object of study	Aspect	Extracted information	Approach	LUC
(i) Empirical studies that examine consequences of a decision based on a case study, (ii) Studies that either examine method aspects, method and empirical case aspects, or non-CLCA case aspects, (iii) Method development for CLCI modelling.	(i) Material (ii) Component (iii) Building (iv) Building stock	Scale Time horizon Market delimitation Market volume trend Affected supplier Substitution	Small or large Short-, medium-, and/or long-term Identification or modelling method Yes, if included N/A, if not included	Not declared 0/0 -1/+1 Dynamic time-dependent biogenic carbon, Carbon stock boundary i.e, above ground, below ground, thinning, only timber carbon stock.	dLUC included (yes/no) iLUC included (yes/no) Influence of ilUC on GHG impact

Eventually, we compiled the conclusions and outcomes from conducting CLCA on wood in buildings from the reviewed studies. It was completed by reading discussion and conclusion from the papers where the outcomes deviate between methodological aspects and empirical findings.

3. Results

The review process yielded three articles that develop a method for CLCI modelling whereas the remaining ten articles had an empirical perspective, yet six of them combined it with methodological examination. The next paragraphs will focus on intended applications of the studies, the studied scale of change, CLCI aspects, biogenic carbon aspects, and the conclusions of the respective studies.

3.1. Intended applications

Firstly, a CLCA study comprises the definition that it should center on the consequences of a decision [1] [7], which is defined in the intended applications of a study. Table 2 discloses that the studies can be roughly divided in three groups as defined in Table 1, though with some overlap.

Group (i) purely focuses on empirical assessment converged at the principle of consequences of a decision. Group (ii) articles span a broader definition where one center on a case analysis, though, indicating to be descriptive (attributional) [11]. [12,13] assess methodological aspects such as comparing ALCA and CLCA, EoL assumptions but also engage with an assessment of a case study. The studies of [14,15] consider similar scenarios aiming to test sensitivity of various modelling approaches. The former study sway to be descriptive while the latter consequential based on their stated purpose. Ultimately, [16] engage LCA methodological examination including biogenic carbon and LUC aspects, whilst claim to do a CLCA, albeit, they neither allude to attributional nor consequential phrases as intended application.

Group (iii) studies clearly mirror it in their intended applications that they are developing CLCI modelling methods while they exclude appraisal of consequences of a decision because it is not a part of their scope [17,18]. [19] exemplifies a study with a little overlap to group (i) because it mainly intends to be a method development study but also include a case analysis with conclusions.

3.2. *Scale, time horizon, and CLCI methods*

Scale and time horizon play an important role before modelling the CLCI. The ten articles that include time horizon apply the long-term perspective, which align with the four-step procedure default assumption. Time horizon is not a part of three of the studies because they focus on CLCI method development, thus not conducting a full CLCA study. The studies of large-scale changes all incorporate

Table 2. Intended applications and object of study in the articles i.e., level of application from material to building stock level. Group (i), (ii), and (ii) are according to focus of intended applications

	Reference	Intended Applications	Object of Study
Group (i)	[20]	Evaluate the environmental balance of expanding forestry onto marginal agricultural land in the UK to provide more timber for the built environment, accounting for land use effects and product substitution throughout extended wood value chains. Evaluate the impact of forest thinning on production of higher value timber products, and on the environmental balance.	Building stock
	[7]	Assess the potential of reducing GHG emissions from the structural systems of multi-storey buildings by substituting structures of reinforced concrete (RC) with timber structures.	Building
	[21][1]	Assess potential environmental impacts (LCA) and the life cycle costing (LCC) regarding increased use of wood in buildings.	Building
	[22]	Estimate the degree to which a projected expansion in US demand for softwood (SW) lumber and structural panels for construction of low-rise NR buildings would change C (carbon) storage and C emissions.	Building stock
Group (ii)	[12]	Determine the environmental impacts of constructing hybrid wood buildings. Compare ACLA and CLCA to further demonstrate the added value of both approaches on the case study of a hybrid composite buildings.	Building
	[15]	Assess the potential environmental benefits and burdens of introducing circular design alternatives for internal wall assemblies to the Belgian market. Introduce various consequential modelling approaches to understand the relevance and improve the robustness of the results and to explicitly account for the corresponding modelling uncertainty.	Component
	[14]	Validating the potential environmental savings associated to design choices that foster a circular economy with insight in the related methodological and contextual uncertainties and is complemented with an LCC analysis to verify the choices' financial feasibility and sustainability.	Component
	[16]	Assess the combined influence on results of four fundamental methodological challenges in LCA of forestry products.	Material
	[11]	Explore the role of innovative timber building systems in carbon efficient construction. Analyze the lifecycle carbon implications of three timber-frame multi-storey building systems.	Building
	[13]	Test how EoL assumptions influence LCA comparisons of different construction materials. Compare the influence of attributional and consequential approaches to EoL modelling. Study the consequences of choosing one of two engineering alternatives, in other words, the consequences of increased production of either alternative.	Material
Group (iii)	[19]	Evaluate the state of the wood structural market for Non-Residential (NR) buildings by performing a material flow analysis of the EWP (engineering wood products) in the non-residential wood building sector. Evaluate the potential consequences related to the growing engineering wood product (EWP) use.	Building stock

[1] Translated from Danish to English by this study's authors.

	[17]	To propose a procedure for marginal supplier identification that is specific and detailed while maintaining general applicability and practical feasibility.	Material
	[18]	Develop a network analysis-based approach for geographical market delimitation that can be applied consistently to different products and based on data of similar type.	Material

one or more sophisticated modelling. The articles of small-scale changes range broader between only simplistic modelling e.g., assumptions, to more advanced in-study modelling such as network analysis and iterative procedure (see Table 3).

Table 3 presents four studies that disregard identification of market delimitation, five are not including market volume trend analysis, two avoid affected supplier identification, and three omit substitution. The three studies that omit substitution belongs to group (iii), thus their purpose is to only develop a CLCI modelling method. Market delimitation methods stretch from assumptions, ecoinvent, and author choices over literature references to in-study modelling as network analysis and iterative procedure. Market volume trend is mainly approached by linear regression analysis of trade and production data but more advanced methods such as MFA and a forest carbon model were employed. Affected supplier identification range from assumptions, authors' choice, statistics, ecoinvent to literature, linear regression to more advanced methods as partial equilibrium (PE) model, empirical model, forest carbon model, network analysis, and iterative procedure. Level of specification differ greatly independently of the related CLCI modelling method.

3.3. Biogenic carbon mechanisms

Six papers specify their biogenic carbon approach where they all six consider replanting of harvested trees or a constant carbon stock. Two studies adopt the -1/+1 method for the flow of stored biogenic carbon [11,20]. The latter study present a quite detailed carbon flow after harvest and involve the influence of thinning. Advancing the modelling of biogenic carbon requires a dynamic approach, which three of the papers implemented based on the Bern carbon cycle method [7,16,21]. [7] use the dynamic approach of [6], while [16] (use also a static scenario) and [21] rely on the dynamic approach of [10]. The dynamic biogenic carbon method reflects the relation of storage time of the biogenic carbon and the rotation period of the tree [7]. In [16] their time-dependence incorporates a characterization factor that accounts 1 kg biogenic carbon emission in year zero as 1 kg CO2 whereas it decreases non-linearly towards 0 kg CO2 at the designated time horizon e.g., GWP of 100 years.

Table 3. Overview of consequential aspects in the studies, and modelling method of market delimitation, market volume trend, and affected supplier. Scale of change can be small or large. Studied time horizon of change is derived from the papers if explicitly described or if a reference period is defined: 0-5 years are short-term, 6-10 years are medium-term, and 10+ years are long-term.

Reference	Scale	Time Horizon	Market Delimitation	Market Volume Trend	Affected Supplier	Substitution
[12]	Small	Long-term	N/A	Literature	ecoinvent, literature	Yes
[15]	Small	Long-term	Network analysis, iterative procedure	Linear regression	Network analysis, iterative procedure	Yes
[14]	Small	Long-term	Network analysis, iterative procedure	Linear regression	Network analysis, iterative procedure	Yes
[19]	Large	Long-term	Author's choice	MFA	Statistics	N/A
[20]	Large	Long-term	Assumptions	Forest carbon model	Forest carbon model	Yes
[17]	Small	Long-term	Iterative procedure	Linear regression	Iterative procedure	N/A
[16]	Small	Long-term	Assumptions, literature	N/A	Assumptions, author's choice	Yes
[18]	Small	n/a	Network analysis	Linear regression	Linear regression	N/A
[7]	Small	Long-term	N/A	N/A	Assumptions, ecoinvent	Yes

[21]	Small	Long-term	Iterative procedure	Statistics	Assumptions, statistics	Yes
[22]	Large	Long-term	Empirical model, PE model	N/A	Empirical model, PE model	Yes
[11]	Small	n/a	N/A	N/A	N/A	Yes
[13]	Small	n/a	N/A	N/A	N/A	Yes

Eventually, [22] employ a dynamic CLCA to track biogenic carbon flows over time based on an integrated PE model and empirical forest models.

In three of the dynamic biogenic carbon studies, they exclude consideration of the carbon stock contained in soil and general belowground, slash, and foliage [11,20,21]. Finally, the forest carbon stock included in the other three studies are both tracked aboveground and belowground [7,16,22].

3.4. Conclusions of using CLCA on wood products in the built environment

One study found the most contributing phase to be the production stage for ALCA and use stage for CLCA [12]. Divergently, [11] identified the production stage as the most contributing using CLCA. The choice of either ALCA or CLCA would not affect the relative impacts of the building in the two studies. Instead, the absolute impacts differs with the choice of attributional and consequential approach due the use of respectively allocation, and substitution and choice of avoided processes [7,13]. Further, wood multi-storey buildings perform better than its concrete structure equivalent in both ALCA and CLCA approaches [7]. In multi-storey wood buildings, CLT exhibit the better environmental performance regarding GHG-emissions followed by modularized structures, and finally beam and columns as the least preferred option [11]. In general, increasing wood use in multi-storey buildings would lead to GHG-reduction benefits [20–22]. However, this increase in wood could raise steel consumption, thus, affecting negatively the GHG-reduction benefits [12].

A twofold substitution benefit often lead to some of the main GHG-reduction potentials of wood in buildings. First, studies that displace buildings of concrete and steel with wood overall yields better performance of the wood building. Hence, it appears more climate friendly to have wood buildings if it is not leading to excess use of wood material in contrast to if the building was of concrete and steel [20–22]. Second, the substitution benefits of wood residues along the timber value chain offset GHG-emissions due to the avoidance of fossil energy consumption, which is may be overestimated if the study consider the wood carbon neutral [7,11,20].

iLUC from increased timber production, thus forestry, modify GHG-mitigation benefits depending on how the iLUC was considered [20]. Still, the study yielded net-reductions of GHG when it included iLUC. Another study reported that the inclusion of iLUC yield a net-emission of GHG from the wooden buildings under examination [16].

4. **Discussion**

Three facets of CLCA on wood in buildings were studied in this review: (1) definition of the intended application in the goal setting, (2) setting scale and time horizon, and modelling the CLCI , (3) inclusion of biogenic carbon aspects. Additionally, conclusions and learnings from the studies were conducted.

4.1. Intended applications

The four studies that empirically analyze consequences of a decision, group (i), have buildings or building stock as object of study. Therefore, CLCA of components and materials require more empirical assessment focus, even though materials are more well-covered in group (ii) and (iii). Contrary, building stock level needs greater representation in the literature when analyzing effects of methodological choices.

Overall, the studies generally focus on a broad range of purposes from methodological aspects of either consequential, more attributional, or general LCA as well as method development, to the group (i) studies that aim at empirical assessment of consequences of wood use on smaller and larger scale. CLCA on wood in buildings should therefore intend further elaboration on both methodological elements and empirical assessment of more cases. Particularly to improve understanding of method limitations and consequences of increasing use of wood for construction in different regions.

4.2. Scale, time horizon, and CLCI modelling

The small-scale studies implement a variety of inventory modelling methods across and internally in studies. It might induce some inherent uncertainty to robustness of outcomes and comparison of analyses. This is in line with a study of overall CLCA in the built environment where CLCA studies, despite the four-step procedure, lack systematicity in identifying the market and suppliers sensitive to a change in demand [23]

Applying assumptions and the consequential ecoinvent database would ease operationalization CLCI modelling, though, both might often be a generalization that is not specific to the study. Anyhow, assumptions of market or affected supplier can be specific for small-scale changes of for instance materials with low weight to cost ratio, thus would geographical location limit the market delimitation options to be local. Instead literature studies can be very detailed and appropriate for CLCI modelling, but has to be market specific to the respective study to avoid generalization across geographical locations [14].

The network analysis and iterative procedure originates from two of the three reviewed method development studies [17,18]. The latter's strength is a systematic stepwise identification of the market and marginal countries [17]. It incorporates a market inclusion threshold that can be regulated for practicality, compatible with both retro- and prospective data, and can further identify marginal technologies if data exist. Besides, markets are based on incoming trade and by performing linear regression on the trade data of exporting countries the steepest inclined curve work as a proxy for competitiveness. These trade data appear often aggregated at country or coarser levels; thus, it sometimes can be difficult to get more detailed data. Per contra, its consistency and practical applicability emerge as useful for small-scale CLCAs.

The network analysis ensures markets based on global cluster analysis of trade and production data. This means that the location of change would not affect the composition of the overall market as in the iterative procedure. Otherwise, the limitations are like the iterative procedure. This consideration of global trade with a systematic top-down workflow can be useful for CLCI modelling at both small- and large-scale to capture representative market boundaries.

For large-sacle changes, the combined PE and empirical forest model integrate alterations in the forest supply chain from a change in demand, dynamic biogenic carbon sequestering, forest management, and consumption of wood for other applications than building materials. The uncertainty lies with elasticity assumptions, which determine when a price increase induces forest investments. Further, predictions of forest stock development and carbon reduction potential often deviate in wood and forest studies compared to reality [14]. The MFA for CLCI modelling demonstrates similar features of the combined PE and empirical forest model by using forecasted developments of wood with supply and demand effects [19]. Nevertheless, the resource availability is not reflected, and the approach disregard other sectors consuming wood resources. One more limitation is the insufficient accessibility of data input e.g., the share of the structural material cost of the total building costs. Finally, the forest carbon model of [20] delivers a detailed value chain of the considered wood products and outcoming residues. Nevertheless, it is decoupled from projections of future demand. It further use assumptions for identifying the market and tree type, which reduce consistency. Consequently, elaborating knowledge and studies of empirical and methodological aspects of CLCA on wood in buildings plays an imperative role to better understand and inform policies on the consequences of building with more wood.

4.3. Biogenic carbon accounting implications

Only three studies model dynamic biogenic carbon, which might result in the remaining studies to potentially underestimate the GHG-mitigation effect of using long-lasting wood products for buildings. Hene, the GHG-reduction benefit of substitution fossil energy with wood residues might be amplified as in Dodoo et al. [11] As a result, the reference period and rotation period becomes important parameters to include as a part of a CLCA study of wood building products [22]. The assumption that replanting occur after harvesting is necessary for wood buildings to potentially work as carbon sinks but it might be questioned if that takes place in reality in all wood demand cases. Consequently, there might be further investigation of this in the built environment when demanding wood. Additionally, the completeness of included forest carbon stock also affects results and might have more focus in coming studies instead of only including the carbon stock of the wood timber.

Five of the studies incorporates dLUC, while three of these consider iLUC. iLUC sometimes have effect on the total carbon emissions of a wood building [10] as seen in [16], which could overestimate the potential of wood as carbon mitigating product. Despite, iLUC still lack agreement of a common modelling approach [16], thus, the choice of iLUC approach have a varying degree of influence on the final carbon emissions of wood buildings [20]. Since only three studies integrate iLUC, future studies should consider reporting it but as a separated explicit impact in view of its lack of consensus modelling. This would add to the knowledge of the impact of iLUC of the total GHG emissions.

Most of the studies focusing on biogenic carbon aspects decrease their CLCI modelling focus or even only apply system expansion as the single consequential element. Further, only one study consider the availability of material as well as other sectors' demand, which should be important to reflect in large-scale studies [22].

4.4. Learnings from CLCA on wood in the built environment

The contribution analysis of CLCA on wood in buildings diverge between production stage and use stage as the most contributing to impacts, whereas it is the production stage for the ALCA approach. Therefore, wood in buildings need more research on the area of difference in contribution analysis between ALCA and CLCA to understand what is missing when only ALCA is applied for design choices. The application of either allocation or substitution play a major role in the differences between absolute outcomes of ALCA and CLCA. However, the application of ALCA or CLCA are not appearing to influence that wood multi-storey buildings have less GHG-emissions than the concrete equivalent [24].

The studies generally conclude that wood multi-storey buildings either provide a net-GHG reduction or perform better than conventional equivalents. Some of the determining effects are the substitution benefits of respectively avoided concrete or steel consumption and avoided fossil energy by wood residues being incinerated. Additionally, some of the studies with fossil energy substitution as GHG-reduction aspect are not including dynamic biogenic carbon, which could overestimate these reduction benefits [11,13]. Modelling of EoL scenarios also influence the impact of wood in buildings along with the share of virgin material of displaced steel [14,15]. Hence, future research could be advised to inspect EoL scenarios in their CLCA of wood in buildings as a sensitivity analysis.

5. **Conclusion**

The intended applications of the reviewed CLCA studies on buildings focus primarily on either testing methodological aspects of CLCA, general LCA, biogenic carbon, or method development. This indicates that CLCA of wood in buildings are at an early-stage implementation that need elaboration to improve its usefulness as a decision support tool for informing policy.

The studies apply a diverse pool of CLCI modelling methods. A few method-development studies propose a more consistent modelling of market delimitation, market trend, and affected supplier. Other studies apply these approaches to cases. Some modelling methods mirror the theoretical framework of market mechanisms to a greater extent than others. However, future insights and elaboration of CLCA might focus on increased understanding of sensitivity to (i) EoL scenarios, (ii) inclusion criteria of market and affected suppliers, (iii) the relevancy and robustness of using assumptions, literature, or other CLCI methods that is not modelled as a part of the respective study. Further, the chosen CLCI modelling approach should be considered in relation to the scale of change, and generally the object of study i.e., large-scale studies might use more sophisticated modelling. Iterative procedure and network analysis appear useful for small-scale CLCAs with its consistent approach and practical applicability to select the size of the marginal mixes. Network analysis and MFA are advantageous to large-scale decision support due to consistency, based on global trade for the former, and for the latter including relationship of price and demand, and future macro trends of the building and resource type under study.

Some studies comprise biogenic carbon and LUC aspects, though, they tend to reduce CLCA elements and vice versa. This may be due to the scarce experience of CLCA in the built environment, where dealing with the complexity of the modelling appears as the main effort. Therefore, a greater focus should be on including dynamic biogenic carbon flow and consider iLUC aspects separately together with an elaborated CLCA approach. This will better reflect real world carbon flows and the capability for wooden buildings to work as carbon sinks and nuance the GHG-reductions from residues substituting fossil energy.

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