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Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland

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ABSTRACT

The aim of this study is to investigate the economic, environmental and technological challenges, as well as the environmental potential, of prolonging the life cycle of construction materials with focus on structural timber in Finland. To achieve this, a literature review was conducted along with interviews with actors pertinent to timber construction. Moreover, a case study of life cycle environmental impact assessment was conducted to quantify the potential of reusing timber to abate global warming and other environmental burden. The literature review highlighted the possibility of reusing structural timber, but pointed to the need for efficient and standardized assessment criteria. The interviews indicated interest towards the concept of circular economy applied to construction and demolition wood material, although this appears to be driven more by policy and regulation rather than for business reasons. Therefore, a reconfigured conceptual framework to achieve circularity for wood is proposed, where material brokers would be used to connect different actors along the value chain. The paper concludes with a case study showing that reusing structural timber components can result in a significant reduction of the environmental burden.

1. Introduction

Generally speaking, the need to pursue a more sustainable future is widely acknowledged, not only because of the material and energy crisis, but also because of concerns about rapid climate change. To help this transformation, the European Union (EU) has been advocating a shift towards a circular economy (CE) to reduce waste as well as to increase resource efficiency (European Commission, 2014b; European Commission, 2015). In its broadest sense, the concept of CE encompasses social and environmental aspects, in addition to economic considerations. The CE works as a strategy that aims to maximize material value and the utilization of available resources in a product through (closed) circular material flows, thus creating added value, decreasing waste, cutting primary resource consumption and reducing environmental burden (Ellen MacArthur Foundation, 2017).

The construction sector has recently started to attract a considerable amount of attention because of its substantial climate impact and consumption of raw materials and energy, thereby contributing significantly to the global environmental burden. In Europe, it presently accounts for about 36% of CO_2 emissions and 40% of total energy consumption (European Commission, 2014a). The sector also consumes enormous amounts of materials, especially minerals and ferrous metals, but also wood. The environmental impact associated with the extraction and processing of these materials is immense and so, clearly, ways of reducing the consumption of primary resources in this sector is of the utmost importance. Utilizing wastes arising from the demolition of buildings is an effective way to help reduce this burden and is clearly within the frame of the CE.

The Official Journal of the European Union (European Commission, 2008) prioritized a waste hierarchy, where the preferred order of dealing with materials use is as follows: prevention, preparing for re-use, recycling, recovery and, finally, disposal. It also set ambitious quantitative targets for construction and demolition (C&D) waste management and energy from renewable resources (see Birdlife Europe and the European Environmental Bureau, 2015; European Commission, 2009). In addition, an EU protocol (European Commission, 2016) and guidelines (European Commission, 2018) for C&D waste management, as well as audits, have been published to enhance confidence in, and the

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implementation of, CE. These goals and documents support CE strategy and the cascading[1] of C&D materials is not only feasible, but imperative, to help implement the strategy. By cascading, materials can be utilized for a longer time, which reduces waste and the need for virgin raw materials as well as the energy associated with processing; however, it should be noted that energy is generally required for reprocessing and this can outweigh the potential benefits of cascading. In addition, cascading contributes to the abatement of climate change and other environmental burdens.

In 2016, there was about 2.54 billion tons of waste generated in the member countries of the European Union, which highlights the magnitude of the problem (Eurostat, 2016). It has been stated in European Commission, 2018 that C&D waste is one of the heaviest and most voluminous waste streams generated in the EU, accounting for approximately a quarter of all waste generated and consisting of numerous materials that could be recycled. The cascading of C&D wood material could make a significant contribution to the EUs target of cascading C&D waste (European Commission, 2008), as the recovered wood substitutes other materials and helps reduce the greenhouse gas (GHG) emissions originating from their production.

Regarding the feasibility of cascading C&D waste, several barriers have been identified, including cost-effectiveness, quality, legislation and political will, as well as demand from the wood sector (Husgafvel et al. (2018)). Furthermore, studies that have investigated the environmental and even economic benefit of wood cascading have mostly been conducted at the product (e.g. particleboard) instead of project (e.g. timber building) level[2]. So far, it seems that there has been no study that has considered the macro-scale together with different actors (such as manufacturers, policymakers, waste management enterprises, etc.) along the wood value chain.

For the purposes of cascading, the elements of a building can be divided into two main groups: load-bearing elements (e.g. foundations, walls, floor slabs, columns, beams) and elements without a main load-bearing function (e.g. light/partition walls, façades). Buildings are usually designed for a life span of 50 years (EN 1990, 2006), meaning that the structural safety of the entire building must be guaranteed for this period without any major repairs. Elements without a main load-bearing function are usually easy to repair or replace and have been discussed in the context of cascading accordingly (Höglmeier et al., 2016; Sakaguchi, 2014). In contrast, load-bearing elements are usually more difficult to replace as they are commonly designed for the entire life of the building. Nevertheless, after deconstruction they can still be used in another building if their mechanical properties can be guaranteed for the next 50 years, thereby ensuring the structural safety. Discussion about cascading, especially reusing load-bearing elements (structural components) is lacking, mainly due to the technical challenges involved. Even so, load-bearing elements account for the largest share, both by volume and by weight, in a building and would be the key elements to focus on in order to achieve climate change mitigation through cascading. Among all cascading scenarios, reuse has the highest priority and, most probably, maximizes the materials value.

The aim of the study reported herein was to investigate the challenges to and potential for cascading C&D timber[3] in order to prolong the life cycle and combat climate change under the current challenges of resource scarcity and the need for sustainability. Due to the complexity of cascading structural elements made from different construction materials, this paper mainly focuses on the case for reusing structural timber elements. The most relevant concerns and obstacles, as well as the potential for cascading C&D timber, have been addressed from three aspects: economic, environmental and technical. For successful implementation of CE in the existing construction industry, all these aspects need to be considered as they are interrelated. The following research questions were studied: (i) what are the structural, economic and environmental limitations and concerns of wood cascading, (ii) what is the economic feasibility of cascading wood in Finland and (iii) what is the potential of climate change abatement by reusing structural timber?

The paper starts with a literature review of the current research and practice relating to cascading timber. Then it provides an overview of the current situation of cascading C&D timber in Finland and introduces the interview and case study methods of investigating the economic and environmental potential. The results from a series of interviews that focused on the economics of prolonging the life cycle of construction timber by cascading at the material/product level is presented and discussed. The interviews concentrated on reusing structural timber albeit other cascading scenarios were included as different cascading scenarios might co-exist for the same element where reuse might be the preferred scenario. Finally, in order to quantify the potential for combating climate change by reusing timber at the project level, a life cycle assessment (LCA) case study on timber halls was conducted. The results of the LCA study are presented including extensive environmental impact indicators with special focus on the climate change category.

2. Cascading timber: Literature review

The following literature review highlights the key economic, environmental and structural engineering issues pertaining to the circularity of structural timber elements.

2.1. Key economic issues

Over the past few decades, a number of theories, as well as practices, have been developed relating to the economics of cascading C&D waste materials.

Two prevailing concepts commonly in use are CE and cascading utilization (CU). The two concepts are similar and are both geared towards resource efficiency by supporting the multiple use of resources (Mair and Stern, 2017). Even though there is no consensus on the definition of CU, it can be stated that CE provides a more holistic approach whilst CU focuses on various end-of-life (EoL) utilization scenarios. The CU concept is mainly applicable to bio-based materials and their use from high- to low-value products. Apart from the basic 3Rs principle (Reduction, Reuse, Recycling) of CE, CU also includes energy production from EoL materials.

To implement CE in relation to wood use, missing actors or agencies need to be identified and new links between relevant actors should be established. Vis et al., 2016, for example, identified that a lack of cooperation and knowledge in the value chain was a market barrier to the cascading use of wood. On the other hand, considering circularity amongst actors should be advocated and, as mentioned in (de Wit et al., 2018) , the most relevant strategies for CE in housing are design for the future and collaboration to create joint value.

According to Pomponi and Moncaster (2017), many challenges and constraints exist when applying circularity to buildings. One of the main challenges is that the change in tendering priorities from the cheapest alternative to more open collaboration between contractors. This has been advocated in the academic literature (e.g. Cheshire, 2016); however, behavioral reaction affecting decision-making has rarely been examined, despite it having a noticeable role in circularity in construction. For example, as indicated in Huuhka and Hakanen, 2015 that, with regard to the potential of reusing steel, concrete and timber load-bearing building components in Finland, concrete has the lowest potential, whilst prefabricated steel has the highest. The potential of

[1] For purposes of discussion, reusing, recycling, and other material recovery of C&D timber are collectively termed 'cascading' in this paper.

[2] Here the project means the whole building or infrastructure is considered as one entity.

[3] For simplification, in this paper, C&D timber components and wood-based products are collectively termed 'C&D timber'. Hazardous treated timber (e.g. creosote, chromated copper arsenate) are not explicitly considered in this study.

timber was considered to be similar to that of steel.

As to practices for cascading wood, some measures have been taken in European countries. For example, in the Netherlands, the dumping of reusable C&D waste is prohibited and regulation forces the precise sorting of C&D waste and its sale for the reuse. Consequently, several companies specializing in C&D waste treatment have been established and the amount of recycled and reused waste has been increased to about 90% (in 2002) of all construction waste. Waste wood was only a small part of these recycled materials as it was mainly chipped and exported to other countries (Pirhonen et al., 2011). Another example is the state of Bavaria (Germany) that has approached the issue from a cluster perspective, which also considered actors outside the industry boundaries. They emphasized material efficiency, life cycle analysis, product certification and industry actors that were previously not considered to be part of the wood sector (Winder and Bobar, 2018).

2.2. Key environmental issues

Discussion about the environmental impact of wood cascading has been ongoing for some time (Thonemann and Schumann, 2018). Nevertheless, a rather limited number of studies exist and fewer still that are related to the cascading of structural timber components. Exceptions are Sandin et al. (2014) who investigated the recycling of glue-laminated wooden beams through modelling the EoL process of two roof structural elements and Vis et al., 2014 who focused on cascading in the wood sector and conducted a number of case studies, including one timber frame construction.

There are limited quantitative LCA studies on the EoL of wood and, as previously stated, most are focused at the product level instead of project or building level. For example, Thonemann and Schumann (2018) conducted a systematic literature review on the cascading of wood-based products with respect to environmental impact, where it was found that the focus on resource efficiency (at the core of cascading) was missing in most of the studies. In addition, significant variations have been noted in system boundaries, functional unit (FU), assumptions and assessment methods (e.g. Niu and Fink, 2019; Thonemann and Schumann, 2018). Thus, from a holistic perspective, the environmental performance of wood cascading is still unclear, as the evidence is not entirely conclusive due to these variances in individual studies. Moreover, consideration of biogenic carbon uptake has not been uniformly agreed upon when conducting LCA studies. For example, Höglmeier et al. (2016) assumed that the wood in wood products was carbon neutral when calculating the balance by LCA, whereas Vis et al., 2014 calculated the biogenic carbon uptake of wood. So far, there is no uniform consensus about the environmental consequences of cascading wood products, not even C&D timber.

Studies about cascading wood have shown the positive impact especially in terms of CO_2 emissions and raw material reduction (e.g. Höglmeier et al., 2016; Sikkema et al., 2013; Vis et al., 2014). With these EoL studies on wood-based products, two LCA approaches have been used: attributional (cut-off) and consequential (substitution) approaches. The former is descriptive and commonly applied, whilst the latter is change-oriented and rarely used. Sandin et al. (2014) compared the two LCA approaches for evaluating environmental impact and the results indicated that the choice of these two approaches did not seem to influence the relative performance, though the absolute values varied. Moreover, the influence of the number of cascading steps and the resource efficiency of the cascading systems considered should be analyzed (e.g. European Environmental Agency, 2011; Höglmeier et al., 2015; Höglmeier et al., 2016). Mehr et al. (2018) assessed environmentally optimal wood use patterns under varying wood cascading scenarios in Switzerland. The results indicated that multiple cascading of wood could decrease the environmental impacts. Waste wood processing efficiency, the carbon storage effect of wood (considering biogenic carbon) and the cascading options available were observed to be the driving factors for the environmental impact of future wood use scenarios. The ISO 14044 (2006) standard recommends using 'system expansion' modeling to avoid the allocation of systems with joint production, which is common for wood-based products. However, there is no advice on choosing the correct process for the 'system expansion', thus the LCA practitioner has to decide this based on the study object and the purpose of the assessment.

To standardize and quantify the environmental impact of products, the so-called Environmental Product Declaration (EPD) has been introduced which specifies LCA with Product Category Rules (PCR). Guidelines for the development construction products EPDs are defined in EN 15804 (2012). There, several scenarios for each life cycle stage of the building are provided, but it does not contain the cradle-to-cradle option, which makes reuse and recycling after the EoL stage of the building still optional.

2.3. Key structural timber issues

In order to guarantee the safe use of recovered timber as a structural material, its mechanical properties have to be known. Apart from the natural aging phenomena of wood and the duration of load (DOL, static fatigue), the presence of (local) mechanical damage and biological attack must be considered. For the detection of mechanical and biological damage, a wide variety of assessment methods are available (Dietsch and Köhler, 2010). The aging phenomena of wood has already been investigated in several studies. For example, Cavalli et al., 2016 presented a comprehensive literature review where the individual studies showed a large variety of results, including both an increase and a reduction in the mechanical properties of timber over time. Nevertheless, most of the research agrees that bending strength and bending stiffness are either not, or, are only marginally, affected by aging. However, it has to be mentioned that investigating the aging phenomena is rather difficult due, in particular, to the large natural variability in the mechanical properties of wood (e.g. Fink and Köhler, 2011; Isaksson, 1999) along with the DOL effect.

The DOL effect is a characteristic of timber, as strength is dependent on the intensity and duration of the applied load. Here continuous static loading at relatively high loading levels results in a strength degradation of timber. In the past, several models have been developed to characterize the DOL effects; a comprehensive review of the principles and the DOL models that have been developed is presented in Svensson (2009).

In addition to mechanical properties, standardization of the timber product has to be considered. Structural timber, as well as timber for further processing into engineered wood products, is strength graded according to the European and national grading standards. However, there is no specific grading guidance and standardization for reprocessed structural timber or C&D timber. Even EN 14081-1 (2016) specifies that structural timber that has previously been graded shall not be re-graded to the same or different grades unless special dispensation is given. In addition, existing grading standardization sets limits for cross-sectional area for grading (e.g. EN 14081-1, 2016). If the structural timber obtained from C&D waste is expected to be reused, further processing (e.g. planing) that affects the final cross-sectional area might be needed, which may exceed the limit of the cross-sectional size required by the existing standards.

3. Current cascading situation of C&D timber in Finland

As a wood producing country, Finland exports a large share of structural timber and wood products and consequently cascading occurs outside Finland. This results in a significantly lower cascading factor than other EU consumer countries (see Sokka et al., 2015). Nevertheless, the average recycling rate of C&D waste in Finland is among the lowest in the EU (see Monier et al., 2011). As noted by Pirhonen et al., 2011, energy recovery from waste wood is currently considered to be best practice in Finland and other Nordic countries, from both a technical and an economic point of view. Nonetheless, they (Pirhonen et al., 2011) also addressed that the EU and its waste legislation was geared towards recycling. To reach the EUs recycling targets, it will be necessary to divert part of the C&D waste stream from energy recovery to material recovery.

In Finland, about 38% of buildings are made of timber and most of these are detached houses, rather than large-scale timber structures (Koskela et al., 2011). In 2016, the construction sector was responsible for 14 million tons of C&D waste, of which over 40% was wood, which is a significantly larger share compared to central and southern Europe, where in general it is about 5% (Official Statistics of Finland OSF, 2018c; Peuranen and Hakaste, 2014). Only a very small proportion of C&D waste wood is recovered for material purposes; in 2016 for instance, about 96% of waste wood (mostly from C&D waste) was burned for energy with the remainder being recovered in material form (Official Statistics of Finland OSF, 2018a). Although Finland has already met the goal of 27% renewable energy production stipulated in the EU Action 2030 (European Commission, 2013), the 40% GHG reduction target has not yet been achieved (Official Statistics of Finland OSF, 2018b, Official Statistics of Finland OSF, 2018d; Official Statistics of Finland OSF, 2018e). Considering these aspects, material recovery should be prioritized over energy recovery in general. However, the optimal choice might be case specific, depending on aspects such as the transportation distance and the processing requirements of the recovered wood.

In Finland, timber buildings are generally demolished mechanically using an excavator equipped to grab and crush the structure. During demolition, the interior is first dismantled by hand and then the building structure is grabbed and crushed piece-by-piece. Finally, the waste is separated and sorted into containers for final disposal. The priority in demolition is efficiency and cost (Sakaguchi (2014)), implying that the buildings are not deconstructed with consideration for the reuse of the building elements. As the C&D timber is usually first shredded, then ferrous metals are separated magnetically. In order to reuse wood, the waste management process needs to be enhanced.

In order to provide a general overview of the environmental and economic impacts of the Finnish C&D waste management system, Dahlbo et al., 2015 conducted a study in which a scheme was presented for the most common C&D waste management system in the country. The scheme included five main waste fractions and corresponding treatment lines: metal, concrete & minerals, wood, miscellaneous and mixed waste. The system began with waste generation and sorting and ended at the point where outputs, such as material or waste-based fuels, were recovered. The study also included an environmental life cycle costing analysis for the above five waste fractions, it was found that the wood fraction had large volume and produced medium profits.

The wood industry in Finland mainly manufactures primary products, thus the availability and the price of the raw material are crucial. The monetary value of the virgin raw wood improves with the minimization of the amount of waste generated during the sawing process and the fabrication of engineered wood products, whilst the environmental burden reduces through avoiding the consumption of fossil fuels during the production process. In Finland, approximately 75% of the total fuel consumption in sawmills comes from biofuel; and in most of the large sawmills, heat and electricity are generated by their own power plants using wood residues during manufacturing process (Takano et al., 2014). Though wood residues and waste generated from the manufacturing process are efficiently used for energy, the life cycle material value of a wood product is generally not maximized. For this reason, the implementation of cascading is a priority.

A reformed Waste Act came into force in January 2020. Accordingly, the Finnish Ministry of the Environment developed and commissioned a platform for the waste materials market, which requires waste holders to use the platform for managing their waste and by-products. The municipality is also responsible for providing supplementary waste management services in three situations: 1) if waste holders cannot find private service provision from this platform, or 2) the waste is suitable for processing in the municipalitys waste management system, or 3) the value of the need for the municipalitys supplementary waste management service is less than EUR 2,000 per year (Ympäristöministeriö, 2020).

4. Methods

4.1. Qualitative interviews

In order to identify the economic potential for prolonging the life cycle of construction timber by cascading at the material/product level, a series of interviews were conducted. Before the interviews, a conceptual framework for the business ecosystem related to cascading solid timber was postulated and constructed from existing research, business ecosystem's theory and the authors empirical knowledge (based on the methodology described in Maxwell (2013)). This conceptual framework (see Fig. 1) aimed at illustrating a simplified model for actors of the existing business ecosystem in relation to the material flow of wood, addressing the CE approach to cascading solid timber as well as to derive essential questions from the actors. The relevant actors start from the forest owners through a linear system to the timber waste manager at the end of life.

Qualitative interviews and responses of interviews were analyzed and used to explore the barriers, potential solutions and insights into cascading C&D timber. Face-to-face interviews were conducted with different actors involved in the wood construction sector, soliciting opinions about technological, economic and political approaches to the circular system in the entire wood industry. We conducted 21 interviews (year 2018, duration 0.5-1.5h), which provided an overview of the potential ecosystem and the actors involved within it. For confidentiality purposes the interviewees remain anonymous. A classification and description of the interviewees is listed in Table 1. The interview questions were derived from the conceptual framework shown in Fig. 1 (the template is attached as an Appendix, Rasi (2018)). The interviews were semi-structured in order to maintain the natural flow of the discussion (Marshall and Rossman, 2014). The analysis of responses of interviews was conducted based on the meeting memos and transcripts, with the aim to construct a systemic view of the topic, which enabled the various interdependencies of the actors and relative relations. The opinions from the interviewees were collected and categorized. The categorization was intended to provide a clear view, but there were some opinions interrelated in more than one aspect.

4.2. Case study

A streamlined LCA case study to investigate environmental potential by prolonging the life cycle of construction wood material was performed. The case study took virtual structures as the research object, and explored the maximum potential in a rather realistic manner.

4.2.1. Object of the case study

The objects studied were two timber halls each with a 50-year service life. Hall 2 was assumed to be built as a substitute for Hall 1, after the end of Hall 1's service life; both halls had the same structural systems. This case study was limited to and focused on the glulam beams of the roof structure. Hall 2 was assumed to be larger than Hall 1, resulting in a larger total volume (expressed by $V_{1,total}$ and $V_{2,total}$) of material used for the glulam beams in the roof structure: $V_{1,total} = 50m^3$ and $V_{2,total} = 80m^3$. The individual glulam beams in Hall 2 were slightly smaller, $V_{2,beam} = 0.8V_{1,beam}$ than those in Hall 1, assuming some reprocessing of the beams was required before the reuse in Hall 2. The material loss of 20% due to transport and reprocessing might be even conservative. Höglmeier et al. (2015) assessed a technical yield of 95% including transportation and processing for the area of Bavaria, which was assumed to be representative for Europe. The strength class of all glulam beams was assumed to be GL32c.

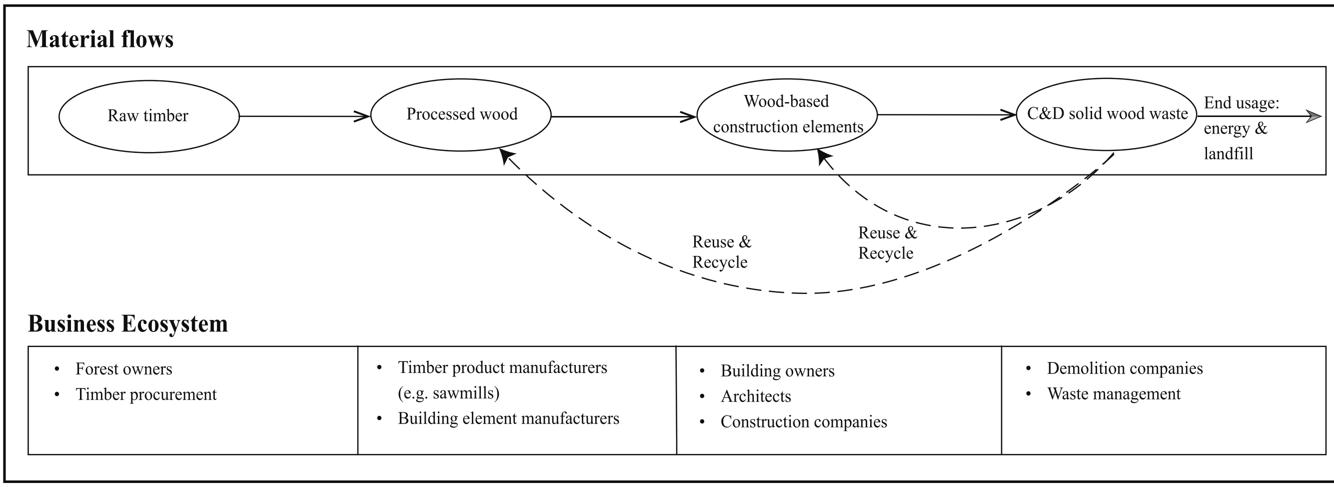

Fig. 1. Conceptual framework of business ecosystem around the life cycle of C&D wood, the arrows with solid lines represent the current material flows, whilst the dashed arrows indicate the potential flows for wood cascading.

Table 1
Clarification and description of the interviewees.

Sectors	Interviewees (Number of interviewees)
Forestry	Sustainable development manager (1)
Manufacturing industry	Specialist, vice president of R&D Unit (3)
Construction sector	Environmental manager, project engineer, general engineer, architects (5)
Environmental & waste management and demolition	Communications manager and business controller, operation manager, environmental manger, service coordinator and process engineer, specialist (5)
Other experts, consultants and policymakers	CEO (Chief Executive Officer), professor, research scientist, consultant, senior expert, specialist, team manager (7)

4.2.2. EoL scenarios

In order to investigate the influence on the environmental impact of reusing the glulam beams, two EoL scenarios were considered:

No cascading (reference scenario): The glulam beams of both halls were manufactured from virgin raw wood and all beams were incinerated for energy recovery at the EoL.

Cascading: All glulam beams of Hall 1 were produced from virgin raw wood and were reused in Hall 2. The necessary additional glulam beams in Hall 2 were produced from virgin raw wood. The glulam beams from Hall 2 and the byproducts from further processing (20% of Hall 1) ended up in incineration for energy recovery.

Under both scenarios, the two halls had the same FU which was defined as glulam beams of two timber halls function for a total service life of 100 years. Thus, for all the activities occurring at the EoL of both halls, the corresponding environmental impact or benefit was enclosed inside the defined system boundary, which was the whole life cycle of the two timber halls.

4.2.3. Assumptions related to the case study

Several assumptions and simplifications were used to facilitate this streamlined LCA study and to reduce the number of influencing factors. The LCA calculation encompassed the whole life cycle (cradle-to-grave) of the two halls, excluding the construction process and use stages. Both stages were assumed to be the same (based on the current average technology and empirical methods); thus, for simplicity, their environmental impact was omitted. The total sum of transport distance multiplied by the amount of wood materials is assumed to remain unchanged between the two scenarios; accordingly, the environmental impact associated with material transportation was excluded. The processing of the glulam beams in Hall 2 that originated from Hall 1 included only cutting and planing. The structural properties of the glulam beams originating from Hall 1 were expected to fulfill the structural requirement for reuse. The energy recovery efficiency was assumed to exceed the required 60% in the C3 module - 'Waste processing' defined in EN 15804 (2012). In addition, no distinction was made between the combustion systems for the burning of primary, residual and waste wood. The origin of wood used for both halls was assumed from a local forest that was under sustainable management, thus, it was reasonable to assume the wood to be carbon neutral. Since there is no consensus on whether and how the biogenic carbon benefits of wood should be considered, the methods presented in the ILCD handbook EUR 24708 (2010) and EN 16449 (2014) were adopted, and the biogenic carbon uptake of the glulam beam was calculated and expressed separately.

4.3. Assessment methods and tool of the case study

An attributional LCA approach was adopted. Ecoinvent v3.5 (Wernet et al., 2016) was chosen as the Life Cycle Inventory (LCI) database for the case study, applying three (widely used) Life Cycle Impact Assessment (LCIA) methods. These were *CML 2001, ILCD 2.0 2018*, and *ReCiPe midpoint (H)* V*1.13*. Various LCIA methods were adopted in order to reduce the level of bias with respect to different impact categories. The Allocation at the Point of Substitution (APOS) system model defined in Ecoinvent (Wernet et al., 2016) was chosen for the LCA calculation, Cut-off system model was also applied as a counterpoint in the sensitivity analysis. Accordingly, the environmental impact of both halls was calculated and summarized.

5. Results and discussion

5.1. Qualitative interviews

5.1.1. Barriers and feasibility of reusing C&D timber

Through the interviews with actors from the wood construction sector, the following technical barriers were identified:

- wood products used in construction are manufactured for only one-time use
- doubts about long-term quality and constant supply of C&D timber
- unmotivated to reuse and recycle C&D timber, since at present they are primarily and efficiently going to energy recovery
- lack of actors and destinations for higher value through reusing or recycling of wood

- feasibility constraints such as a lack of standardized procedures for reusing C&D timber
- lower value of C&D waste timber compared to other C&D waste materials such as metals.

In terms of economic issues, the interviewees expressed concern about cost efficiency and profitability, the feasibility of sorting C&D timber and reconfiguration of the value chain. For the value chain, the interviewees expressed concerns regarding the (i) uncertain popularity of wood construction in the future, (ii) the low demolition cost compared to the total construction cost and (iii) labor- and cost-intensive waste sorting. It was also mentioned that building owners determined the value of the end-life of the building, but their decision-making was often based on short-term profits. The demolition execution is outsourced to waste management companies, who have the right to decide the procedure and destination of materials originating from the site. A phenomenon in the waste management industry is the consolidation of actors into bigger organizations, but it is uncertain whether the consolidation can increase the efficiency of wood material flows.

Although the industry expressed mainly critical comments, the interviews brought up a number of things which could promote cascading C&D timber (list in Table 2). With respect to the market and economy, the interviewees suggested potential solutions such as considering the recycling of C&D timber in the design phase, introducing pre-demolition audits and better networks connecting the waste provider and customer. The interviews also pointed to political and sectorial visions that encourage the cascading of C&D timber. These included new construction sector regulations seeming to support wood construction, scattered municipalities that have been advocating wood construction, lobbying organizations and companies that have been seeking to influence legislation with regard to construction material selection and corresponding waste, and legislation to enforce greater change in the reuse and recycling of C&D timber. To summarize the interview findings, we identified that all actors involved in timber construction and C&D waste management are keen on new solutions, which could enable the reuse and recycling of C&D timber; but nobody is willing to be the initiator of new solutions, rather looking for others to offer them.

Table 2
Recommendations, visions, and perceptions for the circularity of C&D wood from the interviewees.

Division	Recommendations, visions and perceptions
Market & Economic	New actors enabling the reuse of C&D waste wood are needed, although the nature of such actors is still unclear.
	Better networks would enable effective distribution of material streams from waste management.
	Pre-demolition auditors could help the material efficiency at the end-of-life of buildings.
	Incentives to consider recycling already in the design phase could steer the market to a new direction.
	Digital marketplaces could support the exchange of waste materials.
Governmental	Lobbying organizations and companies from the construction sector and waste management industry seek to influence legislation to match their interests.
	Some municipalities advocate the wood construction, but the field is scattered.
	Municipalities could enforce rules for construction materials and reusing them, although they are rarely applied in reality.
	New regulations of construction sector seem to support the wood construction.
	Legislative power seems to be the only option to enforce greater change for the reuse and recycling of C&D waste wood.
Behavioral	All actors expressed interest towards new resolutions and actors that would enable reuse and recycling of wood.
	Yet, no actor seems particularly interested or willing to innovate new solutions.
	Many perceive that recycling of C&D waste wood is minuscule problem in comparison to other material streams.
	It is mostly agreed that the change to recycling practices should come from the market and industries themselves.

5.1.2. CE framework for wood cascading

The current business ecosystem of wood is rather linear (as shown in Fig. 1) and to enable a circular ecosystem, we suggested a reconfigured business ecosystem framework, as shown in Fig. 2. In Fig. 2, the solid black-lined boxes and arrows represent the current life cycle of wood, indicating that cascading C&D timber is missing and connections inside the system are linear. The dashed black lines and the solid green lines represent the reconfigured conceptual circular framework, where the missing streams - cascading C&D timber associated with a material broker (as the connector between the wood provider and consumer) are added. In detail, the conceptualization of the reconfigured business ecosystem introduces two major alterations: one is related to design in the early stage of the wood life cycle (raw material, manufacturing, construction), the other is modification to the EoL management (end-of-life and beyond). The former alteration aims to enforce circular design and design for deconstruction (DfD) principles, the latter is to promote the emergence of pre-demolition auditors and material brokers in the ecosystem. Through the reconfigured ecosystem, the connection could be strengthened and the system is free to circulate. Moreover, EU standardization on the reuse and recycling of C&D waste materials also encourages and supports these activities. However, the accumulation of direct and indirect effects on the business ecosystem of either of these two alterations remains uncertain. Another issue that must be mentioned is that, through the business ecosystem analysis it is perceived that every action carries multiple consequences, even subtle changes might cause unexpected outcomes.

5.1.3. Discussion

It has to be mentioned that, the validity of the data and findings depends on several factors such as the subjective nature of the study. Moreover, a key issue for concern about validity was the interviewers/ researcher's ability to identify and counteract subjectivity such as researcher bias or reactivity (Maxwell (2013)). The validity of the business ecosystem framework was carefully reconfigured accordingly, in order to account for the increased understanding of the actors role and the intertwined supporting and opposing factors towards a circular C&D timber system.

In addition, the profitability or cost of the two proposed alterations along with different cascading scenarios need to be further studied. For instance, which sub-process(es) of each cascading scenario contributes the most to the life cycle cost and impact, or which cascading scenario may result in higher material value. Taking structural steel material as an example, Yeung et al. (2017) stated that DfD would positively impact the value of reused steel, as reusing rather than recycling structural steel led to greater CO_2 emission reductions per tonne of steel, though resulted in higher costs under North American conditions at that time. Such a phenomenon may also occur to the structural timber in Finland.

In principle, there is a clear gap between the policy/regulation requirements and implementation in practice. Though actors in the wood sector in Finland expressed interest in and, in general, willingness to cascade C&D timber, profitability and the stability of the market were their main concerns, moreover, nobody wanted to initiate new solutions to enable the reuse and recycling of C&D timber. The reformed Finnish Waste Act that came into force in January 2020 to some extent bridges the gap, as it provides a better network connecting the waste provider and customer. However, more discussion between policymakers/ governmental sector and participants involved in the wood sector is needed, where practical solutions may be developed and implemented. Furthermore, a framework for the decision-making process for cascading options may be required, where both cost and reliability of reusing structural timber should be considered. Similar studies have been conducted for reusing structural steel (e.g. Yeung et al. (2015)), which may be used as references for reusing structural timber.

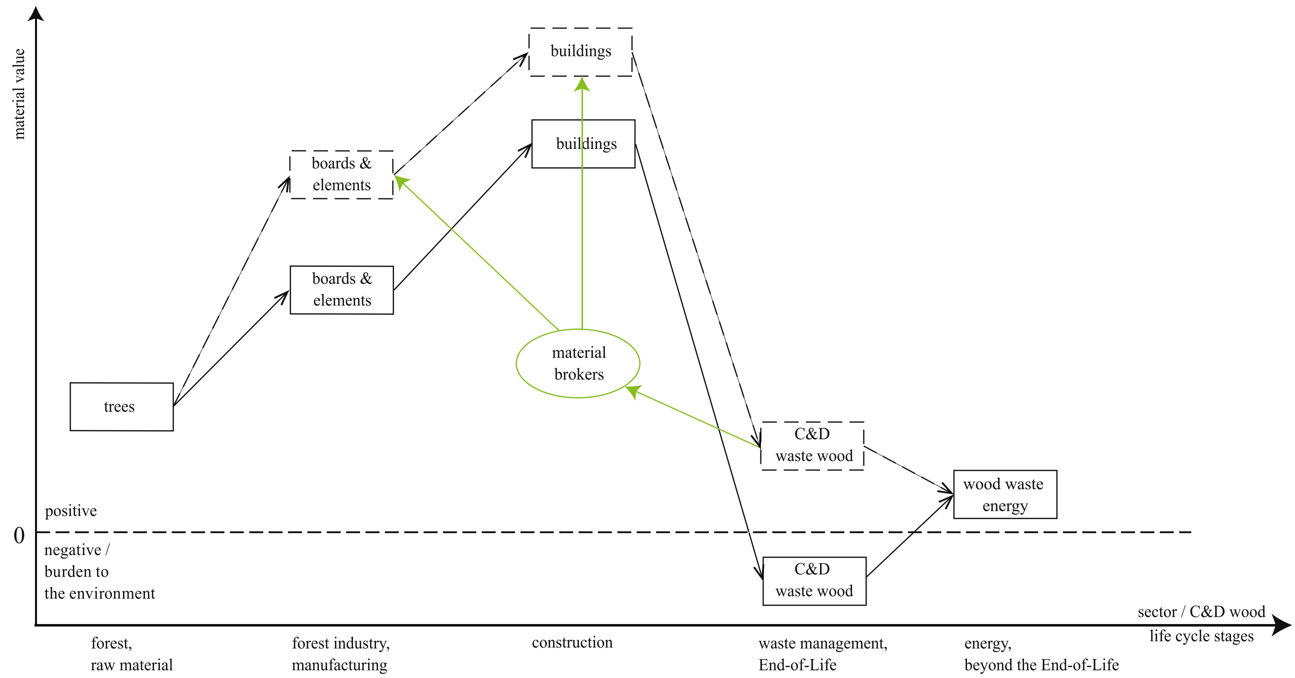

Fig. 2. The updated conceptual framework for cascading C&D wood in Finland, with further elaboration of the suggested reconfiguration. The existing wood products module is illustrated with solid black lines, the dashed ones represent the suggested value-added wood products module, the green ones represent the reconfigured connection in the circular ecosystem.

5.2. Case study

The LCA results include the following two parts: global warming potential (GWP) expressed by the carbon footprint indicator *GWP100* (expressed as a factor of CO_2 equivalent in kg CO_2-eq.) as defined in EN 15804 (2012) and extensive categorized environmental impacts. Partial LCA results of the case study are shown in Fig. 3 and Table 3.

5.2.1. Results of the LCA case study

Global warming potential

If wood is considered to be carbon neutral, the results show a reduction in the *GWP100* of about 30% for all LCIA methods and system models investigated (see Fig. 3a). When considering the biogenic carbon uptake of wood (negative CO_2-eq. value), the *GWP100* benefits seems to be reduced under both system models (see Fig. 3b). However, reusing timber is still beneficial, as it provides the possibility to substitute other primary materials such as concrete, or allows time for trees to grow before felling for production (inducing the biogenic carbon uptake). The global warming benefit resulting from the substitution of conventional building materials become obvious by comparing the environmental impact caused by manufacturing. The GWP of 1m^3 of average ready-mix concrete is 273 kg CO_2-eq. (Unibeton Readymix, 2012) and the GWP of 1m^3 glulam is -656 kg CO_2-eq. or 62 kg CO_2-eq. with and without considering the biogenic carbon uptake of wood respectively (Moelven Töreboda, 2016). Both Unibeton Readymix, 2012 and Moelven Töreboda, 2016 are EPD files that comply with ISO 14025 (2006) and EN 15804 (2012) and the enclosed stages are A1-A3 defined in EN 15804 (2012). At the building level, GWP of a timber building is about half to two-thirds of the one from an alternative concrete building, considering timber as carbon neutral material and including material production and EoL stages only (Buchanan et al. (2013)).

Extensive categorized environmental impacts

In order to have a full view of the total environmental impact, midpoint assessment methods with various categories were utilized. Taking the results obtained by applying the *ReCiPe midpoint (H)* V*1.13* method as an example, as shown in Table 3, within the two system models, the cascading scenario leads to a reduction in all environmental

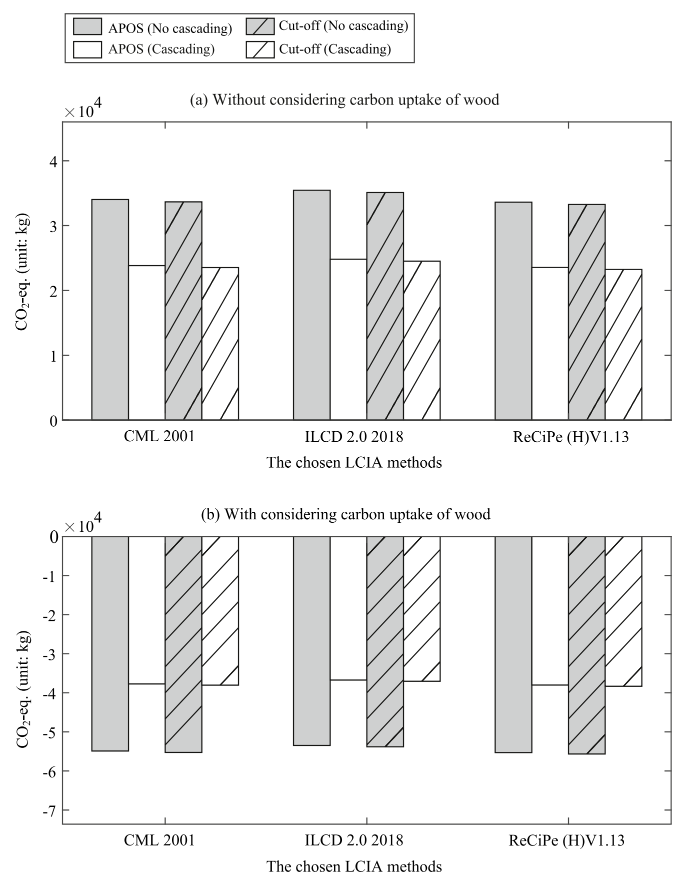

Fig. 3. CO_2-eq. values of the case study by applying different LCIA methods under two scenarios.

Table 3
Various environmental impact of cascading scenario relative to the reference scenario under *ReCiPe midpoint (H)* V*1.13* method (in %).

Environmental impact category	APOS	Cut-off
Ionising radiation (IRP_HE)	72.1%	70.2%
Marine ecotoxicity (METPinf)	70.4%	70.3%
Marine eutrophication (MEP)	69.5%	69.4%
Metal depletion (MDP)	73.4%	73.5%
Natural land transformation (NLTP)*	69.0%	68.9%
Ozone depletion (ODPinf)	70.0%	69.7%
Particulate matter formation (PMFP)	69.8%	69.8%
Photochemical oxidant formation (POFP)	69.6%	69.6%
Terrestrial acidification (TAP100))	70.0%	69.9%
Terrestrial ecotoxicity (TETPinf)	69.6%	69.5%
Urban land occupation (ULOP)	69.5%	69.4%
Water depletion (WDP)	69.9%	69.7%

Note *: Negative values, indicating that the influence of reusing waste wood on NLTP led to relatively less benefits.

impact categories, such as marine eutrophication, metal depletion and ozone depletion. The reduction is similar for both systems models, where the least reduction occurs in metal depletion (MDP). The reduction varies slightly between the two system models, ranging from 69.5% to 73.4% under APOS, and 69.4% to 73.5% under Cut-off. The other LCIA methods used (*CML 2001, ILCD 2.0 2018*) leads to similar results in respect to the reduction between the two system models.

5.2.2. Discussion

The simplified LCA case study presented here is intended to estimate the environmental potential for the reuse of C&D timber. It has to be noted that the results are only valid for the specific assumptions and system boundary. In addition, service life and sizes of timber halls may be different in the real situation, thus the reduction rate of adverse environmental impacts may vary. In general, the LCA practitioner should be careful when selecting the system boundary and model, especially when recycled or reused materials are involved. The climate change abatement and other environmental benefit of cascading C&D timber is obvious in the case study, but the magnitude depends on various influencing factors in practice, such as deconstruction method and duration, volumes and the characteristics of the timber materials being reused, transport distances, cascading manner/scenario and efficiency, the energy consumption of the cascading process, quality control and strength verification.

6. Conclusions

The challenges of resource scarcity and rapid climate change is urging society to move towards more sustainable solutions for the construction sector. Timber, as a widely available and naturally grown material is of particular importance in helping to achieve the environmental goals that have been set by the EU and national authorities. Using timber in construction has increased in recent decades. Nevertheless, the circular economy of timber has seldom been considered or put into practice. This paper aimed to investigate the challenges and potential for prolonging the life cycle of construction timber material and combat climate change through cascading. Therefore, a literature review, interviews with experts from the various sectors involved and a case study were undertaken to identify the economic, environmental and technical challenges in reusing timber, as well the associated potential environmental benefit. The most relevant findings identified are:

- Prolonging the life cycle of building materials has a significant environmental influence as it substitutes virgin raw materials needed for production and reduces the corresponding carbon footprint.
- The main obstacles and concerns to reusing structural timber relate to guaranteeing strength and safety. Reusing structural timber can be achieved technically, but efficient and standardized assessment criteria to guarantee its mechanical properties, thereby ensuring the structural safety of buildings, are needed.
- It is preferable to prioritize material recovery rather than energy recovery and to consider prolonging the life cycle of wood and its storage of biogenic carbon.
- The concept for the CE of structural timber attracts broad interest along with concerns about its cost efficiency and market uncertainty from different actors in the timber industry in Finland. The driving force for initiating the CE of structural timber is expected to come from policy and regulation.
- In order to approach CE for wood in construction, as yet unidentified actors are needed to guarantee the economic value of the waste material along the entire value chain. A reconfigured approach/framework for uplifting the material value of wood is presented.
- Based on a simplified case study, the reduction of the environmental burden when reusing structural components made from wood was estimated and indicates a great potential when the wood is considered as carbon neutral. Considering the biogenic carbon uptake of wood, the environmental benefit is hard to quantify unless the effect of substituting conventional materials in other projects is considered. Nevertheless, reusing structural timber components is beneficial regarding combating global warming, no matter whether biogenic carbon uptake is considered or not.

CRediT authorship contribution statement

Yishu Niu: Conceptualization, Investigation, Methodology, Formal analysis, Visualization, Writing - original draft. **Kaarle Rasi:** Conceptualization, Investigation, Methodology. **Mark Hughes:** Conceptualization, Writing - review & editing. **Minna Halme:** Conceptualization, Writing - review & editing. **Gerhard Fink:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Interview Template Questions

Opening script

This semi-structured interview is part of an empirical research for my Master's thesis titled "The practices and barriers for cascading solid timber: Business Ecosystem in Finland."

The interviewees consist of various actors within business ecosystem for potential timber cascading. The interview will last about 45 minutes to one hour. With your permission, the audio of this interview will be recorded and the interviewer will also take additional notes during the interview. Do you have any questions before we start?

Warm-up questions

- Could you introduce yourself and your organization?
- How is your organization involved with timber? What is its role and importance?
- Do you have any previous experiences or sentiments about cascading timber? If yes, what kind of?

General situation regarding the business ecosystem for

cascading timber

- Could you describe the current environment in the business ecosystem?
- Who / what are the most important actors involved in the business environment, and what are their roles?
- How involved are you with other actors in the supply chain?
- How is the relationship between the organization and the industry?
- Which actors' collaboration would you need the most to be able to reuse timber? Why?
- Where do you see that your organization and the industry will be in five years from now in terms of cascading timber?

Technical aspects

- How feasible do you consider applying cascading timber practices for your organization in the future?
- What would be the technical constraints preventing your organization from reusing timber?
- What technical factors would enable your organization to reuse timber?
- How important do you see digitalization and its role to enable cascading timber?

Policies & Legislation, restricting or supporting

- How is your organization responding/reacting to EU waste management policies and targets?
- What is your opinion of the current policies for waste and material reuse? In your view, how do the current policies restrict and/or support reuse?
- What kind of policies would encourage your organization to adopt timber cascading practices?

Viability of cascading timber

- What would make cascading timber more attractive and profitable in general?
- What are the requirements to make cascading timber profitable for your organization?
- How would the competencies need to be developed in your organization and industry to make cascading timber viable?

Ending the interview

- Is there still something that you would like to share or would be useful for me to know? What would you like to know from other actors?

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