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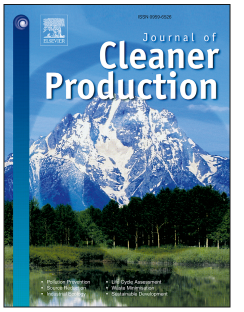

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A circular business model for material reuse in buildings: implications on value creation

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Abstract

Buildings are responsible for a third of global greenhouse gas emissions. A large share of their life cycle impacts is from emissions embedded in materials. Material reuse has the potential to reduce the embedded impacts, since reused materials often have lower environmental footprints than primary materials. Institutional settings and the structure of the building sector pose multiple barriers for businesses developing and commercialising products with reused materials. Although material reuse is claimed to create multidimensional values for several stakeholders, the implications on value creation are still insufficiently understood and taken into account in decision-making.

This study presents a business model by a pioneering Scandinavian company offering three building products with reused materials (i.e. windows, wood cladding, and concrete). Through a multi methods approach, it investigates and discusses the business models' implications on value creation for the firm, value chain partners, customers, and the environment. Findings point to a significant potential for reuse to be price-competitive with linear production practices, to offer value for customers and partners in the value chain network, and to provide significant reductions in environmental impacts. Implications on value creation at industry and macro-economic level, if the business model would be upscaled, should be further investigated.

1. Introduction

Buildings are responsible for a third of global greenhouse gas emissions (UNEP 2009), with a large share of their life cycle impacts embedded in building materials (Cabeza et al. 2014). A solution to reducing the embedded impacts from primary production is the use of secondary materials (e.g. by-products and waste materials) for producing building materials (in this paper referred to as material reuse) (Höglmeier et al. 2013; Nußholz et al. 2019; Malmqvist et al. 2018; Cabeza et al. 2013; Moncaster et al. 2019).

Material reuse has long since been promoted in the field of urban mining. The urban mine with its multitude of anthropogenic stocks is viewed as promising source of secondary material supply (Baccini and Brunner 2012; Editorial 2015) with large material flows available from construction and demolition (Simon and Holm 2018; Koutamanis et al. 2018). In recent years, in the transition towards a circular economy, the use of secondary materials in the building sector has attracted increased attention (EllenMacArthurFoundation 2017; ING 2017; BAMB 2016; Adams et al. 2017). According to several studies, the building sector has a high potential for implementing circular economy strategies and generating both environmental and economic gains (EllenMacArthurFoundation 2017; ING 2017; Koutamanis et al. 2018). Others discuss additional benefits, such as new jobs (EllenMacArthurFoundation 2017; ING 2017; Trinomics et al. 2018) and superior customer value (Schenkel et al. 2015; Moreno et al. 2016).

For economic viability, material reuse needs to be accompanied by adequate business models capable of commercializing price-competitive products that meet regulatory standards and deliver strong sustainability benefits. The business model lens is valuable to study questions related to the associated innovation processes. For instance, how companies create value while adhering to circular economy principles (e.g. new products and technologies, revised value propositions, value chain networks) (Nußholz et al. 2019; ING 2017; Adams et al. 2017). Also, what value the business model creates for the firm and its customers (Wirtz et al. 2016; Massa and Tucci 2014) and for other stakeholders (e.g. the environment or society) are questions of interest in business model analysis (Massa and Tucci 2013; Bocken et al. 2014; Lüdeke-Freund 2010; Evans et al. 2017).

Although new business models for material reuse in the building sector have recently emerged, their diffusion is still slow (Adams et al. 2017; Hart et al. 2019). Hart et al. (2019) find that limited understanding of the impacts of material reuse is one of the main barriers for companies to engage in developing circular economy solutions in the building sector. Developing products with reused materials that are price-competitive with primary resources remains a challenge (Adams et al. 2017; Hart et al. 2019) as innovations for material reuse often require technology development and upfront investments (Hart et al. 2019; Hopkinson et al. 2018). The product's market success and sustainability impacts are often uncertain (Hansen et al. 2009; Nußholz et al. 2019). Overall, the "business and environmental case" for material reuse is still largely underexplored (Hart et al. 2019; BAMB 2016) and it lacks rigorous case studies that could validate value creation of reuse strategies (Hart et al. 2019).

In this paper, we aim to advance understanding of the implications on value creation of a business models for material reuse in building products. We use a single case study of a business model employed by a pioneering Scandinavian company, which commercialises *windows*, *wood cladding*, and *concrete* with reused materials. The study explores the implications on value creation of their material reuse business model in terms of:

(1) financial structure and viability of the case company,
(2) employment creation and value for partners in the value chain network,
(3) customer value,
(4) environmental impact reductions.

Building on sustainability evaluation practices, the four indicators and were developed to uncover value creation beyond financial metrics and explore the viability of the business model for multiple stakeholders (i.e. customers, value chain partners, environment).

The paper proceeds with a review of the relevant background literature (section 2), a description of the methodology (section 3), and the results of the case evaluation (section 4). Section 5 presents the discussion and Section 6 presents the conclusion.

2. Literature background

2.1 Circular business model innovation in the building sector

The potential of material reuse to reduce embedded emissions associated with buildings has gained recognition among policy makers (Danish_EPA 2015a, 2015b), companies (3XN 2016; Vandkunsten et al. 2016; BAMB 2016; Rebrick 2019), and academic scholars (Malmqvist et al. 2018; Nygaard Rasmussen et al. 2017; Durmisevic 2006; Moncaster et al. 2019; Cabeza et al. 2013). An increasing number of services, products and processes for material reuse are being developed in the building sector and commercialized in new business models (e.g. Rebrick, New Horizon, Spaces4You, Madaster). These new business models vary in their types (e.g. operating vs. facilitating material reuse (Whalen 2019)), and offer solutions at different steps in the value chain (e.g. building design, building operation, and demolition to recover materials), or for different building layers (e.g. facades, structural elements, interiors).

Despite these developments, research reports that the building sector remains largely discouraging of circular economy implementation. Common barrier reported in literature include the emphasis on financial metrices and return on investment, a lack recovery infrastructure, and inadequate design of buildings for material recovery (Hart et al. 2019; Adams et al. 2017; Nußholz et al. 2019).

To overcome such barriers, business model innovation has been one of the focus areas to advance circular economy and material reuse practices in the industry and capitalize on the associated opportunities (Ness and Xing 2017; Hopkinson et al. 2018; Nußholz and Milios 2017).

Business models define a set of elements that allows mapping the organizational architecture to *create*, *deliver* and *capture value* (Osterwalder and Pigneur 2010) (Massa et al. 2017; Massa and Tucci 2013). In traditional business model research, value is typically considered as a financial value for the firm and customers (Massa and Tucci 2014). In the realm of circular and sustainable business models, value is understood more broadly to consider a wider range of stakeholders, such as value chain partners, the environment and society (Massa and Tucci 2014; Lüdeke-Freund 2010; Bocken et al. 2014; Freudenreich et al. 2019).

Innovating the business model can refer to establishing a new business model or reconfiguring the elements of an existing business model (Zott and Amit 2010; Massa and Tucci 2014). Business models goes beyond traditional innovation areas, such as products or production processes (Zott et al. 2011) and allows researchers to study how new products and processes are brought to the market through designing value creation processes and value networks (e.g. suppliers) (Massa and Tucci 2014; Osterwalder et al. 2005; Zott and Amit 2010; Zott et al. 2011).

Just as in traditional, linear business models, circular business models in the building sector need to be designed to ensure economic viability and customer value and will consist of similar business model elements to commercialise products or services. A unique characteristic, however, is their objective to manage both economic and environmental issues and optimise the value creation in more than one sustainability dimension.

2.2 Value creation of circular business models for material reuse

Literature reports on a variety of implications on value creation from to circular economy strategies in general, and material reuse for building products in particular.

Recent studies highlight that few *financial* analyses of the business case for material reuse have been published within the building and construction sector (Ghisellini et al. 2018; Hart et al. 2019). Studies on circular business practices in general show high costs associated with labour labor (Whalen et al. 2017) and reverse logistics (Kissling et al. 2013). Linder (2013) and Linder et al. (2015) emphasize risks from uncertain prices of secondary materials. Other studies report potential cost savings from lower priced secondary materials (Verian et al. 2013; Moreno et al. 2016). In the context of building products, Ferreira et al. (2015) show that to meet regulatory requirements, the addition of new (and costly) materials can be necessary. Jung et al. (2015) suggest total costs are dependent on the value chain structure, identifying transportation distances, site conditions, and materials quantities as main determinants of costs in concrete recovery and reuse.

Material reuse is associated with *employment creation* and *value for network partners*. Through capitalizing on the ‘inner circles’ of the circular economy framework, which maintain value embedded in products and materials at higher level (EllenMacArthurFoundation 2017, 2016; ING 2017), new value adding activities for the recovery and reuse process may be organised (Wells and Seitz 2005; Singh and Ordoñez 2015). Hestin et al. (2015) show that these activities are on average more labour intensive than heat recovery and may thus have potential to increase net job creation. Several recent studies identified potential for positive net job creation impacts from increased circular economy activities, studying different sectors and regions, and using various types of economic input output models (Wijkman and Skånberg 2015; Hestin et al. 2015; Milios et al. 2018; Trinomics et al. 2018; IISD 2018). Assessing jobs created as outcomes of circular economy projects, rather than projections, are less prominent in literature. Ward et al. (2013) review different indicators for job creation across the EU. They suggest that if assessing jobs created directly from a program, indicators should be reported in full-time equivalents and unambiguously defined to allow for comparability.

In addition, material reuse is often associated with superior *customer value*. Mokhlesian and Holmen (2012) highlight that green building development, such as circular economy implementation, has the potential to reduce total life cycle costs, although, according to Vatalis et al. (2013), the dominating perception is that environmental sustainability increases initial investment costs, which is reported to be key in decision-making in the sector (BAMB 2016; Azcarate Aguerre et al. 2018). Other potential financial benefits for customers include the ability to charge a premium for buildings with lower environmental impacts (Witjes et al. 2016; Klotz et al. 2007). Also, improved competitive advantage, (Witjes et al. 2016; Schenkel et al. 2015), and innovation, as well as user value (e.g. quality, design and ease of use), are discussed as potential customer benefits (Schenkel et al. 2015; Klotz et al. 2007). Finally, reduced environmental impacts, e.g. from raw material consumption and waste, may have positive effects on corporate image and marketing (Witjes et al. 2016; Schenkel et al. 2015; Klotz et al. 2007).

Much evidence exists that material reuse has significant potential for *environmental impact reductions*, although to varying extent depending on material streams and products (Cabeza et al. 2014; Nußholz et al. 2019; Ortiz et al. 2009; Ingrao et al. 2014). Environmental impact reductions form material reuse depend on the individual case and the processes affected by reuse (Zink and Geyer 2017; Geyer et al. 2016). Environmental benefits from using secondary materials vary depending on, for instance, the recovery processes that are required to ensure that the secondary product fulfils the same functional requirements as the avoided primary product (Vadenbo et al. 2017). For instance, Nußholz et al. (2019) find that brick reuse has a carbon saving potential of 99% compared with the primary-based alternative, and plastic reuse for façades from a wood-plastic composite a carbon saving potential of 70-50%.

3. Methods and data collection

This study combines a case study research with a multi method approach to explore implications on value creation of a business model offering material reuse in the building sector. Section 3.1 offers a description of the case companies' business model. Section 3.2 explains the evaluation and indicator selection approach and Section 3.3 the approach to data collection and analysis.

3.1 A circular business model for material reuse in buildings

This study employs a single case study of a pioneering Scandinavian company offering circular solutions in the building sector. The company developed a novel business model for recovering and reusing three material streams from urban material stocks, i.e. secondary glass, wood, and concrete. Materials were developed into new products for a residential building project between November 2017 to October 2018. Production and installation are outsourced and the case company manages the value chains illustrated in Table 2. Customers of the three reuse products were two Scandinavian building developers and investors, developing about 20 residential houses in the same urban area. Table 1 summarises the main dimensions of the business model.

Table 1 Description of case company's business model.

Business model dimensions	**Business model design**
Value proposition	Customers were two Scandinavian building developers and investors that developed about 20 residential houses. Building products are designed to comply with the same standards as linear benchmark products (e.g. price, quality, aesthetics, functionality, safety), but with a reduced environmental impact.
Value creation	The case company was responsible for product development and project management of the three reuse products, including the material sourcing. Manufacturing and installation (described in Figure 1) were outsourced to value chain partners but overlooked by the case company. Next to product development, the company consist of an architecture branch. This helps capitalise on building design capabilities to incorporate material reuse and to offer integrated circular economy building solutions.
Value capture	Main revenues are from building developers' payments. In addition, the company was granted a national innovation subsidy that helped cover a share of the project management and innovation costs related to the project. Costs occurred mainly for R&D, production and project management.

The manufacturing processes and value chains are illustrated in Table 2 and Figure 1.

Table 2 Description of the three products.

Material	Characterization reuse strategy	Process description

Wood	By-product use	Wood is obtained from by-products and lower-grade production of a plank producer in proximity of the case company. Through cutting, surface treatment and mounting, the wood is developed into floor and façade cladding (indoor and outdoor).
Glass	Material reuse	Post-consumer windows are collected from demolition sides and dismantled to obtain glass. Glass is assembled into new windows by adding customized frames and a second layer to comply with energy efficiency standards.
Concrete	Material recycling	Post-consumer concrete from demolition side is crushed into aggregates and through mixing with primary cement and other concrete components developed into new concrete.

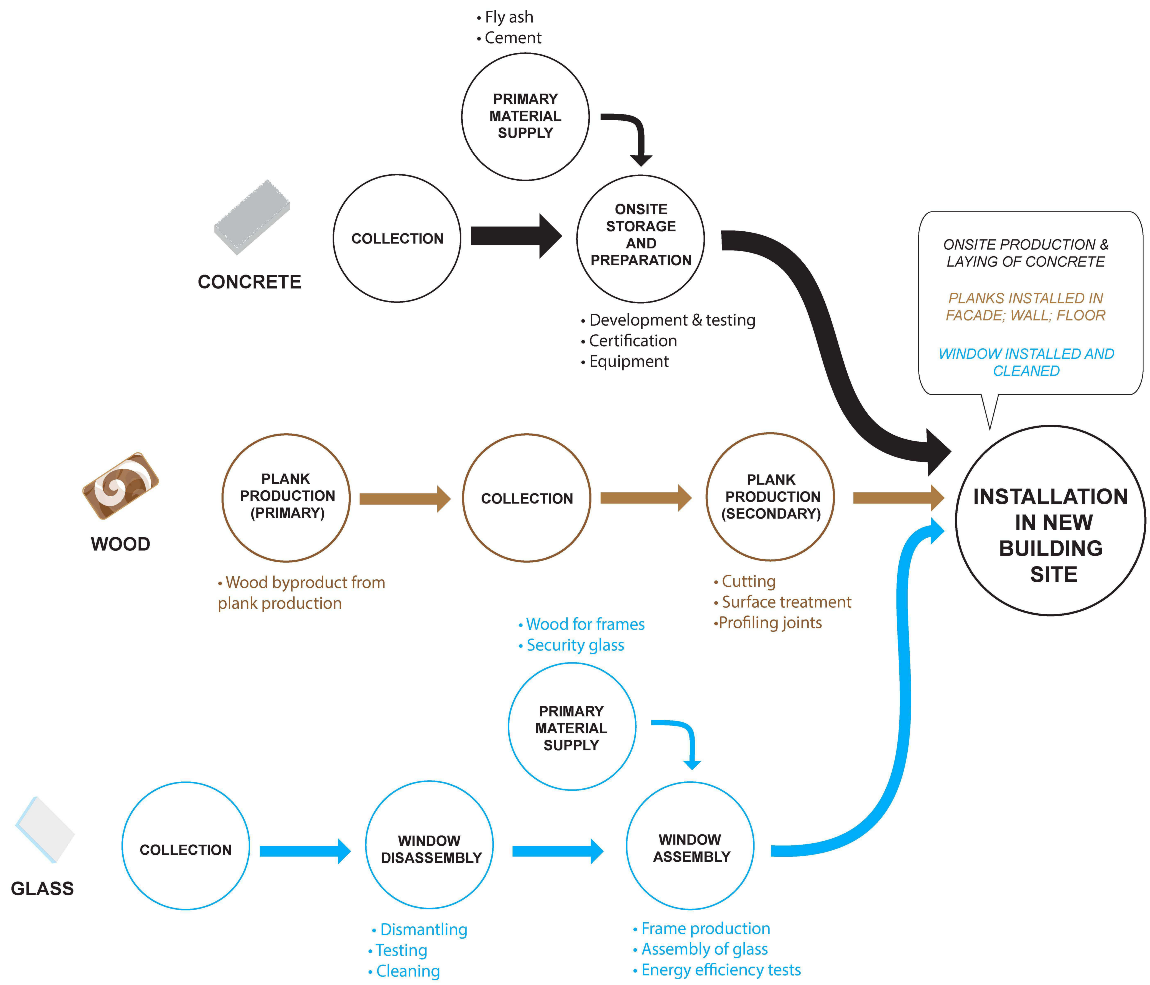

Figure 1 Overview on value chain and processes of the three products.

The single case study design with its three sub-units (i.e. wood, windows, and concrete) was chosen to allow for a deeper understanding of the impacts of commercializing material reuse in products as to date research that captures the value creation of business models for reuse in the building sector is largely absent (Hart et al. 2019). Although single case study approaches pose limits to generalisability, they are regarded beneficial for providing in-depth, data-rich descriptions of a phenomenon (Yin 2013). If thoroughly executed, single case study approaches are sources of concrete, context-dependent knowledge that produce exemplars of a phenomenon in a systematic way (Flyvbjerg 2006). The narrative such exemplars produce can reduce complexity of a real life phenomenon and are considered to play a central role in the development of scientific knowledge (Flyvbjerg 2006).

3.2 Evaluation approach and indicators

The evaluation approach in this study followed the two steps suggested by Lüdeke-Freund and Schaltegger (2017) to conduct integrated sustainability evaluations at a business model level.

In the *first step*, value aspects of materiality to the case were identified. This was done by reviewing literature on material reuse in the building sector, circular economy and resources efficiency, sustainable business models, and green construction (section 2.2). Three business developers and one senior architect from the case company, as well as a sustainability manager of a leading Scandinavian building developer were also consulted. Focus was on impacts that were closely related to building materials and products (e.g. impacts from production, waste generation, costs of building products), rather than impacts that result from design choices at building level (e.g. biodiversity, affordable housing). By reviewing sustainability assessment approaches and their indicators (e.g. KPIs in the building sector, Global Reporting Initiative), suitable indicators to operationalize the value aspects were identified.

In the *second step*, the list of pre-selected indicators was discussed with the three business developers and the senior architect of the case company. This resulted in a final set of indicators that was deemed suitable to uncover the most relevant implications on value creation of the business model for material reuse for different stakeholders. As such, the evaluation design was predominantly informed by practitioners' views on key value implications related to their business model and relevance of indicators to industry stakeholders. In addition, indicator selection was determined by feasibility considerations in regard to resources, time and data accessibility (Turcu 2013) . Final selection included four indicators:

(1) **Financial structure and viability**: Implications on the case company's financial structure and viability are investigated by identifying costs and revenues.
(2) **Employment creation and value for partners in the value chain network**: Implications for other firms in the value network are investigated by calculating overall employment creation and identifying business opportunities for other actors in the value network that would not occur in linear production practices.
(3) **Customer value**: Benefits from material reuse for building developers and investors are investigated.
(4) **Environmental impact reductions:** Environmental impact reductions compared with linear reference products are examined along multiple impact categories, focusing on Global Warming Potential (GWP).

3.3 Data collection and analysis

Data collection and analysis was conducted in the period between September 2018 and January 2019 through multiple qualitative and quantitative methods.

3.3.1 Financial structure and viability

A cost structure analysis for each of the three reuse products was performed to identify the case company's costs and revenues and discuss implications on financial viability. Cost structures were analysed in two steps. Firstly, the cost factors (i.e. activities and inputs) in the product development of reuse products were identified to group and organize invoices and related costs. All relevant company invoices were reviewed and company employees were interviewed to understand productions steps and material inputs required for each reuse reuse product. After identifying the generic value chain activities and inputs for each reuse products, every single invoice from the project was allocated to its cost factor. Company employees were consulted to verify accurate understanding of financial data and value chains and results of the cost structure analysis were compared to the total project costs to ensure accuracy. Financial viability was analysed based on business case analysis available among the case company's accounting data.

3.3.2 Employment creation and value for partners in the value chain network

To develop an estimate of employment creation impacts, estimates of hours spent on the project by the case company and project partners (i.e. material suppliers, manufacturers, installers) were collected. For this, both accounting data of the case company and surveys with project partners were used. The resulting sum of total work hours was converted into an equivalent of *full-time employment for half a year* for one person *(FTE)* (Ward et al. 2013). The FTE equivalent was calculated by dividing the total number of hours by an average of work hours per week in Scandinavia (37hrs) and the number of months of work per half year.

Our focus was on impacts at business model level and assessing outcomes of the project rather than projections from upscaling material reuse practices. Therefore, net employment in other sectors and potential substitution effects that would occur when upscaling the business model were outside our scope. Given the current scale of business activities in the studied business model, it is unlikely that material reuse has traceable substitution impacts in other industries. However, when aiming to upscale the production strategies in the industry, changes at macro-economic level and shifts in economic activities in other sectors are important to consider.

To add to the insights on employment creation, qualitative analysis of the value chain processes was performed to investigate new or improved business opportunities for value chain partners. For this, the production processes for wood, glass, and concrete were studied to identify whether (1) *new* value adding activities were realized compared with conventional, linear material recovery, or whether (2) some of the value chain processes were *more labour intensive*.

3.3.3 Customer value

A survey of the building developers and investors was conducted to assess customer value and potential benefits from material reuse. To develop the survey, we first performed a literature review to identify the most relevant value drivers and their indicators for building developers and investors. The literature included academic studies on value creation from circular practices (Schenkel et al. 2015; Park et al. 2010; Witjes et al. 2016), sustainability assessment of buildings (Klotz et al. 2007; Celik and Attaran 2011), and traditional value metrics in building development that are related to the choice of building products (van Bueren and Broekhans 2013; Zaeri et al. 2016). Secondly, the compiled list of indicators was discussed with managers of three Scandinavian building developers (one involved in the case project and two others) asking them to rank the indicators according to their perceived relevance and to add value drivers that were missing in the list. The final list of indicators was categorized into three overarching groups, i.e. (1) Business value, (2) Stakeholder value and product performance, and (3) Green Leadership (Figure 2).

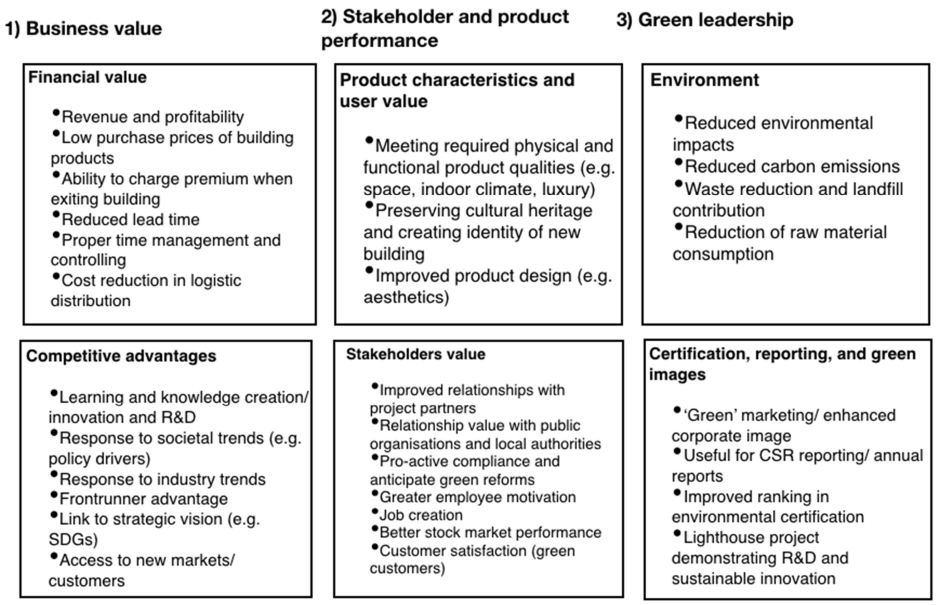

Figure 2 Overview on categories and indicators for customer value assessment.

After the development of the survey, building developers of the case project were contacted. For each of the two companies, two employees (holding positions of *Sustainability director*, *Project development*, *Business development director*, and *Public relations manager*) ranked to what extent different types of value were realised from material reuse on a scale of 0-3, with 0 representing "not realized" and 3 "fully realized". A limitation of the self-assessment was the timing of the survey as it is expected some of the potential benefits (e.g. financial performance, economies of scale) will only materialize in the future. Other benefits (e.g. marketing effects) had already materialized at the time of the evaluation.

3.3.4 Environmental impacts

To assess environmental impacts of the three reuse products, we conducted life cycle impact assessments (LCA) of each reuse product following the *European Product Standard EN15804*. For the wood products, the *product category rule for wood and wood-based products for use in construction (EN16485)* was used. System boundaries were set at cradle to gate. LCAs modelled in SimaPro using the Ecoinvent 3.4 database. For impact categorizations, we used ILCD's mid-point approach, as its method for Global Warming Potential (GWP) takes into account biogenic carbon and carbon storage as prescribed by the IPCC 2007 method. Models containing the processes used and their contributions to GWP are presented in Appendixes A to C. Data for modelling the reuse products was based on internal company data. To model reference products, publicly available data was used (also see Table 3 for key assumptions and their references).

We used global warming potential (GWP) as indication of carbon saving potential and also discussed the impacts in other impact categories when significant savings or trade-offs were observed. It should be noted that environmental assessment was conducted for the total amount of secondary-based building materials in the construction project. This does not equal the total amount of windows or concrete used in the building, as for some also primary-based materials were used.

Table 3 Overview on products, processes, and critical assumptions for LCA models.

Windows (1195,88 m2)		
Secondary-based product	**Primary-based reference product**	**Critical assumptions**
Facade window with wood-frame and two layers of double layered glass (primary and secondary). • Disassembly of post-consumer windows • Manufacturing of wood frame • Input of reused glass • Input of primary glass (normal and security glass) • Paint for wooden frame • Transport	Facade window with aluminium-wood frame with three layered glass. • Manufacturing of wood-aluminium frame • Input of primary glass, three layers (normal and security glass) • Transport	• Layers of glass of reference product • Aluminium-wood frame as it is the standard in the industry • Share of reused glass in reuse product
Concrete (837m3)		
Secondary-based product	**Primary-based reference product**	**Critical assumptions**
Concrete containing secondary aggregates • Secondary aggregates • Sand • Cement • Water • Plasticiser • Transport	Concrete containing primary gravel as aggregate • Primary aggregates • Sand • Cement • Water • Plasticiser • Transport	• Transport distances lower for secondary gravel as sources with close distance
Wood (3755 m2)		
Secondary-based product	**Primary-based reference product**	**Critical assumptions**
Cladding from wood plank off-cuts • 2nd grade wood • Transport • Steel • Paint	Cladding from primary wood • 1st grade wood • Transport • Steel • Paint	• Allocation approach

4. Results

This section presents implications on value creation in regard to the four indicators.

4.1 Financial structure and viability

The case company was able to recover all costs for the three reuse products in the first production line, yet with only modest profit. Because of data confidentiality, only implications on financial viability are discussed.

We find that for all three products, there is a significant potential for improving the financial value. Production of products can be optimized through leaner production processes, fixed costs (e.g. initial R&D costs) will be reduced in future production lines and economies of scale can be utilized. Thus, even without the innovation subsidy that helped cover R&D related costs, a viable business case in future production lines, where R&D related costs will be significantly lower, appears feasible.

The vast majority of revenues stemmed from the building developers' payments, and to smaller share from the innovation grand. The latter made up about 1% of total revenues for the wood products, 4% for windows, and 11% for concrete.

Cost differed considerably among the three products (Figure 3Figure 4Figure 5). In the case of *windows*, the largest share of total costs resulted from production (above 80%), while material sourcing costs were below 5% (to respect data confidentiality, results of the cost structure analysis are presented only in relative terms). In the case of *concrete*, the largest share of total costs resulted from production (a large share stemming from rental of production equipment), but also primary material sourcing (e.g. cement) was a significant cost driver. R&D costs were around 10% of total costs. For the case of *wood*, the largest share of costs resulted from material sourcing of off-cuts, which are of high-quality wood, followed by production costs.

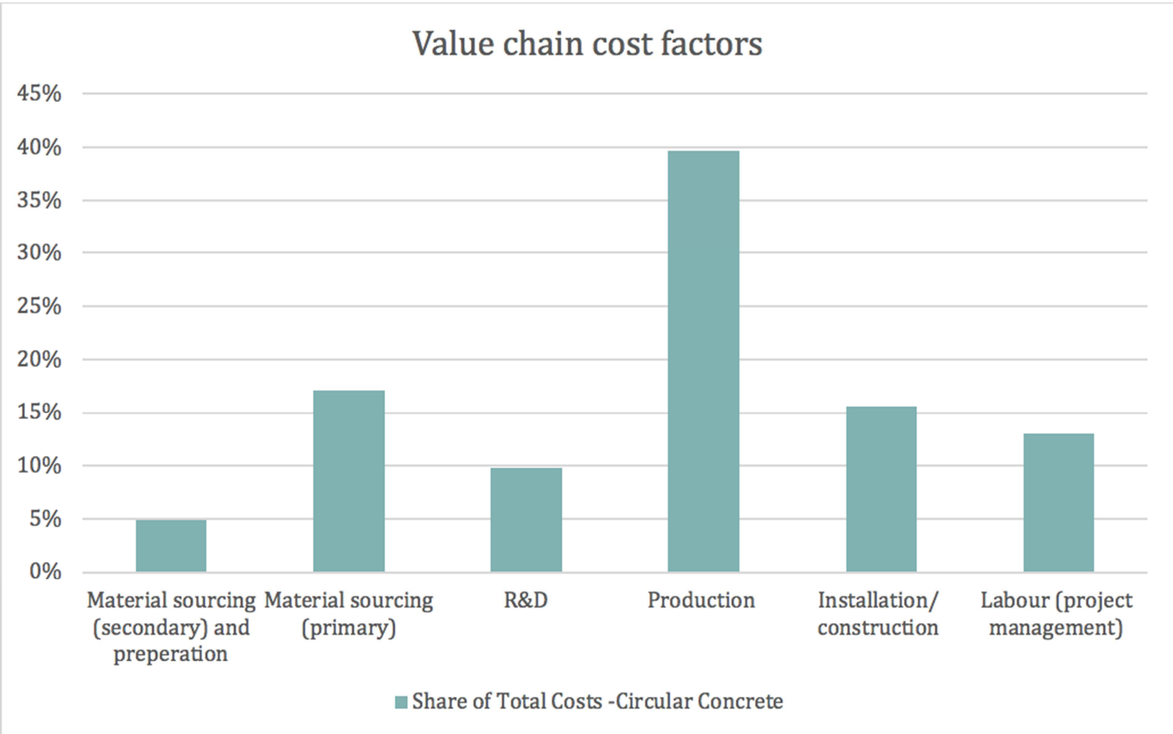

Figure 3 Costs drivers secondary-based concrete

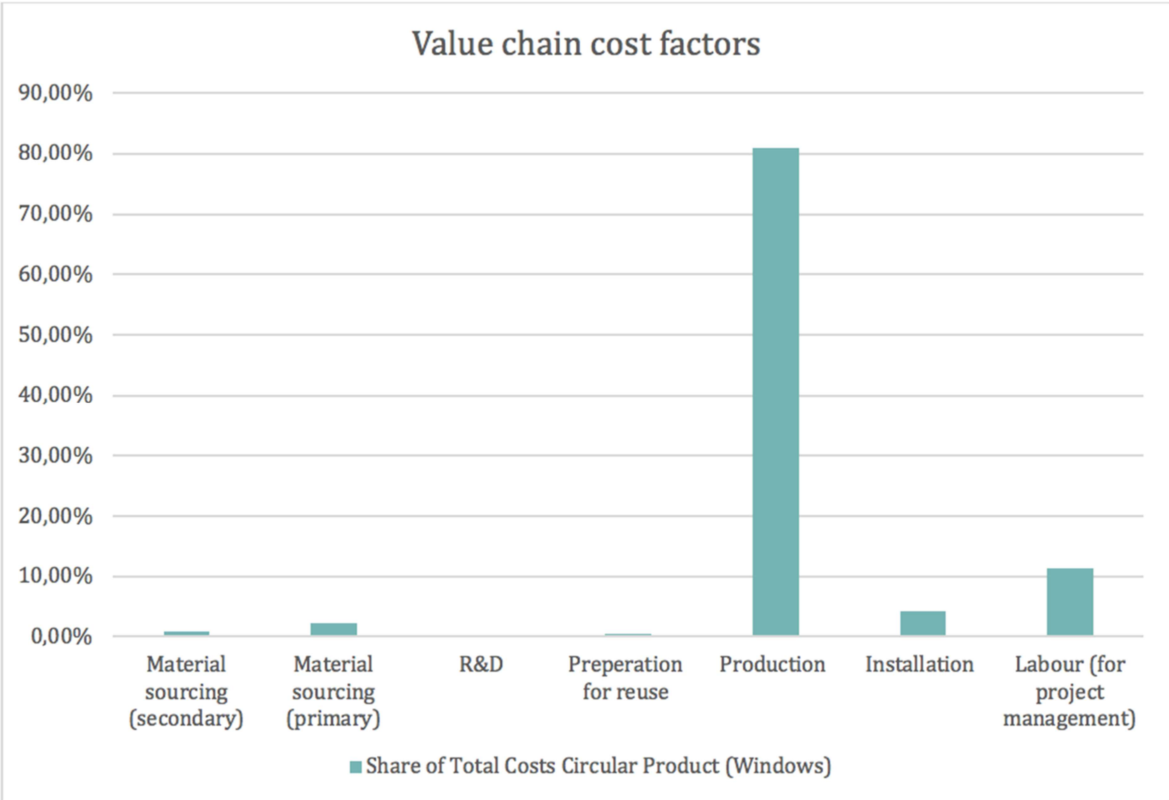

Figure 4 Costs drivers secondary-based windows.

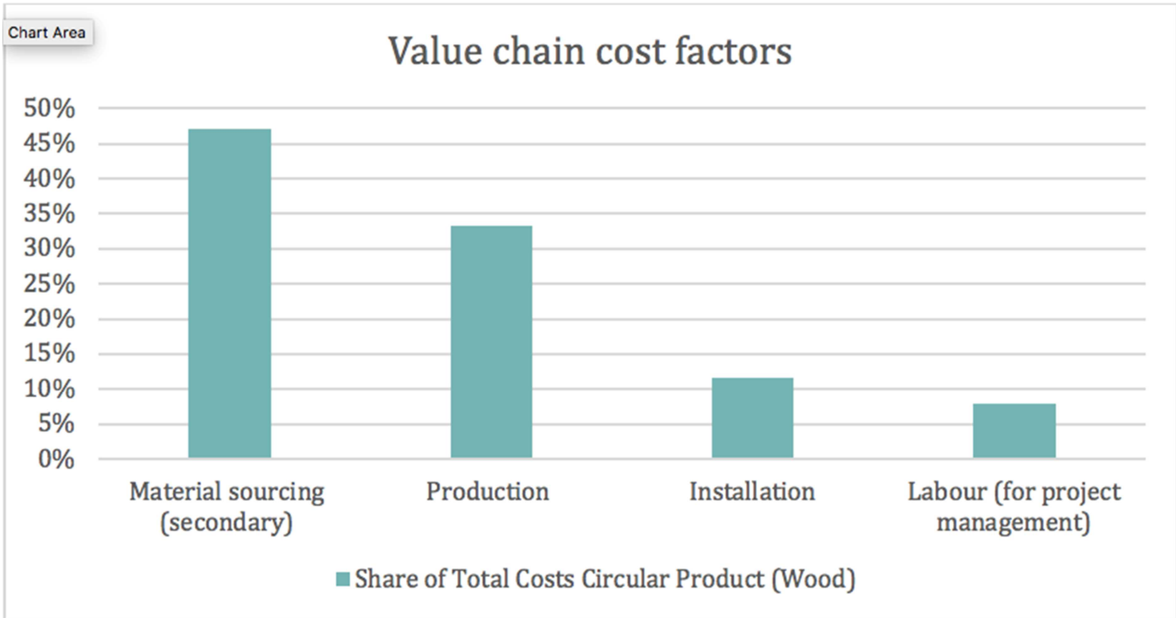

Figure 5 Cost drivers of secondary-based wood cladding

4.2 Employment creation and value for partners in the value chain network

The total number of work hours throughout the course of the project was equal to 18.4 jobs (equivalent to half a year of full-time employment) (see Section 3.3.2). Production of windows generated the equivalent of 2.8, wood reuse – 13.2, and concrete – 2.4 jobs. The higher number in the case of wood reuse can be attributed to labour intensive profiling and installation of planks for floors and cladding, which are shorter than conventional planks.

Table 4 Overview of jobs created during the course of the project.

Products	**Total hours spent**	**Months full-time work created** (37hrs per week)	**Jobs created** (eq. to half a year of full-time employment)
Windows	2 500	16,9	2,8
Concrete	2 170,5	14,7	2,4
Wood (cladding and floors)	11 700	79,1	13,2
TOTAL	**16 370,5**	**110,6**	**18,4**

To gain additional insights on value created for partners in the network, we analysed the reuse processes to identify *(1) new* and *(2) more labour-intensive business activities* compared with linear production. This revealed that reuse strategies offered new business opportunities to material suppliers and manufacturers in the value chain.

Regarding *(1) new value-adding activities*, firstly, the disassembly of post-consumer windows can be considered as a new business activity that does not occur in linear production practices. Secondly, wood recovery offered a new income opportunity for the supplier of off-cuts, that were previously only stored as there was no demand other than for heat recovery. Thirdly, the project enabled the reuse of glass that would usually be material-recycled, now providing a higher income for suppliers.

In addition, several *(2) more labour-intensive processes* compared with conventional, linear production took place. Firstly, the installation of wood cladding as planks are shorter and, secondly, manufacturing of new window frames due to multiple layers.

4.3 Customer value

Regarding the category *business value*, findings show that building developers and investors highly valued the innovation and knowledge creation effects from the project, but also the opportunity to respond to societal trends (each ranked with a mean score of 3/3 points), to gain a frontrunner advantage and to realize their company's strategic vision (e.g. SDGs) (each ranked with 2.3/3 points). Financial benefits for building developers and investors were not identified (e.g. 'low purchase price of building products' (0/3) and 'ability to charge premium when exiting building' (0.3/3)). This may partly stem from the additional costs for R&D required for the development of the first production line, but also from timing of the evaluation, when it was not yet possible to evaluate long-term financial performance including effects from economies of scale of the products.

In the category *stakeholder value and product performance*, indicators received varied scores. Meeting required physical and functional product qualities (2.3/3), and improved relationships with project partners (2.3/3) achieved the highest scores. Lower scores were given to job creation effects (0.7/ 3), which may partly be a result of lacking evaluation and knowledge on employment creation at the time of the survey.

Regarding *green leadership*, value creation was most strongly reported in regard to improvements in corporate image (3/3) and CSR reporting (2/3). As the buildings were not sustainability certified, benefits of improved ranking in sustainability assessment schemes (e.g. LEED, BREAM, DGNB) were not relevant. Realization of environmental improvements (i.e. reduced carbon emissions, waste reduction and landfill contribution, reduction in raw material consumption) were ranked with 2.1/3. This may again result from the timing of the evaluation, where LCAs by external consultants were still under preparation and only LCAs conducted during product development were available.

4.4 Environmental impacts

The findings on each product's carbon saving potential (CSP) presented in Table 5 show that environmental impact reductions are significant, but differ strongly between the three alternatives.

For the case of windows, LCA results suggest a carbon saving potential of 56 t-CO2-eq, which is 77% lower than the primary materials-based reference product. However, as the secondary material-based product contains more materials per m2 window and has a different ratio of wood and glass compared with the reference product, LCA results indicate several trade-offs with other impact categories. For instance, due to the high wood content, the secondary-based product performs worse in acidification and land-use impact categories.

The secondary-based concrete performs better in all impact categories compared to primary concrete. Its carbon saving potential is 11 t-CO2 eq, and thus 4% lower than the reference product. As 91% GWP impact of the reference product stems from cement and only 5% from primary gravel, using secondary aggregates in the concrete can only achieve incremental GWP savings. However, LCA results show that using secondary aggregates in concrete, has the potential to reduce land use impacts by 37%, mineral fossil and renewable resource depletion - by 30%, and water resource depletion and human toxicity (cancer effects) by 20%.

The wood products (co-product of plank production) are estimated to have an overall carbon saving potential of 73.3 t CO2 eq in the production stage, as the wood product provides a carbon storage. However, the *product category rule for wood and wood-based products for use in construction (EN16485)* (Section 3.3.4) prescribes a physical mass allocation approach. Employing physical mass allocation renders the benefit of the stored carbon of co-products equal to the main product (planks), even if the next cascading step of the co-product provides carbon storage rather than incineration with heat recovery. This would imply for practice that a lower cascading level such as heat recovery was equally preferable from a CO2-emission point of view than further processing of the co-product for cladding purposes and prolonging the carbon storage. This contradicts with recent studies that find that the extended carbon saving function and primary material substitution of co-product use can be considered relevant to decrease environmental impacts at product level (Mehr et al. 2018; Taylor et al. 2017).

As standards are developed with a product focus, they do not adequately reflect the benefits of material cascading of wood in the overall system. We find that this can be regarded as a limitation of the standard when applied to circular material strategies, which is also highlighted by Taylor et al. (2017) who suggest that economic allocation (in which environmental impacts are allocated based on economic value of the product and co-product) can be more appropriate to capture environmental savings of the co-products.

Table 5 LCA Results of GWP Impact Category for each reuse product.

	Concrete	**Windows**	**Wood**
Final results of primary-based product (t CO2 eq)	271	72,5	73,3
Final result of secondary-based product (t CO2 eq)	260	16,5	73,3
CSP (t CO2 eq)	11	56	n.a.
CSP (%)	4%	77%	n.a.

5. Discussion

This section presents the discussion of implications on value creation in regard to the four indicators.

5.1 What are implications of material reuse for the business model's financial structure and viability?

The case company was able to recover all investment and production costs after the first production line, although with modest profits and the help of an innovation grant. As the innovation grant only covered a part of R&D related costs, which are significantly lower in future production lines, material reuse has potential to be financially viable also without the innovation grant. It should be noted that this study investigated a first production line, when integration of value chain activities and optimization of production practices were still at their early stage. We argue that with effects of scaling and efficiency improvements, financial viability has high potential to be price-competitive with linear production practices. As such, also integration of material reuse in companies operating linear business models may be attractive.

Nevertheless, findings also indicate that financial viability of material reuse can be a challenging endeavour. Products with reused materials can require substantive manufacturing processes and input of (costly) primary materials, while also secondary material inputs may still cause substantial costs (Figure 3Figure 4Figure 5). The wide-spread assumptions that reuse strategies gain cost savings from reduced costs for materials may not always be realized. To safeguard financial viability, it requires careful product and value chain design and control of cost factors to ensure that total cost do not exceed those of primary-based products.

5.2 What are implications of material reuse for employment and value for network partners?

With a total of 18.4 jobs created (eq. to 6 months of full-time employment) the business model clearly created employment. Given that reuse products contained several processes that are more labour intensive than primary production (e.g. installation of wood cladding as planks are shorter, disassembly of post-consumer windows, and manufacturing of new window frames), there is indication that material reuse can lead to increased employment compared with linear production practices. Employment creation can be expected to be lower in future production lines as about a third of all labour occurred from R&D activities that will be lower in future. Improved product design, more integrated, and lean manufacturing processes may reduce labour intensity.

Findings resonate with common assumptions that business models for material reuse result in wider economic benefits for partners in the value network (ING 2017; EllenMacArthurFoundation 2017, 2015). Value chains that were established for material recovery, manufacturing, and installation of reuse products, provided new or improved revenue streams for secondary material suppliers and manufacturers that capture the economic value of the ‘inner circles’ (EllenMacArthurFoundation 2015).

Given the current scale of the business model, it is unlikely that manufacturing activities have traceable substitution effects in other industries (i.e. new value adding production activities minus value adding activities for primary products that are substituted). However, to assess net economic impacts and employment creation if the business model was upscaled, more comprehensive, econometric analyses are needed. Also, investigation of the types of jobs created or the geographic location of jobs can be of interest for policy-makers (Trinomics et al. 2018).

5.3 What are implications of material reuse for customer value of building developers and investors?

All three products were designed to be as price and quality competitive with linear reference products as possible. We find that building developers and investors assessed the products with reused materials overall positively. They indicated customer value across all three investigated categories, but at the time of the evaluation gave no indication of superior financial benefits from material reuse. This may partly stem from the additional costs for R&D required for the first production line, but also from the timing of the evaluation, at which exit and long-term financial performance of the building was unknown, as well as effects of economies of scale.

Nevertheless, building developers and investors reported several non-financial benefits from material reuse, including the opportunity to innovate and create knowledge that may render their organizations more prepared for societal trends or future changes in legislation. In addition, gaining a frontrunner advantage and contribution to the companies' strategic vision (e.g. SDGs) was clearly reported as a benefit, as well as the development of products that can deliver significant environmental improvements, and potentially future cost savings through efficiency improvements in production.

5.4 What are implications of material reuse for environmental impacts?

Life cycle assessment of the three reuse products indicates significant environmental impact reductions (Section 4.4, Table 5). A key finding is that the carbon saving potential between the three solutions differs significantly (e.g. 4% for secondary-based concrete and 77% for secondary-based windows) and that trade-offs between different impacts categories exits.

Another finding is that material reuse cannot always address the main contributing processes of a product. Our LCA shows, for instance, that concrete cannot offer high reductions in climate change impacts compared with primary-based concrete. This is because cement production accounts for 91% of total GWP impacts and cannot be lowered through using secondary aggregates. However, the reuse products performed better across all impact categories with significant improvements in land use impacts (37%), mineral fossil and renewable resource depletion, as well as water depletion and human toxicity (30%). As such, despite the relatively low carbon saving potential, the reuse products can be seen to contribute to a gradual development of a more sustainable product that has the potential to improve regional processes.

An overall finding is that environmental impact reductions are not realized by default. It requires careful consideration of product design and value chain processes to realize environmental impacts. Building products underlie strict regulations (e.g. energy-efficiency and safety) and may thus require significant input of primary materials to meet current construction standards. Impacts from primary materials that need to be added during the production can outweigh the benefits from using secondary materials and also unavoidable processes (e.g. transport, cement input) may have significant contributions to environmental impacts.

6. Conclusion

This study examined a business model by a pioneering Scandinavian company offering three building products with reused materials from urban mines (i.e. windows, wood cladding, and concrete) and its implications on value creation. Implications on value creation were considered for multiple stakeholders such as the case company, customers, value chain partners, and environment, which helps evaluate whether material reuse is overall a viable industrial business model with improved sustainability outcomes and whether the required innovations and institutional transition are worth pursuing. The study contributes to this in two ways.

Firstly, the study advances understanding of the implications from material reuse on value creation for different stakeholders. An overall finding is that although in the first production line, financial viability for the case company was modest, through increased production efficiency and economy of scales, material reuse has potential to become a price-competitive production practice. Findings indicated that material reuse provided new business opportunities for value chain partners, in particular material suppliers and created significant employment. In addition, the business model was found to provide a superior customer value, in terms of innovation, knowledge creation, ability to respond to societal trends, and positive reputational and marketing effects. The findings from LCAs indicate that all three products deliver clear environmental improvements at product level. However, the reductions of environmental impact differ between the three alternatives and several trade-offs among different impact categories exist.

Secondly, the study summarised considerations to warrant *financial and environmental benefits* as material reuse does not by default result in financial and environmental savings (Section 5.1 and 5.4). This is because products with reused materials can require substantial manufacturing processes and input of primary materials to get material into a condition and to a location suitable for reuse, especially as building products underlie strict regulations (e.g. energy-efficiency and construction safety).

To warrant *financial benefits* and price-competitiveness with linear products, processes and inputs need to be managed carefully to ensure that the extra costs for recovery manufacturing processes do not outweigh potential cost savings from secondary material use. The more processes and material inputs a reuse product requires, the less likely it becomes to derive price-competitiveness only from potential cost savings from lower-priced secondary materials. Thus, optimization, integration of value chains and economies of scale are identified as key requirements to develop competitiveness with linear value chains.

To warrant *environmental benefits*, it requires careful operationalization of material reuse to achieve environmental improvements as unavoidable processes (e.g. transport, cement input) can be dominant contributions to the total environmental impacts. There are exceptions where secondary material use cannot address the main contributing processes. In the case of concrete, for instance, cement input accounts for 91% of total GWP impacts and cannot be lowered through using secondary aggregates.

Several methodological limitations pertained to this multi methods research.

Firstly, this research evaluates the case company's business model and its impacts at a specific point in time. Impacts are only a first snap-shot of emerging value chains and product designs. Improved product design or more integrated, lean value chains could improve for instance potential for carbon savings and financial value, but also reduce job creation effects. The results may have also been influenced through the timing of the survey for the customer value assessment. The project had received a lot of publicity and had positive effects on building developers' marketing. Other potential impacts, especially financial value for building developers and investors, may only materialize in the future (e.g. exit performance of the building, economies of scale of the products).

Secondly, applying LCA to circular economy practices (i.e. product systems with secondary material use) is relatively new and bears methodological challenges (Rasmussen et al. 2018; Häfliger et al. 2017; Taylor et al. 2017). For instance, in the case of the wood products, the product category rule's prescribed allocation approach (Section 3.3.4) was not able to capture the benefits of cascading wood co-products. We find that the LCA standards' focus on products, is a limitation to capture impacts from material reuse and cascading.

Future research is needed to investigate environmental and economic impacts of material reuse at industry level if the business model was upscaled. Consequential LCAs and econometric analyses of scaled-up models of circular solutions are needed to account for net value added and net job creation impacts across the entire economy, as well as environmental savings at industry level that consider market and substitution effects. Another avenue for future research could be to further explore potential societal benefits from material reuse and which methods and indicators are suitable for such assessment, as well as advancing LCA standards to be better suited for capturing benefits from material cascading.

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Appendix A: Process models and contributions of LCAs on windows

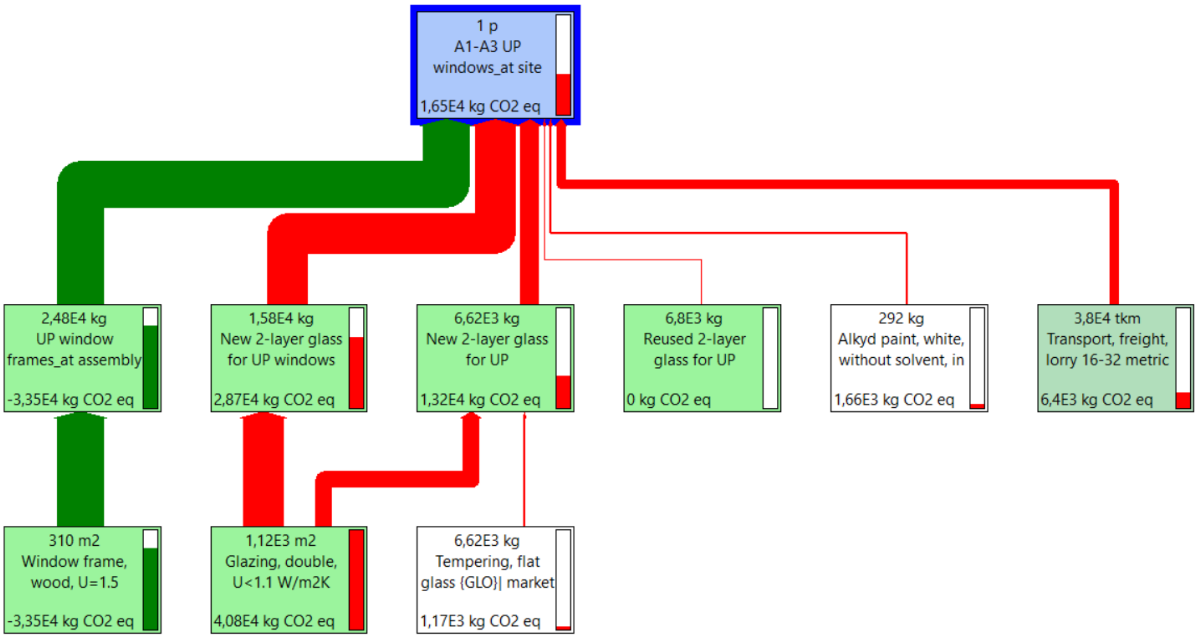

Figure 6 LCA Process and GWP Results of window with reused glass.

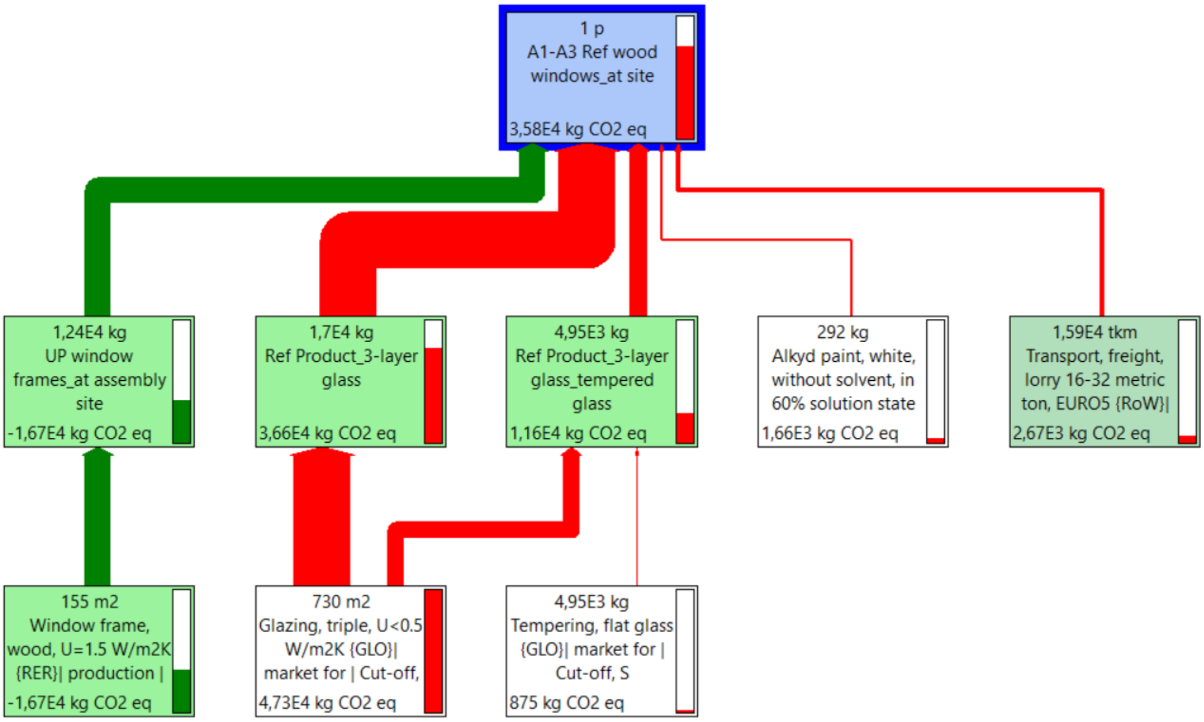

Figure 7 LCA process and GWP results of window reference product (with wood frame).

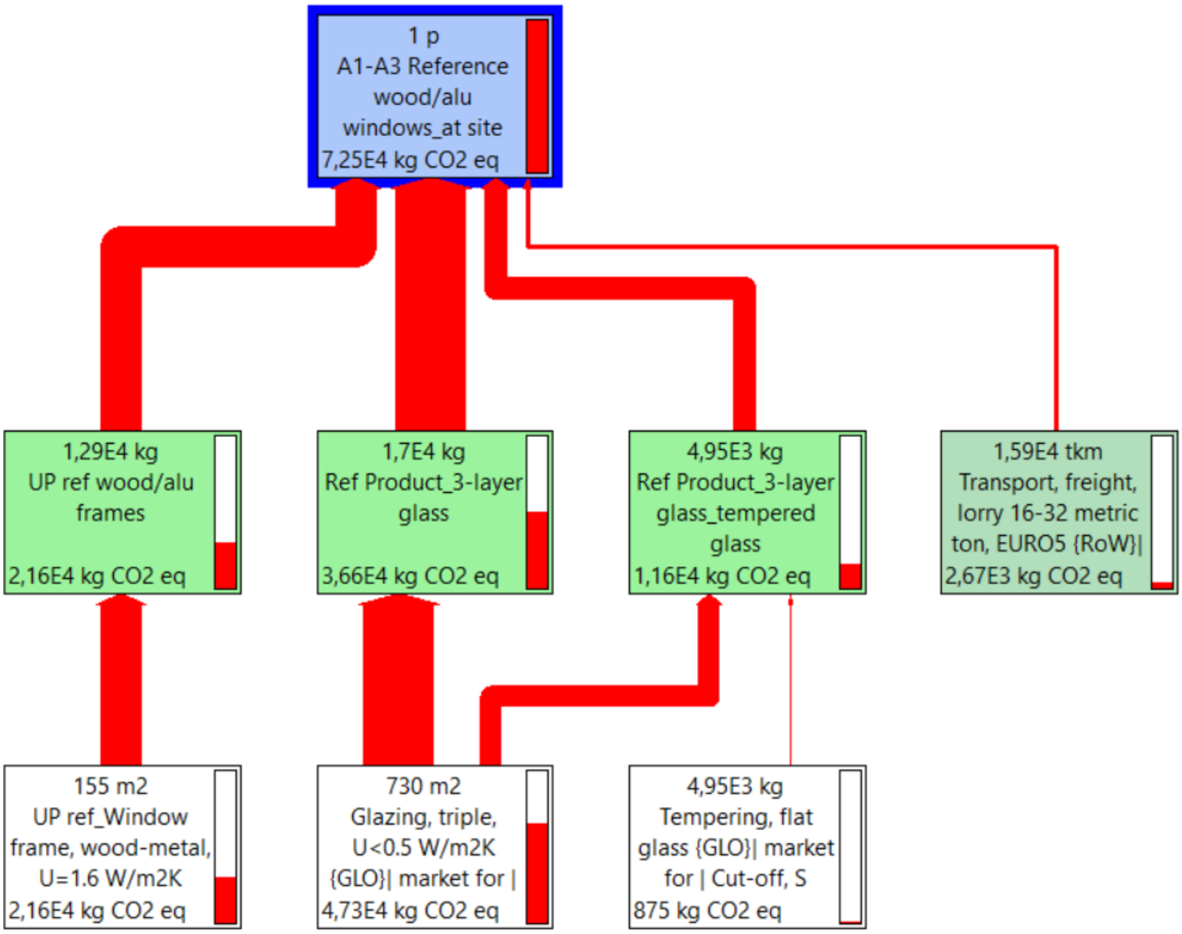

Figure 8 LCA process and GWP results of window reference product (with wood-alu frame).

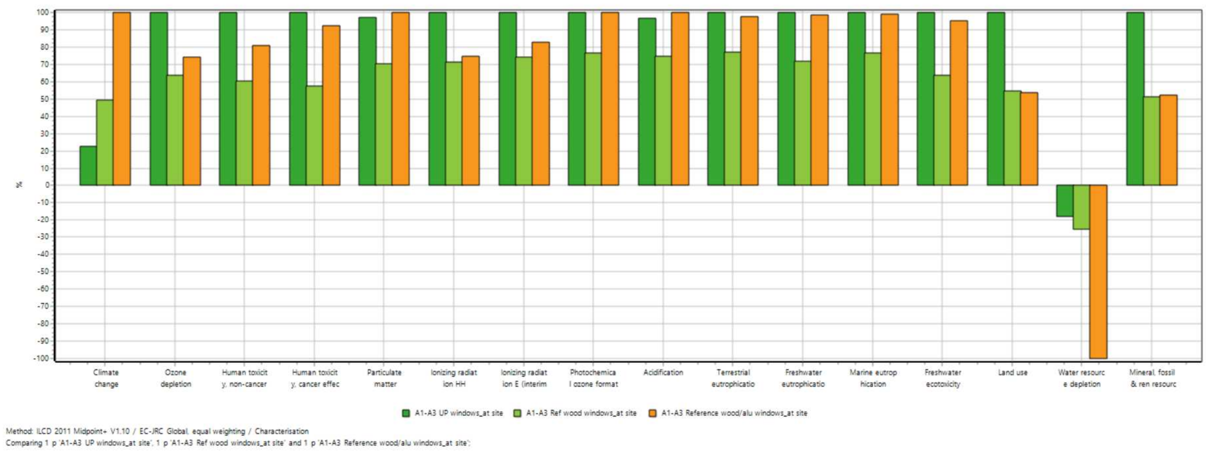

Figure 9 LCA results for window with material reuse and two reference products (wood frame and alu-wood frame).

Appendix B: Process models and contributions of LCAs on concrete

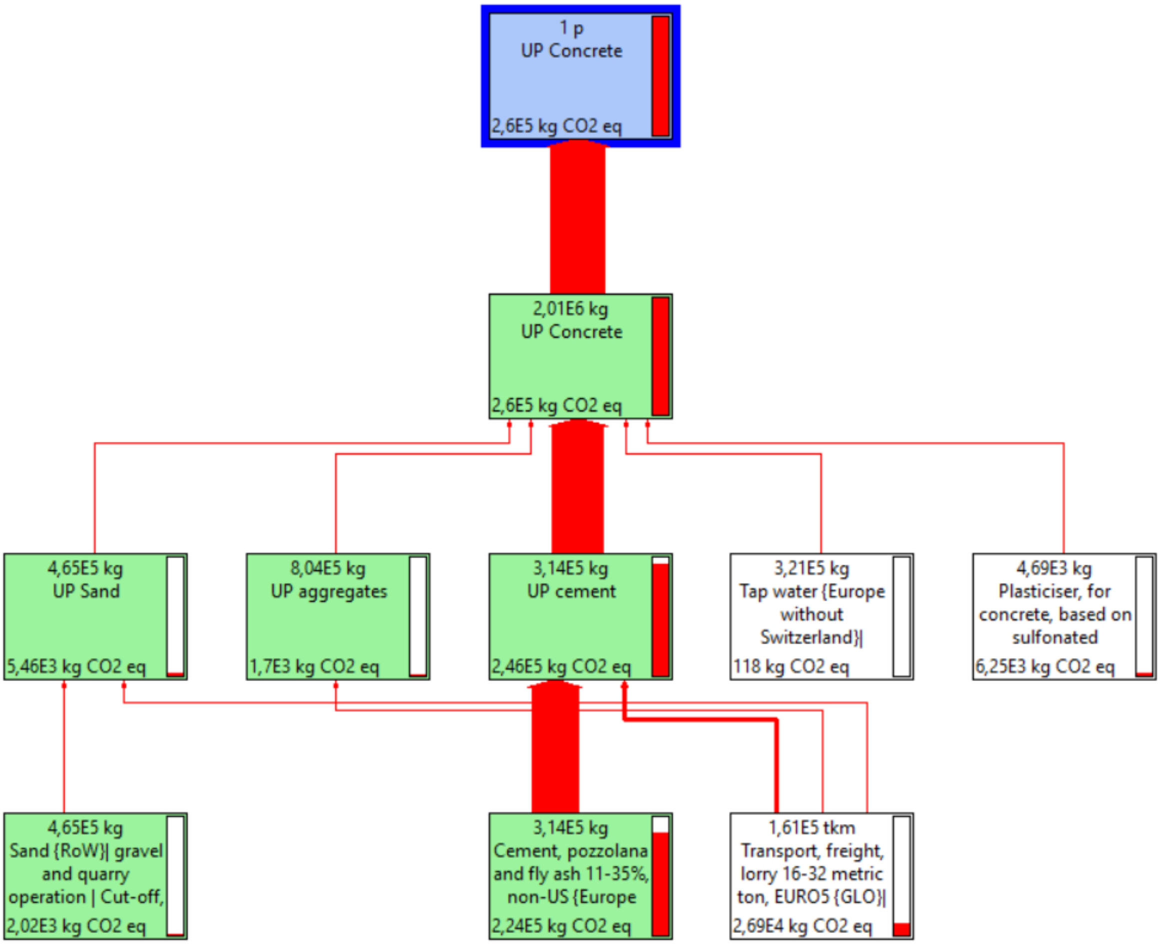

Figure 10 LCA process and GWP results of concrete reuse.

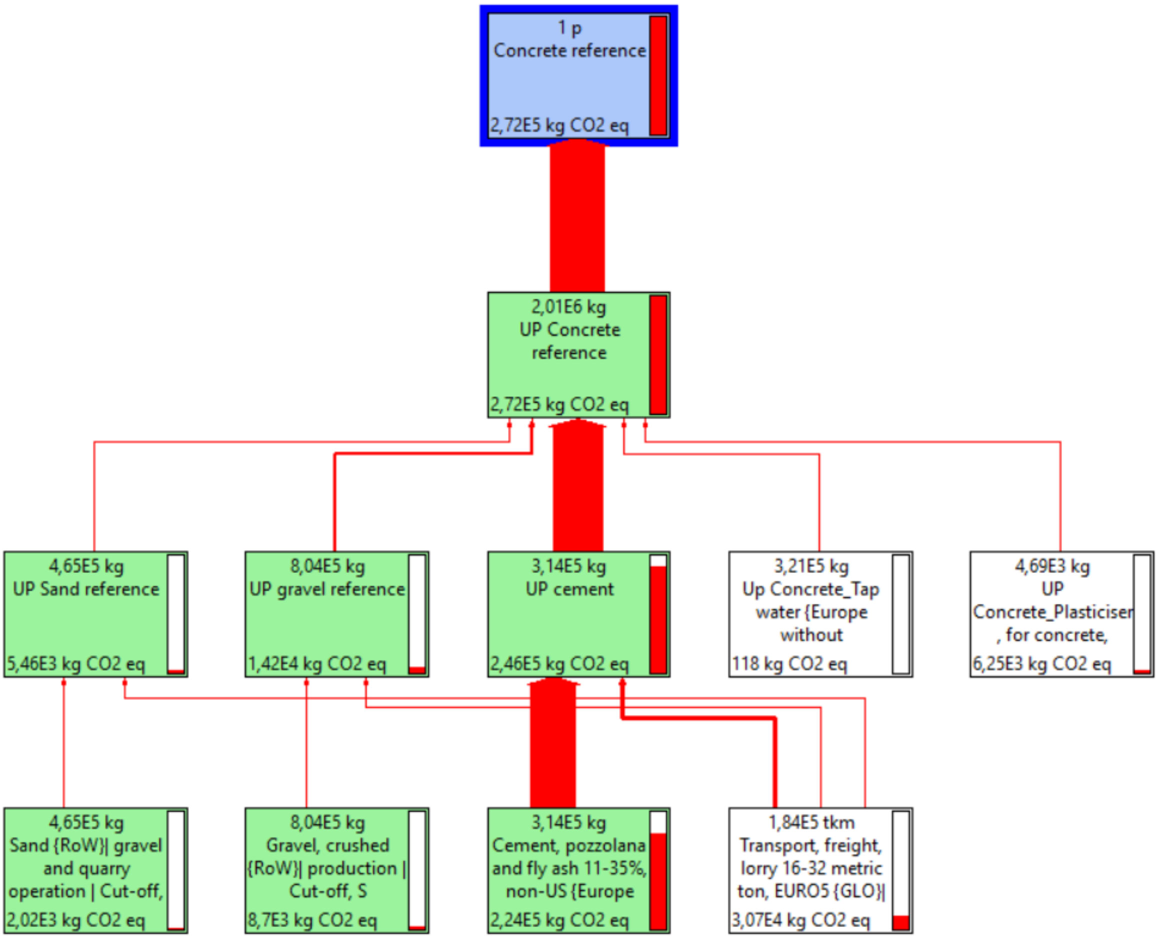

Figure 11 LCA process and GWP results of concrete reference product.

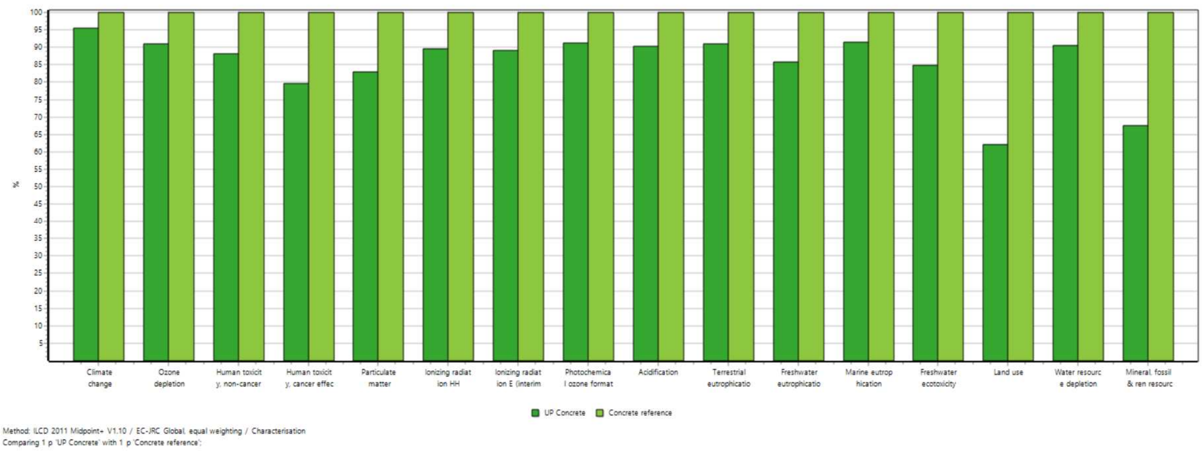

Figure 12 LCA results for concrete reuse solution and reference product.

Appendix C: Process models and contributions of LCAs on wood cladding

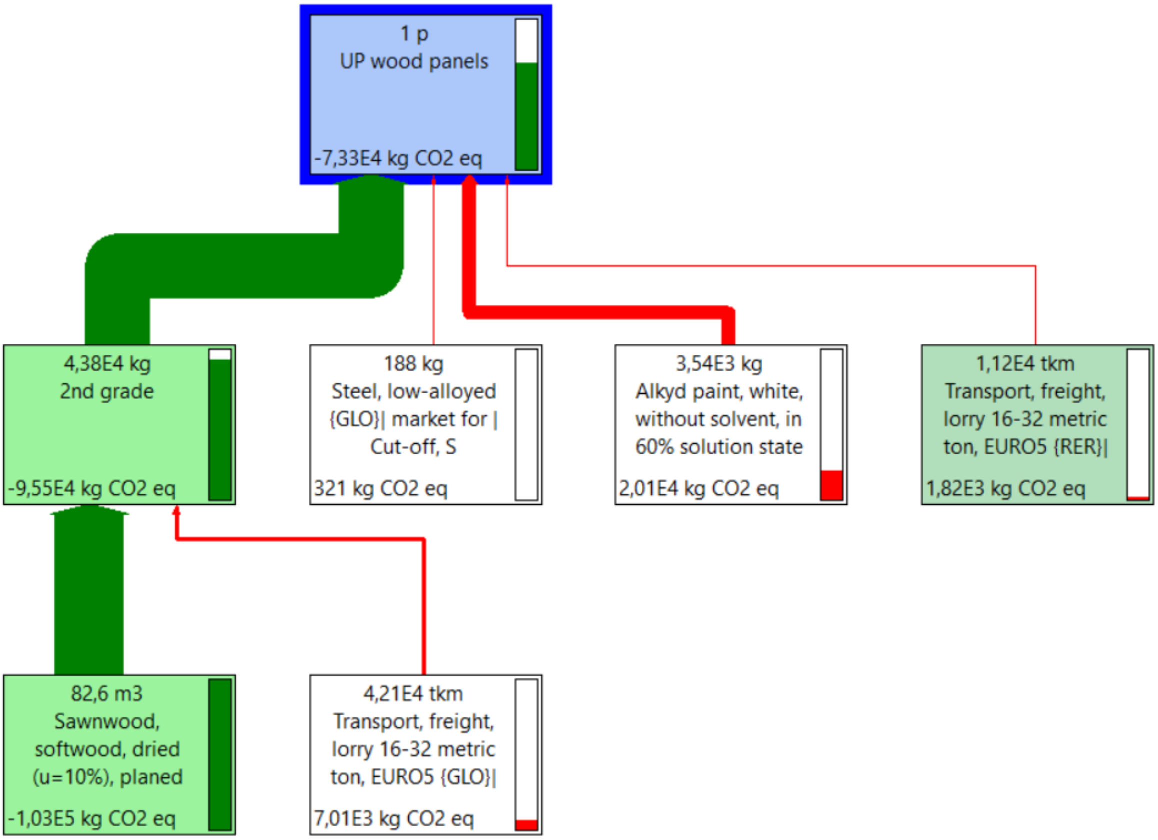

Figure 13 LCA process and GWP results of wood reuse solutions.

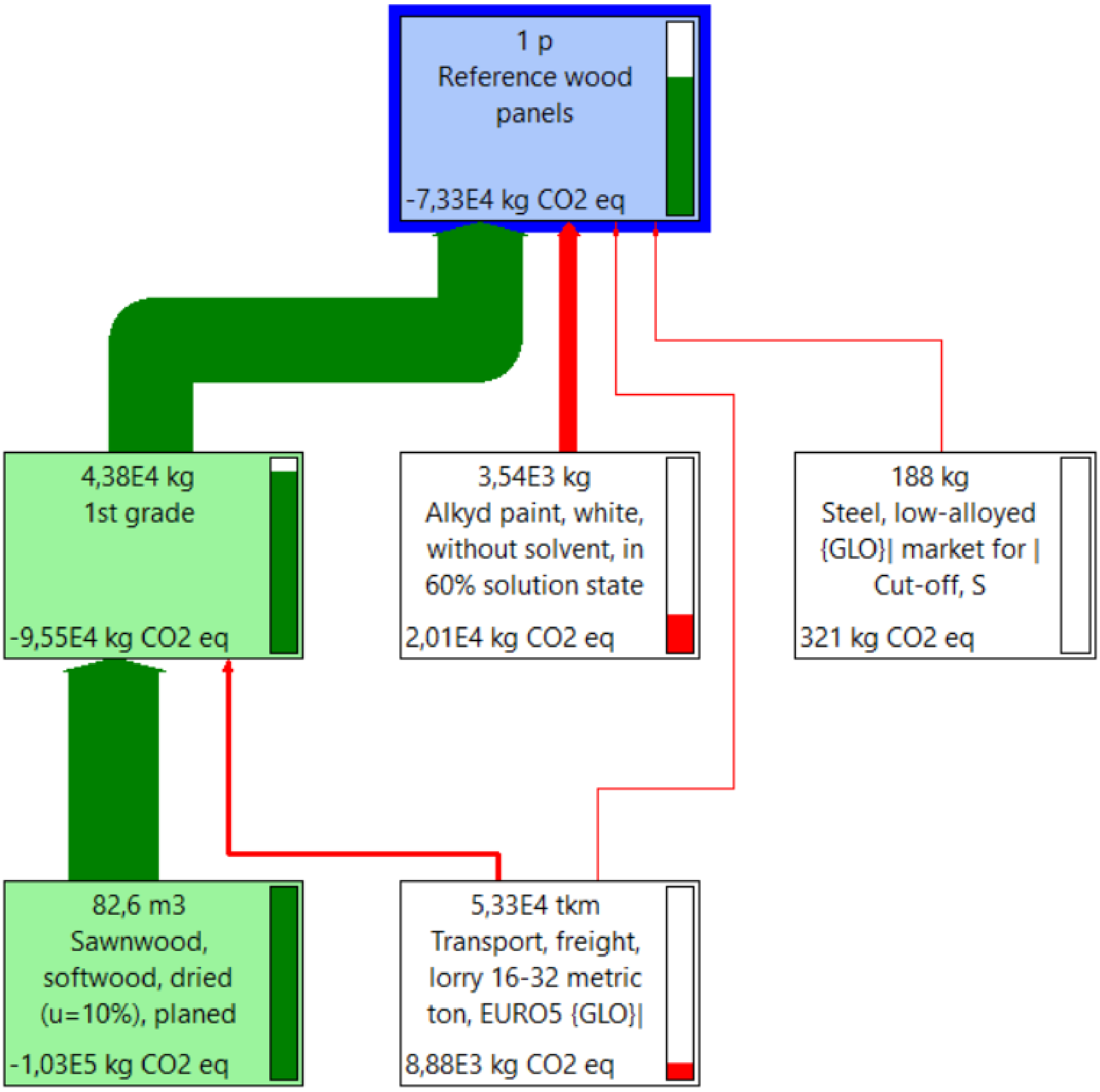

Figure 14 LCA process and GWP results of wood reference product.

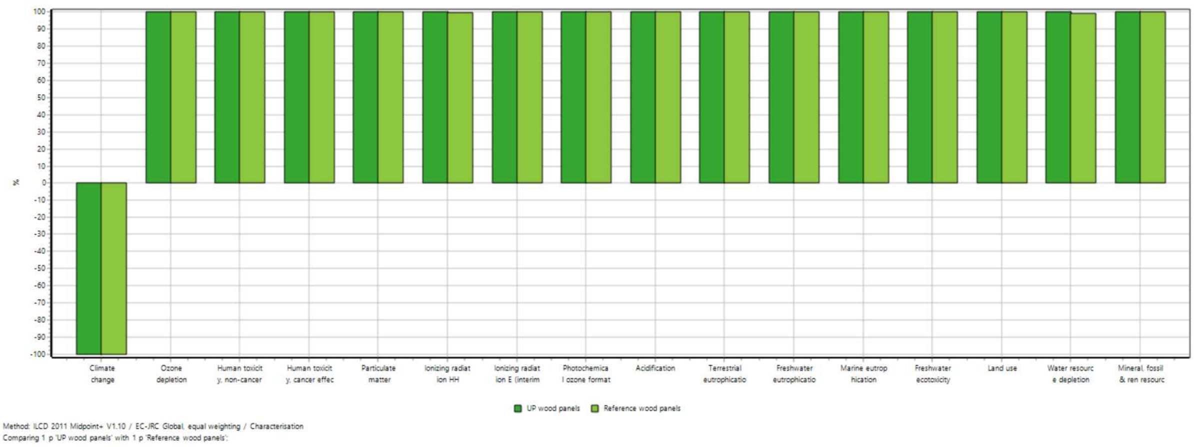

Figure 15 LCA results for wood reuse solution and reference product.