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Material reuse in buildings: Implications of a circular business model for sustainable value creation

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Abstract

Buildings are responsible for a third of global greenhouse gas emissions. A large proportion of their life cycle impacts derives from emissions embedded in materials. Material reuse has the potential to reduce these embedded impacts, since reused materials often have smaller environmental footprints than primary materials. Institutional settings and the structure of the building sector pose multiple barriers to businesses developing and commercialising products based on reused materials. Although material reuse is claimed to create multidimensional values for several stakeholders, the implications on value creation are still insufficiently understood and considered in decision-making. This study presents a business model developed by a pioneering Scandinavian company offering three building products based on reused materials – windows, wood cladding, and concrete. Using a multi-methods approach, the study investigates and discusses implications of the business model in creating value for the firm, value chain partners, customers, and the environment. Findings indicate the business model has significant potential to ensure that reuse is 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. If the business model were to be upscaled, implications for value creation at industry and macro-economic level should be further investigated.

1. Introduction

Buildings are responsible for a third of global greenhouse gas emissions (UNEP 2009), with a large proportion 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, referred to in this paper 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 been promoted in the field of urban mining for many years. The urban mine with its multitude of anthropogenic stocks is viewed as a promising source of secondary material supply (Baccini and Brunner 2012; Cossu and Williams 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, material reuse in the building sector has attracted increasing attention (EllenMacArthurFoundation 2017; ING 2017; BAMB 2016; Adams et al. 2017). According to several studies, the building sector has great potential for implementing circular economy strategies and generating both environmental and economic gains (EllenMacArthurFoundation 2017; ING 2017; Koutamanis et al. 2018). Other potential benefits include 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 appropriate business models capable of commercialising price-competitive products that meet regulatory standards and deliver strong sustainability benefits. The business model lens is valuable for studying questions relating to the associated innovation processes, such as how companies create value while adhering to circular economy principles through new products and technologies, revised value propositions, and value chain networks (Nußholz et al. 2019; ING 2017; Adams et al. 2017). Other issues of interest in business model analysis include what value the business model creates for the firm and its customers (Wirtz et al. 2016; Massa and Tucci 2014) and for other stakeholders, such as the environment or society (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 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 to companies engaging 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). Meanwhile, the product's market success and sustainability impacts are often uncertain (Hansen et al. 2009; Nußholz et al. 2019). 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 how a business model for material reuse in building products affects value creation. We use a single case study of a business model employed by a pioneering Scandinavian company, which commercialises *windows*, *wood cladding*, and *concrete* made from reused materials. The study explores how their material reuse business model affects value creation 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 were developed to examine value creation beyond financial metrics and explore the viability of the business model for multiple stakeholders (i.e. customers, value chain partners, the 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 the conclusion is presented in section 6.

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 commercialised 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 indicates that the building sector is still largely discouraging implementation of the circular economy. Common barriers reported in the literature include the emphasis on financial metrics and return on investment, the lack of 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 in advancing circular economy and material reuse practices in the industry, and capitalising on the associated opportunities (Ness and Xing 2017; Hopkinson et al. 2018; Nußholz and Milios 2017).

Business models define a set of elements that allow mapping of the organisational 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 encompass 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 go beyond traditional innovation areas, such as products or production processes (Zott et al. 2011) and allow researchers to study how new products and processes are brought to the market through 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).

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. However, a unique characteristic is their objective to manage both economic and environmental issues and to optimise value creation in more than one sustainability dimension.

2.2 Value creation of circular business models for material reuse

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

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

Material reuse is also associated with *employment creation* and *value for network partners*. By capitalising on the 'inner circles' of the circular economy framework, which maintain value embedded in products and materials at higher levels (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 generally more labour intensive than heat recovery, so may have potential to increase net job creation. Several recent studies identify potential for net job creation from increased circular economy activities, in different sectors and regions, and using various types of economic inputoutput models (Wijkman and Skånberg 2015; Hestin et al. 2015; Milios et al. 2018; Trinomics et al. 2018; IISD 2018). Assessment of jobs created as outcomes of circular economy projects, rather than projections, feature less in the literature. Ward et al. (2013) review different indicators for job creation across the EU. They suggest that, if assessing jobs created directly from a programme, indicators should be reported in full-time equivalents and unambiguously defined to allow comparisons.

Material reuse is often associated with superior *customer value*. Mokhlesian and Holmen (2012) show that green building development, such as circular economy implementation, has the potential to reduce total life cycle costs. However, 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 building 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 and Lozano 2016; Klotz et al. 2007). Improved competitive advantage (Witjes and Lozano 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 and Lozano 2016; Schenkel et al. 2015; Klotz et al. 2007).

There is much evidence that material reuse has significant potential for *environmental impact reductions*, although the extent varies according to material streams and products (Cabeza et al. 2014; Nußholz et al. 2019; Ortiz et al. 2009; Ingrao et al. 2014). Environmental impact reductions from 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 according to, for instance, the recovery processes required to ensure that the secondary product fulfils the same functional requirements as the replaced 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 when making façades from a wood-plastic composite has a carbon saving potential of 70-50%.

3. Methods and data collection

This study combines case study research with a multi-method approach to explore how a business model offering material reuse in the building sector affects value creation. 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 and 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 were designed to comply with the same standards as linear benchmark products in terms of price, quality, aesthetics, functionality, and 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 overseen by the case company. In addition to product development, the company has an architecture division, enabling it to capitalise on building design capabilities to incorporate material reuse and to offer integrated circular economy building solutions.
Value capture	Main revenues concern payments to building developers. The company was also granted a national innovation subsidy that helped cover part of the project management and innovation costs related to the project. Costs incurred mainly involved 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	Characterisation reuse strategy	Process description
Wood	By-product use	Wood is obtained from by-products and lower-grade production of a plank producer close to 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 sites and dismantled to obtain the 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 sites is crushed into aggregates and mixed with primary cement and other concrete components to form new concrete.

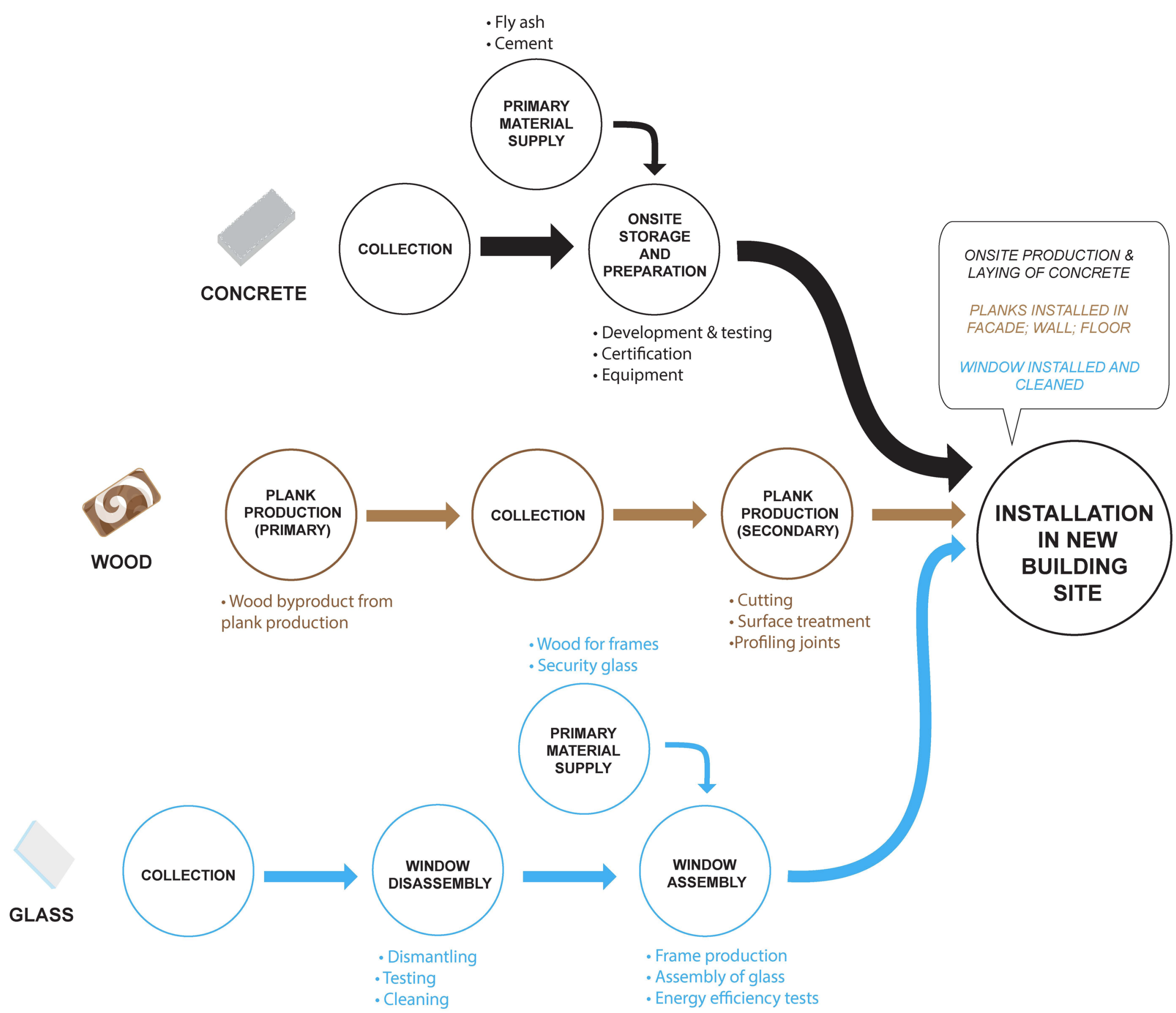

Figure 1 Overview of value chain and processes for the three products.

The single case study design with its three sub-units (wood, windows, and concrete) was chosen to enable a deeper understanding of the impacts of commercialising material reuse in products. To date, little research has examined the value creation in business models for reuse in the building sector (Hart et al. 2019). Although single case studies limit generalisability, they are regarded as beneficial in providing in-depth, data-rich descriptions of a phenomenon (Yin 2013). If comprehensively executed, single case study approaches are sources of tangible, context-dependent knowledge that produce exemplars of a phenomenon in a systematic way (Flyvbjerg 2006). The narrative such exemplars produce can reduce the complexity of a real-life phenomenon and they 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) for conducting integrated sustainability evaluations at business model level.

In the first step, value aspects of materiality relating to the case were identified. This was done by reviewing literature on material reuse in the building sector, circular economy and resource efficiency, sustainable business models, and green construction (section 2.2). Three business developers and one senior architect from the case company, and a sustainability manager of a leading Scandinavian building developer, were also consulted. The 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 for operationalising 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 regarded as suitable for identifying the most relevant implications of how the business model creates value for different stakeholders. 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 with regard to resources, time and data accessibility (Turcu 2013). The final indicators selected were:

(1) **Financial structure and viability**: Implications for 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 was collected and analysed in the period September 2018 to January 2019 through a variety of qualitative and quantitative methods.

3.3.1 Financial structure and viability

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

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

Estimates of hours spent on the project by the case company and project partners (i.e. material suppliers, manufacturers, installers) were collected to analyse the impact on employment creation. Accounting data of the case company and surveys with project partners were used for this analysis. 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 (37 hrs) 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 the scope of our study. 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 macroeconomic level and shifts in economic activities in other sectors are important to consider.

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 created 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 helped 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 and Lozano 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). The compiled list of indicators was then discussed with managers of three Scandinavian building developers (one involved in the case project and two others), and they were asked to rank the indicators according to their perceived relevance and to add value drivers that were missing from the list. The final list of indicators was categorised into three overarching groups, i.e. (1) Business value, (2) Stakeholder value and product performance, and (3) Green leadership (Figure 2).

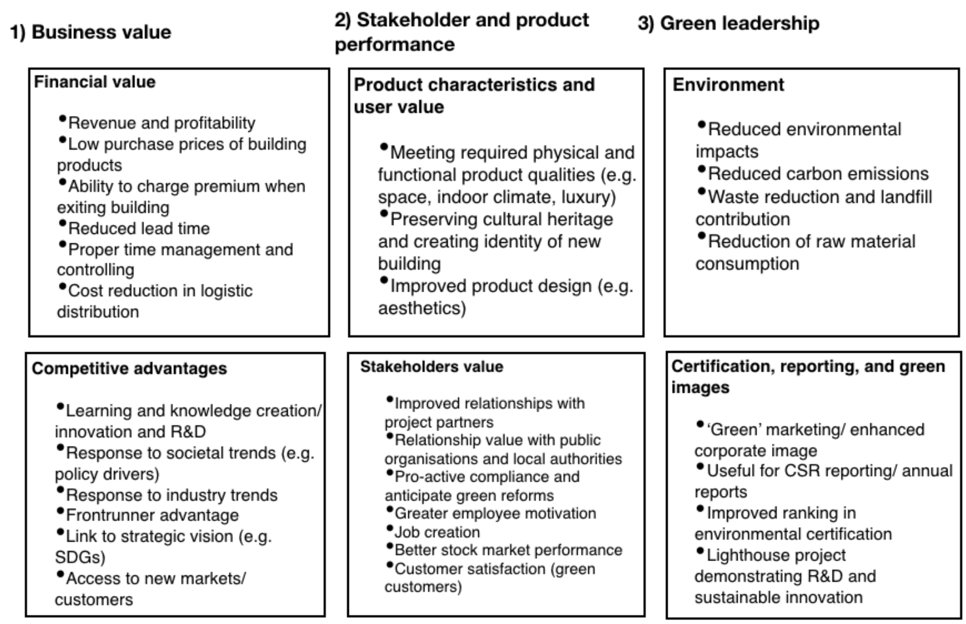

Figure 2 Overview of categories and indicators for customer value assessment.

Once the survey had been prepared, building developers of the case project were contacted. For each of the two companies, two employees (holding the positions *Sustainability Director*, *Project Development*, *Business Development Director*, and *Public Relations Manager*) ranked the extent to which different types of value were realised from material reuse on a scale of 0-3, with 0 representing "not realised" and 3 "fully realised". A limitation of the self-assessment was the timing of the survey, as some of the potential benefits (e.g. financial performance, economies of scale) are only expected to materialise in the future. Other benefits (e.g. marketing effects) had already materialised 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 were modelled in SimaPro using the Ecoinvent 3.4 database. For impact categorisations, 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. Publicly available data was used to model reference projects (also see Table 3 for key assumptions and their references).

We used global warming potential (GWP) as an 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 primary-based materials were also used.

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

<table>
<tr><td colspan="3">Windows (1195.88 m2)</td></tr>
<tr><td>Secondary-based product</td><td>Primary-based reference product</td><td>Critical assumptions</td></tr>
<tr><td>Facade window with wood-frame and double-layered glass (primary and secondary).
• Disassembly of post-consumer windows
• Manufacturing of wood frame
• Insertion of reused glass
• Insertion of primary glass (normal and security glass)
• Paint for wooden frame
• Transport</td><td>Facade window with aluminium-wood frame and triple-layered glass.
• Manufacturing of wood-aluminium frame
• Insertion of primary glass, three layers (normal and security glass)
• Transport</td><td>• Layers of glass of reference product
• Aluminium-wood frame as it is the standard in the industry
• Proportion of reused glass in reuse product</td></tr>
<tr><td colspan="3">Concrete (837m3)</td></tr>
<tr><td>Secondary-based product</td><td>Primary-based reference product</td><td>Critical assumptions</td></tr>
<tr><td>Concrete containing secondary aggregates
• Secondary aggregates
• Sand
• Cement
• Water
• Plasticiser
• Transport</td><td>Concrete containing primary gravel as aggregate
• Primary aggregates
• Sand
• Cement
• Water
• Plasticiser
• Transport</td><td>• Transport distances lower for secondary gravel because of local sourcing</td></tr>
<tr><td colspan="3">Wood (3755 m2)</td></tr>
<tr><td>Secondary-based product</td><td>Primary-based reference product</td><td>Critical assumptions</td></tr>
<tr><td>Cladding from wood plank off-cuts
• 2nd grade wood
• Transport
• Steel
• Paint</td><td>Cladding from primary wood
• 1st grade wood
• Transport
• Steel
• Paint</td><td>• Allocation approach</td></tr>
</table>

4. Results

This section presents implications for value creation with 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, but with only modest profit. For reasons of data confidentiality, only implications on financial viability are discussed. There is a significant potential for improving the financial value for all three products. Production can be optimised 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 utilised. Even without the innovation subsidy that helped cover R&D costs, a viable business case in future production lines, where R&D costs will be significantly lower, seems feasible.

Regarding the financial structure, the vast majority of revenues stemmed from the building developers' payments, with smaller proportions from the innovation grant. The latter comprises about 1% of total revenues for the wood products, 4% for windows, and 11% for concrete. Costs varied considerably among the three products (Figure 3Figure 4Figure 5). In the case of *windows*, the largest proportion of total costs derived from production (above 80%), while material sourcing costs were below 5% (for reasons of data confidentiality, results of the cost structure analysis are presented only in relative terms). In the case of *concrete*, the largest proportion of total costs derived from production (with much stemming from rental of production equipment), but primary material sourcing (e.g. cement) was also a significant cost driver. R&D costs were around 10% of total costs. In the case of *wood*, the largest proportion of costs resulted from material sourcing of off-cuts, which are of high-quality wood, followed by production costs.

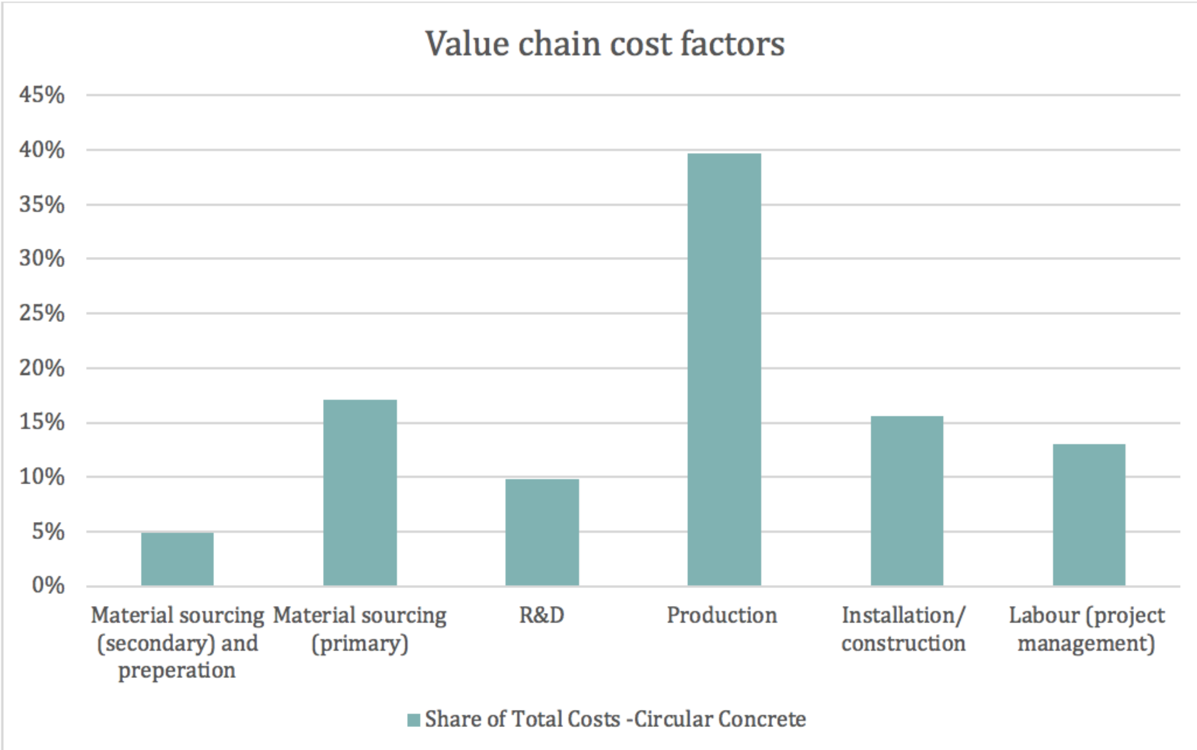

Figure 3 Costs drivers for secondary-based concrete.

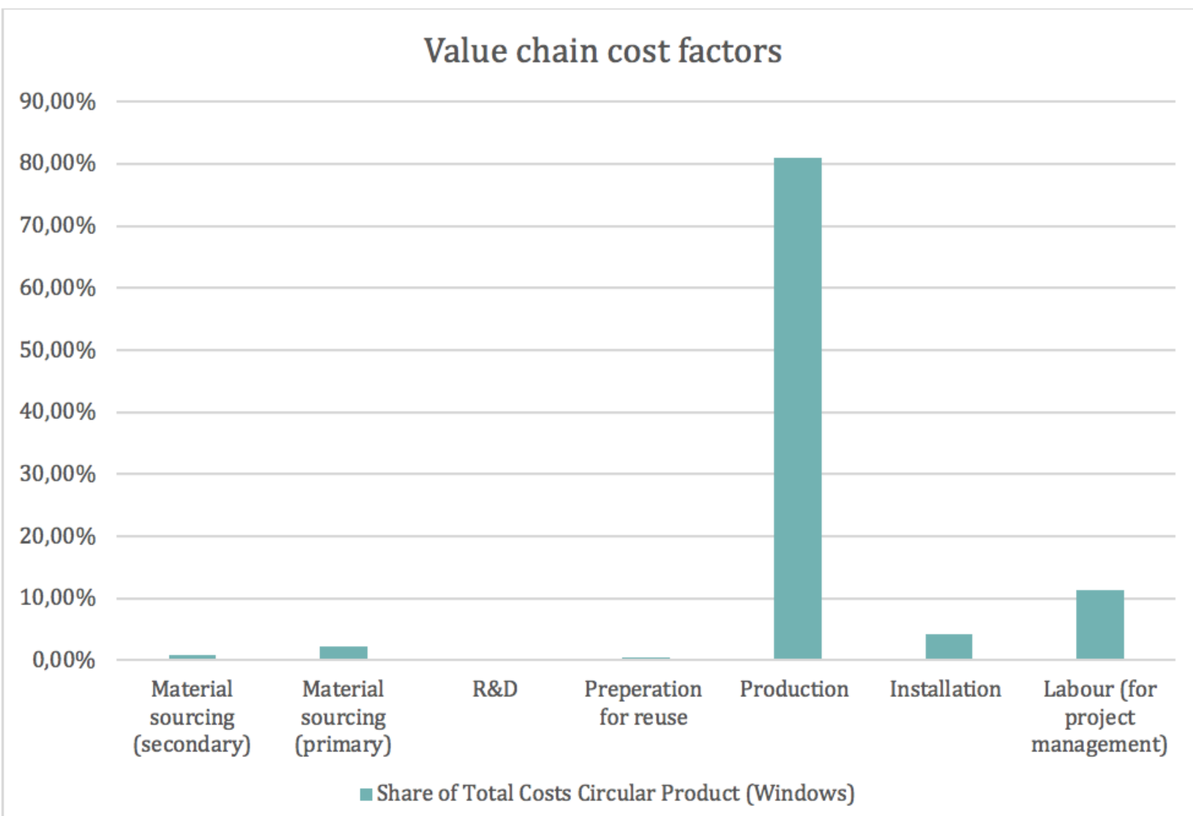

Figure 4 Costs drivers for secondary-based windows.

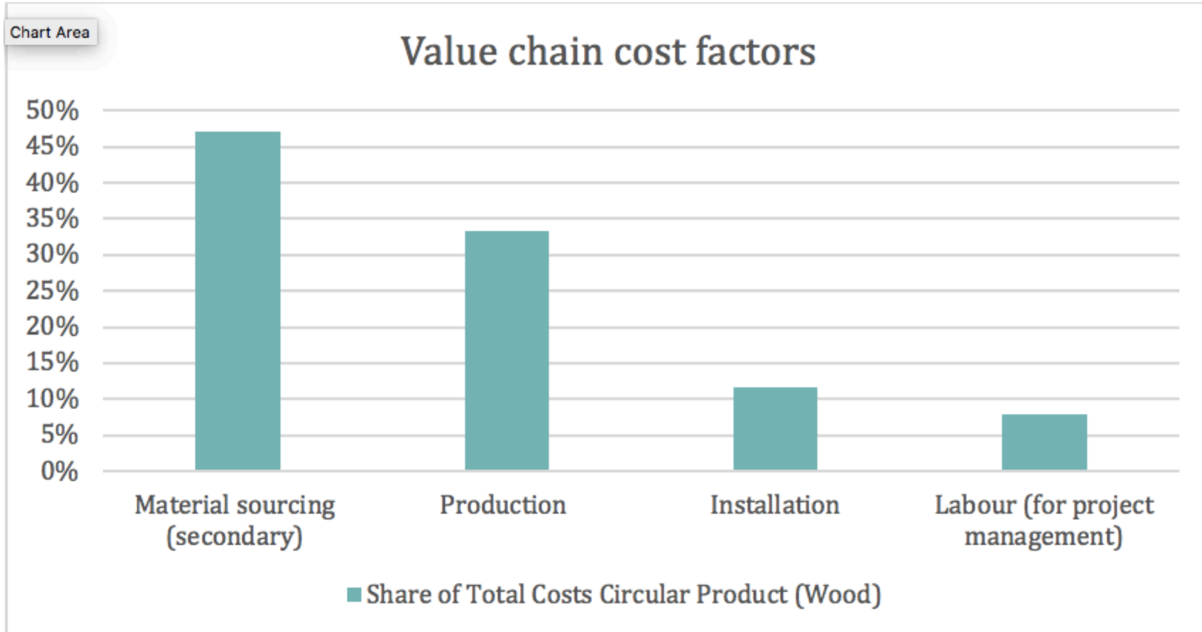

Figure 5 Cost drivers for secondary-based wood cladding.

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 jobs, wood reuse 13.2 jobs, 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** (37 hrs 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**

We also 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.

For *new value-adding activities*, the disassembly of post-consumer windows can be considered as a new business activity that does not occur in linear production practices. Also, wood recovery offered a new income opportunity for the supplier of off-cuts, which were previously only stored, as there was no demand other than for heat recovery. The project enabled the reuse of glass that would normally be recycled, but that now provides a higher income for suppliers.

Several *more labour-intensive processes* compared with conventional, linear production were created: the installation of wood cladding, as planks are shorter, and manufacture of new window frames to accommodate multiple layers of glass.

4.3 Customer value

Findings regarding *business value* show that building developers and investors valued highly the innovation and knowledge generated in 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 realise 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 of R&D required for the development of the first production line, but also from the timing of the evaluation; 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*, scores for the indicators varied. Satisfying the 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 due to a lack of evaluation and knowledge on employment creation at the time of the survey.

Value creation in *green leadership* was most strongly reported with 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. Realisation of environmental improvements (i.e. reduced carbon emissions, waste reduction and landfill contribution, reduction in raw material consumption) were ranked 2.1/3. Again, this may be due to 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 carbon saving potential (CSP) of each product is presented in Table 5, and indicates that environmental impact reductions are significant, but vary greatly between the three alternatives.

LCA results for windows 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 to 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 the 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, so 4% lower than the reference product. As 91% of the 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. In practice, this would imply that a lower cascading level, such as heat recovery, was equally preferable from a CO2-emission point of view than further processing the co-product for cladding purposes and prolonging the carbon storage. This contradicts recent studies, which find that the extended carbon saving function and primary material substitution of co-product use can be considered relevant to reducing 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. 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). These authors suggest that economic allocation (in which environmental impacts are allocated based on economic value of the product and co-product) may be more appropriate for capturing 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 a discussion of implications of the model for value creation with regard to the four indicators.

5.1 What are the 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 profits were modest, and with the help of an innovation grant. As the innovation grant only covered a part of R&D costs, which will be significantly lower in future production lines, material reuse has potential to be financially viable even without the innovation grant. It should be noted that this study investigated a first production line, when integration of value chain activities and optimisation of production practices were still in their early stages. We argue that, with economies of scale and efficiency improvements, financial viability has great potential to become more price-competitive compared with linear production practices. Integration of material reuse in companies operating linear business models may be attractive.

Nevertheless, findings also indicate that achieving financial viability of material reuse can be challenging. Products made from reused materials can require substantial manufacturing processes and input of (costly) primary materials, while secondary material inputs may still generate substantial costs (Figure 3Figure 4Figure 5). The widespread assumption that reuse strategies generate cost savings by reducing costs for materials may not always hold true. Financial viability requires careful product and value chain design and control of cost factors to ensure that total costs do not exceed those of primary-based products.

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

With a total of 18.4 jobs created (equivalent to six 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 an indication that material reuse can increase 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 concerned R&D activities of which there will be less in the future. Improved product design and more integrated and leaner manufacturing processes may reduce labour intensity.

Findings resonate with common assumptions that business models for material reuse generate 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, helping them to 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 were upscaled, more comprehensive, econometric analyses are needed. Investigation of the types of jobs created or the geographical location of jobs could also be of interest for policy-makers (Trinomics et al. 2018).

5.3 What are the implications of material reuse for customer value?

All three products were designed to be as competitive as possible against linear reference products in terms of price and quality. We found that building developers and investors were generally positive to the products made from reused materials. Customer value was demonstrated across all three investigated categories but, at the time of the evaluation, material reuse gave no indication of superior financial benefits. This may partly stem from the additional costs of R&D required for the first production line, but also from the timing of the evaluation, because exit and long-term financial performance of the building, along with effects of economies of scale, were unknown.

Nevertheless, building developers and investors reported several non-financial benefits from material reuse, including the opportunity to innovate and create knowledge that may put their organisations in a better position to adapt to societal trends or future changes in legislation. Gaining a frontrunner advantage and contributing to the companies' strategic vision (e.g. SDGs) were clear benefits, as well as the development of products that can deliver significant environmental improvements, and potentially future cost savings through improvements in production efficiency.

5.4 What are the implications of material reuse for environmental impacts?

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

Another finding is that material reuse cannot always address the main contributing processes of a product. Our LCA shows that concrete cannot significantly reduce climate change impacts compared with primary-based concrete. This is because cement production accounts for 91% of total GWP impacts and cannot be reduced by 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 contribute to a gradual development of a more sustainable product with the potential to improve regional processes.

An overall finding is that environmental impact reductions are not realised by default. Product design and value chain processes must be carefully considered before environmental impacts can be improved. Building products are governed by strict regulations on, for example, energy-efficiency and safety, so may require significant input of primary materials to meet current construction standards. Impacts from primary materials that need to be added during production can outweigh the benefits from using secondary materials, and unavoidable processes (e.g. transport, cement input) may also contribute significantly to environmental impacts.

6. Conclusion

This study examined a business model implemented by a pioneering Scandinavian company, which offers three building products made from reused materials from urban mines (i.e. windows, wood cladding, and concrete), and its implications for value creation. The implications were considered for multiple stakeholders, such as the case company, customers, value chain partners, and the environment, allowing evaluation of whether material reuse is 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 of material reuse for value creation for different stakeholders. In the first production line, financial viability for the case company was modest, deriving from increased production efficiency and economies of scale, and material reuse has the 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. 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 effects on reputation and marketing. The findings from LCAs indicated that all three products delivered clear environmental improvements at product level, but the reductions of environmental impact differed between the three alternatives and there were several trade-offs between different impact categories.

Secondly, the study summarised considerations with regard to *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 made from reused materials may require substantial manufacturing processes and input of primary materials to transform the material into a condition and a location suitable for reuse, especially as building products are governed by strict regulations on, for example, energy-efficiency and construction safety.

If reuse is to generate *financial benefits* and become price-competitive with linear products, processes and inputs must be managed carefully, to ensure that the extra costs of recovery manufacturing processes do not outweigh potential cost savings from secondary material use. The more processes and material inputs required by a reuse product, the less likely it is to become price-competitive through potential cost savings from lower-priced secondary materials.

Optimisation, integration of value chains, and economies of scale are identified as key requirements to improve the competitiveness against linear value chains.

Generation of *environmental benefits* requires careful operationalisation of material reuse to achieve environmental improvements, as unavoidable processes (e.g. transport, cement input) may be dominant contributions to the total environmental impacts. There are exceptions where secondary material use cannot improve the main processes that contribute to environmental impact. In the case of concrete, for instance, cement input accounts for 91% of total GWP impacts, and this figure cannot be reduced by using secondary aggregates.

The multi-methods research approach used in this study has several methodological limitations.

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

Applying LCA to circular economy practices (i.e. product systems with secondary material use) is relatively new and entails 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 focus of the LCA standards on products is a limitation to capturing impacts from material reuse and cascading.

Future research is needed to investigate the environmental and economic impacts of material reuse at industry level if the business model were to be 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 explore potential societal benefits from material reuse and the methods and indicators that are suitable for such an assessment, as well as developing LCA standards to make them more suitable for capturing benefits generated by material cascading.

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J.N. initiated the paper, developed the research design, collaborated with the case company, collected and analysed all data (making a minor contribution in the life cycle assessment), and compiled the full draft. F.N.R. conducted the life cycle assessment, collected required data, and provided feedback in the review process. K.W. assisted with the conceptual development of the financial analysis, contributed to the review of the background literature, and provided feedback in the review process. A.P. contributed to the review of the background literature and provided feedback in the review process.

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Appendix A: Process models and contributions shown by LCAs for windows.

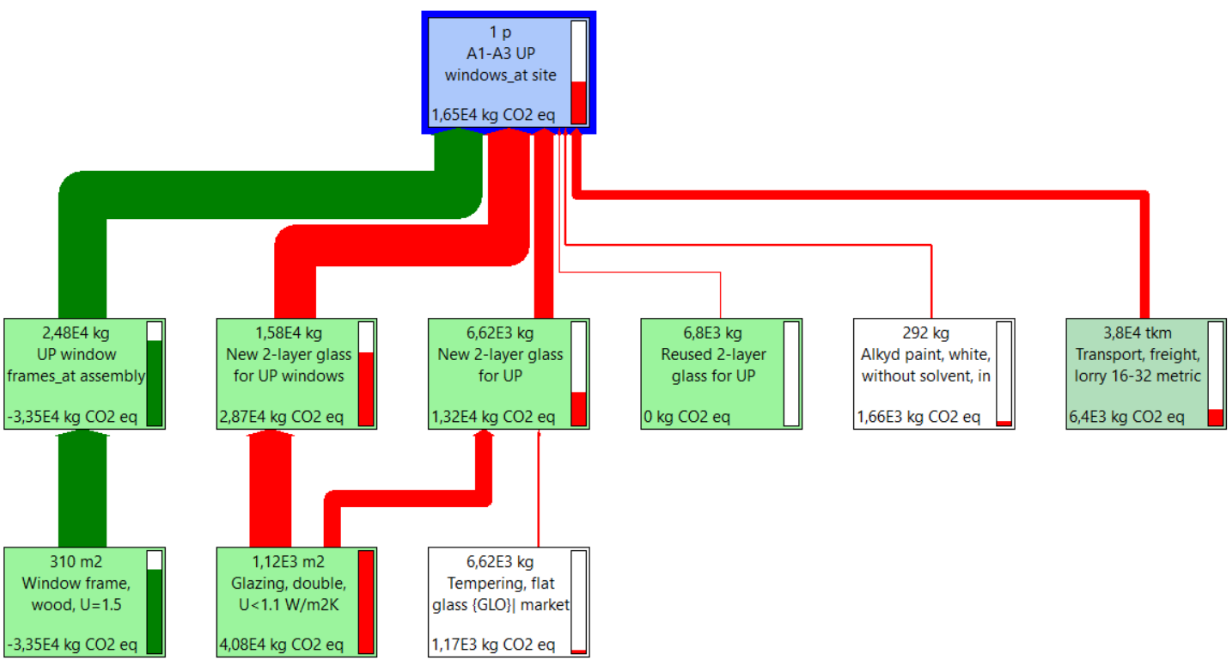

Figure 6 LCA process and GWP results for windows with reused glass.

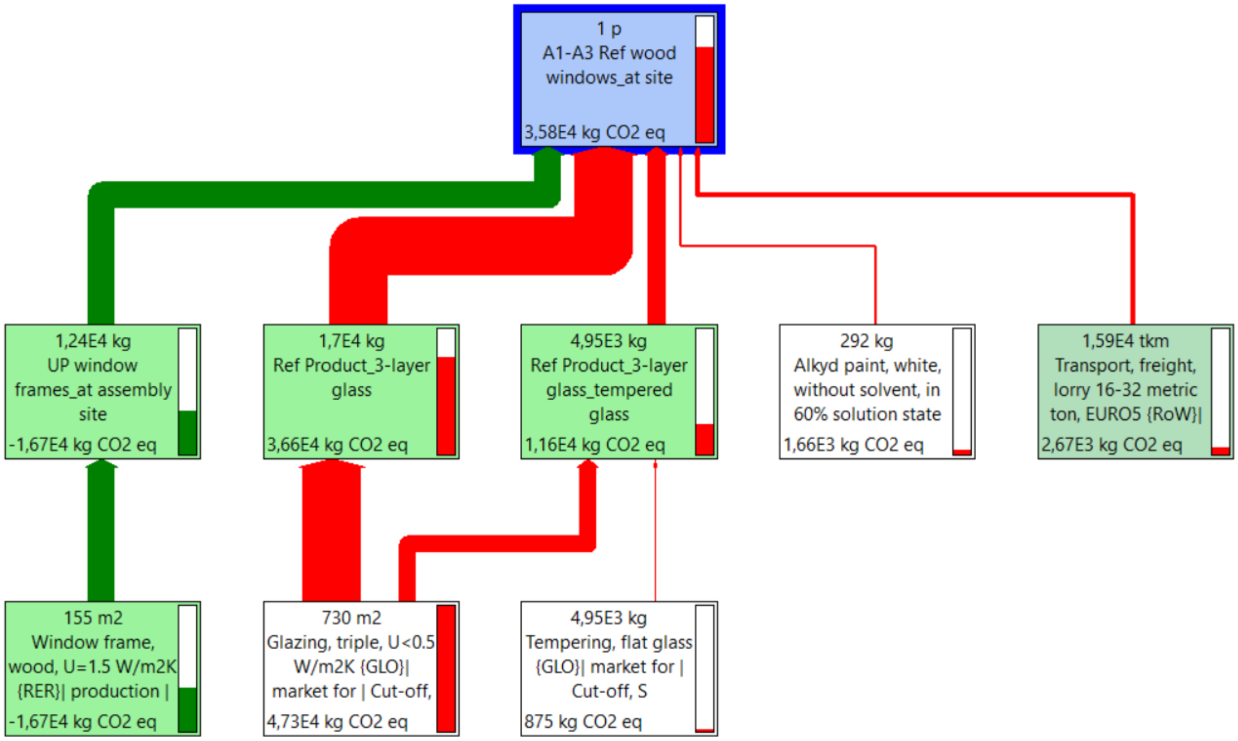

Figure 7 LCA process and GWP results for window reference product (with wood frame).

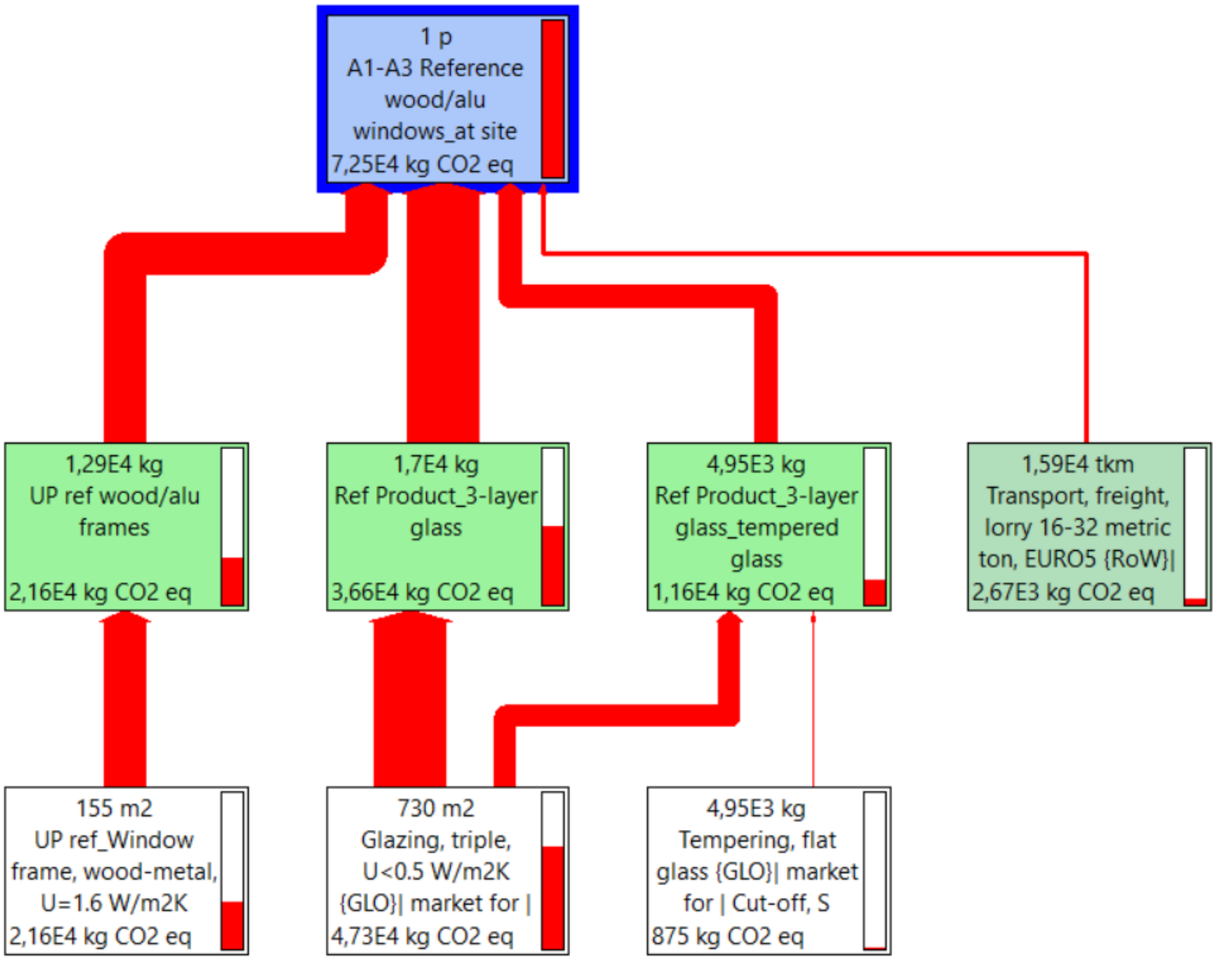

Figure 8 LCA process and GWP results for window reference product (with wood-aluminium frame).

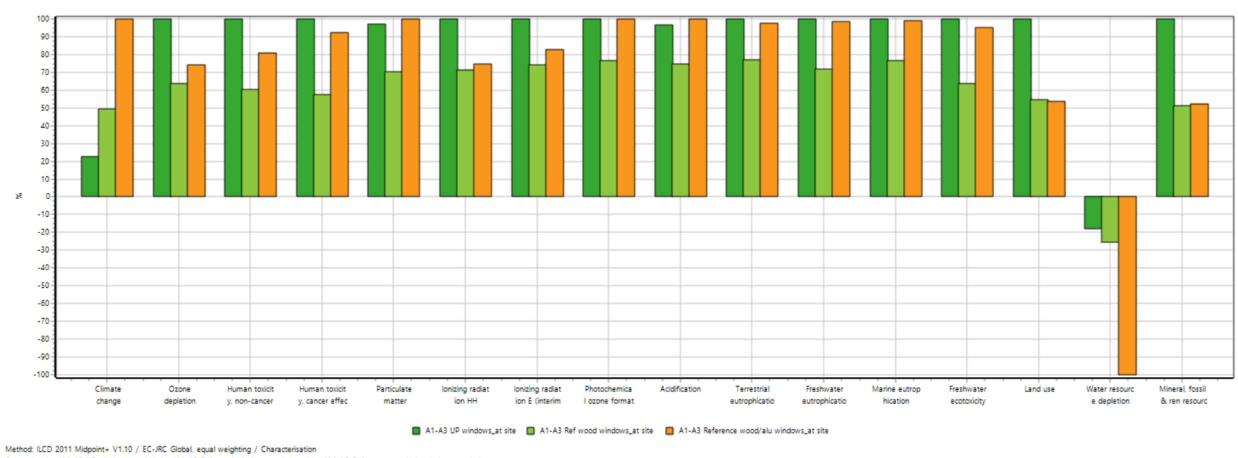

Figure 9 LCA results for window with material reuse and two reference products (wood frame and alu-wood frame).

Appendix B: Process models and contributions shown by LCAs for concrete

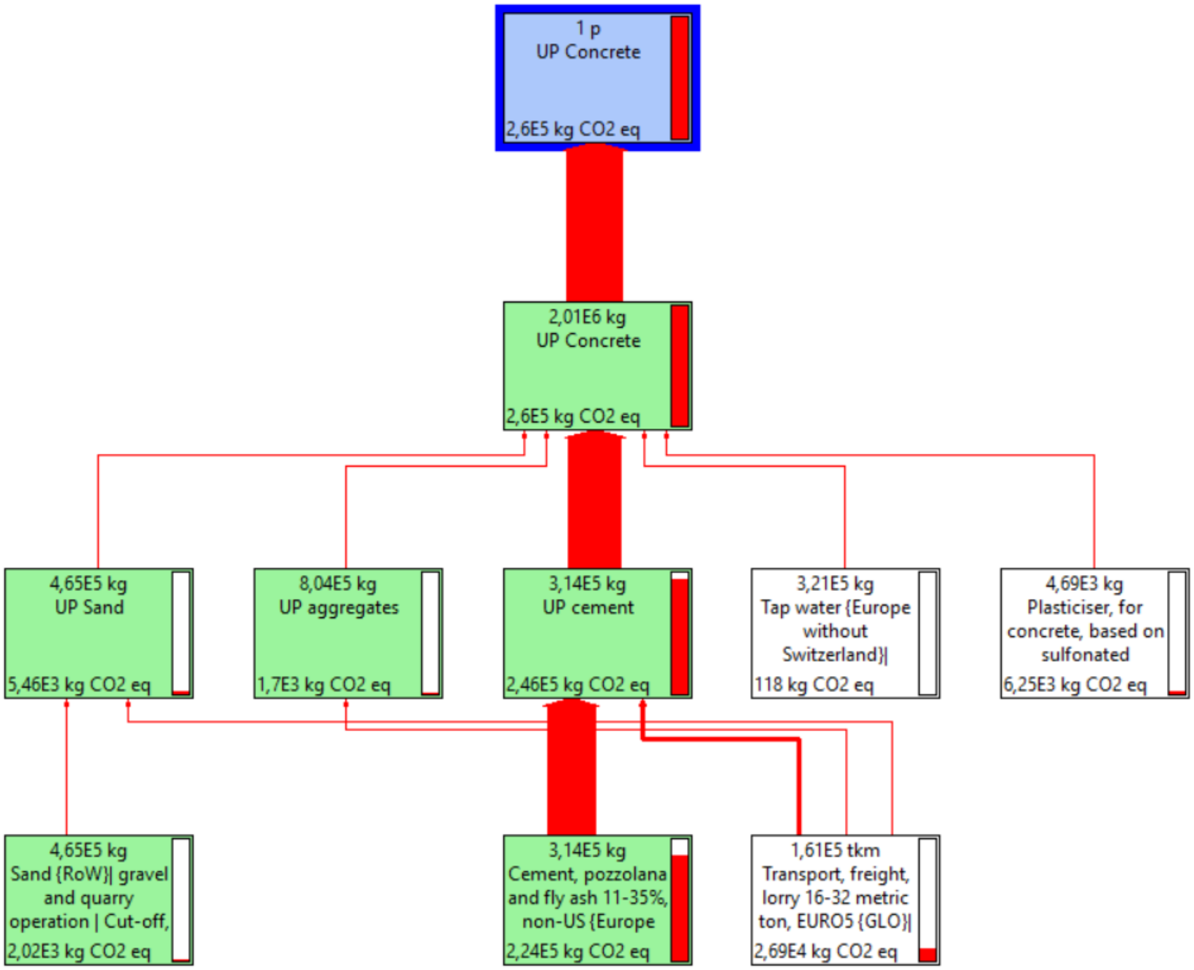

Figure 10 LCA process and GWP results for concrete reuse.

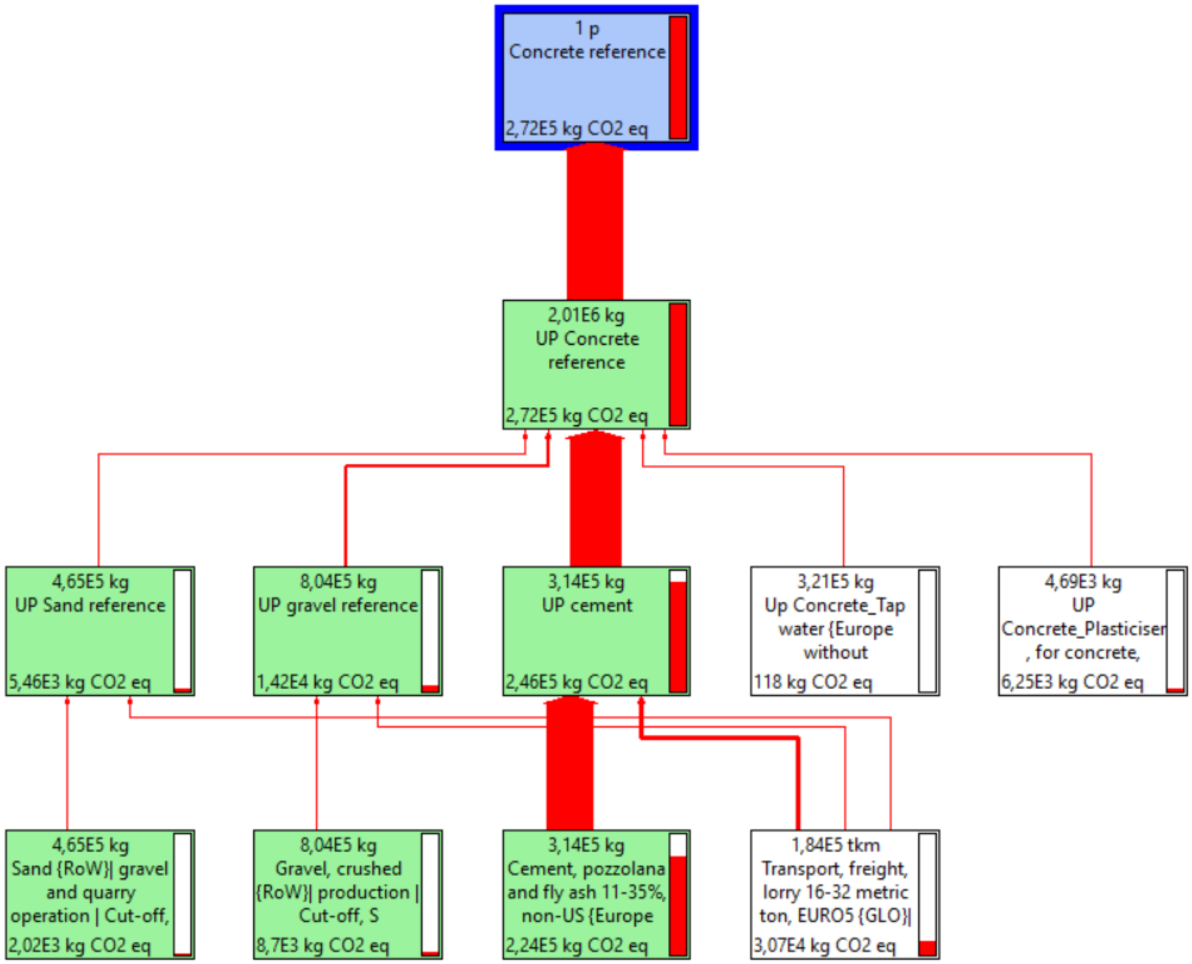

Figure 11 LCA process and GWP results for concrete reference product.

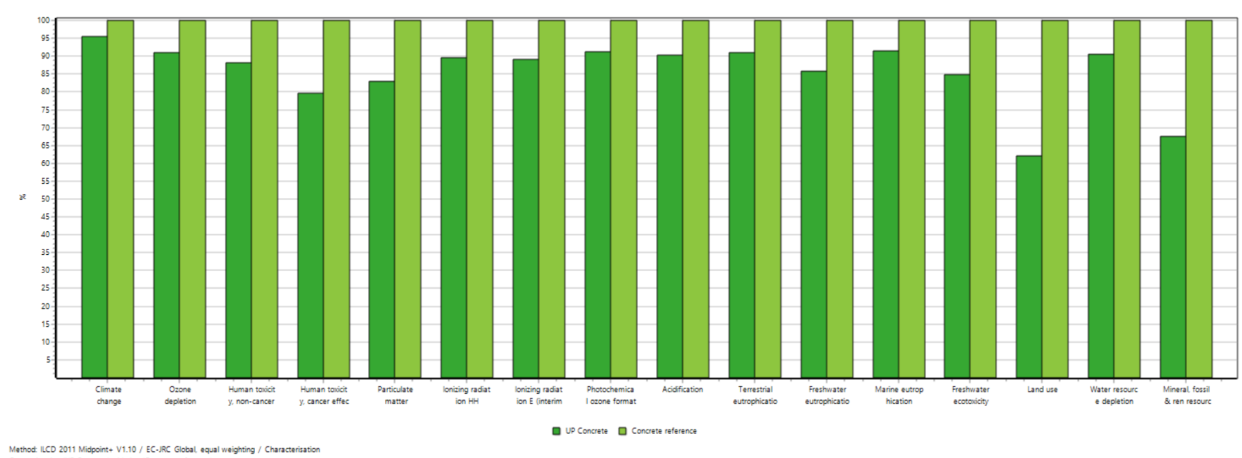

Figure 12 LCA results for concrete reuse solution and reference product.

Appendix C: Process models and contributions shown by LCAs for wood cladding.

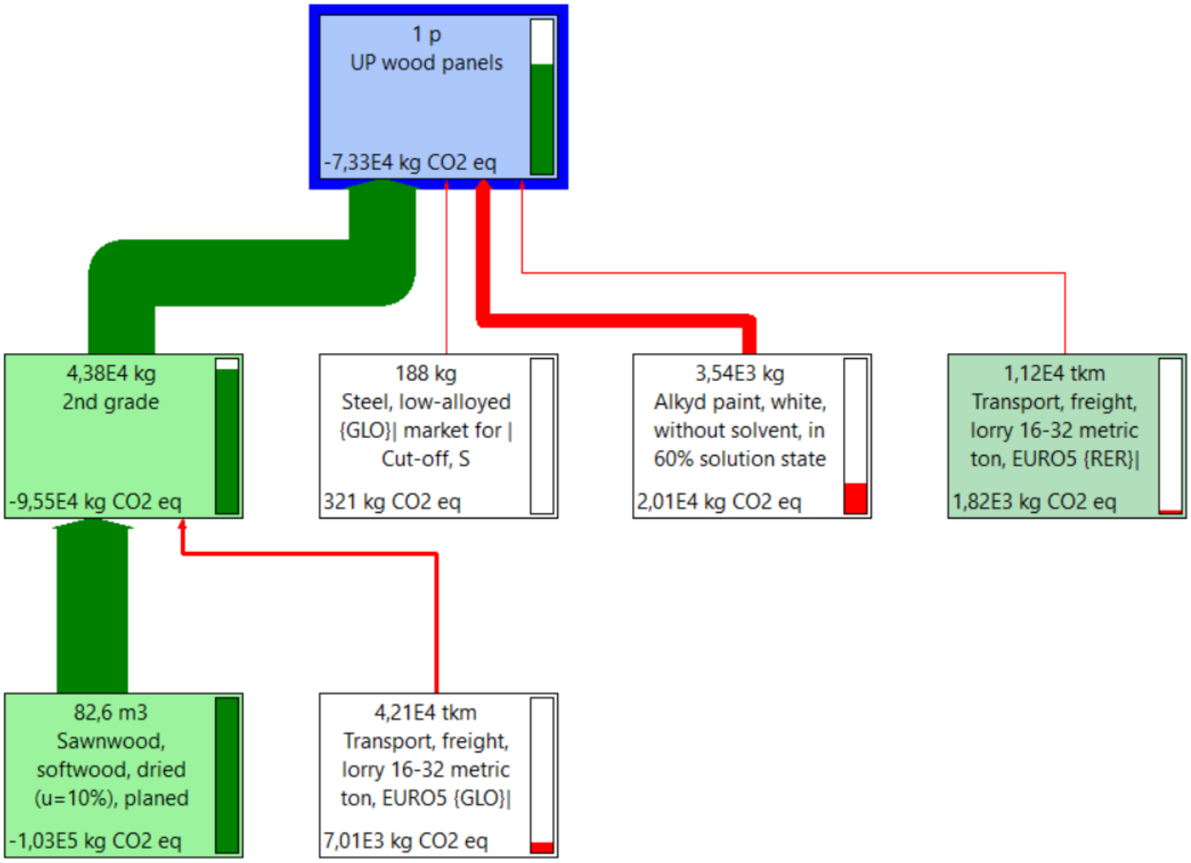

Figure 13 LCA process and GWP results for wood reuse solutions.

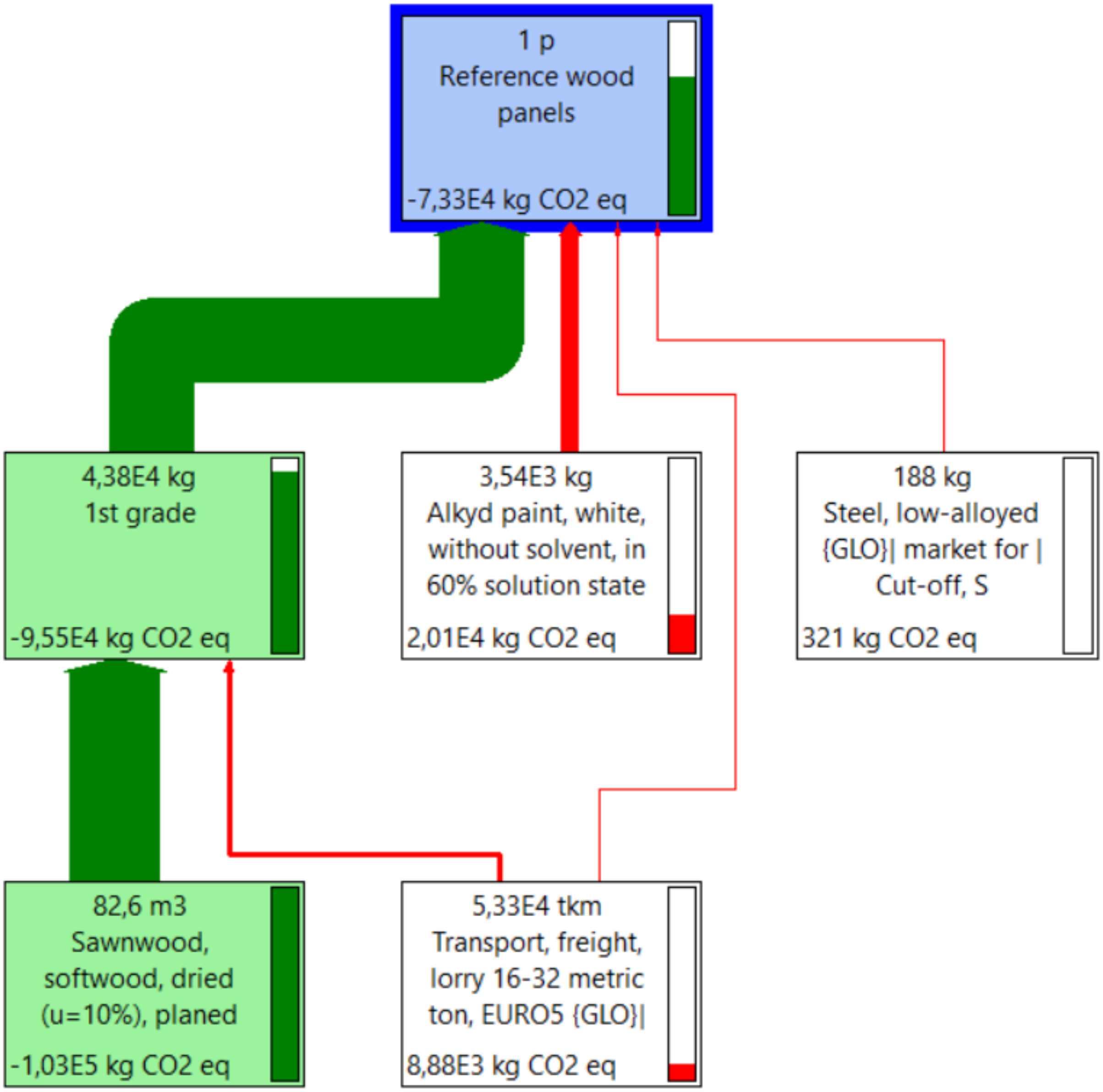

Figure 14 LCA process and GWP results for wood reference product.

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