Circular building materials: Carbon saving potential and the role of business model innovation and public policy

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Circular building materials: Carbon saving potential and the role of business model innovation and public policy.

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Abstract

Buildings are responsible for a third of global greenhouse gas emissions, with much of their life cycle impacts stemming from embodied impacts of building materials. Both at EU and Member State level, circular economy and resource efficiency policies are promoting production of lower-impact building materials with secondary material input. However, secondary material strategies do not result in carbon saving by default, and depend on businesses developing effective and economic applications that can overcome the many barriers to closing material loops. This paper aims to advance understanding of the relevance of secondary material for decarbonisation of the building sector, as well as the interplay of business model innovation and policy instruments in this transition. We used a comparative case study of three pioneering Scandinavian companies that produce circular building materials to estimate the carbon saving potential of using secondary material. We also examined business model innovations to implement strategies, and companies’ experienced and desired policies to help remove barriers. The results show clearly that all three cases offer potential for carbon savings. As the savings vary significantly, findings suggest that careful consideration of affected processes and markets is a key to attaining carbon savings. Business model innovations to enable secondary material use involve establishing key partnerships to access secondary materials, developing recovery process and technology, targeting customer segments that value lower environmental impacts, and considering life cycle costs. Public policies that can help companies remove barriers include 1) incorporating reuse of higher material value in construction and demolition waste targets, and 2) incentivising waste collection and recovery markets to offer recovered material at higher value.

Highlights

- Bricks, concrete and wood-plastic composites from secondary materials offer significant reductions in carbon emissions, both at product and industry level.
- Careful consideration of affected processes and markets at product and industry level is key to attaining carbon savings through use of secondary materials.
- Key business model innovations to enable secondary material use involve establishing key partnerships to access secondary materials, developing recovery process and technology, targeting customer segments that value lower environmental impacts and consider life cycle costs.
- A set of public policies can help companies remove barriers to using secondary materials, such as 1) incorporating reuse at higher material value in construction and demolition waste targets, and 2) incentivising waste collection and recovery markets to offer recovered material at higher value.

1. Introduction

If global warming is to be limited to the critical maximum level of +2°C compared to pre-industrial temperatures, substantial reductions of greenhouse gas emissions are required in the next couple of decades (Pachauri et al., 2014). The building sector is a major contributor to global carbon emissions, and is responsible for as much as one-third of global greenhouse gas emissions (UNEP, 2009).

Carbon emissions from a building’s life cycle and the resulting contributions to global warming can be divided into operational and embodied impacts. While operational impacts result from the energy required for operating the building in the use phase (e.g. heating and cooling), embodied impacts result from processes in the life cycle of building materials (e.g. production, refurbishment, and end-of-life) (Rasmussen, Malmqvist, Moncaster, Wiberg, & Birgisdóttir, 2018; Shadram & Mikkavaara, 2018). As energy efficiency of new buildings during their use phase is improving, embodied impacts make up an increasing proportion of the total life cycle impacts, often more than 50% (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014), so addressing these impacts is vital for helping to decarbonise the building sector.

A solution to reducing embodied carbon emissions is the use of by-products and waste materials (in this study referred to as secondary materials) for producing building materials (Höglmeier, Weber-Blaschke, & Richter, 2013; Ingrao et al., 2014; Intini & Kühtz, 2011; Malmqvist et al., 2018). Despite the potential, environmental improvements may be undermined if the processes needed to transport materials to a suitable state or location for reuse have a greater environmental impact than the impacts resulting from production of the primary material alternative (Gala, Raugei, & Fullana-i-Palmer, 2015; Vadenbo, Hellweg, & Astrup, 2017) (Geyer, Kuczenski, Zink, & Henderson, 2016). Assessment of the life cycle impacts are needed to determine whether a secondary material strategy helps to mitigate climate change.
For economic viability, secondary material use needs to be accompanied by business models capable of capitalising on secondary material strategy and delivering strong mitigation outcomes. Innovating a company’s business model helps align the company’s logic of doing business with a secondary material strategy. This can help remove barriers to using secondary materials or leverage partner networks to capitalise on the embedded economic and environmental value in materials. Despite the enabling role of business model innovation, utilisation of secondary materials in construction of new buildings remains low (Herczeg et al., 2014). In a predominantly linear sector, in which externalities of waste generation and resource extraction are insufficiently internalised in prices, companies still encounter numerous barriers to using secondary materials (Mont, Plepsys, Whalen, & Nußholz, 2017). Alongside companies’ innovations in business models, a systematic change in the policy landscape is required to help companies overcome the barriers to using secondary materials.

In this paper, we aim to advance understanding of the relevance of secondary material use to help decarbonise the building sector, and the interplay of business model innovation and policy instruments to enable this transition. A comparative case study design, based on three pioneering Danish and Swedish companies producing building materials with secondary material input, is used to address the following questions:

(1) How have companies adjusted their business model to employ secondary materials in the production of building materials?
(2) What is the carbon savings potential of each innovation at product and industry level?
(3) What barriers do companies face when upscaling their operations, and which policies could potentially remove the barriers?

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

2. Literature background
This section reviews the literature background on business model innovation (section 2.1) and policy interventions to promote secondary material use (section 2.2).

2.1 Business model innovation for secondary material use

The need to reduce embodied emissions associated with buildings is gaining recognition among policy makers at national and EU level, as well as companies. To make this financially viable, the transition needs to be accompanied by implementation of innovative business models capable of capitalising on secondary material strategy and delivering strong carbon mitigation outcomes. One type of such business models are
business models based on circular economy principles (Bocken, Short, Rana, & Evans, 2014). Circular business models aim to utilise embedded economic and environmental value in products and materials for as long as possible, for instance through substituting primary materials with secondary materials (Nußholz, 2017, 2018). Business models are understood as a management tool to study the organisational structure and value creation processes of businesses, defining the core logic of how a company creates, delivers, and captures value (Osterwalder & Pigneur, 2010).

Table 1 Core activities in a business model.

<table>
<thead>
<tr>
<th>Value dimension</th>
<th>Corresponding question</th>
<th>Business model elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value proposition</td>
<td>What value is provided and to whom?</td>
<td>Product/service offer and value proposition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Customer segment</td>
</tr>
<tr>
<td>Value creation and delivery</td>
<td>How is value provided?</td>
<td>Resources and capabilities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partner network</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Value chain activities</td>
</tr>
<tr>
<td>Value capture</td>
<td>How does the company make profit and capture other forms of value?</td>
<td>Financial structure (costs and revenue flows)</td>
</tr>
</tbody>
</table>

Source: Based on Osterwalder and Pigneur (2010) and Demil & Lecoq (2010).

Business model innovation offers options to shape a business model’s value creation logic to one aligned with circular principles (Nancy Bocken, de Pauw, Bakker, & van der Grinten, 2016; Nußholz, 2017). This particularly applies if all value dimensions, i.e. what value is proposed, how value is created, delivered and captured (Table 1), are rethought to incorporate circular principles, so deviating from linear practice is more likely to be successful.

Although companies in the building sector have applied circular practices for some time, such as by reusing metals, tighter regulation and internalisation of externalities (Adams, Osmani, Thorpe, & Thornback, 2017; ING, 2017) are driving companies to embed circular principles in their business models, moving towards recovering material flows that are more difficult to reuse and at higher level of value (e.g. at component level rather than material level). Several studies highlight the economic potential of various business models around circular practices, such as accessing and reselling building materials from construction and demolition sites and dismantling of buildings (EllenMacArthurFoundation, 2016; ING, 2017). In particular, production and design using secondary building materials is thought to have good potential for economic and environmental value creation (EllenMacArthurFoundation, 2017).

Despite the potential for innovative business models, barriers to creating value from recovery of secondary materials remain. Barriers identified in existing research include an unclear financial case, low value of material at the end of life, a lack of market mechanisms to aid recovery, warranty issues of using reused materials (Adams et al.,
2017), and a lack of access to sufficient quantity and quality of secondary materials (Milios, 2017; Nußholz & Milios, 2017).

2.2 Policy interventions to support secondary material use

Both at EU and Member State level, several policy instruments have been designed to promote resource efficiency and closed material loops in the building sector (Kylili & Fokaides, 2017). At EU level, the Roadmap to a Resource Efficient Europe (COM(2011) 571 final), the Communication on resource efficiency opportunities in the building sector (COM(2014) 445 final), the Waste Framework Directive (2008/98/EC), and the Circular Economy Action Plan (COM(2015) 614 final) aim at improving resource efficiency throughout the life cycle of buildings. Although the set of policies comprises measures at different life cycle phases (e.g. improved design, sustainable materials and production), current efforts focus on increasing recycling of construction and demolition waste (CDW) to meet the 70% CDW recovery and recycling target of the Waste Framework Directive. However, this target is only addressing the quality of recycled materials to a limited extent.

In addition to the policy instruments that set the framework for more resource efficient closed-loop buildings, a number of instruments have been introduced that target specific life cycle phases. To support production of building materials with secondary materials, building material standards are being devised that provide technical specifications and certify quality and safety of secondary building materials. These standards are voluntary and have been developed either on the initiative of sector actors in collaboration with standardisation authorities or mandated by a competent authority at EU or Member State level (Tecchio, McAlister, Mathieux, & Ardente, 2017).

While EU-wide standards are under the responsibility of the European Standardisation Organisations (e.g. CEN), national standardisation authorities (e.g. DS in Denmark and SIS in Sweden) are authorised to develop national standards. In addition, environmental product declarations (EPDs) have proliferated, in which producers can provide standardised information about the environmental performance of their products and materials. EPDs facilitate tracking the environmental performance of products upstream and have become influential in purchasing decisions (Passer et al., 2015). Initial efforts have been made to devise economic instruments to serve as an incentive for using secondary materials over primary materials. Examples are the taxes on primary materials (e.g. aggregates) applied in the majority of EU Member States (EEA, 2016) and reduced Value Added Tax (VAT) for recycled materials in the Czech Republic (Deloitte, 2016).

At the design and planning phase, the EU and national building codes can play a role in promoting use of secondary materials. Building codes are binding sets of rules for
obtaining construction permits that ensure compliance with public health, safety and material standards (Listokin & Hattis, 2005). Traditionally, building codes did not include standards to reduce environmental impacts, but in recent years, European Commission mandates (e.g. M/515, M/128, M/130 etc.) led to amendment of the EU Building Codes (Eurocodes) to incorporate climate impact concerns.

There are also voluntary building certification schemes (e.g. BREEAM, DGNB, HQE, LEED) that account for material use and sound management of CDW. In Sweden, for instance, the certification scheme Miljöbyggnad has been introduced to improve sustainability of materials in buildings (Høibye & Sand, 2018), while in Denmark the DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) scheme has been introduced (Miljøstyrelsen, 2017).

At the end of life of a building, selective demolition practices and separation of waste at source have been paramount in providing clean, recyclable waste fractions for reuse. Although the separation and collection of CDW by material stream has been mandated in most EU countries through CDW management legislations, selective demolition practices are not widespread (Deloitte, 2016). Conducting pre-demolition audits can help achieve this goal, by providing a comprehensive inventory of materials in the building that is to be demolished (Akanbi et al., 2018). Traditionally, pre-demolition audits have primarily focused on identifying and isolating hazardous waste fractions and ensuring their separate collection to purify remaining waste fractions, but the auditing of reuse and recycling opportunities of materials is expected to become increasingly mandatory (Deloitte, 2016), such as in the Austrian ‘Recycled Construction Materials Ordinance’ (Recycling Baustoffverordnung, BGBl. II Nr. 181/2015).

3. Methods and data collection

This study employs a mixed-method approach. It combines a comparative case study design, involving three pioneering cases of Danish and Swedish companies producing building materials with secondary material input, with a desk study of LCA data.

3.1 Case study design

A comparative case study design is employed, based on three cases of companies applying strategies for secondary material use in the Danish and Swedish building sector. Although case studies are sometimes criticised for lack of generalisability, they are beneficial for providing in-depth descriptions (Yin, 2009) of a small number of research units that comprise a strategic sample of a phenomenon (Verschuren, Doorewaard, & Mellion, 2010). Fitting the explorative character of this research, companies were selected to represent different positions in the value chain for buildings and different strategies for secondary material use. The case studies involve (1) a
company manufacturing wood-plastic composite (WPC) for plank products (PolyPlank), (2) an architecture company developing the use of, and designing with, secondary concrete, (Lendager), and (3) a company operating at the end-of-life collecting bricks, and preparing and selling them for reuse (Gamle Mursten) (Table 2). While PolyPlank and Lendager each employ more sustainability strategies and offer additional products, this study focuses only on their strategies for secondary material use described below (Table 2).

Table 2 Overview of case study companies and strategies for secondary material use.

<table>
<thead>
<tr>
<th>Case company</th>
<th>PolyPlank</th>
<th>Lendager</th>
<th>Gamle Mursten</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Manufacturing company producing a material composite and planks of by-products from the wood and plastic industry</td>
<td>Architecture company founded with the goal of becoming a sustainability and circular economy leader</td>
<td>Company sorting, cleaning, testing, selling secondary bricks for reuse</td>
</tr>
<tr>
<td>Value chain positions</td>
<td>Material and component production</td>
<td>Material and component production, design, end-of-life</td>
<td>Material and component production, end-of-life</td>
</tr>
<tr>
<td>Offered product</td>
<td>Construction products from planks (e.g. fences, terrace floors) from recyclable, long-life composite material made from by-products</td>
<td>Sustainability-focused building design, e.g. locally sourced aggregates for secondary concrete</td>
<td>Sorted and cleaned used bricks or brick facade panels</td>
</tr>
<tr>
<td>Substitution strategy</td>
<td>Substitutes primary wood and HDPE with wood and HDPE from secondary production</td>
<td>Primary aggregate is substituted with concrete aggregate</td>
<td>Substitutes new bricks with reused bricks</td>
</tr>
<tr>
<td>Source of secondary materials</td>
<td>By-products from wood and plastics industry</td>
<td>Crushed concrete from demolished buildings</td>
<td>Bricks from demolished buildings</td>
</tr>
<tr>
<td>Country</td>
<td>Sweden</td>
<td>Denmark</td>
<td>Denmark</td>
</tr>
<tr>
<td>Number of employees</td>
<td>20</td>
<td>38</td>
<td>23</td>
</tr>
</tbody>
</table>

All three companies operate in a similar regulatory framework, which increases their comparability. Denmark and Sweden were chosen because both countries have strong government support through pioneering circular economy policy programmes (Miljøministeriet, 2014; Naturvårdsverket, 2012; SOU, 2017), with policy initiatives specifically targeting the construction sector (StateOfGreen, 2017).

An expanded qualitative, interdisciplinary research approach was employed, between May 2017 and January 2018. Various methods for generating data were combined to
enable in-depth analysis and triangulation of findings. Methods of data collection included semi-structured interviews to increase understanding of the business model (section 3.1), a survey to help identify barriers and policy interventions (section 3.2), and a review of existing LCA data (section 3.3).

3.1.1 Semi-structured interviews

Data collection began with analysis of company reports and websites as preparation for interview sessions. Based on analysis of publicly available data, a semi-structured interview guide was prepared, including information on the company’s business models, main barriers to operation, and potentially relevant policy information. Three interviews were held, each lasting about one hour, with company representatives, two of them with the company’s CEO and the third with a senior consultant. Interviews were used to identify elements of each company’s operating business model and their experienced barriers and drivers.

3.1.2 Survey analysis

All interviewed company representatives were asked to complete a survey after the interview. The aim was to identify the barriers experienced by case companies relating to use of secondary materials, as well as policy interventions that could help lift these barriers. The survey protocol consisted of statements on barriers and policy interventions that the respondents were asked to score on a Likert-type scale of 1-5 (5 being most important/relevant) according to their business experience.

Statements on business barriers and potential policy interventions were formulated after a review of academic literature and policy reports (see section 2), as well as the interviews held with company representatives on their business model (in case these brought up information of barriers or desired policies). The survey protocol thereby combined well-documented literature findings together with empirical material from companies’ business practices. The survey protocol is presented in the annex of this manuscript.

The aim of conducting a follow-up survey was to identify the barriers and policy interventions that are relevant to companies (disregarding how important barriers or policy interventions are in relation to each other), and how significant these are to companies. Respondents were given the opportunity to add comments to their scores and explain why/why not various statements were important to their business operations. Respondents were also asked to enter additional barriers and/or policy interventions (if any) that the authors had missed in the survey protocol, to ensure a valid and comprehensive inventory of possible barriers and policy interventions. Where needed, the authors followed-up on the company representatives’ answers via phone
and email correspondence, to clarify the results of the survey or discuss respondents’ submitted comments.

3.2 Review of environmental data and calculation of carbon savings potential

Carbon saving potentials are estimated via life cycle assessment (LCA) data on CO$_2$ equivalents at product level and at industry level. At product level, we calculate the carbon saving potential ($Sp$) as follows:

$$Sp = Em_v - Em_s$$  \[1\]

where $Em_v$ is the emissions generated from production of the primary product and $Em_s$ is the emissions from production of the secondary-based product. Estimations of carbon saving potentials at industry level refer to the theoretical potential for carbon savings if the total annual demand of the product had been calculated using the secondary material strategy. We calculate the industry level potential ($Si$) as follows:

$$Si = Sp \times Ms$$  \[2\]

where $Ms$ is the total supply of secondary material eligible for substitution, taking into account the constraints in supply of secondary materials (i.e. industry-wide production of the secondary-based product requires more secondary materials than are available) or demand for the secondary-based product (i.e. supply of secondary materials exceeds the demand for manufacturing secondary-based products).

Data on carbon saving potentials and for the system analysis of the three strategies are compiled from secondary sources. For the PolyPlank case, data on emissions from primary- and secondary-based WPC production is taken from Somerhuber et al. (2017). The same source provides insight into the processes avoided by using secondary materials, as well as the processes that can be critical to obtain low carbon emissions in secondary-based production. Available material for substitution at industry level is taken from the company's website (PolyPlank, 2018) and Carus et al. (2015).

For the Lendager case, data on emissions from primary production of gravel is taken from the Ecoinvent Database 3.3, which also contains information on the main contributing processes that can be avoided by using secondary materials (Ecoinvent 3.3, 2016b). Manufacturing emissions of secondary-based aggregate are taken from Arm et al. (2017). A report by the Danish EPA (2015) is used as a source for critical processes to obtain low carbon emissions and the annual Danish amounts of concrete waste available for recycling.
For the Gamle Mursten case, data on emissions from primary production of bricks is taken from the Ecoinvent database 3.3, which also provides the main contributing processes that can be avoided by using secondary materials (Ecoinvent_3.3, 2016a). Manufacturing emissions from secondary-based brick production are taken from the company's EPD (2017). A report by Copenhagen Municipality (2017) lists processes that can be critical in obtaining low carbon emissions when using secondary bricks. Annual amounts of brick waste available for substitution are taken from a report by the Danish EPA (2016).

All LCA data of the secondary sources uses the ‘recycled content’ approach as specified in the EN 15804 standard on environmental product declarations for the end-of-life process. In this approach, production impacts from the use of primary materials are allocated fully to the first system that uses the primary materials (Frischknecht, 2010), thereby ensuring methodological consistency. Section 5.1 offer a critical discussion of the secondary data used.

4. Findings from case study analysis

This section presents the case companies’ business models. The focus is on the innovative elements critical for use of secondary materials (section 4.1), the estimated carbon savings potential (section 4.2), and the main barriers the case companies experienced, as well as the identified policy interventions that could help lift barriers (section 4.3).

4.1 Findings on business model innovations for secondary material use

Manufacturing company Polyplank developed a process to transform plastic waste and wood fibres into a moisture-resistant and recyclable composite material (PolyPlank material) that is manufactured into a variety of plank products for buildings (Lindahl, Sundin, & Sakao, 2014). In addition to reusing secondary materials, PolyPlank implements other circular strategies, such as longevity and recyclability of their products, enabling a distinct value proposition that centres around reduced environmental impact and life cycle costs. Targeted customers are primarily public housing associations. The patented, closed-loop process, along with sales channels and securing access to sufficient quantities and quality of secondary materials, are critical for creating and delivering value. Value capture includes cost for secondary materials, manufacturing processes and labour, while revenue is generated from the sales of products.

Architecture company Lendager has specialised in circular economy solutions and has aligned much of its core business with circular principles. The company offers building
solutions with a lower environmental impact, while guaranteeing the same standards with regard to price, quality, aesthetic value, functionality and safety. Aesthetics of reused materials have been made an integral part of their value proposition. Targeted customers are organisations that are open to reuse and interested in more environmentally friendly solutions (e.g. public housing organisations to meet DGNB or LEED certification standards).

The company has been involved in testing a mobile concrete recycling plant, which will be set up on demolition sites and create and deliver value from reuse of concrete. Lendager has also entered into a joint venture with a Danish gravel mining company to scale up secondary concrete production and improve compatibility with primary concrete producers (Ingeniøren, 2018). In a measure to move beyond application of secondary concrete in construction classified as ‘low-safety’, the company has established a partner network to develop certification standards that assure quality. The company generates revenue from the contractors for a building to capture value, but also uses public funding that supports technology development. Main costs relate to labour, materials, and research and development.

Gamle Mursten has developed sorting and cleaning technology that enables reuse of different types of bricks (hand-cleaned or machine-cleaned) recovered from demolition sites. The value proposition includes a competitive price and quality with primary bricks, reduced environmental impact, and the unique look of the reused bricks. To create and deliver value, supportive innovations in the business model include the development of cleaning and stacking technology, as well as a supplier network to ensure sufficient access to used bricks. Establishing a supply base was a time-intensive process, as demolition companies currently dispose of bricks to save labour, time, and costs. Another critical innovation was the development of certification standards to assure the quality of bricks to customers. Partner networks, consisting of research institutes, governmental organisations, and consumer protection organisations, were set up for this purpose. Value is captured through sales of the bricks, while the companies’ costs involve purchase of used bricks, labour, and technology development and production facilities.

<table>
<thead>
<tr>
<th>Value dimensions</th>
<th>Design of value dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value proposition</strong></td>
<td><strong>Polyplank</strong></td>
</tr>
<tr>
<td>• Moisture-resistant, recyclable composite material</td>
<td>• Circular economy solutions with lower environmental impact</td>
</tr>
<tr>
<td>• Reduced environmental impact and lifecycle costs</td>
<td>• Same standards with regard to price, quality, aesthetics, functionality and safety</td>
</tr>
<tr>
<td>• Public housing organisations</td>
<td>• Customers interested in more environmentally friendly solutions</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 3 Overview of case companies’ business model innovations.*
4.2 Findings on carbon saving potential from secondary material use

The findings on carbon saving potential presented in Table 4 suggest that companies’ strategies offer potentials for carbon saving at both product and industry level. At product level, potentials from replacing primary with secondary materials are: 1) 0.95-1.42 kg CO₂-eq avoided per kg WPC produced, 2) 0.008 kg CO₂-eq avoided per kg aggregate prepared for concrete production, and 3) 0.025 kg CO₂-eq avoided per kg brick manufactured. This means that products from secondary materials compared to their primary alternatives can reduce carbon emissions by a factor of approximately 2-3 for Polyplank and Lendager and a factor of 100 for Gamle Mursten (Table 4).

At industry level, the brick case shows the highest carbon saving potential, with estimated annual savings of 25,300 tons CO₂ in Denmark. The annual carbon saving potential of the concrete case is around 7,300 tonnes CO₂ in Denmark. This saving requires the successful processing and utilisation of nearly 900,000 tonnes of concrete waste. The annual carbon saving potential of WPC production is estimated at 12,400-18,400 tonnes CO₂ for the Scandinavian market, although there is some uncertainty because it has not been possible to determine how much of the current production of WPC already uses secondary materials in the production line.


<table>
<thead>
<tr>
<th>Value creation and delivery</th>
<th>(e.g. public housing organisations to meet DGNB or LEED certification standards)</th>
<th>Value capture</th>
<th>(e.g. public housing organisations to meet DGNB or LEED certification standards)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Patented closed-loop process</td>
<td>• Development of cleaning and stacking technology</td>
<td>• Costs for secondary materials and manufacturing processes</td>
<td>• Costs for purchase of used bricks, labour, and technology development facilities</td>
</tr>
<tr>
<td>• Key partners for secondary material supply to access sufficient volumes and quality of secondary materials</td>
<td>• Supplier network to ensure sufficient access to used bricks</td>
<td>• Sales channels</td>
<td>• Revenue from sales of bricks</td>
</tr>
<tr>
<td>• Development of cleaning and stacking technology</td>
<td>• Partner network to develop certification standard</td>
<td>• Key partners for secondary material supply to access sufficient volumes and quality of secondary materials</td>
<td>• Partner network to develop certification standard</td>
</tr>
<tr>
<td>• Partner network for mobile concrete recycling plant</td>
<td>• Joint venture with gravel mining company</td>
<td>• Revenue from sales of products</td>
<td>• Partnership for mobile concrete recycling plant</td>
</tr>
<tr>
<td>• Development of cleaning and stacking technology</td>
<td>• Joint venture with gravel mining company</td>
<td>• Key partners for secondary material supply to access sufficient volumes and quality of secondary materials</td>
<td>• Partner network to develop certification standard</td>
</tr>
<tr>
<td>• Key partners for secondary material supply to access sufficient volumes and quality of secondary materials</td>
<td>• Partner network to develop certification standard</td>
<td>• Sale channels</td>
<td>• Partnership for mobile concrete recycling plant</td>
</tr>
<tr>
<td>• Partner network to develop certification standard</td>
<td>• Development of cleaning and stacking technology</td>
<td>• Costs for secondary materials and manufacturing processes</td>
<td>• Partnership for mobile concrete recycling plant</td>
</tr>
<tr>
<td>• Costs for labour materials and research and development</td>
<td>• Supervisor network to ensure sufficient access to used bricks</td>
<td>• Key partners for secondary material supply to access sufficient volumes and quality of secondary materials</td>
<td>• Partner network to develop certification standard</td>
</tr>
<tr>
<td>• Revenue from contractors and public innovation funding for technology development</td>
<td>• Development of cleaning and stacking technology</td>
<td>• Revenue from sales of products</td>
<td>• Partnership for mobile concrete recycling plant</td>
</tr>
<tr>
<td>• Costs for purchase of used bricks, labour, and technology development facilities</td>
<td>• Supplier network to ensure sufficient access to used bricks</td>
<td>• Key partners for secondary material supply to access sufficient volumes and quality of secondary materials</td>
<td>• Partner network to develop certification standard</td>
</tr>
</tbody>
</table>

1 The reported quantity for annual brick waste takes into account that only bricks from buildings constructed before the 1960s can be recycled at product level. Brickwork from later years uses cement-based mortar, which impedes reuse. Numbers of annual production of WPC represent the European market (in 2012).
<table>
<thead>
<tr>
<th><strong>Primary product</strong></th>
<th>30-60% wood + 30-60% plastics from primary sources, 10% additives</th>
<th>Natural aggregates</th>
<th>New bricks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Secondary-based product</strong></td>
<td>WPC: 30-60% wood + 30-60% plastics from secondary sources, 10% additives</td>
<td>Concrete recycled on-site as aggregate</td>
<td>Cleaned secondary bricks</td>
</tr>
<tr>
<td><strong>Manufacturing emissions (Em) in kg CO2-eq/kg primary product</strong></td>
<td>1.73 - 2.18 (^1)</td>
<td>0.012 ([3])</td>
<td>0.256 ([5])</td>
</tr>
<tr>
<td><strong>Manufacturing emissions (Em) in kg CO2-eq/kg secondary-based product</strong></td>
<td>0.76 - 0.78 (^1)</td>
<td>0.004 ([2])</td>
<td>0.0027 ([4])</td>
</tr>
<tr>
<td><strong>Product level carbon saving potential (Sp) in kg CO2-eq/kg product</strong></td>
<td>0.95 - 1.42(^2)</td>
<td>0.008</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Main CO2-eq contributing processes avoided by use of secondary product</strong></td>
<td>• High-density polyethylene (HDPE) production ([1])</td>
<td>• Transport ([3])</td>
<td>Combustion of fuels for firing, etc. ([5])</td>
</tr>
<tr>
<td><strong>Factors influencing actual potential on product level</strong></td>
<td>• Provision of energy for drying of wood particles ([1])</td>
<td>• Transport processes</td>
<td>• Transport processes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Substitutability of aggregate ([7])</td>
<td>• Recycling rate ([9])</td>
</tr>
<tr>
<td><strong>Industry level</strong></td>
<td><strong>WPC, Scandinavian market:</strong> 13 (based on ([10]) and ([6]))</td>
<td>Concrete waste registered in Denmark: 900 ([7])</td>
<td>Brick waste registered in Denmark: 99.7 ([8])</td>
</tr>
<tr>
<td><strong>Industry level carbon saving potential (Si) in 1000 tonnes CO2-equivalent</strong></td>
<td>12.4 - 18.4</td>
<td>7.3</td>
<td>25.3</td>
</tr>
</tbody>
</table>

The theoretical carbon saving at product level is influenced by a range of factors (see Table 4), depending on the affected processes in production of primary alternatives. In the case of the WPC, carbon saving results mainly from the avoided process of primary HDPE production. Savings from secondary concrete mainly derive from the avoided transport processes but also from avoided gravel quarry operations, and for reused bricks, the savings are mainly attributed to the avoided use of (fossil) fuels for firing, curing and drying processes.

This has several implications for realising the carbon savings potential from secondary material strategies. In the case of WPC, sufficient secondary HDPE needs to be in place.

\(^2\) The range in emissions of the WPC case results from accounting for varying ratios of wood/plastic in WPC production. Reported CO2 values do not contain stored, biogenic carbon.
For concrete recycling, the geographical proximity of the sites producing concrete waste is significant, along with the sites using concrete waste as a substitution (Silva, de Brito, & Dhir, 2017; Vieira, Calmon, & Coelho, 2016). Also, the substitutability of the concrete aggregates, i.e. the ratio at which the crushed concrete can replace primary aggregates (e.g. 1:1 or below), is significant, as the need for new cement can outweigh initial carbon savings (Danish EPA, 2015). For brick reuse, the recycling rate is a key determinant for realising the carbon saving potential, requiring technology to facilitate high recycling rate of, and reduce losses from, the deconstructed brickwork (Copenhagen Municipality, 2017).

4.3 Findings on companies’ barriers and desired policy interventions

Findings suggest that the three companies are affected by similar business and regulatory barriers to reusing secondary materials. Main barriers to their operations are: (1) increasing market share and sales is difficult; (2) the limited access to sufficient quantity and quality of secondary materials; (3) the lack of effective separate collection and recovery infrastructure; and (4) arrangements in the waste and resource management market, which is dominated by a few market actors with low incentives for cooperation and recovery at higher material value.

PolyPlank, for instance, reported difficulties in accessing secondary materials, as only a few market actors dominate recovery and sale of plastic waste in Sweden. The two Danish companies reported a widespread lack of cooperation with demolition contractors and recycling actors to jointly recover materials from construction sites. Currently, small markets and limited prospects for profit curtail the interest of demolition and waste management companies in engaging in recovery operations (Miljøstyrelsen, 2017).

Enablers ranked highly by all three companies are: (1) building design for modularity, deconstruction and reuse/recycling to reduce costs for deconstruction/demolition operations and increasing quality of materials; (2) compulsory sorting on-site and separate collection and treatment of the construction materials through amendment of national building codes, or the introduction of obligatory CDW management plans for acquiring a building permit; (3) increasing the number of companies engaged in recovery and sale of resources in order to enhance competition and increase supply and diversity in offers; (4) improving certification of recovered materials to reduce uncertainty and lack of trust from the construction contractors and engineers; and (5) increasing the uptake of circular economy principles in public procurement.

The two Danish companies also reported recognition of the issue in the public debate and increased leadership of policy actors as important enablers. They also suggested ambitious targets for reuse and recycling, as well as investment in research and
development for waste separation and treatment technology (e.g. to enhance feasibility and reduce costs of cleaning cement mortar from old bricks).

Findings suggest that, while some companies’ needs are addressed by policies, e.g. the possibility to develop standards, other needs are not addressed, such as the diversification of waste market participation, and market development for secondary materials (e.g. through public procurement). Other necessary developments might be slow, such as improvements in mandatory selective demolition and waste infrastructure. In addition, economic instruments are largely absent in the existing policy package.

5. Discussion

5.1 Do secondary building materials have the potential to help decarbonise the building sector?

The findings suggest that secondary building materials offer significant potential for carbon emission reductions, at product and at industry level. However, there are notable differences between the carbon savings potentials and emissions of the case studies, varying between 1% of carbon emissions compared to primary alternatives for the brick reuse case and 30-50% of carbon emissions for the secondary WPC and concrete aggregate compared to primary alternatives.

Sensitivity to influencing factors also varies. At product level, carbon saving potentials are dependent on process-related factors, such as transport distances for the concrete aggregate and energy used for drying post-consumer wood particles for the WPC. These factors can vary between material producers or projects, for instance based on differences in geographical distance to construction projects, production technologies used, and value chain partners. It should be considered that variations in carbon saving potentials also affect results of the potential at industry level, as this is calculated based on the potential at product level.

If secondary material strategies are implemented at industry level, indirect environmental effects, e.g. from market dynamics, can alter the estimated carbon saving potentials. Depending on market dynamics, use of secondary materials may not reduce the total amount of primary materials used in an economy, which undermines the carbon potential at industry level (Zink & Geyer, 2017). In the case of PolyPlank, the company's demand for secondary HDPE often exceeds available supply. Policy development to support secondary material use at industry level requires careful consideration of the macro-level consequences (European Commission - JRC, 2010). As such consequential evaluation of the carbon potential is outside the scope of this paper, it should be considered in future decision-making on upscaling specific strategies at industry level.
It should be noted that this analysis focuses on decarbonisation, while a range of categories and indicators exist for evaluating different aspects of environmental performance via LCA. Although carbon footprint is frequently used as a proxy for environmental burdens, this single indicator focus can lead to the burden shifting to other categories, e.g. ecotoxicity potentials, if the categories do not correlate. However, recent research indicates strong correlations between carbon footprint and most other categories of CML and ReCiPe impact assessment methods, providing analyses are within sectoral levels, e.g. building construction (Kalbar, Birkved, Karmakar, Nygaard, & Hauschild, 2017).

The compilation of secondary data sources used for this analysis adds a level of uncertainty to the carbon saving results. The calculated numbers should be used with caution, bearing in mind that even though LCA data is from sources using a consistent approach to end-of-life modelling, they may still be based on different background LCA databases, and thereby different system boundaries. The use of secondary data sources also means that results are not necessarily representative of the actual companies, so the results only illustrate the generic and approximate carbon potential of the strategies, at company level as well as industry level. All data used is taken from LCA data reviewed by peers or third parties following the EN 15804 standardised methodology, which ensures methodological consistency. However, a critical examination of all assumptions and modelling choices of the reviewed LCA results was outside the scope of this paper.

5.2 What role do business model innovation and policy support play in enabling secondary building materials?

Companies’ entrepreneurial activities play a vital role in developing and utilising secondary building materials and creating market offers. All three case companies have adjusted their business models to create market offers based on secondary material. Critical business model innovations revolve around development of recovery technologies and capabilities, partner networks to access secondary materials, and identifying right customer segments that value lower environmental impact and life cycle costs as well as distinct aesthetics. In addition, fluctuations in quantity and quality of available secondary materials required all companies to operate more flexibly.

One major barrier remaining is the access to secondary materials. Both Lendager (secondary concrete) and Gamle Mursten (brick reuse) have addressed this by moving beyond their traditional value chain position (e.g. manufacturing or architectural design of buildings) and developing capabilities and resources to include demolition and recovery of materials. The lack of market demand for products from secondary materials was also reported as a barrier. Lendager and Gamle Mursten addressed this by developing national standards that certify quality of their products.
Overall, companies that are prepared to make holistic changes in their business model to integrate circular principles are better equipped to employ secondary materials and remove barriers. However, the selected case companies may not be representative of conventional companies in the building sector that may be less inclined to innovate their business model, thereby experiencing barriers even more profoundly.

Policy interventions appear to be crucial in removing the remaining barriers for companies. Market development, both for availability of waste materials and sales of secondary building materials, was reported as a main barrier, despite policies aimed at improving the management of CDW. This could be because current targets address quantities of materials, but not quality or economic aspects that are vital to enable reuse of materials from construction and demolition at higher material value.

The potential of pre-demolition audit and selective demolition to generate availability of materials for recovery at higher value has not been realised (section 2.3). These are not yet mandatory and would need to be broadened to include criteria for identification of reuse options (in addition to the current aim of identifying hazardous waste fractions). Findings also indicate that the lack of interest of established actors in the waste management market in promoting higher-value material reuse has not been addressed.

The development of standards for secondary materials appeared to be helpful in generating trust in quality of circular building materials and facilitating market access (section 4.1). Also, building certifications have helped generate demand, but these remain voluntary. However, the integration of criteria for resource efficiency in mandatory national building codes or in public procurement, as well as economic instruments to make prices more compatible with primary materials, are underutilised.

6. Conclusion

This paper has contributed to understanding the relevance of strategies for using secondary materials in the building sector to decarbonise the sector, and understanding the interplay of policy and business model innovation to advance production strategies with secondary materials. We used a comparative case study of three pioneering Scandinavian companies that produce building materials with secondary material input to estimate carbon saving potential of the three strategies. We also examined companies’ business model innovations to facilitate use of secondary materials, the barriers companies are experiencing that prevent them upscaling their operations, and the policies that could help remove the barriers.
The calculated carbon saving potentials at product level suggest that the secondary-based products emit carbon corresponding to 30-50% of the primary production alternatives for concrete aggregate and WPC respectively, and only 1% of the primary alternative product for the bricks. At industry level, the annual carbon saving potentials from applying the analysed strategies amounts to 12,400-18,400 kg CO2-equivalent for secondary wood-plastics composite in Scandinavia (WPC), 7,300 kg CO2-equivalent for secondary concrete aggregates in Denmark, and 25,300 kg CO2-equivalents for brick reuse in Denmark.

Carbon saving potentials depend on which of the harmful processes in primary material production are replaced through secondary materials use and the indirect consequences at industry level. An overall finding is that, although all three cases offer carbon emission reductions at product and industry level, notable differences are seen between the carbon savings potentials of each strategy, as well as their sensitivity to impact of influencing factors. Processes and markets must be carefully considered at product and industry level to ensure actual carbon savings, especially if strategies are selected for support by policy initiatives.

Critical business model innovations to implement use of secondary materials were found to revolve around development of recovery technologies and capabilities, partner networks to access secondary materials, and identifying right customer segments that value lower environmental impact and life cycle costs and aesthetics. The business environment for companies aiming to use secondary materials remains largely discouraging. While companies were able to address some of the experienced barriers by innovating their business model (e.g. overcoming lack of access to discarded materials by operating demolition and recovery activities themselves), additional policy interventions are crucial to remove other remaining barriers.

A set of policy interventions was identified, aimed at promoting secondary building materials. These include objectives for reuse at higher material value in CDW recycling targets, making pre-demolition audits for identifying reuse opportunities mandatory, and employing selective demolition. Incentives must be available to companies in the waste collection and recovery markets to offer recovered material at higher value, as the few dominating market actors currently limit access to waste materials. The case study companies were positive to integration of criteria for resource efficiency in the mandatory national building codes or in public procurement requirements, as well as economic instruments to account for the externalities of primary materials.

While this study focused on companies employing secondary materials, it should be noted that policy measures to support secondary building materials should address the entire life cycle and various circular strategies, e.g. design for disassembly, that can be applied to buildings (see Nussholz & Milios (2017) for an overview). Only systematic
change in value chains through a coordinated and carefully designed mix of policy instruments (Milios, 2017) can advance the transition towards closed loops in the building value chain. Another limitation of this study concerns the focus on the carbon saving potentials of selected strategies, neglecting potential trade-offs with other impact categories. Nevertheless, it provides a first indication of the importance of the strategies in helping to decarbonise the building sector.

Future research could investigate the significance of other LCA impact categories, to ensure that environmental impacts are not simply shifted from one category to another. Another area could be to examine the indirect effects of strategies at industry level, to ascertain whether environmental benefits at product level might be offset through changes occurring at industry level. Lastly, future research could also consider the economic value generated from using secondary materials, and investigate implications for companies’ financial structures in more detail.

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