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Closing the material loops for construction and demolition waste: The circular economy on the island Bornholm, Denmark

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ABSTRACT

The article explores the creation of a closed-loop production and consumption value chain, based on a case study carried out on the island of Bornholm, Denmark. Tests and demonstration of practices and procedures to reuse and recycle construction and demolition waste were conducted, including: (1) developing and implementing resource mapping and selective demolition procedures at three rural demolition projects, (2) assessing the CO_2 reduction potentials associated with recycling the selected materials, (3) assessing the value and potential business models that could support the utilization of the materials, and, (4) creating a network between local stakeholders. Based on these activities, the article analyses and discuss economic and practical barriers and potentials for looping materials from demolished buildings back into the construction of new buildings. Finally, the article discusses how the lessons learned from Bornholm could be transferred to other islands and remote areas that are considering adopting a circular economy in their construction and demolition sectors.

1. Introduction

There is an urgent need to reduce the environmental footprint of the existing linear production and consumption system (Stahel, 2016). During the last 100 years, there has been a close correlation between economic growth and resource consumption (UNEP, 2011). Valuable resources are extracted from nature and turned into goods which generate waste and emissions during their production and end-of-life waste treatment. The recycling of waste is often technically challenging and economically impossible. The linear economic system requires huge material inputs and generates large amounts of emissions and other waste (Oberle et al., 2019). As the world economy continues to expand, the global production of waste is expected to increase with up to 70% by 2050 (Kaza et al., 2018). Most of the waste produced is expected to end up in landfills or in incineration plants (Kaza et al., 2018). The inherently unsustainable nature of this global consumption and production system requires a new economic model. Thus, the circular economy has been proposed by businesses, policy makers and researchers as a framework for such a new model (EMF, 2012; Stahel, 2016; WBCSD, 2017).

1.1. The circular economy

The circular economy can be characterised as an umbrella concept (Blomsma and Brennan, 2017) that covers several strategies focused on minimising, reusing, recycling, and recovering materials and resources that flow through the economy (Bocken et al., 2016; Christensen and Hauggaard-Nielsen, 2020; Kirchherr et al., 2017). The circular economy combines two system perspectives: (1) the material system that is composed of the physical flow of materials running through the economy and (2) the economic system covering the use value, revenues and economic costs associated with these flows (Christensen, 2021).

Several studies have assessed the degree of circularity at a global, national, or regional scale using material flow analysis tools and procedures (Aguilar-Hernandez et al., 2019a; Haas et al., 2015, 2020). These studies quantify the so-called circularity gap as the amount of recovered waste as a share of primary material input to the economy, or in a slightly more refined manner as the waste generated, plus the stock depletion, minus the recovered materials (Aguilar-Hernandez et al., 2019b). This circularity gap index thereby provides a simple and rough way to assess how far an economy is from realising a closed-loop production and consumption system. Aguilar-Hernandez et al. (2019b) assessed the circularity gap of 43 nations and found a low degree of

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circularity, and therefore, they proposed interventions for closing the material loop of nations focusing on improved waste management systems, closing supply chains, increasing resource efficiency, and extending product lifetimes. However, the main weakness of studies based on economy-wide material flow accounts is the rough data sets that measure flows in tonnes with little attention to how the value of the flows may differ. When measuring the circularity gap, a tonne of low-value crushed concrete counts the same as a tonne of high-value construction bricks.

1.2. Circular construction and demolition

The construction and demolition sectors have a huge environmental impact in terms of resource consumption, energy use, emissions, and waste generation. Construction and demolition waste (CDW) is the largest waste stream in the EU (EEA, 2019a). Measured by volume, CDW represents one-third of all waste produced in the EU (European Commission, 2017). Most EU countries have met the 2020 recovery target in the Waste Framework Directive for 70% recovery of CDW; however, the high recovery rates are achieved primarily through backfilling in which valuable materials are crushed and used as filling materials in, for example, road construction (EEA, 2019b). There is a significant environmental and resource potential with increased reuse and improved recycling, which would also capture a higher economic value from CDW (Silva et al., 2017a). However, addressing the circularity gap of the construction and demolition sectors is complicated by the long lifetime of buildings and infrastructure, causing a delay between inflow and outflow (Augiseau and Barles, 2017). If net addition to stock exceeds the outflow from demolition (Mayer et al., 2018), this hinders the overall potential for closed cycle of resources. The gap between demolition and construction is further complicated by the way in which the construction and demolition value chain is constituted. This value chain does not operate as a single production line, but as separate projects each with several operations having their own time frame and involving a shifting variety of parties (Leising et al., 2018).

1.3. Potential of and barriers to the circular economy in the construction sector

The circular economy is increasingly seen as a framework for reducing waste and increasing reuse and recycling within the construction and demolition sectors (EEA, 2019b). Hossain et al. (2020) argue that research on the circular economy in the construction and demolition sectors primarily addresses supply chain issues and the recovery of construction materials for reuse.

Although there is huge potential in establishing a circular economy in the construction and demolition sectors, there are also technical, legal, and behavioural barriers that need to be overcome before the potential can be realised. Mahpour (2018) conducted a literature review on the barriers to the adoption of the circular economy in construction, which suggested that, due to a lack of experience, the main technical barrier is the lack of effective processes, which makes circular practices more complicated and time-consuming. Legal barriers include inadequate policies and legal frameworks that would prioritise the promotion of the circular economy. Some legal frameworks even hinder the application of secondary resources (e.g., in terms of quality criteria). Behavioural barriers consist of user preferences (e.g., due to uncertainty about the performance of recirculated materials), but also business as usual, as there is limited experience in how to apply circular criteria in tenders and offers.

Table 1 Reusing and recycling CDW in new construction also depends on the competence and knowledge of the clients and companies involved in developing buildings. Overcoming the barriers to the circular economy requires a wide set of stakeholders along the value chain to change their practices. Selective demolition needs to be developed and implemented to conserve the economic value of construction elements and materials (Coelho and De Brito, 2011a; Pantini and Rigamonti, 2020a). Implementing such practices requires enhancing competence and creating know-how amongst the companies involved in demolition. Besides promoting practices for deconstruction and sorting secondary materials, quality assessments are crucial for ensuring that aggregates match the grade required for an application. This can be enhanced by promoting certification methods, including systematising methods for sorting and quality control (Silva et al., 2017b). Quality assessments must be supported by common rules and standards to assure users and increase confidence (Gálvez-Martos et al., 2018). As the requirement for increased quality control places an increased pressure on documentation, it is important that it is accompanied by tools (e.g., building information modelling and material passports) and knowledge on how to enhance the documentation created during construction and demolition (Won and Cheng, 2017). Business models and market maturation are needed to increase both the supply and demand for reused and recycled CDW to ensure that building elements and materials from demolition can be used in the construction of new buildings. To address the insufficient access to quality material, more companies must be engaged in the promotion of secondary material across the value chain. According to Nußholz et al. (2019), this is inhibited as the mainstream market is dominated by a few companies with low incentives to engage in reuse and recycling. Thus, the establishment of local networks that promote collaboration in the value chains is essential for realizing mature markets and for creating profitable business cases.

Table 1
Technical, legal and behavioural barriers to selective demolition, quality assessments and business model needed for a circular economy in construction.

		Barriers
Selective demolition	Technical	Lack of experience and complex material compositions in buildings (structures, joints and hazardous substances) inhibit effective selective demolition with high-quality output
	Legal	Legal frameworks lack incentives or obligations for sorting and reporting CDW by source
	Behavioural	Selective demolition is not a priority when tendering; it is seen as an extra cost and a deviation from conventional practice
Quality assessment	Technical	Certification and quality control are complex and unique for each product group, and there is a lack knowledge on how and what information to collect
	Legal	Inadequate legal frameworks for promoting the relation between waste management regulation and product regulation
	Behavioural	Publishing documentation that meets quality criteria for secondary resources is not common practice
Business model	Technical	Inefficient methods reduce the profitability of circular business cases
	Legal	Complex legal landscape and harmonised standards makes circular business cases time-consuming and hence, uncompetitive with the low costs for virgin material
	Behavioural	Uncertainty of performance and availability of secondary resources inhibit demand

1.4. Islands as testing grounds for the transformation towards a circular economy

Several studies suggest that islands are ideal testing grounds for participatory projects aimed at co-production of knowledge due to naturally determined geographical boundaries (Deschenes and Chertow, 2004; Fuldauer et al., 2019; Noll et al., 2019a). Additionally, the literature indicates that many smaller islands are challenged with management of waste flows that often end up as dumps or inefficient recycling schemes (Mohammadi et al., 2021) often due to the lack of sustainable waste management systems (Elgie et al., 2021). In a recent study Noll et al. (2022) showed, using material and energy flow analysis, how a Greek island (Samothraki), over last decade, had transformed from a circular biophysical economy towards an economy reliant on largescale inflows and outflows of materials and energy. Illustrating a development pattern that is likely to be identical for many island economies around the world. Millette et al. (2019) used material flow analysis to study plastic waste flows in Trinidad and Tobago and identified potentials for improved recycling that could support decision-making in relation to local waste management. Focussing on e-waste Mohammadi et al. (2021) performed an historic analysis of e-waste flows related to five Caribbean island-states and found a significant rise in waste flows. The studies suggest that island, to support a sustainable development, should break away from the linear economy associated with large inflows and outflows of materials, energy, and waste. To support islands in this endeavour, knowledge about potentials and barriers for implementation of circular economy must be developed. There is additionally a need for practical experiences with closing the material loops (for materials such as e-waste, plastics, CDW etc.) to develop competences, know-how and knowledge. Here, more knowledge on collaboration between public authorities, knowledge institutions and private companies is needed to close the knowledge gap.

1.5. The island of Bornholm, Denmark, as a testing ground

This article is empirically based on a case study carried out on Bornholm, Denmark, with the intention of co-producing knowledge in collaboration with knowledge institutions, local governments, and private businesses (Caniglia et al., 2021) about the potential of and barriers to closing material loops in a geographically semi-closed system.

The island Bornholm is in the Baltic Sea. It has an area of 588 km^2 and approximately 40,000 permanent inhabitants. The island was chosen as a testing ground for several reasons. *First*, it is a semi-closed environment. Construction materials and waste must be transported in and out on ferries, resulting in geographically determined system boundaries for the analysis. Since the local construction industry is limited, the potential future demand for construction materials and the potential generation of waste can more easily be quantified. The geographically fixed system boundaries facilitate an analysis of the potential for creating a closed-loop production and consumption system for the local construction sector. *Secondly*, the municipality on the island has proposed ambitious policies targeting the transformation to a circular economy, as Bornholm Municipality is determined to be a leading municipality for the circular economy. Its vision is described in *Bright Green Island* (Bornholm Municipality, 2018) and *Bornholm showing the way – without waste 2032* (BOFA, 2019). It is implementing initiatives that aim to close material loops and foster a circular economy on the island.

The building stock on Bornholm was mainly constructed before 1960, and 20.6% was built before 1900. Almost 25% of the buildings are used for agriculture and 6% are used for vacation purposes. The materials used in the buildings on the island were, to a large extent, determined by their functions and intended use. There are many buildings with wooden frames, such as timbered houses. Tiles and brick are common construction materials. Due to the age of the houses and the materials used in them, much of the building stock is worthy of conservation. Many of the buildings were constructed without contaminating substances, such as asbestos and PCBs, which also makes the reuse and recycling of CDW easier. The age of the buildings, however, does not guarantee that all materials will be harmless, as substances such as lead paint have been used in older buildings.

Construction activity on Bornholm is generally lower than the rest of the country and primarily related to agriculture, industry, tourism, and small private construction. This may be due to the island's relatively small population and delimited geography, leading to a below-national-average demand for construction materials.

Waste management on the island is organised by the municipal waste company BOFA. BOFA operates the waste incineration plant (with a capacity to incinerate 20,000 tonnes MSW per year) and a landfill site (for materials such as contaminated inorganic building materials, contaminated soil, sludge from sewage treatment plants and asbestos. There exist no known illegal dumping sites. Recyclable wastes (e.g., CDW) are managed at one of the 6 recycling stations on the island that are also operated by BOFA. The recycling stations can be used free of charge for private users, for example to dispose CDW from private construction and demolition projects, while commercial users must pay a fee. Private households pay a monthly waste fee that covers expenses for all waste management associated with MSW, including expenses to operate recycling stations. Companies in the construction sector can also chose to use private waste contractors, instead of public recycling stations, to manage CDW. This is typically the case for larger construction projects whereas small scale contractors use the recycling stations for low volume CDW.

This article explores how the loop in construction and demolition value chains can be closed to increase the reuse and recycling of CDW. The study is empirically based on a case study during which circular economy practices and procedures were developed, tested, and demonstrated. The article is organised with a methods section (Section 2), a result section (Section 3) that presents the results of three selective demolition projects carried out on the island, followed by a discussion (Section 4) about barriers and potentials for looping the materials back into construction of new buildings.

2. Methods

2.1. Case study approach

Following Flyvbjerg (2006), the article is based on a case study approach that explores how to create closed-loop value chains in construction and demolition on an island that constitute a semi-closed production and consumption system. The empirical data for the study was obtained from a research project carried out on the island of Bornholm, Denmark. The data from the project activities was collected, managed, and analysed by the authors who participated actively in the project. The project was designed as a co-innovation project between Bornholm Municipality, Roskilde University (authoring this article), the waste company BOFA and two private consultants, in which the authors collaborated with multiple stakeholders in the co-production of new knowledge (Caniglia et al., 2021). In line with the philosophy of Modus 2 research (Gibbons et al., 1994; Nowotny et al., 2003), the authors engaged in close collaboration with the stakeholders involved to define the research questions, collect, and review data, and draw conclusions.

The study presented in this paper used a mixed methods approach (Johnson and Onwuegbuzie, 2007) to analyse three demolition projects conducted on the island Bornholm and to explore pathways and business models for looping materials back into construction of new buildings. The demolished houses were traditional run-down rural houses that were abandoned due to urbanisation processes on the island – like rural areas in most of Europe that are depopulated a similar way.

Different types of data were collected and analysed. This approach facilitated an analysis based on a combination of quantitative data primarily collected from the demolition projects, with qualitative information, collected from workshops carried out with stakeholders involved in the value chain. The data from the demolition projects were collected and analysed to assess quantities of different types of recyclable materials, the costs and market value of the materials and to assess the potential CO_2 reduction potential associated with the recycling of the materials. In the case study the project partners thereafter collaborated with local stakeholders involved in the construction sector on the island to identify the potentials and barriers to the creation of a circular value chain in for CDW in a geographically limited area.

2.2. Pre-demolition procedures

Prior to each demolition, the municipality carried out a pre-demolition audit covering a resource mapping of the materials available for reuse and a legally mandatory environmental screening to identify potential hazardous materials. The resource mapping was based on a template and procedure developed by Danish Machine Stations and Contractors (an association for Danish contractors). The template is an excel sheet that is used during a physical, visual audit. During the audits of the buildings, materials in the building were identified and registered. The data for the resource mapping was collected by the authors and presented in the results section of the article. A pre-demolition audit, however, can never assess the *actual* amounts that are available for reuse as materials may turn out in a poorer or better condition than anticipated. The study therefore assesses the initial resource mapping against the actual materials that were allocated for recycling after the demolition. The data for from this comparison is presented in the results section of the article, and the relation between the amounts of materials registered in the resource mapping and the actual amounts is presented in the article as the *utilisation rate* in percent.

2.3. Selective demolition procedures

The three selective demolition tests were partially funded by the municipal demolition fund managed by Bornholm Municipality (who was also a partner in the research project) and carried out by private contractors according to procedures developed and/or identified by the project partners.

The three demolished houses were typical run-down country houses containing materials of potentially high conservation values such as wood, bricks, stone, and reusable doors. The three houses constituted a total floor area of 1333 m^2.

The demolition-contractors (a local company on the island) were instructed, by the municipality as a part of the demolition contract, to use a selective demolition guideline. The demolition-contractors did not have any training prior to the selective demolition, but they had sporadic experience with extracting individual materials for reuse or disposal.

During the demolition procedure, the time spent and data about the materials recovered for reuse or recycling were recorded by the demolition contractor. The materials selected for reuse were bricks, granite blocks, beams, wooden floorboards, tiles, and doors with frames. The data was collected by the municipality and transferred to the authors, analysed, and presented in the results section.

2.4. Market analysis and calculation and calculation of costs

Additional time spent by the municipality to conduct resource mapping (working hours spent) was registered and the data was obtained by the authors. The demolition contractor was instructed to assess the time/costs used to selective demolish specific parts of the buildings to make it possible to identify which materials (e.g., bricks, stone, wooden beams, wooden floors, tiles, and doors) that were time consuming and costly to selectively demolish. The total costs associated with the selective demolition procedure was assessed by adding the additional time spent by the municipality and the costs spent by the demolition contractor. The cost figures presented in the result section (Table 3) thereby illustrate additional working hours spent by the municipality plus the total costs used by the demolition contractor to selectively demolish the three buildings.

The potential sales values were determined through a market analysis (Jensen 2020). The market analysis estimated the values of similar materials on the market, using existing online sales platforms in Denmark. The economic data are associated with a significant uncertainty as the values were obtained from different online sources (online platforms for reused and recyclable construction materials) and geographically not located on the island. The most reliable data were for the reuse of bricks, as there is a relatively mature market for reused bricks in Denmark.

The (potential) profit factor was identified by dividing total (potential) sales value by the total cost.

Table 2
Recyclable materials from the three demolition projects.

Material	Resource mapping	Amount for reuse	Utilisation rate*
Bricks	121.1 tonnes	82 tonnes	68%
Granite blocks	22 pieces	19 pieces	86%
Wooden beams	12.2 m^3	12.1 m^3	99%
Wooden floorboards	219.6 m^2	94.6 m^2	43%
Tiles	107.0 m^2	92.8 m^2	87%
Doors with frames	42	40	95%

* The utilisation rate is the percentage of materials that were reused out of the total amount of materials that were estimated to be available for reuse.

Table 3
Total cost associated with the demolition and estimated sales value.

Material	Total cost (DKK)	Total estimated average sales value (DKK)	Average profit factor
Bricks	354,510	788,777	2.2
Granite blocks	4604	12,069	2.6
Wooden beams	22,635	19,463	0.9
Wooden floorboards	16,098	82,928	5.2
Tiles	12,029	25,037	2.1
Doors with frames	28,415	29,688	1.0

2.5. Calculating CO2 reduction potential

To assess the potential CO_2 reduction associated with reusing or recycling materials, a climate impact assessment was conducted focussing exclusively on CO_2 emissions in a lifecycle perspective. The goal of the assessment was to assess the potential CO_2 savings from reusing and recycling demolished materials from the three demolition projects, to identify hotspots and to evaluate where reuse of demolished materials would generate the highest potential climate impact reduction.

The scope of the study was limited to the production phase in the main calculations and based on emission factors from the GaBi LCA database (GaBi, 2019) combined with reported values (Danish EPA, 2013; VTT, 2013). These emission factors were combined with data from the three demolition projects (presented in Table 2). The Bornholm Municipality obtained data from the demolition contractor about quantities of recyclable and reusable CDW and additionally performed physical inspections of the materials to ensure that the correct quantities were reported. The authors thereafter received these data from the municipality (presented in Table 2). The functional unit was not assessed in this calculation, and it was, therefore, implicitly assumed that the materials retained their technical properties when reused.

2.6. Identifying pathways to feedback CDW into construction of new buildings

Pathways to loop building materials from the three demolished buildings back into construction of new buildings on the island were thereafter explored. Materials from the selective demolition was assessed according to volume and potential economic value (based on the market analysis) and bricks, wooden floorboards, wooden beams, and doors with frames were selected. The authors held a series of online and physical meetings with representatives from the municipality before and after the demolition of the three buildings to discuss the best practical pathways to loop the demolished materials back into construction of new buildings. These meetings also involved the local waste company BOFA and local companies in the construction sector. The primary challenge in this part was to identify practically and durable ways to reuse and/or recycle the building materials in new constructions on the island. The involvement of the local construction companies was mainly achieved through a series of seminars where results from the demolition were discussed. The results from these activities are discussed in the discussion sector of the paper.

3. Results: reusing and recycling CDW

3.1. Results from test demolitions

During the demolition, time spent (working hours) and quantitative data about the materials recovered were recorded by the demolishers and obtained by the authors. Initially, there were challenges in collecting the data due to the implementation of new workflows in the demolition procedures.

As a practical result of the project one of the demolition contractors subsequently incorporated the recording of relevant data into their standard demolition procedures. In addition, the company trained its employees on selective demolition because they saw it as a future business opportunity and because the municipality (partly because of the project) made selective demolition a requirement for future demolition projects supported by the municipal demolition fund.

Table 2 illustrates the amounts of materials available, the actual amount generated for reuse and the utilisation rate. The utilisation rate is the percentage of the resource mappings that were collected for reuse or recycling. These findings indicate that some materials are easier to selectively recover and reuse or recycle than others. The total amount of materials for reuse and recycling was lower than anticipated in the initial resource mappings as some materials were in poorer condition than expected (e.g., wooden floorboards) and therefore, were less well suited for reuse or recycling.

Determining the potential market values and assessing the willingness of consumers to actually buy reused materials was a challenge and the data presented in Table 3 are therefore associated with relatively high uncertainty. Accurate assessment of the value of such materials is difficult due to the limited availability of market data as a reference. Also, the market data used for the assessment are based on national databases that covers the whole country (Denmark) and demand condition are most likely different on the studied island. As an example, the demolished buildings contained tiles that were originally locally produced on the island. These tiles were manufactured until 1997 when the local factory closed. They, therefore, have conservation value on the island when, for example, restoring historic fisherman's houses. However, the market for these tiles is very small and no market data were available.

Table 4 presents the results of the climate impact assessment (CO_2-eq. The results can primarily be used to identify hotspots where reuse is environmentally most worthwhile.

When evaluating the data from the utilisation rate in Table 2, the profit factor in Table 3 and the assessment of CO_2-eq reduction in Table 4, it is possible to conclude that bricks have the highest environmental and economic potential, even though the utilisation rate was only 68%. Tiles and wooden floorboards, on the other hand, have a higher CO_2-eq reduction potential and a higher profit factor, but the analysis nevertheless indicates that these materials are less attractive to reuse due to low number of tiles available and the low utilisation rate for wooden floorboards.

The CO_2 calculations also illustrate that there is a significant uncertainty associated with the exact amount of CO_2 that can be expected to be reduced from reusing the demolished materials. Different values were used for bricks, wooden floorboards and tiles to explore

Table 4
CO_2 assessment.

Material	Quantity	Process and reference	unit	C-intensity	Carbon footprint avoided from material reuse	
Bricks I	82 kg	EU 28 Facing brick, EN 15,804 A1-A3 Clay based (GaBi, 2019)	kg CO_2-eq/kg	0,24	t CO_2-eq	19.96
Bricks II	82 kg	Report value (Danish EPA, 2013)	kg CO_2-eq/kg	0,1036	t CO_2-eq	8.50
Granite stone	1.881 kg	EU-28: Tiles and slabs from natural stone (average) - Euroroc (A4) ts-EPD (GaBi, 2019)	kg CO_2-eq/ton	20,5	t CO_2-eq	0.04
Wooden beams	3.901 kg	EU-28: Solid construction timber (softwood) (EN15804 A1-A3) ts (GaBi, 2019)	kg CO_2-eq/m3	161	t CO_2-eq	0.63
Wooden floorboards I	20 kg	AU: Hardwood timber, kiln-dried, dressed, untreated (EN 15,804 A1-A3) FWPA (GaBi, 2019)	kg CO_2-eq/m3	489	t CO_2-eq	0.34
Wooden floorboards II	20 kg	US: Redwood Decking (California) CORRIM (GaBi, 2019)	kg CO_2-eq/m3	90,3	t CO_2-eq	0.06
Wooden floorboards III	1.864 kg	Report value, Massive Parquet – Germany (VTT 2013)	kg CO_2-eq/kg	2,94	t CO_2-eq	0.14
Tiles I	3.093 kg	CN: Stoneware tiles unglazed ts (GaBi, 2019)	kg CO_2-eq/kg	0,34	t CO_2-eq	0.04
Tiles II	3.093 kg	EU-28: Concrete roof tile (A1-A3) ts	kg CO_2-eq/kg	0,24	t CO_2-eq	0.03
TilesIII	3.093 kg	Ceramic Tile, Finland, Report value (VTT 2013)	kg CO2-eq/kg	0,61	t CO_2-eq	0.08
Internal doors with frames	40 pieces	Internal Door – Sweden (VTT 2013)	kg CO_2-eq/unit (50 kg / door)	18,45	t CO_2-eq	0.74
Total (max)					t CO_2-eq	21.3
Total (min)					t CO_2-eq	10.0
Total (average)					**t CO_2-eq**	**16,2**

*The wooden materials were exclusively biogenic carbon. Samples were used to estimate the m^3 and density of tiles, wooden floorboards and wooden beams. The tiles were 2 cm thick and weighed 1666.66 kg/m^3. The wooden floorboards were 3 cm thick and weighed 656.66 kg/m^3. The wooden beams were 850 cm × 13 cm × 26 cm and weighed 446.66 kg/m^3. An average granite block was estimated to weigh 99 kg and a door with frame 50 kg.

**The amounts of material reused from Table 2 were converted to kilograms using the same densities used to calculate the total CO_2-eq reduction.

uncertainty. Especially the assessment of the heaviest fraction (bricks) results in significantly different climate impact depending on which emission values that are used. However, as the purpose with the assessment was to identify hotspots to assist decision makers when determining which fractions to consider when planning demolition projects, the assessment nevertheless fulfils its purpose.

The potential for CO_2-eq reduction is likely to be overestimated as the calculations were carried out without a reference scenario and therefore, if these materials are reused, substitutes would need to be found for them in the current recycling system. Uncontaminated materials are typically recycled for road filling (bricks, stones and the like) and chipboard (wood). The CO_2-eq emissions from waste management activities, such as crushing bricks for road filling, are abated when materials are reused. However, virgin materials are used as substitutes in the existing recycling system, and emissions for these comprise about 8.5% of the total CO_2-eq reduction potential for this case study and the total CO_2-eq reduction is, therefore, approximately 22.2 tonnes of CO_2-eq.

4. Discussion: closing the loop

Feeding CDW back into the production and consumption system is one out of several pathways for closing the material loop and reducing the circularity gap identified by Aguilar-Hernandez et al. (Aguilar-Hernandez et al., 2019b). Reducing environmental impacts from construction and demolition requires a new attitude to the design of new buildings. However, as the lifetime of buildings is very long compared to those for consumer goods, it is very important to explore how the urban transformation of a vast number of existing buildings can be managed in ways that ensure that the materials and building elements from urban transformation projects are recirculated back into the construction of new buildings. The aim of this study was to explore practical ways to increase the recycling of materials in a semi-closed island economy.

4.1. Looping CDW back into the construction of new buildings

There was no existing marketplace on the island for reused construction materials and consequently no natural outlet for the recovered materials. An important aspect of the case study was exploring potential pathways for feeding CDW back into the construction of new buildings. Thus, the materials were looped back into new construction in the following ways:

- *Bricks* were donated to a start-up company called “Gamle Mursten Bornholm” (in English, Old Bricks Bornholm) following an application organised by the municipality. “Gamle Mursten Bornholm” is affiliated to a company on another Danish island that has developed a method for cleaning, handling and certifying reused bricks.
- *Wooden floorboards* were donated to a project called Wasteman run by the waste company BOFA. They were utilised in the construction of a new type of shed for the recycling stations on the island. These sheds demonstrate to the public and private users of a recycling station how CDW can be reused.
- *Wooden beams, doors with frames and tiles* were all given to demonstration projects. “Møbelfabrikken” used the doors and tiles as a part of their Experimentarium for a sustainable future and circular economy and “MaterialeVærket” used the wooden beams when renewing the recycling station in the city Pedersker, Bornholm.

There were several challenges in looping materials from the demolition projects back into the construction of new buildings. *First*, the relatively low volume, lack of uniformity and relatively inconsistent quality of the materials made it difficult to develop functional business cases. Therefore, the only material fraction that could form a basis for a viable (private) business model were the bricks. Bricks have a standard shape and size, which makes it easier to replace new bricks with used ones, and furthermore makes it possible to establish a certification scheme that can guarantee their quality to potential buyers. In comparison, wooden floorboards and doors vary in size and quality and are, therefore, more challenging to reuse in new constructions. *Second*, a lack of demand for reuse the construction materials was identified as a key challenge, primarily as the stakeholders involved considered the reuse and recycling of CDW to be expensive and cumbersome. Therefore, the materials were mainly donated to support the development of business opportunities or to the development of prototypes and demonstration projects.

The lack of existing marketplaces for CDW was a fundamental challenge for recycling and reuse. Therefore, the municipality was considering implementing both a digital marketplace and a physical marketplace. The digital marketplace could promote the sale of recovered construction materials and building elements prior to demolition and thereby reduce transportation and logistics costs. The physical marketplace is targeted materials that cannot be sold before demolition (such as low-volume materials). They will be stored and subsequently sold to smaller construction projects. The results of the project indicate that a high volume and good uniformity of CDW fractions are essential for viable business models. CDW fractions such as wooden floorboards, doors with frames and wooden beams proved difficult to market due to their low volumes, lack of uniformity and inconsistent quality. Bricks were the only fraction with a viable business case in the private market. The remaining materials could potentially have a business case if appropriate marketplaces (digital or physical) are established and if more houses underwent selective demolition than the three included in this project. Tiles could potentially be included in a business model like that for bricks, especially as the local demand for a certain type of locally produced tiles is high, but again the low volume is the main barrier.

4.2. Reducing CO_2 emissions

Selective demolition is one of the most important steps towards recycling CDW, as traditional demolition typically results in mixed fractions of crushed construction materials that are often most suited for backfilling (Pantini and Rigamonti, 2020b). Selective demolition uses alternative procedures for mapping, separating, and sorting materials for reuse, recycling, and recovery. In theory, selective demolition has several economic and environmental advantages compared to traditional demolition. Pantini and Rigamonti (2020b) used LCA to analyse the environmental benefits of selective demolition and found that they depended on the characteristics of the demolished buildings and the structure of the local markets for the reused and recycled materials. In this study of the demolished building on Bornholm, the potential CO_2 savings from selective demolition and subsequent reuse and recycling of the construction materials were calculated. The results indicate that there was a modest CO_2 saving, primarily from the recycling of bricks.

The experiences from the island of Bornholm are important, as the CO_2 emissions from transporting building materials contribute to the overall greenhouse gas emissions of a construction project. Overall, transportation accounts for 2.4–5.5% of the CO_2 emissions from construction (Sezer and Fredriksson, 2021). The island of Bornholm was a testing ground for embracing local cooperation and having a known buyer (Lyng et al., 2020), which added significant value. Thus, the results from Bornholm can be considered as an experience base. Larger urban environments could benefit from the experiences of Bornholm in transitioning to circular building practices by implementing selective demolition in which local actors across the value chain in a municipality or neighbouring municipalities collaborate with each other to address the circularity gap of the construction and demolition sectors.

4.3. Overcoming economic barriers to recycling of CDW

Economic costs are often considered a constraint to the implementation of selective demolition, as it requires additional time and management. The additional costs must be balanced against the potential economic gains arising from reduced waste management costs (Coelho and De Brito, 2011b). Typically, these potential gains rely heavily on the structure of the local or regional market for recycling and reuse of recovered materials and building elements. The study on Bornholm had several interlinked aims: to identify the additional costs associated with selective demolition, assessing the climate impacts and to create the market conditions for recycling and reusing materials from the three demolished buildings through the development of three different business models. The results indicate that a positive business case for selective demolition can be achieved if uniformity and quantity of the CDW is achieved.

The largest potential profit was associated with wooden floorboards, but large uncertainties are associated with the cost calculations. However, in terms of volume, the bricks constituted by far the largest fraction, and it is, therefore, more likely that it will be possible to establish a lasting business model based on the recirculation of used bricks. Traditional country houses on the island are often constructed from bricks using mortar. Newer brick houses (post-1960) are typically constructed with cement instead of mortar, which makes reuse more difficult. Since most of the country houses that are likely to be demolished within the next 10 years are like the three demonstration houses considered in the study, a viable business case for recycling bricks on the island not only appears realistic but was also demonstrated during the project. This lesson learned may be transferable to other rural areas undergoing the same type of urbanisation in which country houses are abandoned, as people move to urban areas, leaving behind old brick houses that are subsequently demolished.

One example of a similar attempt to reuse CDW is the creative area Musicon in Roskilde Municipality, Denmark. The builder and other engaged stakeholders are developing and testing solutions focusing on the reuse and recycling of CDW. In addition, the project-orientated approach and the creation of local alliances that challenge the take–make–dispose pattern (Norouzi et al., 2021) as well as the idea that building materials and surplus soil must be transported beyond the municipal boundary are crucial, as they contribute to a reduction of CO_2, costs and other environmental impacts related to maintenance, the purchase of building materials, demolition, and disposal. According to Lyng et al. (2020), early in a redevelopment project, the construction client must establish the level of ambition and objectives for the demolition project to ensure that reuse and recycling are a priority. Having a known buyer, e.g., the builder itself, is crucial when planning and executing demolition projects (Lyng et al., 2020). In Musicon and Bornholm, the builders used materials from their own demolition sites in subsequent projects or sold these materials. The advantage of this approach for a geographically delimited area is that it is easier to close the circularity gap between construction and demolition. It increases collaboration between projects that would not otherwise talk to each other and, thus, overcomes some of the challenges in terms of quality and documentation. A system-thinking approach based on a closed-loop system and a greater integration between stakeholders motivated by environmental awareness in the value chain is necessary. This makes sustainable practices easier to implement as a project would encompass the entire life cycle of a building (Munaro et al., 2020). Moreover, the construction value chain would not have to rely on comprehensive material dating sites matching sellers and buyers (i.e., digital material banks) or physical marketplaces with poor security of supply and quality.

4.4. Creating local networks to facilitate reuse and recycling of CDW

To support the creation of a circular value chain, a local network for private companies in the construction and demolition sectors was established, Green Construction Network Bornholm.

The main objective was to create a platform for sharing knowledge, identifying marketplaces and business cases for the recovered materials, and strengthening cooperation between different stakeholders in the value chain. Network meetings were used to disseminate the results of the demolitions and to share knowledge and experience on reuse and recycling of CDW. The municipality was able to increase the motivation for action, and some stakeholders chose to participate in one of the new projects on the island. Furthermore, the networking activities created links between organisations in the value chain. According to the participating companies, the networking has improved communication and knowledge-sharing within the industry and is a breeding ground for future collaborations.

One main challenge was to measure and evaluate the effectiveness of this activity, as building a viable network and sharing knowledge both take time and are difficult to measure quantitatively.

4.5. Bornholm as a testing ground

Deschenes and Chertow (2004b) argue that islands may function as ideal environments for studying and developing solutions to sustainability challenges due to their natural, geographical boundaries. The literature also describes that many islands over time experience increasing challenges associated with waste management (Elgie et al., 2021; Millette et al., 2019; Mohammadi et al., 2021) and that increased circular economy measures, such as increased recycling and improved waste management, is an important trajectory towards a sustainable development on the islands (Elgie et al., 2021). In the presented case study, the geographical boundaries of the island, Bornholm, Denmark, was used as system boundaries for the study. On the studied island, most CDW is managed locally by the waste company BOFA. However, there is a significant influx of new construction materials to the island and a flow of CDW out of the island. Compared to other cities or regions, however, an island economy is still relatively autonomous as the transportation of waste and recyclable materials in and out of the island has additional costs and constraints compared to non-island economies. Additionally, the stakeholder perspective is significantly different from that in non-island areas. The construction sector on the island is composed of a relatively limited group of companies that carry out most of the construction and demolition projects on the island. Companies not based on the island can, of course, also work on construction projects. Architects and building consultants based in the Greater Copenhagen area are also frequently used on the island. Establishing the Green Construction Network Bornholm, that was established during the projects to increase knowledge about circular practices in the construction and demolition sectors, relied on existing relationships between the stakeholders involved. The island perspective thereby significantly enhanced the local network of companies. Finally, the municipality played an important role throughout the project, acting as a facilitator (Christensen, 2021) and anchor point for communication and collaboration between construction companies, the waste company and knowledge institutions. Its ability to fulfil this role was also influenced by the physical boundaries of the island where interpersonal relations are likely to influence the possibility of success or failure significantly more than in larger open systems.

These conditions made it possible to test how the material loop in construction and demolition could be closed to reduce the circularity gap. The contextual conditions limit the generalisation of the results to other geographies, because networks and knowledge exchange between relevant stakeholders will be significantly different in larger urban environments and because the complexity of material flows in and out of the area will be larger. However, as discussed above, urbanisation may also lead to a flow of used construction materials from abandoned rural areas to urban areas. Rural and semi-urban areas often have some of the characteristics that define an island, such as limited flows of materials in and out, local networks of companies that collaborate and rely on interpersonal relationships, and local recycling of demolition waste and building elements. The results from this case study may, therefore, translate better to such contexts.

Based on these reflections, this article suggests that islands (like Bornholm) may function as interesting testing grounds for exploring pathways to a circular economy. The work also has potential for informing solutions in remote rural or semi-rural areas. This suggestion corresponds with research conducted by Eckelman and Chertow (2009), who used material flow accounts to study waste management solutions on Oahu, Hawaii, and by Noll et al. (2019b), who used a mixed methods approach in studying the recycling of CDW on the Greek island of Samothraki.

5. Conclusion

Using a mixed methods approach based on a case study, the article explored the potential of and barriers to the creation of a circular value chain in the construction and demolition sectors. Practices and procedures for recirculating CDW from three demonstration cases were developed, tested and demonstrated, with a focus on resource mapping, selective demolition and the creation of local markets for targeted construction materials. The economic, environmental (CO_2) and practical potential of and barriers to the recirculation of bricks, wooden floorboards, wooden beams, doors with frames and tiles were explored. Based on the results, we conclude that positive business cases appear to be possible for selective demolition, provided that local markets for reused construction materials are established at the same time. Looking at specific fractions of construction materials, the study indicates that uniform products such as bricks (if these are sourced from houses constructed with mortar) are more likely to form the basis of viable business models in emerging markets for reused CDW. For the other materials considered in this study, their low volume, lack of uniformity and relatively inconsistent quality made it challenging to develop functional business cases. Whether it would be possible to expand such business cases to include other types of construction materials is likely to depend on volumes and would require further research covering more than three demolition projects.

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Declaration of Competing Interest

The author declares that they have no conflict of interests. The funders had no role in designing the study; in the collection, analyses or interpretation of data; in the writing of the manuscript, or in the decision to publish it.

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