Assessing the circular re-design of prefabricated building envelope elements for carbon neutral renovation

Ivar J.B. Bergmans[1], Silu Bhochhibhoya[1], Johannes A.W.H. Van Oorschot[1*]

* Corresponding author, john.vanoorschot@zuyd.nl
1 Zuyd University of Applied Sciences, Heerlen, The Netherlands

Abstract
Buildings and the construction industry at large are significant contributors to the catastrophic climate breakdown. The built environment is responsible for 37% of the total global carbon emission, of which about a third arises from the energy used to produce building and construction materials, usually referred to as embodied carbon. One of the key strategies to reduce the environmental impact of buildings is to significantly improve their energy efficiency, which is referred to as deep renovation. Prefabricated building envelope elements intended to prevent heat loss through the building envelope are considered a key deep-renovation technology. Connecting prefabricated elements to a building reflects a potential stream of waste if applied linearly with severe negative environmental impact in terms of natural resource depletion and exposure to pollutants. This article reports on a quantitative Design for Disassembly (Dfd) indicator to assess future recovery potential and, subsequently, its impact on embodied carbon emission of the circular redesign of three different prefabricated building envelope elements. Although none of the redesigned elements are yet considered 100% circular, the development of these three prefabricated building envelope elements showcases that the environmental impact can be substantially reduced following a well-structured and dedicated innovation process. The reduction of the environmental impact is indicated by lower quantities of embodied carbon up to 50% and an improved design for disassembly, reflecting a higher reuse potential of building materials and components. Several limitations and directions for further research were identified to advance the development of circular, prefabricated deep-renovation building envelope elements.

Keywords
deep renovation, circular design, carbon-based design, design for disassembly, embodied carbon

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1 INTRODUCTION

The depletion of raw materials, the high embodied energy and embodied carbon levels, and the high amount of wasted materials in the construction sector in Europe require a transition from linear to circular material use. Buildings are responsible for up to 40% of global greenhouse gas (GHG) emissions, and 15% of global climate emissions come from new construction (Bajzelij et al., 2013; Joensuu et al., 2022). Moreover, 50% of all extracted materials are attributed to buildings (IPCC, 2014; United Nations, 2015; Abouhamed & Abu-Hamd, 2021; Tokede et al., 2022), and according to the European Commission (EC), construction waste accounts for 25% to 30% of all waste generated in the EU (IPCC 2014, EMF, 2015).

One of the problems with buildings' environmental impact is the limited service life, i.e. the period of time a building is in use compared to its actual technical lifespan, meaning the physical existence of a building (Grant & Ries, 2013; Rauf & Crawford, 2015). Many buildings are demolished or substantially altered even though they are still functioning well from a technical point of view (Joensuu et al., 2021). Previous studies showed that the decision to demolish and replace a building can be related to urban growth, causing pressure to increase the floor area ratio, inflexible technical and spatial design to adapt to changing functional needs or too high renovation costs. To summarize, the decision to demolish is, in many cases, the result of failure to adequately meet the demand of the intended end users and thus independent of the technical condition of a building (Huuhka & Lahdensivu, 2016; Joensuu et al., 2021). A study by Marsh (2016) showed that extending a building's lifespan reduces the environmental impact significantly by 29%, 38% and 44% for a lifespan of 80, 100 and 120 years, respectively, compared to an average lifespan of 50 years.

The concept of circular economy (CE) is considered an alternative to current environmentally destructive linear economic models and key to slowing down climate change. The transition towards full circular building practices ultimately helps decrease buildings' environmental footprint and consumption of raw materials. CE can be considered a step to implement restorative and regenerative approaches in which emissions, resource use, and waste generation are reduced through the CE principles of narrowing (efficient resource use), slowing (temporally extended use), and closing (cycling) current and future resource loops (Bocken et al., 2016; Geissdoerfer et al., 2017). In essence, a circular solution is based on 100% renewable energy, and all materials are part of infinite closed loops with the lowest value loss.

Prefabricated building envelope elements, considered a core technology of the EU renovation wave, play an essential role in improving a building's energy efficiency and prolonging its service life (Saheb, 2016). Prefabrication is a manufacturing process that takes place in a specialized facility where various materials are joined together to form a component of the final installation procedure within a controlled environment (Zairul, 2021). Prefabrication is an essential aspect of circular design strategies as it increases the reuse possibilities of building materials and products in modularity (Kuusk et al., 2022). This helps to apply CE in conventional buildings with standard measures and to close the supply chain loop and achieve waste reduction (Minunno et al. 2018). Because of this potential, prefab construction products such as prefabricated building envelope elements have gained growing interest in both science and industry. Bitar, Bergmans & Ritzen (2022) emphasized in their study that assessing Life Cycle Energy Performance (LCEP) is becoming increasingly relevant, accounting for all the operational and embodied carbon exposure during the entire lifespan of a building. Their key finding was that a substantial LCEP is possible close to 100% for a zero-energy building retrofit with circular prefabricated building elements. In a comparative study, Juaristi et al., (2022) showcased that timber-based façades have the potential to substantially reduce the carbon footprint relative to façades constructed with inorganic construction materials (Hildebrand, 2014). Moreover, these authors calculated that the carbon footprint can be further reduced if components are reused in a second life cycle depending on the careful selection and design of construction materials and connections.

However, the application of CE indicators in isolation will not lead by default towards 'systemic circularity' and a reduced environmental footprint. Systemic circularity refers to the idea that a circular design depends on multiple interconnected indicators which influence each other in a continuous and circular manner. Improvement of a single component may adversely affect other parts within this complex system of technical, environmental, social, business, legislative, economic, and innovation impacts (Kubbinga et al., 2018; Antwi-Afari, Ng & Chen, 2022). For example, it has been found that applying DfD strategies to facilitate material reuse can lead to increased initial impact due to greater energy and resource consumption (Roberts et al., 2023). Bitar et al., (2022) emphasized that future research should address the trade-off between embodied carbon and DfD. This particularly calls for empirical studies validating 'systemic' frameworks assessing circularity in the construction industry (Attia and Al-Obaidy, 2021; Lam et al., 2022). Juaristi et al., (2022) further suggest that future works should be on the effect of ageing on reclaiming and reusing construction materials and its impact on efficient material usage, waste, and environmental footprint.

This article, therefore, attempts to contribute by answering the following research question:

Assuming the current system conditions, i.e. value proposition and business model associated with prefab façade elements, remain unchanged, what is the environmental impact in terms of the embodied carbon of circular redesigned prefab building envelope elements?

As an essential key deep-renovation technology, prefabricated building envelope elements improve the energy efficiency of buildings by preventing heat loss through the building envelope. Connecting prefabricated building envelope elements to a building reflects a potential waste stream if applied linearly with severe negative environmental impact in terms of natural resource depletion and exposure to pollutants. This article shows the impact of the circular redesign of three different prefabricated building envelope elements. It reflects on the environmental impact of building envelope elements from three cases associated with the life cycle performance of products and buildings. To gain insight into the life cycle performance, three baseline scenarios from selected partners in three Northern countries are compared with developed designs of more circular variants. Embodied carbon and disassembly potential indices are assessed to evaluate the environmental impact and level of circularity of building envelope elements. Assessing the circular performance and breaking it down into key indicators, such as embodied carbon (cradle-to-gate) and disassemble potential, provided insight into how design choices and material choices influence the life cycle performance of building elements. In this way, suppliers and designers gain insight into how they can influence the environmental footprint of their prefabricated building envelope elements. In sum, this article contributes in the following ways: first, it showcases how the environmental impact of material-intensive construction elements can be substantially reduced by following an eco-design approach and applying circular design strategies. Second, it ties together theories about circular design, life cycle assessment, and technological innovation to adhere to the EU Green Deal.

This article is structured as follows. The following section, section 2, discusses the background of the design strategies being applied in this study to reduce the environmental impacts of prefabricated building envelope elements. Section 3 addresses the methodological approach of our study, followed by the case studies presented in section 4. Section 5 elaborates on the research findings. Finally, the last section discusses the scientific and managerial contributions and possible directions for future research.

2 THEORETICAL FRAMEWORK

This section presents the theoretical framework for the prefabricated building element for carbon-neutral renovation. To measure the level of circularity and the carbon emission of the prefab building envelope element, two important indicators are considered: the Design for Disassembly (DfD) index and embodied carbon.

2.1 PREFABRICATED CIRCULAR BUILDING ENVELOPE ELEMENTS FOR CARBON-NEUTRAL RENOVATION

Prefabricated building envelope elements have been introduced to step up the pace of building renovation to achieve European Union (EU) climate change policies for 2050, i.e. industrial building and modularity and related technological innovations are at the core of boosting the renovation wave (Renz & Zafra Solas, 2016; Saheb, 2016). The application of prefab elements aligns with industrial building principles to raise efficiency by rationalizing the construction process by adopting production technologies and methods found in highly industrialized mass-production industries like automotive. Supported by various national and international innovation programs, such as the EU Horizon and Interreg programs, the development of prefabricated façade technologies industrial has gained growing attention (Barbosa et al., 2017; Bertram et al., 2019; Hofman et al., 2009). Across Europe, multiple prefab façade systems have been developed, validated, and demonstrated, and accordingly, complementary investments have been made to tune the design process, element production, and plug-and-play installation on-site.

However, beyond efficiency gains, the full potential of prefab façade elements has not yet been met, and substantial improvements can be achieved to improve the level of sustainability, circularity, and customization in a way that does not increase project risks, complexity, and building costs of renovation projects (Juaristi et al., 2022; Lam et al., 2022). The level of circularity of prefab façade elements can be substantially improved by facilitating access to individual components of the product system, thereby facilitating refurbishing, reuse, and recycling (Chung et al., 2014; Kimura et al., 2001; Ma & Kremer, 2016; Okudan Kremer et al., 2013). This is especially relevant for components that age more rapidly than parts they interface with or that improve faster, for example, due to higher innovation clock speeds, leading to an opportunity for modular upgrades of the system. As indicated by previous studies, the two most prominent indicators to take into consideration are the design for disassembly index and embodied carbon to subsequently assess the potential to replace, reclaim, and reuse valuable construction materials and reduce the overall environmental footprint (Juaristi et al., 2022; Bitar et al., 2022).

2.2 DESIGN FOR DISASSEMBLY INDEX

In line with the essence of a circular economy, it is key to close material loops by being able to retrieve materials with a minimal loss of quality for the purpose of reuse (EMF, 2015). Thus, to ensure the multi-cycle use of prefabricated building envelope elements and applied components, these elements should be able to be subtracted from the building and dismantled without loss of quality (Potting et al., 2017). To effectively close material loops specific to the building industry, various R-strategies can be applied (see Figure 1). The three most essential R-strategies include one-on-one reuse of building elements, remanufacturing reclaimed materials into new applications, and recycling materials to produce new products. Prioritized by impact, a reuse strategy is preferred over re- or downcycling as fewer natural resources are required with a minimum loss of value.

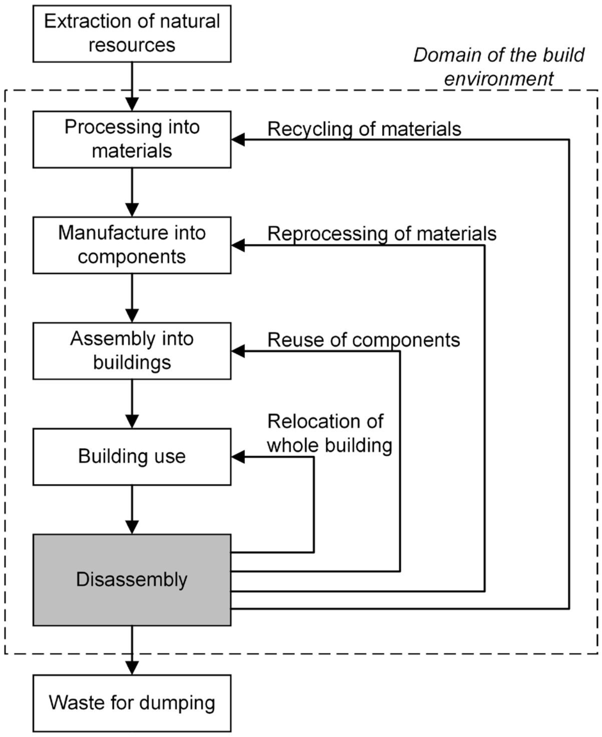


FIG. 1 R-Strategies for closing the material loop (Chini & Florida, 2001)

When closing material loops based on R-strategies, it is essential that materials and products can be easily mined from existing buildings in which they are temporarily stored. It is, therefore, of utmost importance that buildings are Designed for Disassembly (DfD). By default, in closing loops, one should not only consider end-of-life scenarios but also take into account the origin of materials and consider which materials can be reused in a new product design.
The higher the disassembly potential of a building, the easier it is to retrieve products for reuse rather than downcycling and recycling. Reusing mined materials not only contributes to efficient material consumption in the construction sector but intrinsically reduces the carbon emission associated with (re-)processing and transportation (Cottafava & Ritzen, 2021; Lam et al., 2022).
In sum, DfD in the construction sector ties together value retention, efficient material use, and carbon emission reduction.

The DfD index is defined as the degree to which 'objects' can be dismantled at different levels so that the object can retain its function and high-quality reuse can be realized (Durmisevic, 2006). To determine what the above-mentioned 'objects' are and to what level of detail the calculations should be done, the authors refer to the diagram depicted in Figure 2, adopted from Durmisevic (2006), showing the subdivision of different building levels. For this study, prefabricated building envelope elements are considered a part of the façade and, subsequently, a key subsystem of a building. Design for disassembly focuses on the potential to take apart the building envelope elements in their essential construction products and materials. Further reuse of these products and materials is beyond the scope of this study.

A methodology indicating the disassembly potential should assess the extent to which a building system and the products and materials applied in this system can be disassembled. The technical design of a building system, especially oriented on the connections between products and materials, has the most influence on disassembly. Besides the technical design of a building element, it has been suggested that process, financial and human capital aspects could also affect the disassembly potential (Akinade et al., 2017; Van Vliet et al., 2021). The assessment of the DfD index is based on the technical disassembly potential of the connection (DPc), which reflects the ability to disassemble the building envelope element as a whole, and the compositional disassembly potential (DPcp), which reflects how easily a prefabricated building envelope element can be disassembled.

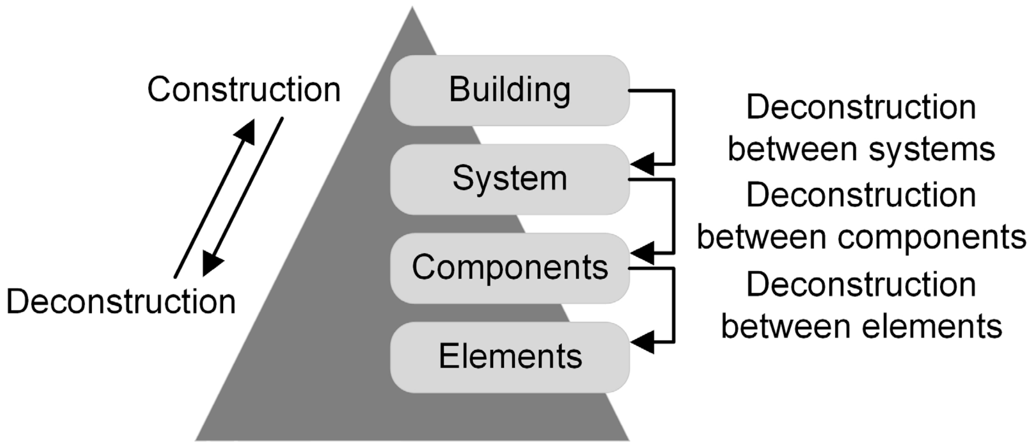


FIG. 2 Hierarchy of building materials being applied in buildings (adopted from Durmisevic, 2006)

2.3 EMBODIED CARBON

Embodied carbon emission is associated with the energy consumption during extraction of raw materials, transportation, manufacturing, assembly, and installation all the way to disassembly, deconstruction, and decomposition (Ritzen et al., 2016; Bhochhibhoya et al., 2016). Hammond & Jones (2011) define embodied carbon as *"the total carbon released from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate."*

Embodied carbon has gained increased attention recently (Pomponi & Moncaster, 2016; Dutil et al., 2011). The relative importance of embodied carbon associated with building materials and elements is increasing as the GHG emission in the operational phase is substantially reduced due to significant progress in creating energy-efficient buildings (Monaha & Powell, 2011; Sartori & Hestnes, 2007; Passer, Kreiner & Maydl, 2012). However, additional energy is often required for manufacturing and transportation of the increased levels of materials and additional technologies for energy-efficient buildings (Monahan & Powell, 2011).

Much research has been conducted to investigate various strategies to reduce the embodied carbon of buildings (Akbarnezhad & Jianzhuang 2017). These strategies are divided into five categories: (1) low-carbon materials (Hammond & Jones, 2008); (2) material minimization and material reduction strategies (Akbarnezhad & Moussavi Nadoushani, 2014); (3) material reuse and recycling strategies (Xiao et al., 2007); (4) local sourcing and transport minimization (Gonzalez & Navarro, 2006); and (5) construction optimization strategies (Guggemos & Horvath, 2005). Related to the three cases in this article, this research focused on categories 1, 2, and 3 because all collected materials for redesigning the prefabricated modular building element were calculated based on these three categories.

In line with the definition of Hammond & Jones (2011) and following the same methodological approach as Bitar et al., (2022), the embodied carbon will be calculated through a cradle-to-gate assessment.

3 METHODOLOGY

3.1 THE ROLE OF CIRCULAR ASSESSMENT IN THE DESIGN PROCESS

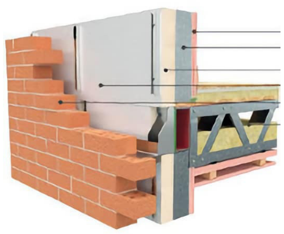
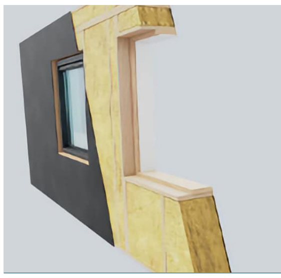
To improve the level of circularity of existing prefabricated building envelope elements, a design science approach was followed that encompasses a reflective design and analysis process consisting of succeeding stages and feedback loops (Roggema, 2016; Sipahi & Kulozu-Uzunboy, 2021; Bitar et al., 2022). The basic stages of the process are followed under the guidance of eco-design strategies, methods, and tools. Eco-design refers to the systematic integration of environmental considerations into the (re-)design process without compromising performance, quality, and cost (Knight & Jenkins, 2009; Keiller, Clements & Charter, 2013; Marques, et al., 2017). Eco-design principles concur with the circular design techniques including design for disassembly (Durmisevic, 2018; Cambier et al., 2020; Eberhardt et al., 2022) and carbon-based design (Häkkinen et al., 2015; Cottafava & Ritzen, 2021; Sobota et al., 2022).

The design process followed in this study consisted of five key stages:

1. Pre-design stage specifying the design challenge and outcome
2. Baseline assessment of environmental impacts associated with the product of its entire life cycle
3. Selecting circular design strategies
4. Circular redesign process: redesigning under the guidance of circular design strategies to reduce the carbon footprint
5. Post-design evaluation of environmental impact; comparing initial and revised design

During the pre-design stage, three prefabricated building elements for the deep-renovation market were selected for circular redesign. As a first selection criterium, only prefabricated building envelope elements for the deep-renovation market were taken into consideration, which have been applied beyond their demonstration status and for which the producers have the ambition to improve the level of circularity and lower the environmental impact. Secondly, we only focused on EU countries with an established market for panelized construction. See also Table 1.

TABLE 1 Case description

Case	Country	Market served	Key driver
Timber frame non-structural building envelope element 	Estonia	Multi-family housing	Governmental support to renovate apartment buildings (social housing) at a large scale with prefab timber frame elements.
Prefab light gauge steel element 	Ireland	Single family housing	Off-site construction – with prefab light gauge steal panels - is considered a fast moving field in the UK and Ireland and recently also considered in the deep-renovation market.
Timber frame non-structural building envelope element 	Netherlands	Single and multi-family housing	Seen as a key technology to renovate terraced housing stimulated by the Dutch Stroomversnel-ling program.

During the second stage, a baseline environmental impact assessment was conducted based on the circular redesign ambitions identified during the pre-design stage. This included the assessment of the embodied carbon emission associated with the cradle-to-gate production of the prefab façade elements (Cao, 2017). The design for disassembly index was calculated to assess the potential reuse of materials and components. During the third stage, the circular design strategies were selected. Following the circular redesign ambitions and the baseline assessment, two circular design strategies were applied: design for disassembly (Durmisevic, 2006; Cambier et al., 2020; Eberhardt et al., 2022) and carbon reduction strategies (Akbarnezhad & Jianzhuang Xiao, 2017). Subsequently, during the fourth stage, the actual redesign of the prefab building envelope elements took place. The output of the design stage was evaluated following the same methodologies as applied in Stage 2 to compare the baseline façade elements with the revised design. If the intermediate evaluation of the conceptual design was not in line with the circular ambitions set in Stage 1, the cycle of design and evaluation was repeated. In the next section, we provide a detailed description of the assessment methodology being applied during post-design evaluation.

3.2 ASSESSMENT METHODOLOGY

The study reflects on the technical and environmental issues when analysing the level of circularity of prefabricated building envelope elements. Within the technical analyses, material separability rate, usage level of recycled products and technical feasibility are related to the disassembly potential. The environmental impact is indicated by embodied carbon. The calculation of the environmental impact is not connected to the disassembly potential, but the balance between both indicators is considered and reflected during the process. This study considered the cradle-to-gate boundary based on the Inventory of Carbon and Energy ICE (Hammond, 2011).

This means that design scenarios are assessed on the basis of calculating the disassembly potential index and embodied carbon, and improved scenarios can be developed based on these calculations. The following subsections describe how the DfD index and embodied carbon were subsequently calculated.

3.2.1 Design for Disassembly Index

The essence of the design for disassembly strategy is to close material loops by increasing the reuse potential of elements and materials. In the prefabrication of building envelop elements, the impact of DfD is crucial to the renovation wave that Europe provides. The disassembly potential, therefore, must be assessed on the element and material level.

The methodology adopted to assess the DfD index was based on Alba Concepts (van Vliet, van Grinsven, Theunizen, 2022) and ISSO assessment (ISSO, 2021). This method assesses the DfD index of the building envelope elements by assessing the connections within the prefabricated building envelope element (Bitar, Bergmans, Ritzen, 2021).

The disassembly potential of the connection (DPc) assesses the ability to disassemble the element or material at the end of its building life. The following factors are part of the disassembly potential of the connection: type and accessibility of the connection. The disassembly potential of the composition (DPcp) assessed how easily an element can be disassembled from the building envelope. The following factors are part of the disassembly potential of the composition.

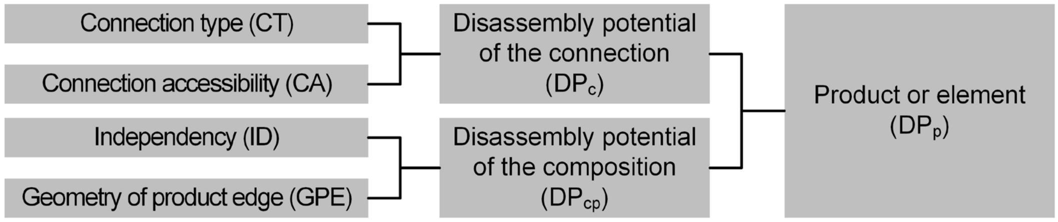


FIG. 3 Step-by-step plan for assessing the disassembly potential of the element.

Figure 3 shows the step-by-step plan for assessing the disassembly potential of the element.

The formula for assessing the disassembly potential of the connection of material n or element n (end-of-life scenarios):

$$\mathrm{Dpc_n} = \frac{2}{\frac{1}{\mathrm{CTn}} + \frac{1}{\mathrm{CAn}}} \qquad [1]$$

The formula for assessing the disassembly potential of the connection and the composition of material n (maintenance scenarios):

$$\mathrm{DPT_n} = \frac{4}{\frac{1}{\mathrm{CTn}} + \frac{1}{\mathrm{CAn}} + \frac{1}{\mathrm{CRn}} + \frac{1}{\mathrm{FCEn}}} \qquad [2]$$

Where:

- DPCn = disassembly potential of the connection (material or element n).
- DPTn = total disassembly potential of the connection and the composition (material n)
- CTn = type of connection of material or element n.
- CAn = accessibility of the connection of material or element n.
- CRn = independency of material n. (crossings)
- FCn = edge geometry of material n. (form containment)

TABLE 2 Scoring matrix disassemble potential (ISSO, 2021)

Type of connection		Score
Dry connection	Loose (no fastening material)	1.00
	Click connection	
	Velcro connection	
	Magnetic connection	
Connection w. added elements	Bolt and nut connection	0.80
	Spring connection	
	Comer connection	
	Screw connection	
	Connection w. added edlments	
Direct integral connection	Pin connection	0.60
	Nail connection	
Soft chemical bond	Lute connection	0.20
	Foam connection	
Hard chemical bond	Glue connection	0.10
	Pouring joint	
	Welded connection	
	Cement bound connection	
	Chemical anchors	
	Hard chemical bond	

Accessibility of connection	Score
Freely accessible	1.00
Accessible with actions that don't cause damage	0.80
Accessible with actions causing repairable damage	0.40
Not accessible – irrepairable damage to object	0.10

Form containment	Score
Open. no inclusion	1.00
Overlap	0.80
Closed. (one side)	0.20

Crossings	Score
No piercing	1.00
Piercing by one or more objects	0.40
Full integration of objects	0.10

As shown in Table 2, a dry connection scores 100% (1.0), and a hard chemical bond scores 10% (0.1). The accessibility of the connection scores 100% (1.0) if it is freely accessible and 10% (0.1) if it is not accessible and causes irreparable damage to objects. The form containment scores 100% (1.0) if there are no obstructions in removing the materials and scores 20% (0.2) if the material is closed on one side. The crossings score 100% if there are no crossings of different materials within the element with different lifespans and score 10% with full integration of materials or elements from different layers.

This study assumes that the building envelope elements are disassembled at the end of the building's life cycle. For this, it is required that parts with a shorter technical life cycle can easily be replaced (cladding), and therefore, the DfD index for these materials was calculated.

3.2.2 Embodied carbon

Embodied carbon is considered among the most accepted scientific indicators to assess the environmental dimension of circularity (Antwi-Afari et al., 2022). In line with the embodied carbon definition of Akbarnezhad & Jianzhuang (2017), the first three strategies were applied in this study (see section 2.3). For calculating the embodied carbon, the ICE database 2011 was used per building material (cradle-to-gate). The ICE database was developed by Hammond and Jones from the Sustainable Energy Research Team (SERT) affiliated with the University of Bath. The database includes LCA information and provides the ECO_2 ($kgCO_2$) on the most common building materials or components. To calculate the embodied carbon of prefab building envelop elements, a bill of materials has to be constructed, which provides insight into the amount and density of materials being applied. As an important intermediate step, the amount of reused material needs to be deducted from the share of virgin used materials. The embodied carbon was calculated for a functional unit of 1 m^2 to compare the three redesigned building envelope elements.

The formula to determine the embodied carbon of the element is:

$$EC0_{2n} = CO2Vn * Dn * V1n \quad [3]$$

Where:

- $EC0_{2n}$ = Embodied carbon per material. (kg)
- CO2Vn = Embodied carbon of the virgin material (ICE database cradle to gate).
- Dn = Density per material (kg/m^3)
- V1n = Volume per material (m^3) per m^2 façade area.

Note that the embodied carbon of the building envelope element per m^2 façade area is the summation of the embodied carbon per material.

4 DESCRIPTION OF THE BUILDING ENVELOPE ELEMENTS

For this study, three demonstrator cases were selected to analyse different types of prefabricated building envelope elements in Northern Europe within the same climatic zone, i.e. a temperate zone, with various materials and designs of the façade system. The three selected building envelope elements are considered mature technologies with relevant product certification. The cases were selected on the potential of closing material loops and reducing the environmental footprint. See Table 3 for an overview of the cases with respect to the design strategy followed and an indication of the key components of the baseline and circular improved building envelope elements. For each demonstrator case, the baseline is indicated, and subsequently, a description of the circular improved design is provided. All three circular redesigned building envelope elements have been tested in mock-ups and/or applied in demonstration projects in the national context.

4.1 DUTCH CASE

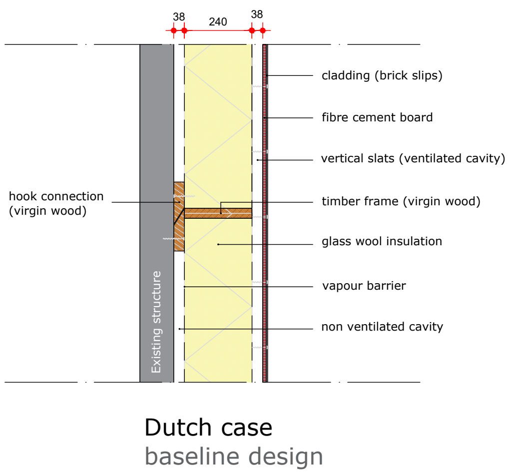


FIG. 4 Baseline set-up of the Dutch element

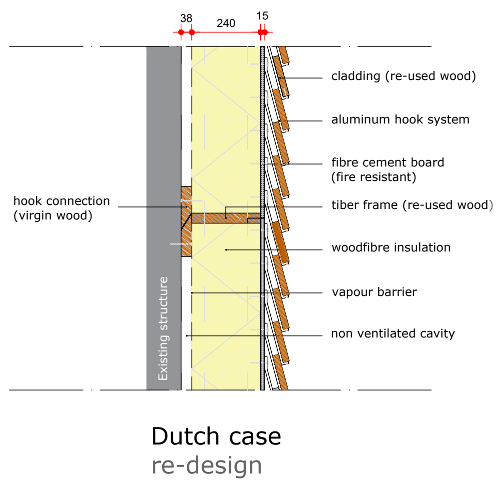


FIG. 5 Redesign set-up of the Dutch element

For the Dutch case, a Structural Insulated Panel System (SIPS) was selected, which can be applied both in newly built and deep-renovation projects, see Figure 4. The redesign (Figure 5) of the building envelope element can be best described as a demountable prefabricated plug-and-play insulation application mounted in front of an existing cavity wall, a substantial part of which consists of materials mined from donor buildings. The building element consists of an insulated timber element and structure, an air cavity, and an additional external wooden cladding. For the timber components, pine wood purlins were mined from a donor building, transported to the factory, and then purified and processed to be reused in the building envelope element. However, not all parts of the building envelope element, especially the parts that contribute to structural and fire safety, were constructed with reused materials, as this would require additional product certification. To avoid the use of chemicals and/or paint to improve durability, the cladding material underwent modification by heat treatment for ageing control (Esteves et al., 2008). The building element showcases a high reuse potential after its initial life cycle. The prefabricated external building element is fastened with screws applying a geometric plug-and-play connection. Also, the components applied in the layered design of the building envelope element are fastened with screws. The cladding is mounted with a hook system, avoiding the use of glue or other chemical connections and allowing the replacement of single components during maintenance over the life cycle of the element.

4.2 ESTONIAN CASE

The Estonian case also involves timber-based SIPS panels. The baseline elements consist of a timber frame-based insulation system with mineral wool insulation and cladding. For a schematic representation of the baseline, see Figure 6.

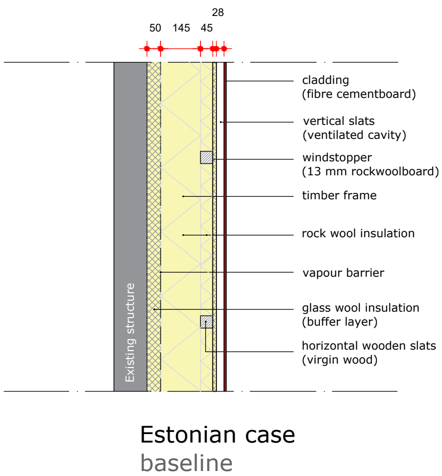


FIG. 6 Baseline set-up of the Estonian element

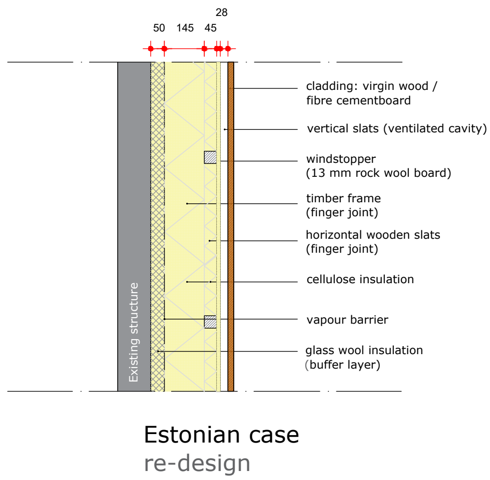


FIG. 7 Redesign set-up of the Estonian element

The focus of redesigning the building envelope element (Figure 7) was increasing the use of biobased or remanufactured materials. Also, the disassembly potential was taken into account for the whole building envelope element and its individual components. The bare structure of the insulation element consists of a 45x145 mm, high-quality (C24) timber frame (virgin material). Horizontal wooden slats (45x45 mm and 45x95 mm) were replaced by finger-jointed lumber to increase the use of remanufactured materials. Nail connections were used to form the bare structure because of higher shear strength compared to a screw connection. In contrast, screw connections can be used for horizontal wooden slats and ventilation gap wooden slats, which allow easier disassembly. Because of fire regulations, rockwool insulation was used instead of the preferred cellulose insulation with a lower carbon footprint. Rockwool board is used as a wind stopper because of its hygrothermal properties (high thermal resistance and vapour permeability). Alternatives like gypsum boards or timber-based boards (e.g., OSB, plywood) were not considered as these materials perform less in terms of thermal resistance and are more sensitive to mould growth. Fibre cement boards are used for façade cladding because of the long service life and limited maintenance. See Figure 7 for the detailed design of the building envelope element.

4.3 IRISH CASE

The Irish baseline consists of a panel system intended for the newly built inner leaf only and repurposing it as a closed panel finished system applicable to the circular renovation market. The baseline building envelope element is being developed from an existing light-gauge steel framing construction system, which is typically insulated with conventional quilt and plastic insulation board and finished with traditional brick or block outer leaves or rendered cement boards. See Figure 8.

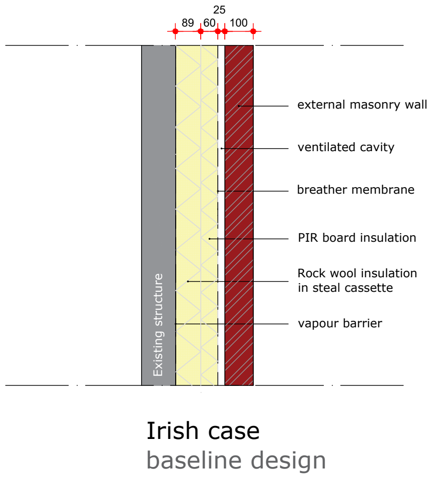


FIG. 8 Baseline set-up of the Irish element

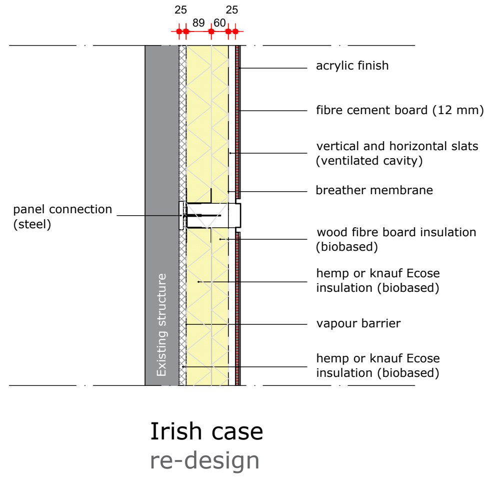


FIG. 9 Redesign set-up of the Irish element

Three main alterations were introduced to improve the level of circularity of the baseline. First, reducing the structural and non-structural steel contents within the panel connection and framing to improve material efficiency and reduce the use of virgin non-renewable materials and resources; second, maximizing the extent of biobased materials and insulation application to reduce the carbon footprint; and third, off-site assembly of all components with reversibility aiming at multi-cycle circular solutions of building materials and components.

In the absence of a developed urban mining context or capacity, it was decided to focus on biobased materials, thus supporting the non-technical circularity cycle as well as associated material benefits — such as low embodied carbon. Following a detailed review of available biobased materials in the Irish market — which highlighted the limited range and notably a lack of Irish or even UK manufacturing of biobased products —, the following solutions were proposed. To replace glass or mineral wool, the insulation between the 89 mm studs will be replaced with a biobased quilt such as hemp or a recycled or enhanced conventional product such as Knauf Ecose. The rainscreen, consisting of a PIR board, is replaced by a biobased wood fibre board such as Pavatex, Gutex, or Steico. These products were envisioned to also contribute to reducing the carbon footprint of the building envelope element and enabling the R-strategies, notably re- cycling. Hierarchical DfD has been a key principle and design strategy in the circular building envelope design, seeking to ensure that the element can be installed and removed in its entirety for potential re-stage application in its entirety and on a wall element level as well as disassembly at lower component and product/ material level. For an overview of the detailed design of the building envelope element, see Figure 9.

5 RESULTS

In this chapter, the improved circular performance of the three different prefabricated building envelope elements is demonstrated based on embodied carbon reduction and the improvement in the design for disassembly potential. The level of circularity is assessed based on both indicators separately. The progression shown per indicator is the difference between the original baseline design and the redesign for each of the three cases separately.

5.1 DISASSEMBLY POTENTIAL

The disassembly potential of the prefabricated building envelope elements indicates the reuse potential of components and materials. Based on that, the baseline building envelope element is compared per case with the redesigned prefabricated building envelope element. The total score depends on the type of connection and the accessibility of the connection in the end-of-life scenario.

The DfD index was calculated for the baseline and the redesigned building envelope element for a) disassembly of the building envelope element and b) disassembly of the materials within the building envelope element.

5.1.1 Dutch case

Table 3 shows the scoring matrix of the disassembly potential of the baseline design of the Dutch case. The results show that the disassembly potential on the element level and material level of the baseline design are 0.83 and 0.74, respectively, whereas the disassembly potential on the element level of the redesigned building envelope element is 0.95 and 0.85 on the material level (shown in Table 4).

TABLE 3 Scoring matrix disassemble potential baseline design

		Score	
Element level		**0.83**	**Disassambly potential**
1. Prefab 1e skin (structure)		1.00	
Connection (existing construction)	Type of connection	1.00	Dry connection
	Accessibility of connection	1.00	Freely accessible
2. Cladding material		0.70	
Connection (wooden slats)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
3. Wooden slats		0.80	
Connection (wooden structure)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
Material level		**0.74**	**Disassambly potential**
1. Cladding material		0.70	
Connection (existing construction)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
2. Wooden slats		0.80	
Connection (wooden structure)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
3. Wooden structure (HSB)		0.73	
Connection (finishing material)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.40	Accessible with actions causing repairable damage
Connection (insolation material)	Type of connection	1.00	Dry connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
Interconnection	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage

TABLE 4 Scoring matrix disassemble potential redesign

		Score	
Element level		**0.95**	**Disassambly potential**
1. Prefab 1e skin (structure)		1.00	
Connection (existing construction)	Type of connection	1.00	Dry connection
	Accessibility of connection	1.00	Freely accessible
2. Prefab 2e skin (Cladding)		0.90	
Connection (wooden slats)	Type of connection	0.80	Connection with added elements
	Accessibility of connection	1.00	Freely accessible
Material level		**0.85**	**Disassambly potential**
1. Cladding material		0.95	
Connection (hook)	Type of connection	1.00	Dry connection
	Accessibility of connection	1.00	Freely accessible
Connection (wooden slats)	Type of connection	0.80	Connection with added elements
	Accessibility of connection	1.00	Freely accessible
2. H20 platen		0.80	
Connection (wooden slats)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
3. Wooden slats		0.90	
Connection to (wooden structure)	Type of connection	0.80	Bolt and nut connection
	Accessibility of connection	1.00	Freely accessible
4. Wooden structure (HSB)		0.73	
Connection (finishing material)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.40	Accessible with actions causing repairable damage
Connection (insolation material)	Type of connection	1.00	Dry connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
Interconnection	Type of connection	0.80	Bolt and nut connection
	Accessibility of connection	0.80	Accessible with actions not causing damage

The DfD index shows that there is a 14% and 15% improvement of disassembly potential on the redesigned prefabricated building element compared to the baseline design on the element and material level, respectively, in the Dutch case. The use of the cladding materials of the redesign connected with the hook system to the frame aiming at multiple reuses of the wood improved the disassembly potential. In contrast, nailed connections are used in the baseline design, which provides less reusability potential.

5.1.2 Estonian case

Table 5 shows the scoring matrix of the disassembly potential of the baseline design of the Estonian case. The results show that the disassembly potential on the element level and material level of the baseline design are 0.85 and 0.77, respectively, whereas the disassembly potential on the element level of the redesigned building envelope element is 0.85 and 0.82 on the material level (shown in Table 6).

TABLE 5 Scoring matrix disassembly potential baseline design

		Score	
Element level		**0.85**	**Disassambly potential**
1. Prefab 1e skin (structure)		0.80	
Connection (existing construction)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
2. Cladding material		0.90	
Connection (wooden slats)	Type of connection	0.80	Screw connection
	Accessibility of connection	1.00	Freely accessible
3. Wooden slats		0.70	
Connection (wooden structure)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
Material level		**0.77**	**Disassambly potential**
1. Cladding material		0.90	
Connection (wooden slats)	Type of connection	0.80	Screw connection
	Accessibility of connection	1.00	Freely accessible
2. Wooden slats		0.70	
Connection (wooden structure)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
3. Wooden structure		0.70	
Connection (finishing material)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
Interconnection (structure)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.80	Accessible with actions not causing damage

TABLE 6 Scoring matrix disassembly potential redesign

		Score	
Element level		**0.85**	**Disassambly potential**
1. Prefab 1e skin (structure)		0.80	
Connection (existing construction)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
2. Cladding		0.90	
Connection (wooden slats)	Type of connection	0.80	Screw connection
	Accessibility of connection	1.00	Freely accessible
3. Wooden slats		0.80	
Connection (wooden structure)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
Material level		**0.82**	**Disassambly potential**
1. Cladding material		0.90	
Connection (wooden slats)	Type of connection	0.80	Screw connection
	Accessibility of connection	1.00	Freely accessible
2. Wooden slats		0.80	
Connection (wooden structure)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
3. Wooden structure		0.75	
Connection (finishing material)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions not causing damage
Interconnection (structure)	Type of connection	0.60	Nail connection
	Accessibility of connection	0.80	Accessible with actions not causing damage

The DfD index of the results shows that there is no change in the disassembly potential on the element level and only a 6% improvement on the material level in the baseline and the redesigned prefabricated envelope element. There is no change in the material use and connection in both scenarios except for the replacement of nail connections with screw connections.

5.1.3 Irish case

Table 7 shows the scoring matrix of the disassembly potential of the baseline design of the Irish case. The results show that the disassembly potential on the element level and the material level of the baseline design are 0.45 and 0.43, respectively, whereas the disassembly potential on the element level of the redesigned building envelope element is 0.80 and 0.72 on the material level (shown in Table 8).

TABLE 7 Scoring matrix disassembly potential baseline design

		Score	
Element level		**0.45**	**Disassambly potential**
1. EWI System		0.45	
Connection (existing construction)	Type	0.80	Connection with added elements
	Accessibility of connection	0.10	Not accessible - irreparable damage to objects
Component Level		0.45	
EWI to Window	Connection to window	0.45	
	Type of connection	0.80	Connection with added elements
	Accessibility of connection	0.10	Not accessible - irreparable damage to objects
Material level		**0.43**	**Disassambly potential**
1. Acrylic Render		0.25	
Connection (insolation)	Type	0.10	Hard chemical bond
	Accessibility	0.40	Accessible with actions causing repairable damage
2. Insulation		0.60	
Connection (existing wall)	Type	0.80	Connection with added elements
	Accessibility	0.40	Accessible with actions causing repairable damage

The DfD index shows that there is a 78 % and a 67 % improvement in the disassembly potential of the redesigned prefabricated building envelope element compared to the baseline design on the element and material level in the Irish case.

The disassembly potential of the redesign is improved on the type and accessibility of the connection compared to the baseline design. Furthermore, the redesign showcases an increase of 21% in the disassembly potential (material level) compared to the baseline. The disassembly potential of the redesign is improved on the material level by replacing hard chemical connections with dry connections compared to the baseline design. Hierarchical DfD has been a key principle and design strategy that results in significant improvement on the element and material level. The score on the element level is especially notable, caused by a premanufactured and modularized wall cladding panel.

TABLE 8 Scoring matrix disassembly potential redesign

		Score	
Element level		**0.80**	**Disassambly potential**
1. Main 2D panel		0.90	
Connection (existing construction)	Type of connection	1.00	Dry connection
	Accessibility of connection	0.80	Accessible with actions that don't cause damage
2. Horiz. Const. Junction		0.70	
Interconnection (construction)	Type of connection	1.00	Dry connection
	Accessibility of connection	0.40	Accessible with actions causing repairable damage

Material level		**0.72**	**Disassambly potential**
1. Acrylic Render		0.55	
Connection (cement board)	Type of connection	0.10	Cement bound connection
	Accessibility of connection	1.00	Freely accessible
2. Cementboard		0.80	
Connection (battens)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions that don't cause damage
3. Timber battens		0.80	
Connection (battens)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions that don't cause damage
4. Breather membrane		0.50	
Connection (woodfibre board)	Type of connection	0.60	Pin connection
	Accessibility of connection	0.40	Accessible with actions causing repairable damage
5. Woodfibre board		0.80	
Connection (metal stud)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions that don't cause damage
6. Metal Stud		0.80	
Connection (back strip/Gaskets)	Type of connection	0.80	Screw connection
	Accessibility of connection	0.80	Accessible with actions that don't cause damage
7. Insolation		1.00	
Connection (metal stud)	Type of connection	1.00	Dry connection
	Accessibility of connection	1.00	Freely accessible
8. Backing Strip and Gaskets		0.50	
Connection (existing structure)	Type of connection	0.60	Pin connection
	Accessibility of connection	0.40	Accessible with actions causing repairable damage

5.2 EMBODIED CARBON

The environmental impact is demonstrated based on the amount of carbon (cradle-to-gate) of the building envelope elements. The functional unit of this study is 1 m^2 of prefabricated building envelope element.

The difference in ECO_2 between the baseline design and the redesign reflects on material choices, materials reduction, and the share of virgin used materials compared to the share of reused materials. Figure 10 shows the comparison of embodied carbon associated with the baseline design and the redesign for all three cases.

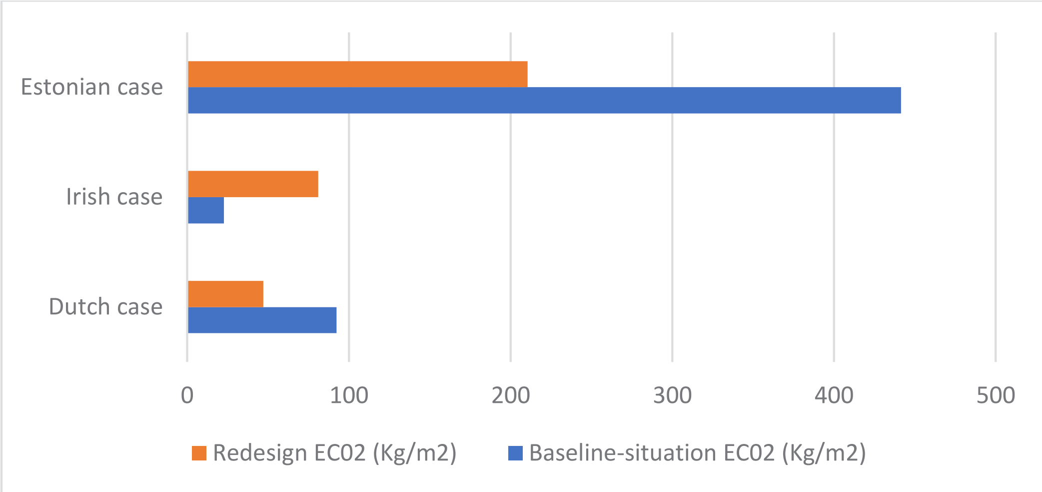


FIG. 10 Embodied carbon emission in baseline and redesign

5.2.1 Dutch case

Results show that the embodied carbon of the baseline design is 19.22 kg/CO_2 per square metre, whereas of the redesigned prefabricated building envelope element, it is 9.06 kg/CO_2 /m^2. The embodied carbon of the redesigned prefabricated envelope element is reduced by 50% compared to the baseline design. The redesign consists of a frame (remanufactured with about 70% reused wood) and the façade cladding (100% reused wood) with a wood fibre insulation that has a high contribution of 8.04 kg/CO_2. The baseline design consists of 100% virgin wood, and the use of glass wool insulation is the main culprit of higher emissions.

5.2.2 Estonian case

The embodied carbon of the redesigned prefabricated building envelope element is reduced by about 47% compared to the baseline design. The redesign showed a total embodied carbon of 16.79 kg/m^2. The baseline design showed an embodied carbon of 31.67 kg/m^2. The environmental impact is improved by a well-considered selection of biobased insulation and remanufactured materials to replace virgin materials. This selection of materials is not only considered in terms of quality and disassembly potential but also of further reuse and upscaling possibilities of the timber frame-based insulation system.

5.2.3 Irish case

The embodied carbon of the redesigned prefabricated building envelope element is increased by about 256% compared to the baseline design. The redesign showed a total embodied carbon of 81.05 kg/m^2. The baseline design showed an embodied carbon of 22.76 kg/m^2.

The cement carrier board alone contributes 68% of embodied carbon compared to other layers in the prefabricated building envelope element. The cement carrier board is used to avoid render layers and for a quality finish with impact resistance, though it contributes higher embodied carbon.

6 DISCUSSION

This study discussed the circular redesign of three different prefabricated building envelope elements in three demonstrator cases (Dutch, Estonian, and Irish). It was guided by the research question: what is the environmental impact in terms of embodied carbon and disassembly potential of circular redesigned prefabricated building envelope elements? By assessing the embodied carbon footprint (cradle-to-gate) and disassembly potential, direct insight is provided into how design choices and material choices influence the life cycle performance of building elements.

All three cases involve a hierarchical design for disassembly approach, resulting in a layered configuration, which facilitates future multi-cycle reuse of the building envelope element as a whole as well as its single components. In contrast to the traditional glued brick slips, the results of the Dutch demonstrator case showed that the use of the cladding materials fixed with a hook system substantially improved the disassembly potential during both maintenance and end-of-life scenarios. In the Estonian case, the improvement of the disassembly potential of redesigned envelope elements is due to separating functional layers and connecting these layers with screw connections which resulted in a higher reuse potential for horizontal and vertical wooden slats. In the Irish case, there is a significant improvement in the disassembly potential of the prefabricated building envelope by replacing traditional masonry with a rendering system that is fixed to the element with a dry connection. The redesign resulted in a demountable, premanufactured, modularized building envelope element. This study revealed that, compared to the baseline, an increase in disassembly potential of up to 100% can be achieved for an end-of-life scenario reusing the building envelope element at large and an increase of up to 49% on the level of materials and components being applied. In line with previous research (Juaristi et al., 2022), this research, therefore, advocates that, based on a careful design process and within the framework of existing product certification, it is possible to substantially increase future reuse potential contributing to improved material efficiency in the construction sector.

The environmental impact is demonstrated based on embodied carbon calculations (cradle-to-gate) of the building envelope elements. The difference in embodied carbon footprint between the baseline design and the redesign reflects the effects of avoiding the use of specific materials and careful material and connection selection to improve the overall material efficiency of building envelope elements. With respect to the material and connection selection, the application of biobased and reused materials was especially taken into account.

Results show that a reduction of 50% of embodied carbon emission can be achieved by reusing 100% of the wood for the façade cladding and 70% for the frame structure in the Dutch case and using biobased insulation and remanufactured materials in the Estonian case. In contrast to previous studies, this research showed that improving the disassembly potential of a construction element in combination with careful material selection can substantially reduce embodied carbon (Roberts et al., 2023). These findings are in line with the definition of systemic circularity, i.e. that a full circular design depends on multiple interconnected indicators with different impacts which influence each other in a continuous and circular manner (Kubbinga et al., 2018; Antwi-Afari et al., 2022).

On the other hand, the embodied carbon is significantly high due to the use of cement carrier boards and other multiple layers in the envelope elements. Designing out these materials is complex as these layers have specific functionalities (like fire safety), which are hard to meet with materials with a low(er) embodied carbon footprint. This is in line with the study by Mazzoli et al. (2022) showing that prefab multi-layered elements, required to meet the criteria of demount ability, reusability, and durability, have a greater embodied carbon due to the presence of larger quantities of materials and higher density.

Although none of the innovative prefabricated building envelope elements are yet considered 100% circular, the development of the three building envelope elements showcases that the environmental impact can be substantially reduced following a well-structured and dedicated design process. The reduction of the environmental impact is indicated by lower quantities of embodied carbon and an improved design for disassembly, reflecting a higher reuse potential of building materials and components.

7 LIMITATIONS AND FUTURE RESEARCH

Several limitations and directions for further research were identified. The three building envelopes redesigned for this study are not yet fully circular. Future research and development should focus on alternative designs to advance the development of fully circular deep-renovation technologies. From a holistic and systemic approach, one key strategy to arrive at fully circular deep-renovation solutions is to apply a 'tectonics of avoidance' approach. This means that at the building level, reduction and production measures — insulation versus renewable energy generation — need to be balanced with the purpose of optimal material application (Ritzen et al., 2016). A second key strategy is to increase the application of biobased materials such as hemp insulation and wood not being preserved, improved, or altered by the use of a chemical agent.

A second limitation is that additional empirical data is needed to advance our understanding of real environmental impact following an eco-design approach. First, empirical data is required to assess the reduction of embodied carbon emission under consideration of multi-cycle reuse of building elements and materials over time, which is considered a missing link in both theory and practice (Lam et al., 2022). Second, as a result of the design for disassembly strategy in combination with the reuse of mined construction materials, this study indicates that multi-cycle reuse depends on the material flow of locally available construction materials and components. Future studies could, therefore, research how to determine geographical territories by comparing the embodied carbon emission of reusing mined materials relative to other materials that can be applied, differentiating for transport distance. Such studies would contribute to the definition of territorial circular economies. They should also include the implications for the business model and supply chain set-up, which are not considered in our research project. Our research project also revealed some methodological limitations. The first methodological limitation concerns the embodied carbon calculation and the application of the ICE database since this database refers to the construction material application in the United Kingdom and is not up to date. However, because of the comparative research approach involving cases from three different countries, this limitation is considered acceptable. For absolute and country-specific impact calculations, we suggest using national-oriented databases (Bitar et al., 2022).

The third issue concerns the application of design for disassembly as a method and indicator. Coherent assessments have been suggested for the hypothesized correlation between life cycle assessment and cyclical use of construction materials, although scientific and empirical evidence is still under development. In order to form a scientific sound and good practical judgments, this coherent framework should account for:

1. Life cycle effects (ageing and applying R-strategies). Technical detachability tells little about the proportion and quality of the material that can be reused after disassembly and, subsequently, its effect on resource efficiency and carbon emission (Juaristi, Sebastiani, & Avesani, 2022).
2. The complexity of element compositions. As the number of components increases with more variation in the type of connections, this has a negative impact on carbon emission. (Lam et al., 2022; Roberts et al., 2023).
3. Degree of prefabrication and market forces in design choices regarding building material or component selection. This study showcased that material and component selection have a strong effect on both disassembly potential and embodied carbon emission.

Addressing the indicated, future research opportunities would be of significant importance from an academic, managerial and policy point of view. This study has contributed by offering a useful foundation for bridging circular design and the assessment of circular building indicators for materializing the transition towards a fully circular and Paris-proof built environment.

8 CONCLUSION

First of all, this study showcases that a reduction of up to 50% of embodied carbon emissions reduction can be achieved by closing material loops based on well-considered R-strategies and local reuse of materials. This indicates that closing material loops can lead to major consequences in terms of environmental impact and advocates treating demolition waste as a potent flow of valuable construction materials. Second, this study revealed that, compared to the baseline, an increase in disassembly potential of up to 100% can be achieved for an end-of-life scenario by reusing the building envelope element at large and an increase of up to 49% on the level of materials and components being applied. The increase in disassembly potential is due to thoughtful design choices based on accessible and dry connections and the degree of prefabrication. The increase in detachability of 50% at the level of construction materials used for the building envelope elements is of limited interest for the assembly process on-site but very important for a potential disassembly process in the factory. The design, viewed at the material level, determines how easily parts or materials of a prefab element can be recovered and/or replaced, and thus the prefab element can be adapted to changing conditions. Furthermore, in terms of eco-efficiency, the degree of reversibility in the factory can provide the opportunity to mine and reuse costly construction materials and components. However, to establish a fully circular design with a disassembly potential of materials close to 100%, further research and development are required. This advancement comes with an initial increase of embodied carbon emissions, and thus, a fully circular design will only reduce the environmental impact if multi-cycle reuse of the elements and the materials applied can be assured.

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