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Design for Reuse and Longevity of Circular Construction Products

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Abstract

The transition to a Circular Economy (CE) in the built environment requires a paradigmatic shift from linear "take-make-dispose" consumption to models that prioritize resource longevity. Design for Longevity (DfL) and Design for Reuse (DfRe) are cornerstone strategies, but their practical implementation is hindered by a lack of unified tools for early-stage design. This chapter addresses this gap by first synthesizing the core technical principles (Design for Disassembly, Adaptability, Modularity) that underpin circular construction.The primary contribution is the development of a novel multi-criteria tool, the "DfLRe assessment system," designed to inform early-stage decision-making. Based on expert surveys, the system evaluates construction products against seven key criteria and ranks the façade systems. This DfLRe system is applied to four common timber façade (TF) typologies. The results reveal critical trade-offs in choosing most suitable products, as the highest-ranking façade system demonstrated poor reusability, while the lowest-carbon option had high maintenance needs. The chapter concludes

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that longevity is not an intrinsic material property but a systemic outcome. The DfLRe framework provides a practical tool for designers to navigate these complex compromises, enabling more informed decisions to slow and close resource loops.

11.1 Introduction

The construction industry is one of the world's largest consumers of raw materials and generators of waste, representing a critical intervention point for the transition toward a circular economy (CE). The traditional linear economic model—characterized by a "take-make-dispose" framework is demonstrably unsustainable. Design for Longevity (DfL) presents a strategic alternative, functioning as a core component of the CE model (Carlsson et al., 2021). DfL aims to design products with an optimal lifetime, extending their utility through practices such as durability, reuse, repair, refurbishment, and remanufacturing (C. A. Bakker et al., 2021). This approach fundamentally "slows the resource loop" by keeping products and materials at their highest value state for as long as possible (Bocken et al., 2016).

Despite growing consensus on its importance, the practical implementation of DfL in the built environment faces significant barriers. Scholarly consensus indicates that the fragmentation of knowledge and the lack of a unified circular design approach impede the diffusion of circularity in the professional practice (Hart et al., 2019). The long lifespans and material intensity of buildings (Hart et al., 2019) demand a tailored and systemic approach.

This chapter provides a critical review and synthesis of the primary strategies supporting and underpinning DfL in circular construction products for facades. At first it analyzes the principles of design for disassembly, adaptability and reuse. Further, an assessment system is established for informing the Design for Reuse and Longevity in chossing a most suitable façade system enabling. The findings are presented followed by discussion and conclusions.

11.2 Methodology

This chapter employs a critical review and synthesis of academic and professional literature to construct a conceptual framework for Design for Reuse and Longevity in the built environment. This study is not empirical but methodological, based on a structured analysis of existing research.

A systematic literature search was conducted utilizing prominent academic databases, including Scopus, Web of Science, and Google Scholar.

Key search terms included "Design for Longevity," "circular economy" AND "Design for Disassembly (DfD)," "Design for Reuse (DfR)," "modular construction".

The selection process prioritized peer-reviewed articles from high-impact journals, seminal conference proceedings, and foundational books published primarily within the last two decades to ensure relevance to contemporary CE discourse. Key policy and regulatory documents, such as the European Commission's proposals, were included to provide essential context for systemic enablers. Non-peer-reviewed sources, articles with a primary focus outside the construction sector, and literature not available in English were excluded.

The selected literature was analyzed using a thematic synthesis approach. The objective of this synthesis is not merely to summarize but to critically analyze and to propose an assessment system to inform the Design for Reuse and Longevity of facades.

11.3 Modularity, Disassembly, Repair and Reuse of Circular Products

The physical embodiment of circular economy principles within a construction product is realized through several approaches and strategies, such as: modularity, Design for Longevity (DfL), Design for Disassembly (DfD), Design for Adaptability (DfA), Design for Repair (DfR), Design for Reuse (DfRe). These interconnected design strategies are the primary technical enablers for extending a product's service life and ensuring its high-value recovery. The technical foundation of longevity is realized through a set of interconnected design strategies that replace monolithic, single-lifecycle architectures with an adaptable "kit of parts" (Ghaffar et al., 2020). Further, we will elaborate the forementioned strategies, followed by product innvovations, eco-labeling and digital product passport.

11.3.1 Modular and repairable product design

A fundamental shift from a linear "take-make-dispose" model to a circular one requires re-evaluating design at the component level. Modularity refers to a design approach where a system is composed of distinct, independent components (modules) with standardized interfaces. This independence is the key to in-use life extension, allowing a single module to be upgraded, repaired, or replaced without necessitating the disposal of the entire product.

Modular and repairable product design are core strategies for embedding longevity and resource efficiency directly into construction products. These approaches aim to "slow the resource loop" by extending a product's useful life and "close the loop" by facilitating high-value material recovery, moving beyond low-grade recycling (Bocken et al., 2016). Modular and prefabricated construction works in synergy with DfD. By manufacturing components in a controlled factory setting, modularity enhances material efficiency, quality control, and waste reduction during the construction phase (Ghaffar et al., 2020). More importantly, these prefabricated systems are inherently designed for assembly and, by extension, disassembly. This modularity allows for greater flexibility and adaptability during the building's use phase, enabling spaces to be reconfigured rather than demolished. When a modular building reaches the end of its initial use, its components retain a high residual value, as they can be easily relocated, repurposed, or returned to the manufacturer (Kamal & Alsweiki, 2022).

11.3.2 Design for Longevity (DfL)

In the hierarchy of Circular Economy (CE) strategies, extending the utilization phase of products—often referred to as "slowing the loop"—is widely recognized as a priority over closing the loop (recycling) (Bocken et al., 2016). While recycling captures residual material value, it necessitates significant energy input for reprocessing. Conversely, Design for Longevity (DfL) aims to preserve the high-value embodied energy, labor, and function integrity of construction products for the longest feasible duration (L. G. Bakker et al., 2014). However, within the built environment, the application of DfL is nuanced, requiring a distinction between physical durability and functional relevance.

Traditionally, the construction industry has equated longevity with physical durability—the ability of a material to withstand wear, pressure, or damage (Kibert, 2012). However, a product designed for maximum physical durability may become an environmental liability if it cannot be adapted when it becomes functionally obsolete. Therefore, effective DfL in a circular context must prioritize the alignment of Technical Service Life (TSL) with Functional Service Life (FSL) (ISO, 2017).

To address the mismatch between TSL and FSL, circular design must adopt a stratified approach to longevity. Authors (Brand, 1995) note the concept of "Shearing Layers," which is modern circular design framework that suggest that construction products should be categorized based on their expected turnover rates.

1. The Structure (30–300 years): These components require maximum physical durability and permanence.
2. The Skin/Façade (20–50 years): These require high durability but must be detachable to allow for thermal upgrading or aesthetic refreshment without damaging the structure.
3. The Services/Space Plan (5–20 years): These components (HVAC, partitions, flooring) face the highest rate of obsolescence.

Consequently, DfL strategies for "Space Plan" products should not focus on infinite durability, but rather on modularity and interoperability, allowing for piecemeal replacement and maintenance (Schmidt et al., 2009). Three distinct strategies emerge for implementing DfL in construction products.

Design for Reliability and Robustness applies to long-life layers (Structure/Skin), where the focus remains on resisting degradation. This involves selecting materials that age gracefully or "patina" rather than corrode, reducing the perceived aesthetic obsolescence that often triggers premature replacement (Mugge et al., 2005).

Design for Maintenance and Repair wich reffers to prolong the functional life of complex products (window systems, HVAC etc.). The design must facilitate access to failure-prone components. This aligns with the "Right to Repair" movement, translating it into construction through accessible service cavities and standardized fasteners (den Hollander et al., 2017).

Design for Upgradability acknowledges that technology evolves faster than the building structure. Circular construction products effectively separate the "performance hardware" from the "static frame."

Finally, it is critical to note that in a Circular Economy, "Longevity" does not imply "Forever." Even the most durable product will eventually reach its End-of-Life (EoL). Therefore, DfL must be intrinsically linked to **Design for Disassembly (DfD)**.

11.3.3 Design for Disassembly (DfD)

Design for Disassembly (DfD) is a methodology that enables the circular potential of modularity. DfD is a design approach of a product to facilitate its non-destructive separation into constituent components at its end-of-service-life (Akinade et al., 2017). This approach facilitates the high-value recovery, reuse, and remanufacturing of components, directly contrasting with conventional demolition, which often results in downcycled or landfilled waste. Key

principles of DfD include using reversible connections (e.g., bolts over adhesives), standardizing components, and ensuring materials are easily accessible and identifiable (Geraedts, 2017). This directly contrasts with traditional construction, which often prioritizes permanence through irreversible chemical bonds (e.g., adhesives, spray foams, welds) and composite materials (Akinade et al., 2017).

Therefore, key principles of DfD include:

- **Reversible Connections:** Prioritizing mechanical fasteners (e.g., bolts, screws, clips) over chemical or thermal bonds (e.g., adhesives, welding). This ensures that components can be non-destructively separated
- **Ensuring Accessibility:** Designing products so that critical components and their connections are physically accessible to maintenance and deconstruction teams.
- **Minimizing Material Complexity:** Avoiding inseparable composites and using a limited palette of pure, non-toxic materials to simplify sorting and high-value reuse.
- **Component Independence:** Designing components so that the failure or required upgrade of one part does not necessitate the replacement of the entire system.
- **Layering:** Separating building systems into layers based on their expected lifespan.
- **Hierarchical Design:** Structuring the product for a logical, reverse-order-of-assembly sequence, often documented in a "disassembly map" or Building Information Model (BIM).

By designing with modularity and DfD in mind, manufacturers create products that are not only easier to install but also inherently adaptable. Research conducting life cycle assessments (LCA) on modular buildings designed for disassembly has shown a dramatic reduction in environmental impacts, including a 63% reduction in global warming potential compared to conventional linear designs, primarily due to the high potential for component reuse (Jayawardana et al., 2023).

The synergy between modularity and DfD is fundamental to designing for longevity. Modularity provides the adaptable structure, while DfD provides the access and reversibility needed for repair. In this manner, a construction product can be transformed from a single-use, disposable item

into a durable "material bank", a repository of high-value components and materials that can be easily accessed, maintained, and redeployed, thereby "slowing the loop" and preserving the economic and environmental value embedded within them (Bocken et al., 2016).

The fundamental tenets of DfD include (Buyle et al., 2013; Cabeza et al., 2014):

1. maintaining accurate documentation of the materials and deconstruction methods,
2. crafting accessible connections and joints to facilitate dismantling,
3. segregating any items that are neither recyclable, reusable nor disposable,
4. creating uncomplicated structures and forms that enable component standardization and dimensional consistency, and
5. designs that consider labor practices, productivity and safety.

The primary enabler of disassembly is the reversibility of its connections. Also, the most direct strategy for enabling DfD is the prioritization of mechanical fasteners (Akinade et al., 2015). Designing with bolts, screws, and clips—rather than adhesives or mortars—is the most direct strategy for enabling Design for Disassembly (DfD) (Akinade et al., 2015).

Authors identify six criteria for assessment of DfD as most recurring in the literature, such as (Attia et al., 2024): type of connection, component accessibility, independence of the component, geometrical composition, treatment and finishing, and dismantling damage. Other criterias occuring in the literature are: Assembly sequence, Degree of freedom, Disassembly safety, Ease of assembly, Functional separation, Reusability, Structural strength etc.

11.3.4 Design for Adaptability

Design for Adaptability (DfA) is a design strategy, suitable for timber-based buildings, focused on future-proofing a structure to allow for reconfiguration or conversion during its lifespan (Lisco & Aulin, 2023). The ISO 208870:2020 principles for DfA suggest that buildings should be: versatile, meaning that new patterns of use should be possible with little change; convertible, meaning non-structural changes can be made easily to accommodate a change in use; and expandable, meaning the ability to easily expand the building vertically or horizontally. Designers must consider key factors to implement DfA effectively, including (Lisco & Aulin, 2023):

- **Flexibility/Adjustability:** Ease of adjusting spatial configuration with minor interventions.
- **Generality/Multifunctionality:** Space usable for different purposes *without* changes.
- **Elasticity/Expandability:** Ability to increase the building's volume (vertically or horizontally) or divide/merge spaces.
- **Dismantlability/Removability:** Ease and effectiveness of removing physical objects/components.
- **Convertibility/Transformability:** Possibility of giving the building a new function.
- **Recyclability/Reusability:** Facilitating the **reuse and recycling** of building parts.

11.3.5 Design for Repair (DfR)

While DfD facilitates end-of-life recovery, Design for Repair (DfR) is the primary strategy for in-use life extension. Central to the "Right to Repair" movement, DfR is defined by the ease with which a product can be restored to a functional state following a fault or degradation (Parajuly et al., 2024). DfR is fundamentally a "slowing the loop" strategy in the circular economy (CE), aiming to keep products and materials in their highest value state for as long as possible, thereby minimizing the need for replacement and resource consumption (Bocken et al., 2016).

Modular design is a key prerequisite for repairability. A product designed as a "black box" (a sealed, integrated unit) is often unrepairable, as a minor fault in one sub-component renders the entire product useless. A modular product, in contrast, is **diagnosable and serviceable**. The design facilitates the "ease of product repair" by ensuring (Parajuly et al., 2024):

1. **Accessibility:** The component most likely to fail (e.g., a gasket, a digital sensor, a movable part) can be accessed without specialized tools or the deconstruction of the entire assembly.
2. **Interchangeability:** Worn-out or broken modules can be swapped for new or refurbished ones, thanks to standardized connections and the availability of spare parts.
3. **Information:** Clear technical information on how to diagnose faults and perform repairs is available to technicians and end-users.

4. **Standardization and Spares:** Products must use common fasteners, and spare parts must be readily available—a significant logistical challenge given the multi-decade lifespan of buildings.
5. **Information Provision:** Clear technical information (e.g., diagnostic guides, repair manuals) must be accessible to technicians and end-users, often via digital platforms (European Commission, 2022).

11.3.6 Design for Reuse (DfRe)

Researchers explore the implementation of reuse strategies for construction materials and structural elements (Bertin et al., 2022). The benefits are constrained by factors like stringent deconstruction and must account for functional downgrading and material losses between usage cycles, as these factors can limit the environmental performance compared to traditional practices (Bertin et al., 2022).

The possible reuse options for prefabricated timber buildings after their EOU are refabrication (Litleskare & Wuyts, 2023), biocycle (Ormondroyd et al., 2016), elemental retrofit (Bertino et al., 2021), transform (Arisya & Suryantini, 2021) and adaptive reuse (Lisco & Aulin, 2023). Authors assess various timber reuse options for prefabricated timber buildings after their end-of-use using the Simultaneous Evaluation of Criteria and Alternatives (SECA) method (Ghobadi & Sepasgozar, 2025).

Several factors hinder the utilizing reprocessed and reused materials such as negative attitudes towards the quality and price (Oyedele et al., 2014) of reusable materials limit their adoption as alternatives to virgin materials (Niu et al., 2021).

Studies show that using wood nails in stud and joist framing, with screws replacing nails elsewhere, and omitting adhesives from the floor panels increased the ease of disassembly. The proposal for wood nails to be used in the framing of wall and floor assemblies reduced the damage to the ends of structural material, resulting in an increase in the extraction of solid timber with a high reuse potential (Walsh & Shotton, 2024). Wood nails were granted technical approval for use in framed structures in Europe in 2023 (Walsh & Shotton, 2024). Several researchers investigate reversible load-bearing assemblies (Brown, 2021; Carradine et al., 2012; Ottenhaus et al., 2023).

11.3.7 Construction products innovations

More advanced material innovation is occurring in the field of "debonding-on-demand" (DoD) systems. This research focuses on **stimuli-responsive**

adhesives (SRAs). These "smart" materials are engineered to maintain a strong, durable bond throughout the product's service life but will "debond"—releasing their grip—when a specific external stimulus is applied. Triggers can include heat (thermo-responsive), light (photo-responsive), or an electrical current (electro-responsive) (Kadhirvel et al., 2022). For example, a laminated panel or façade element assembled with an electro-responsive adhesive could be installed as a permanent, rigid unit.

For a product to be truly circular, its base materials must be recyclable (technical cycle) or biodegradable (biological cycle). Innovation is therefore focused on two parallel tracks: material homogeneity and advanced bio-composites.

First, in the technical cycle, innovation favors design for homogeneity. Instead of complex, multi-material composites, the focus is on developing high-performance mono-materials. A product made from a single type of polymer or a mono-material timber element (e.g., Cross-Laminated Timber made with a reversible adhesive) is far simpler to sort, identify, and reprocess at its end-of-life, preserving its material value across multiple cycles (Eberhardt et al., 2021).

11.3.8 Eco-labeling and Digital Product Passport

Currently, the most prominent information tool in the construction sector is the Type III **Environmental Product Declaration (EPD).** Governed by standards such as ISO 14025 and, more specifically for construction, EN 15804, EPDs provide comprehensive, third-party-verified data on a product's life cycle assessment (LCA) (European Committee for Standardization, 2019). EPDs have been foundational in quantifying environmental impacts such as global warming potential (GWP), resource depletion, and waste generation. In principle, EPDs can be used to communicate circular attributes, such as the use of secondary materials, resource recovery potential, and the "reference service life" (RSL) of a product. For instance, some manufacturers already leverage EPDs to certify extended lifespans (e.g., 50-60 years) and to declare that a product is "engineered to facilitate disassembly, removal and reuse". However, conventional EPDs lack standardized, comparable metrics for key circularity indicators like "dismantlability potential" or "repairability". This "circularity information gap" is what the DPP is intended to resolve.

A Digital Product Passport (DPP) is a digital document that identifies all materials and components within a product or building, detailing their characteristics, origin, and potential for reuse or recycling. A DPP functions

as a dynamic digital record, or "logbook," for a product, tracing its lifecycle from material extraction to installation and beyond.

This data is crucial for "closing the loop" as it provides future stakeholders with the necessary information to make informed decisions about maintenance, repair, and end-of-life recovery. By cataloging a building's contents, material passports transform the structure into a repository of well-defined, valuable assets. This passport contains critical data, including:

- **Material Composition:** Full transparency of all constituent materials, including any hazardous substances, which is vital for safe repair and future recycling.
- **Disassembly and Repair Instructions:** Detailed, manufacturer-provided guides and schematics that "unlock" the product for maintenance, democratizing the ability to repair.
- **Service History:** A log of all maintenance, repairs, and refurbishments, providing a clear provenance and performance record.

This radical transparency fundamentally shifts the power dynamic. The "consumer"—be it a building owner, tenant, or facility manager—is no longer a passive user but an empowered agent (Jrade & Jalaei, 2013). With access to a DPP, a manager can identify a failing component via its BIM model, consult the passport for the correct spare part number and repair protocol, and execute the maintenance efficiently. This system fosters "repair ecosystems" where third-party technicians, and even the users themselves, are granted the information necessary to extend a product's life, thereby severing dependency on proprietary, "black box" solutions and truly activating the product's circular potential.

This concept is expanded by the **Digital Twin,** a dynamic, real-time virtual model of the physical building. Integrating data from **Building Information Modeling** (BIM) and Internet of Things (IoT) sensors, a digital twin can track a building's performance, manage maintenance schedules, and simulate future scenarios, such as disassembly or adaptation (Ghaffar et al., 2020). In the context of longevity, the digital twin allows owners to optimize a product's operational life and provides a precise, virtual guide for its eventual deconstruction, ensuring material recovery is planned and efficient.

11.3.9 Product-as-a-Service (PaaS)

The effective implementation of DfL is also catalyzed by a systemic shift in business models, moving from product sales to Product-as-a-Service (PaaS)

models (Bocken et al., 2016). In a PaaS model, a manufacturer retains ownership of the component (e.g., a façade, lighting, or elevator system) and sells its performance as a service. This creates a powerful economic incentive for the manufacturer to design for maximum longevity, durability, repairability, and disassembly, as they remain responsible for the product's entire lifecycle cost and end-of-life value (Ellen Macarthur Foundation, 2021).

11.4 Case-Study of Design for Reuse in Circular Products

In this section we develop a case-study for analysis of circular products in a façade system.

Researchers note that in the case of timber-based buildings, 65 % of materials are reusable and 35 % are recyclable (Ilgın et al., 2023). In this regard, the Design for Disassembly (DfD) is the key to promoting CE in construction and involves a building design process that allows products, parts and materials to be easily recovered when a building is disassembled.

Regarding the design of facades, researchers propose to design facades so they can be replaced and adapted, make the building envelope independent of the structure; provide means for access to the exterior wall system from both sides; design a versatile envelope capable of accommodating changes to the interior space plan (modular system) (Jockwer et al., 2020) (Jockwer et al., 2020; Lisco & Aulin, 2023).

Reversible connections play a crucial role in Design for Disassembly of timber structures (Ottenhaus et al., 2023). These connections typically fall into several categories:

1. carpentry joints (usually timber-to-timber, depending on bearing and friction);
2. basic fasteners (such as dowel-type elements loaded laterally or axially, applied in timber-to-timber or steel-to-timber joints);
3. connectors incorporating (proprietary) brackets and fixings to link two or more timber components; and
4. specialized connection systems tailored for particular uses (Ottenhaus et al., 2023).

An analysis was conducted on most frequent timber facades systems being used in North Macedonia. Ten construction companies were interviewed and a selection of 4 wall systems was made. The most common façade system and construction products are timber framing with an exterior finish with mortar over a rockwool insulation. Other common product is SIP (structurally insulated panels) which are modularly produced, while CLT (cross-laminated

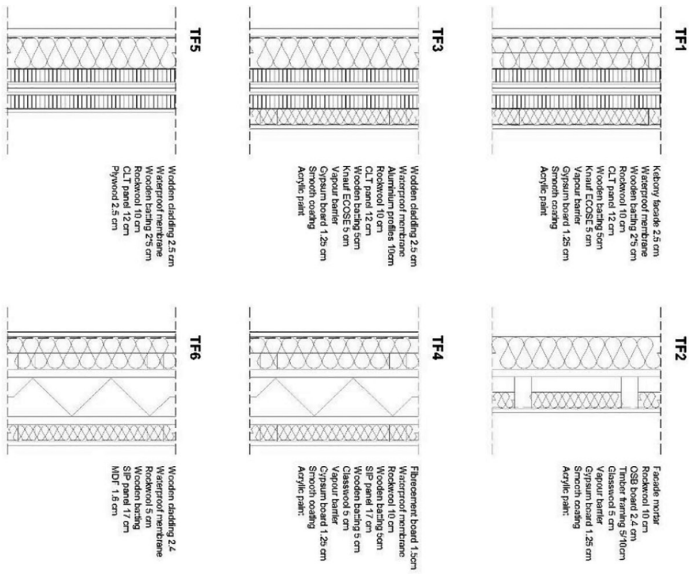

Figure 11.1 Circular construction products in facade.

timber) panels are less frequently used due to their higher cost. The interior finish is most commonly made out of gypsum boards. The exterior finish may vary between façade mortar, fibercement boards or wooden/modified wood products. The four timber façade (TFs) systems and their constituting products are presented in Figure 11.1.

The TFs are mainly consisted of construction products which are recyclable/reusable, with various degree of durability. In terms of brackets and fixings, options include sliding bracket connectors, panel connectors, nut- and anchor-type connectors, among others. General guidelines for designing disassemblable and reusable connections emphasize keeping them within the elastic range; adopting capacity design principles; and incorporating potentially ductile, replaceable elements (acting as fuses) to aid in energy dissipationConventional fasteners like nails, dowels, or screws offer limited suitability for DfD, whereas proprietary brackets may enable reversibility in their designated applications.

11.4.1 Establishing assessment system for Design for Longevity and Reuse

In order to choose most suitable construction products for a façade there needs to be a prompt assessment system which would inform the design team in the early design stage in choosing the most suitable construction products.

The assessment system would support the Design-for- Longevity and Reuse (DfLRe) and the decision making process.

Therefore, a semi-structured survey was conducted among 5 practicing architects and 3 researchers in circular design for choosing a set of criteria for assessment of circular products for façade in the early design stage. The participants were asked to rank the criteria according to their relevance in the early design stage of a façade system and they were given a set of 12 indicators to choose from. The results of the survey narrowed the selection of criteria to the ones which will enable rapid assessment. The criteria that constitute the DfLRe assessment system are:

1. durability,
2. maintenance,
3. ease of assembly,
4. ease of disassembly,
5. modularity,
6. reusability, and
7. embodied carbon.

The criteria durability (reliability) and maintenance reffer to the DfL while the remaining constitute the DfRe component in the DfLRe assessment system. Durability and maintenance consider both the exterior and interior finish materials, their planned service life and the data is gathered from the manufacturers' product warrant.

Ease of assembly is assessed regarding the simplicity of connecting all construction products together in the façade system. Ease of dissemination refers to the simplicity of dismantling the façade system without damaging the products and the need for manual labour or mechanical tools.

The modularity assesses all products within a façade which are modularly produced and joined in the façade element as a module without the need for adjustments during the construction of the façade on-site.

The reusability refers to how many of the construction products within a façade system can be reused after dismantling while preserving their integrity as planned and their primary function within a façade element.

The embodied carbon is calculated for a whole façade system by using the Environmental Product Declarations for each construction product, and the Global Warming Potential (GWP) is only considered.

The DfLRe assessment system was tested on the four case studies of Timber Facades (TFs) elaborated in the previous section. The scoring system

Table 11.1 Assessment of DfR of Circular Construction Products in Facade.

	durability	maintenance	ease of assembly	ease of disassembly	modularity	reusability	embodied carbon	Sum
TF1	3	4	3	2	1	1	1	15
TF2	1	1	1	1	4	3	2	13
TF3	4	3	4	3	3	2	4	23
TF4	2	2	2	4	2	4	3	19

is based on prioritization of the case-studies of TF and ranking them for each of the criteria. The TFs are assessed via direct comparison and ranking by 8 experts which have experience in construction of timber facades. The ranking points are summarized and the TFs with lowest number of points is the most suitable façade type with most adequate circular construction products, Table 11.1.

11.5 Discussion

The proposed assessment system for DfLRe is applied on four case-studies of TFs and it provides direct comparison between different construction products regarding their reusability.

The durability is assessed according to most common life-cycle of the façade finish and manufacturers recommendations. The mortar finish and the fibre cement board provide the most durable exterior, while the wooden products which are exposed to the outside have the shortest life-span, even though in the case of TF1, the kebony façade is a modified wood, treated to be more durable than an untreated wood.

The maintenance criteria takes into account how often would the exterior layer need to be serviced during its lifetime. The fibercement board and façade mortar have the lowest requirements for maintenance, while the wooden façade requires frequent protection from the rain and the sun.

For the criteria ease of assembly, the case-studies were evaluated in terms of complexity of the components and the various tools that might be needed. The TFs which have lower weight and can be manually joined have higher ranking compared to the TFs which have larger components and would require cranes or other mechanization for their connection on site. Therefore the TFs which consist of timber frame products and SIP products have higher ranking as compared to TFs having CLT panels. Similarly the criteria for ease of dissembly was assessed in terms of the need for mechanization for the products dismantling.

With the aspect of modularity all construction products within a façade system have been analyzed. The TF2 has a timber frame structure which is

modular. However, because the rockwoll panels and the mortar finish cannot be physically separated in modules and reused the TF2 has the lowest ranking. Similarly, the TF3 is ranked 3rd because it has a fibrecement board.

The reusability of the elements assesses all products in the façade system. Because the TF2 and TF4 have components which cannot be dismantled without being damaged, such as the façade products, they have the lowest ranking.

The GWP for all construction products within a TF were calculated according to the products` EPDs. The results show that the TF1 with predominantly wooden products, i.e. wooden battings and façade and CLT panels has the lowest embodied carbon. The TF3 has higher GWP due to the aluminum profiles and the TF4 due to the fibercement board.

11.6 Conclusion

This research chapter aims to address the critical need for a systemic transition from a linear to a Circular Economy in the built environment, focusing on the cornerstone strategies of Design for Longevity (DfL) and Design for Reuse (DfR). The study confirmed that the practical implementation of these principles is hindered not by a lack of singular solutions, but by a fragmentation of knowledge and the absence of practical tools to navigate complex design trade-offs. Longevity, this chapter argues, is not an intrinsic material property but a systemic outcome, achievable only through an integrated approach.

The literature review synthesized the core technical principles required for this transition, establishing that DfL is intrinsically linked to and dependent upon Modularity, Design for Disassembly (DfD), Design for Adaptability (DfA), and Design for Repair (DfR). These physical design strategies, however, remain inert without a framework of systemic enablers. The research identified Digital Product Passports (DPPs) and Digital Twins as the critical information infrastructure necessary to manage a product's extended life.

The primary contribution of this chapter is the development and preliminary application of the DfLRe assessment system which is a multi-criteria tool for early-stage design assessment. By synthesizing expert opinion into seven key criteria this system provides a rapid, comparative method for evaluating construction products.

The application of the DfLRe system to four common timber façade (TF) typologies in North Macedonia yielded significant insights. It revealed that no single, currently available system is "perfectly circular." Instead, designers face a series of trade-offs. TF2, while ranked highest overall,

demonstrated a critical flaw in its low potential for modularity and reuse, as some of its components are chemically and physically bonded. TF1, which has higher ranking on embodied carbon and reusability, has higher maintenance requirements of its external timber finish. TF3 and TF4 show that the inclusion of components like aluminum profiles and fibercement boards introduces increased embodied carbon and reusability challenges.

The findings underscore that there is no single solution but specific compromises need to take place in each product and design choice. It successfully bridges the theory-practice gap by equipping architects and designers with a tangible framework to make informed decisions that align with a project's specific circularity goals.

11.6.1 Limitations and future research

This study is primarily methodological and its findings are contextual. The DfLRe assessment system was developed through a limited expert survey and applied to a specific typology (timber façades) in a single geographical region (North Macedonia). Future research should focus on the wider empirical validation of the DfLRe assessment system. It should be applied to a more diverse range of construction products (e.g., interior partitions, flooring) and in different international contexts. Furthermore, this qualitative and technical assessment should be integrated with quantitative Life Cycle Costing (LCC) and full Life Cycle Assessment (LCA) to build a comprehensive decision-making model that includes economic viability.

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