Journal of Cleaner Production 536 (2025) 147140

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

A framework for circular facade design: Systematic review of design strategies and performance indicators

Hamad Alabdulrazzaq [a,b,*], Eugenia Gasparri [a], Arianna Brambilla [a], Shady Attia [c]

[a] School of Architecture, Design and Planning, The University of Sydney, 148, City Road, Darlington, 2006, NSW, Australia
[b] Department of Architecture, College of Architecture and Planning, Imam Abdulrahman Bin Faisal University, Dammam, 31451, Saudi Arabia
[c] Université Catholique de Louvain-la-Neuve, Architecture et Climat, Louvain-la-Neuve, 1348, Belgium

ARTICLE INFO

Keywords:
Circular façade
Circular economy
KPIs
Circularity indicators
Design strategies

ABSTRACT

In the construction industry, efforts to enhance energy efficiency and reduce operational carbon have contributed to a rise in embodied carbon, especially in façades. With shorter service lives than building structures, façades often require multiple interventions or replacements. Under the traditional "cradle-to-grave" model, they also generate significant waste with limited recovery potential. Circular economy (CE) principles offer a pathway to reduce waste, improve material efficiency, and promote reuse and recycling. However, implementing CE principles requires consistent methods for designing, assessing, and tracking circularity. Despite growing interest in CE, existing frameworks for circular façades lack standardisation, particularly in design strategies and Key Performance Indicators (KPIs), making evaluation difficult for complex façade systems. To address this gap, this study conducts a systematic literature review of 122 studies, identifying 13 strategies and 24 KPIs for façades. These findings underpin a novel Circular Façade Design Framework (CFD-F), which structures strategies and KPIs across five façade lifecycle stages. The framework is aligned with CE principles at material, part, and component levels, drawing upon elements of previously published methods and frameworks. It also introduces a refined definition of circular façades to address conceptual gaps. The framework is demonstrated in a unitised curtain wall case study, showing its potential to guide design, evaluate circularity, and support early decisions. While limited by the absence of practitioner and empirical validation, future research should expand its application and integrate environmental and economic assessments. For practice and policy, the CFD-F provides architects, façade engineers, sustainability consultants, and decision-makers with a practical tool to embed circular design strategies into projects from the earliest stages.

1. Introduction

The construction sector is a major consumer of energy and resources. It also generates more waste than any other economic sector (Giorgi et al., 2022; Khadim et al., 2022). Global statistics show that the building industry is responsible for 40 % of energy consumption, 30 % of raw material usage, and 25 % of water consumption (Bilal et al., 2020; Cottafava and Ritzen, 2021; van Stijn et al., 2022). It also accounts for over 25 % of all European Union (EU) waste and contributes 33 % of global greenhouse gas (GHG) emissions (Akbarieh et al., 2020; Cottafava and Ritzen, 2021). In developing countries, the building industry contributes an even higher percentage of GHG emissions. This underscores the need to reassess the building lifecycle comprehensively.

Within this context, the building façades play a critical role in both operational energy performance and embodied carbon impacts. Although façades usually represent a smaller share of building mass compared to structural systems, they can contribute between 10 % and 30 % of total embodied emissions (Hartwell et al., 2021; Khadim et al., 2022). Their prominence in high-rise and multi-storey typologies makes them a key opportunity for applying circular design and supporting the transition to net-zero built environments (Luo et al., 2020; Wang et al., 2024). However, stricter energy regulations and rising comfort demands have driven the trend toward increasingly complex, layered, and high-performance façades. These developments have intensified embodied impacts (Hartwell et al., 2021). Systems with non-standard components, adhesives, and composite materials are often designed on

* Corresponding author. School of Architecture, Design and Planning, The University of Sydney, 148, City Road, Darlington, 2006, NSW, Australia.
E-mail addresses: Hala2855@uni.sydney.edu.au (H. Alabdulrazzaq), eugenia.gasparri@sydney.edu.au (E. Gasparri), arianna.brambilla@sydney.edu.au (A. Brambilla), shady.attia@uliege.be (S. Attia).

https://doi.org/10.1016/j.jclepro.2025.147140
Received 18 December 2024; Received in revised form 9 November 2025; Accepted 17 November 2025

a cradle-to-grave basis, with limited consideration for reuse or recovery (Askar et al., 2021). Compared with structural or foundational systems, façades are replaced more frequently, typically every 20–25 years due to functional wear or aesthetic obsolescence. In contrast, structural and foundation layers usually last the entire building's lifespan (Cheong et al., 2024; Hartwell et al., 2021). Façade assemblies also integrate metals, polymers, wood, and coatings, making them materially complex and more difficult to separate or recycle (Bedon et al., 2019; M.ElBatran and Ismaeel, 2021; Orlowski, 2020). The widespread use of adhesives, fire retardants, and synthetic coatings creates permanent bonds or toxic residues that hinder disassembly (Hartwell et al., 2021; Leiden et al., 2020; Mendy et al., 2023). Connection types further influence circular potential. Dry connections, such as bolts, allow for disassembly and reuse. Wet connections, like cast-in-place concrete, often damage components during removal (Atta et al., 2021; Cogurcu and Uzun, 2022; Liu et al., 2024; Ma et al., 2023). These characteristics make façades both a challenge and a high-leverage opportunity for circular intervention. This justifies their focus in this study (Ghorbany et al., 2025; Patterson, 2022; Roberts et al., 2023; Sandak et al., 2020).

Despite the growing importance of circular economy (CE) strategies in construction, their application to façades remains underdeveloped. While CE principles have been increasingly applied at the building scale, façade-specific lifecycles, material complexity, and disassembly challenges are not captured by existing frameworks or indicators (Bocken et al., 2016; Hartwell et al., 2021). Currently, there is no clear definition of a "circular façade" nor standardised protocols for its implementation. Existing key performance indicators (KPIs) are fragmented and general. In addition, lifecycle performance and system integration of circular façade systems are under-quantified. Current policies and standards are too general, leaving a gap in façade-level applications. Altogether, these shortcomings highlight the absence of a coherent framework that unifies CE principles, façade-specific strategies, and KPIs. This framework draws upon elements of previously published methods and initiatives, adapting them for façade-specific evaluation. Building on these gaps, this study investigates the following research question: **How can design strategies and KPIs be systematically integrated into a framework tailored to circular façade design?**

To address this question, the study pursues three objectives:

- Develop a façade-specific framework that integrates CE principles, design strategies, and KPIs into a unified assessment and guidance tool.
- Demonstrate the framework's application through a case study of a unitised curtain wall system.
- Highlight the framework's potential for guiding early-stage design decisions, improving circularity performance, and supporting lifecycle-based evaluation.

The following sections introduce CE in construction (1.1), discuss façade-specific challenges (1.2), and review existing frameworks and KPIs (1.3).

1.1. Circular economy in construction

In contrast to a linear model, the circular economy (CE) seeks to replace the traditional "take-make-dispose" approach. CE keeps resources in use for as long as possible through recycling, reusing, and regenerating materials. In buildings, this means designing with the entire lifecycle of materials in mind. It minimises waste and environmental impact through improved resource management (Hartwell et al., 2021). By applying CE principles to building design, the construction sector can significantly reduce embodied carbon. It can also promote the reuse and recycling of materials, contributing to the sustainability of the built environment (Stahel, 2016).

An essential first step is to understand the key definitions of CE clearly. Kirchherr et al. (2017) examined 114 CE definitions and identified the most diffused, credited to the EMF (2015): "An industrial system that is intentionally and effectively restorative or regenerative. This definition replaces the 'end-of-life' concept with restoration, transitions to using renewable energy, eliminates harmful chemicals that hinder reuse, and strives to reduce waste through improved design of materials, products, systems, and business models." Another widely cited definition describes CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by narrowing, slowing, and closing material and energy loops" (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Stahel, 2016; van Stijn et al., 2022). Bocken et al. (2016) advanced understanding of CE by categorising design strategies into circular design principles. These principles provide a structured approach to managing resource flows more sustainably across the product lifecycle. They identified three key approaches within these principles. Narrowing loops aims to minimise resource use through efficiency. Slowing loops focuses on extending product lifespan through durability and reuse. Closing loops involves recycling materials back into production at the end of their lifecycle (Bocken et al., 2016; Caldas et al., 2022; Stahel, 2016; van Stijn et al., 2022). These principles serve as the baseline for façade-focused investigations, where circularity encounters unique material and lifecycle challenges.

1.2. Circularity in façade systems

Research on Circular Façade Design (CFD-F) has gained momentum in response to growing concerns over resource depletion, waste generation, and embodied carbon in the built environment. Façades play a central role in this discourse. They influence not only operational performance but also material intensity and the potential to support circular economy (CE) objectives. Hartwell et al. (2021) emphasise CFD-F's importance in reducing embodied carbon and improving material efficiency. They highlight strategies such as design for disassembly, modularity, and the reuse of façade elements. However, implementation remains limited. The lack of standardised design-for-disassembly protocols and the complexity of separating multi-material assemblies are persistent barriers. Façades are also often replaced for aesthetic rather than technical reasons, contributing to avoidable material waste.

A further challenge is the absence of guidance and incentives for architects and clients to integrate circular principles early in the design process. van Stijn et al. (2022) examined comparative LCA and MFA data on modular and bio-based façades. Their results demonstrate clear environmental benefits through reduced use of virgin materials. However, their study—and others—highlight persistent gaps in assessing long-term circular impacts, particularly in terms of embodied energy and the complexity of reuse. Gulck et al. (2021) developed a façade circularity assessment method focused on early-stage design. Mazzoli et al. (2022) evaluated modular PREFAB versus traditional ETICS systems. They demonstrated the higher circular potential of prefabricated solutions. However, lifecycle performance remains under-quantified, and system integration is underexplored. Despite these contributions, a clear and agreed-upon definition of a "circular façade" remains undefined. The industry also lacks consensus on structuring façade-level circularity and measuring outcomes through standardised design strategies or performance metrics. While these studies advance the field, they remain fragmented. A systematic framework linking strategies, KPIs, and lifecycle stages is missing.

1.3. Existing frameworks and KPIs

Several initiatives provide a foundation for circular design in the construction industry. The Ellen Machado and Morioka (2021) defines CE principles and business models, but offers only high-level guidance, without operational details at the façade or component levels. This gap in operational detail at the façade and component level highlights the need for frameworks that translate high-level CE principles into measurable, actionable strategies with clearly defined KPIs for façade systems. The BAMB (Buildings As Material Banks) project introduced tools such as material passports and reversible design protocols (BAMB, 2016). However, it was developed mainly at the whole-building scale, with limited façade-specific KPIs. Its tools remain focused on general material/component data, leaving a lack of façade-specific protocols, KPIs, or metrics for measuring disassembly and reuse potential. Transitioning from traditional façade systems to CFD-F requires a shift in both product configuration and design approach. Gasparri et al. (2022) argue in Rethinking Building Skins that façades should be viewed as continuous elements of the building lifecycle rather than discrete architectural features. This view aligns with the circular lifecycle stages proposed by the CIRCuIT project, which categorises strategies across materials, parts, and components (see Fig. 1) (Cartwright et al., 2021). Table 1 summarises these lifecycle categories.

While Klein (2013) model captures the traditional linear process; the CIRCuIT framework and Gasparri's lifecycle perspective provide a strong foundation to advance CFD-F. These models highlight the importance of system-level strategies that reduce environmental impact, promote reuse, and support long-term resource efficiency. However, operationalising lifecycle mapping into practical design strategies and measurable performance indicators for façades remains an unresolved challenge.

Although CIRCuIT offers a strong conceptual foundation, its strategies remain general and lack measurable indicators tailored to façades. This reflects a broader gap across existing frameworks. EMF sets principles, BAMB focuses on building-scale tools, and CIRCuIT provides lifecycle mapping. Yet none of these offer a façade-specific framework that integrates CE principles, design strategies, and quantifiable KPIs.

Key Performance Indicators (KPIs) in architecture are essential for evaluating how well a design, system, or process meets CE goals. This study adopts the definition of KPIs from Chan and Chan (2004), who describe them as tools for measuring and tracking progress toward objectives. Similarly, Shear et al. (2003) and OECD (2014) define indicators as variables—quantitative or qualitative—that reflect change, impact, or performance across interventions. Several studies have reviewed KPIs for circularity in the built environment. Parchomenko et al. (2019) grouped 63 CE indicators into three themes: resource efficiency, material flows, and product-focused metrics. They also highlighted gaps in addressing value retention. Saidani et al. (2019) compiled 55 indicators and categorised them by circularity level (micro, meso, macro). However, they noted limited consistency across sectors. Kristensen and Mosgaard (2020) analysed 30 product-level indicators and found that most focused on end-of-life management, with less emphasis on disassembly or lifetime extension. Façade-specific studies have also emerged. Gulck et al. (2021) developed an early-stage façade assessment method with six parameters, including component dependency and flexibility for reuse. However, the study assumed static lifespans and did not consider reuse cycles. Shevchenko and Cluzel (2023) proposed the Circular Product Design (CPD) Toolkit with design diagnostics, but real-world testing is still limited. Mazzoli et al. (2022) evaluated PREFAB versus traditional ETICS systems and concluded that PREFAB systems better supported circularity, though lifecycle integration was not fully explored.

Table 1
Circular lifecycle stage categories, based on (Cartwright et al., 2021).

Lifecycle stage	Definitions
Design	This category includes any indicators that influence the design of the building, specifically at the levels of the building, products, materials, and components.
Materials input	This category describes any indicators influencing the cradle-to-gate stage buildings and products/materials/components.
Lifespan and in-use performance	These indicators assess how efficiently value is extracted and how waste is avoided during the in-use phase of materials in products, buildings, or building stocks (cities).
Circular Potential	These indicators demonstrate the potential for in-use products or buildings to retain the value of materials and minimise waste.
Outflows and recirculation	These indicators measure the actual quantities and fates of materials that emerge at the end-of-life stage within a building.

From a policy perspective, the Level(s) framework, developed by the European Commission, introduces CE indicators across lifecycle stages and scales. Indicators such as 2.3, "Design for adaptability and renovation," and 2.4, "Design for deconstruction, reuse and recycling," are highly relevant to façades. These systems need modularity, flexibility, and disassembly to enable material circularity (Dodd et al., 2017). However, Level(s) remains general and lacks detailed guidance at the component level, particularly for complex façade assemblies where modularity and reversibility are critical. ISO 59020 (2024) offers a standardised framework for circularity assessment through three stages: boundary setting, data collection and indicator selection, and circularity evaluation. The standard includes indicators for inflows (e.g., recycled or renewable content) and outflows (e.g., reuse or recyclability rates). While useful for broad CE measurement, ISO 59020 lacks the specificity and adaptability required for evaluating complex, layered façade systems, where material interactions and reversibility significantly impact

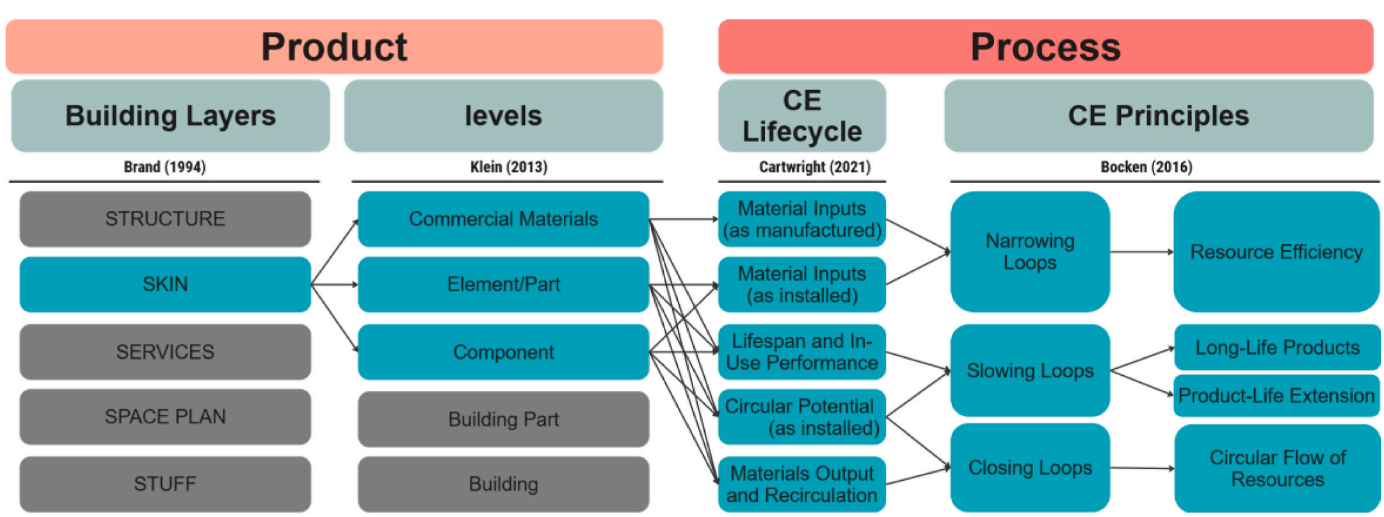


Fig. 1. Integrated mapping of Product and Process dimensions for façade circularity, showing building layers (Brand, 1994) linked to product levels (Klein, 2013), circular economy lifecycle stages (adapted from Cartwright et al., 2021), and CE principles (Bocken et al., 2016).

circular potential. These gaps are synthesised in Table 2. These shortcomings across frameworks and KPIs highlight the need for a coherent Circular Façade Design Framework (CFD-F). Such a framework must integrate CE principles, façade-specific strategies, and measurable indicators across lifecycle stages.

This paper follows this structure: Section 1 introduces the topic and provides background; Section 2 outlines the research methodology; Section 3 presents the data analysis and discusses the results and implementation example; Section 4 concludes the paper, highlights the study's limitations, and discusses opportunities for future direction.

2. Methodology

This study adopts a hybrid review methodology to provide a comprehensive understanding of the Circular Façade Design Framework (CFD-F). It combines the strengths of different literature analysis techniques. The rationale for this hybrid approach comes from the fragmented and diverse nature of existing research on circular economy (CE) principles, especially when applied to façades and building layers (Fink, 2019). Systematic reviews offer rigour and transparency but rely on narrow search terms and database results. Scientometric analysis provides insights into research trends, but may overlook detailed content analysis (Fisch and Block, 2018). To overcome these limitations, this study integrates document screening, scientometric analysis, and a systematic literature review (SLR). This combination ensures breadth and depth of analysis, while maintaining transparency and reproducibility (Moher et al., 2015; Page et al., 2021). The adoption of this hybrid methodology was essential for several reasons:

- Limited façade-specific literature: Existing work on CFD-F is limited. Expanding the scope to include building layers enabled a more robust analysis while keeping relevance to façade systems.
- Need to capture quantitative and qualitative insights: Scientometric analysis revealed research evolution, trends, and keyword co-occurrence. The SLR supported an in-depth content analysis of CFD-F strategies and KPIs.
- Mapping strategies across lifecycle and product levels: Developing the CFD-F framework required a structured understanding of where and how strategies are applied — at the material, part, or component level — and across different lifecycle stages.

This hybrid methodology enabled a rigorous and systematic analysis of circularity in façades. It identified research gaps, system-level challenges, and opportunities for developing façade-specific circular design strategies and measurable KPIs.

2.1. Document screening

The document screening process focused on Circular Economy (CE) topics relevant to façades and building layers, circular design strategies, and performance indicators. The aim was to compile a dataset that shows how circular principles are applied to façades, particularly in relation to design strategies and measurable performance metrics. The screening targeted English-language publications and used three primary databases. Scopus was chosen for its extensive coverage and strong bibliometric features (Baker et al., 2021; Kumar et al., 2022). Web of Science was valued for its indexing accuracy and access to historic literature (Lee et al., 2024). Google Scholar was used as a supplementary source to capture grey literature not indexed elsewhere (Farooque et al., 2019). Using this combination reduced bias and ensured both breadth and depth in the dataset (Fink, 2019; Moher et al., 2015). The review covered the period from 2016 to June 2023. The starting point corresponds to the Paris Agreement in 2016, which accelerated the adoption of CE principles in the built environment (UNFCCC, 2015). The endpoint reflects the cut-off date of this study.

Search queries were developed around four themes: Circular Economy, building façades and layers, design, and performance indicators. Queries used Boolean operators and wildcard symbols to maximise relevance and scope (see Table 3 for detailed keyword categories). The inclusion criteria prioritised publications that explicitly addressed CE at the building level with reference to façades or building layers. Studies had to discuss design strategies or measurable Key Performance Indicators (KPIs) and be published in English within the specified timeframe. The exclusion criteria removed documents outside the defined language or time window. Studies focused on unrelated domains, such as urban metabolism, generic LCA-only research, or energy modelling without circular design, were excluded. Additionally, foundational texts, including international standards and key government policies, were manually added to enhance coverage. This initial screening generated a working dataset of relevant publications. It was later refined through the systematic review process described in Section 2.3.

2.2. Scientometric review

The scientometric review employed statistical methods to explore research trends related to CE strategies for CFD-F and associated KPIs. Publications were systematically organised using EndNote. Keyword co-occurrence maps were generated in VOSviewer to visualise frequently

Table 3
Search strategy: Key areas and keywords.

Category	keywords
Circular Economy	"Circular economy," "Circularity," "Circular Design," and "Design waste"
Façades and building layers	"Façade," "Building Envelope," "Built Environment," and "Building"
Design Strategies	"Design strategi*," "guideline*," "Design for Disassembly," "Design out waste," "Design for modularity," "Design for adaptability," "Design for reuse," "Design for X," "DFX," and "DFD,"
Performance Indicators	"Assessment," "tool*," "indicator*," and "KPI*"

Table 2
Comparison of major frameworks for circular design and assessment.

Framework	Scope	Lifecycle Coverage	KPIs Provided	Façade Applicability	Key Limitation
EMF (2015)	Whole-building, business models	Conceptual, design to end-of-life	No explicit KPIs	Indirect	Too general; lacks façade-specific operationalisation
BAMB (2016)	Whole-building, materials, products	Full lifecycle (RBD, material passports)	General (non-façade-specific) indicators	Indirect	Whole-building tools; no parameters for façade disassembly
CIRCuIT Cartwright, (2021)	Materials, parts, components	Lifecycle mapping (reuse, recycling)	No façade-specific KPIs	Partial	Strong conceptual base, but lacks measurable façade indicators
Level(s) (2017)	EU policy framework, whole-building	Lifecycle indicators	Yes, but broad (e.g., adaptability, deconstruction)	Indirect	Indicators not tailored to multi-layer façade assemblies
ISO 59020 (2024)	Cross-sector standard	Three-stage circularity assessment	Core inflow/outflow indicators	Indirect	Too broad; cannot capture layered façade complexity or reversibility

used terms such as "Circular Economy," "Design Strategies," "Building Layers," and "KPIs (van Eck and Waltman, 2010). These visualisations offered insight into recurring themes and the evolution of CFD-F research. Microsoft Excel was used to chart publication trends from 2016 to 2023. The results showed a notable increase in research activity, likely driven by the evolution of sustainability regulations and CE-related policy frameworks. The scientometric analysis provided a clear overview of key developments and recurring themes. It also supported the development of a structured framework for CFD-F.

Including scientometric analysis alongside the SLR added value by quantitatively mapping the research landscape and identifying influential themes. Network visualisations revealed connections between design strategies, CE principles, and lifecycle stages. For example, "design for disassembly" often appeared with modularity and pre-end-of-life recovery strategies. This deeper insight into thematic relationships and research gaps informed the development of façade-specific KPIs. It also strengthened the link between literature patterns and the framework structure.

2.3. Systematic review

This study adopts a systematic literature review (SLR) approach to examine CFD-F strategies and KPIs related to façade systems. The process followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure reliability and transparency (Page et al., 2021). The screening process is shown in Fig. 2 and summarised in Table 4. In total, 418 records were initially identified (Scopus: 316; WoS: 102). After removing duplicates and screening, 136 full texts were assessed. Of these, 43 were excluded for not meeting the inclusion criteria (e.g., not façade-focused or lacking strategies/KPIs). To supplement peer-reviewed sources, 29 grey literature documents (e.g., websites, government reports, standards, and organisational publications) were added. This resulted in a final dataset of 122 publications (93 from database screening and 29 from grey literature).

Table 4
Summary of the screening and selection process (PRISMA steps).

Category	keywords	
Identification	Records identified: Scopus (316), Web of Science (102)	418
Duplicates	Removed	31
Screening	Titles/abstracts screened; excluded for not addressing façades or CE design (e.g., urban metabolism, LCA-only, energy modelling)	387 screened → 251 excluded
Eligibility	Full-text articles assessed; excluded: not façade/building layer (14), no design strategies or KPIs (29)	136 assessed → 43 excluded
Other sources	Grey literature: websites (3), government reports (4), standards (1), organisation reports (4), citation search (17)	29
Final dataset	**Publications included (93 from screening + 29 grey)**	**122**

Formal saturation testing was not conducted. However, the final 122 studies encompassed the full range of strategies and KPIs across the CE and façade literature. This provided a robust evidence base while avoiding redundancy. Screening and coding were conducted by a single reviewer, which may introduce bias. Clear inclusion/exclusion rules, as well as coding categories, were applied to enhance consistency.

Publications were manually categorised based on their primary contribution. Categories included circularity principles, lifecycle stages, design strategies, performance indicators, and case studies supporting validation. This ensured that literature relevant to façade layers and circularity was represented, even when not explicitly labelled as CFD-F. The refined dataset enabled detailed content analysis, which informed the development of the CFD-F. By grounding its findings in both peer-reviewed and grey literature, the review strengthens the validity and applicability of the proposed circular strategies and KPIs.

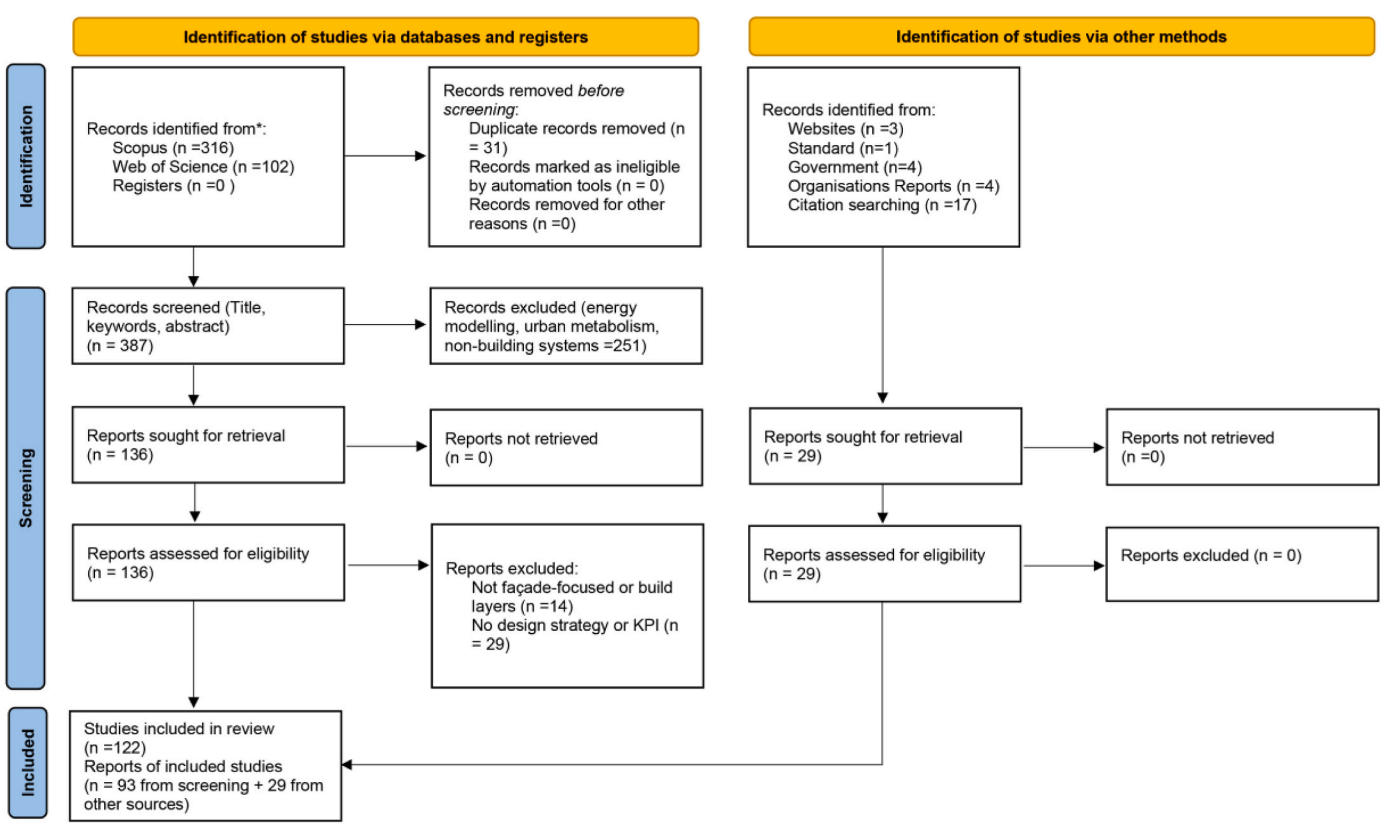


Fig. 2. The Systematic Search Process, Detailing the Steps of Identification, Screening, and Inclusion. Adapted from PRISMA 2020 guidelines (Page et al., 2021).

2.4. Conceptual framework for article classification

This section outlines the methodological structure used to evaluate and categorise literature related to CFD-F. The aim is to systematically classify existing research based on key themes that contribute to the development of CFD-F strategies and façade-specific Key Performance Indicators (KPIs). The analysis is structured around two dimensions: Product and Process. These are adapted from the classification model proposed by Gasparri et al. (2022).

The product dimension focuses on the structural characteristics of the façade system. It covers four core building layers: structure, skin, services, and space planning (Brand, 1994). Within each layer, design strategies are identified at three façade product levels—materials, parts, and components. This clarifies where and how circularity is embedded in façade systems (Cartwright et al., 2021; Klein, 2013; van Stijn and Gruis, 2020). The classification highlights whether strategies such as disassembly or modularity are applied at the material, part, or component level. The process dimension addresses the lifecycle perspective. It emphasises the transition from linear to circular methodologies. Articles are classified into two categories within this dimension:

- CE Principles: Research is mapped against the CE strategies of narrowing, slowing, and closing loops, as defined by Stahel (2016), Bocken et al. (2016) and Moreno et al. (2016). This enables evaluation of how each study applies these principles during the design, use, and end-of-life phases.
- Circular Lifecycle Stages: Design strategies and KPIs are classified into five key stages: Material Inputs (as manufactured and installed), Lifespan and In-Use Performance, Circular Potential (pre-end-of-life), and Outputs and Recirculation. These categories draw from Cartwright et al. (2021), Gasparri et al. (2022), and Klein (2013) They align with the lifecycle scope of the CFD-F framework developed in this study.

Coding criteria were explicitly applied:

- A design strategy was coded if the study described a specific design action (e.g., design for disassembly, modularity, adaptability, reuse).
- A KPI was coded if it provided a measurable or quantifiable indicator (e.g., recyclability index, % recovery, service-life extension).
- A principle was coded if the study explicitly linked strategies or KPIs to CE loop logic (narrow, slow, close).
- Each publication could be assigned to multiple categories when relevant.

Coding was performed using ATLAS.ti and Excel, ensuring consistent tagging across the product–process dimensions (ATLAS.ti Scientific Software Development GmbH, 2023). Results were then integrated by linking categories conceptually (CE principle → lifecycle stage → strategy → KPI). This systematic mapping clarified how strategies and indicators operationalise circularity in façades. Finally, definitions of "circular façade" were examined. Where inconsistencies appeared, a unified definition was proposed to guide future research and practical application.

3. Results

3.1. Scientometric review results

The scientometric analysis using VOSviewer provided essential insights into the current research landscape on the circular economy (CE) within the built environment. The analysis focused on CFD-F strategies, key performance indicators (KPIs), and façade-related research. This

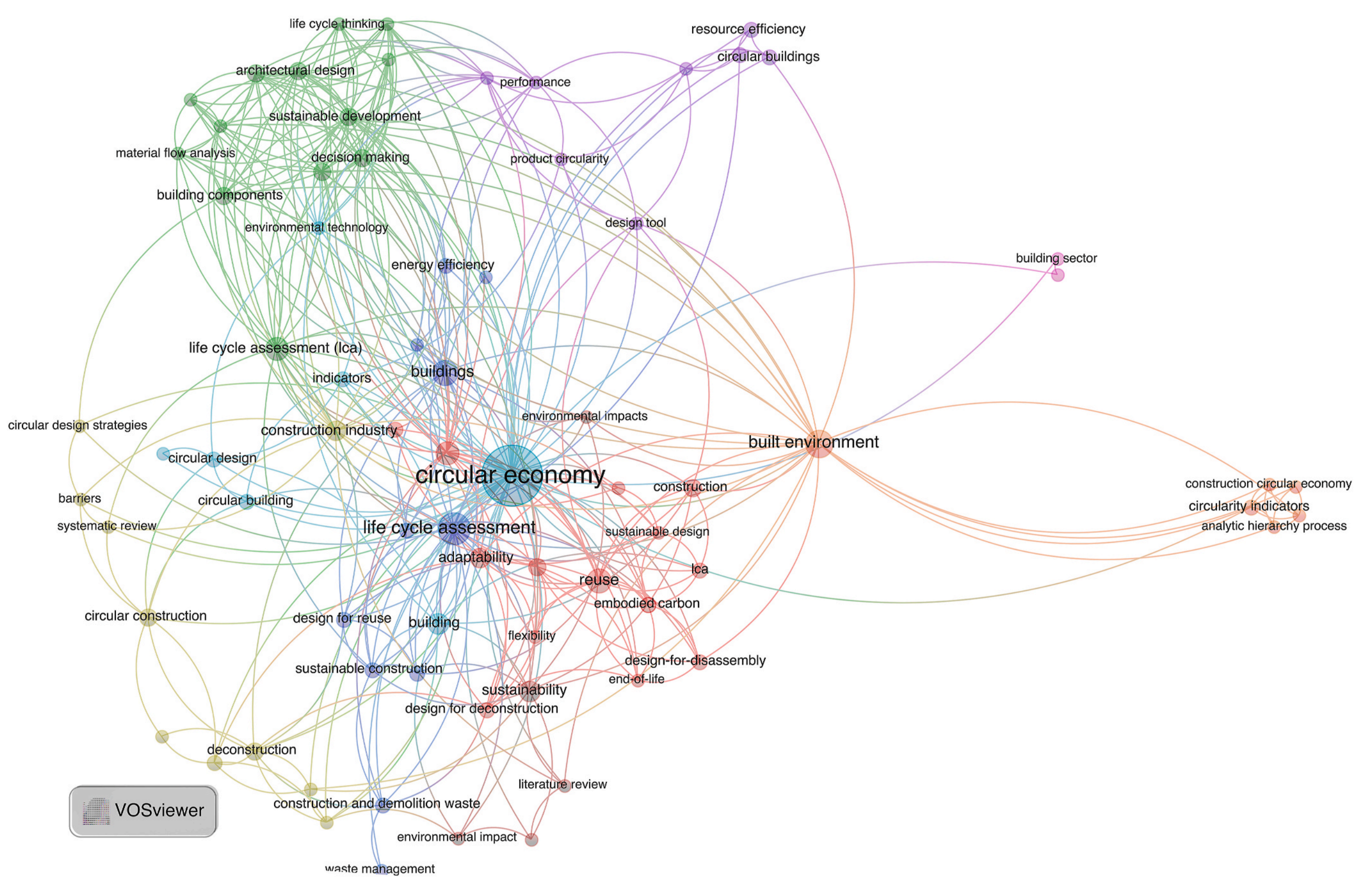


Fig. 3. Keyword Co-occurrence analysis of bibliometric data from all publications, visualised using VOSviewer (van Eck and Waltman, 2010).

keyword co-occurrence analysis identified core themes, emerging design strategies, and performance indicators. These directly informed the development of the CFD-F framework presented in this study. Fig. 3 visualises the bibliometric data of all reviewed publications through VOSviewer software. It highlights central keywords and their relationships based on co-occurrence (van Eck and Waltman, 2010). The size of each node reflects the frequency of a keyword. The thickness of the connecting lines shows the strength of their co-occurrence. The thematic clustering of keywords reflects the major focus areas in CE research. This provided a critical basis for structuring the CFD-F framework, including its lifecycle stages, design strategies, and KPIs.

Central keywords such as "circular economy," "lifecycle assessment," "environmental impact," and "sustainability" dominated the literature. They underscore the importance of minimising environmental impacts across all lifecycle phases of materials and building systems. The prominence of terms like "design for disassembly," "adaptability," and "modularity" directly supported the inclusion of specific design strategies within the CFD-F framework. These were particularly linked to extending product life and facilitating future reuse and recycling.

The frequent appearance of terms such as "low-carbon materials," "eco-design," and "building envelope" emphasised the growing research interest in resource-efficient design and innovative material selection. These themes informed the Material Inputs stage of the framework. They highlight strategies that reduce raw material consumption and encourage the use of recycled or bio-based resources in façade systems.

Performance metrics, represented by keywords such as "embodied energy," "embodied carbon," "resource efficiency," and "energy efficiency," informed the selection and development of KPIs across all lifecycle stages of the CFD-F framework. These KPIs aim to evaluate the environmental performance of façade materials, parts, and components, particularly their energy use, carbon footprint, and potential for reuse or recycling.

The frequent mention of "digital transformation" and "BIM" (Building Information Modelling) reflects the growing integration of data-driven processes into CE research. Digital tools such as BIM, material passports, and digital twins enable real-time data tracking, material documentation, and lifecycle monitoring. They support CFD-F strategies by tracking material flows, optimising resource use, and facilitating reuse or disassembly. In this context, digital transformation refers to the integration of digital technologies, data management tools, and intelligent systems within the building design, construction, and operation phases. Specifically, in circular economy research, it enables real-time data tracking, improved material documentation, and lifecycle monitoring. These are critical for assessing and optimising the performance of KPIs. Tools such as BIM, material passports, and digital twins are increasingly used to support CFD-F strategies. They enable designers and facility managers to track material flows, monitor resource use, and facilitate the future reuse or disassembly of façade components.

Despite the breadth of CE research, the analysis identified a significant gap in studies addressing circularity at the micro-level, specifically at the scale of façade components, parts, and materials. Terms dealing with disassembly challenges, component dependency, modular integration, or reversible connections were relatively limited. This finding reinforces the need for a dedicated framework targeting façade-specific circularity strategies and performance assessment, as proposed in this study.

This approach aligns with previous scientometric studies that applied VOSviewer to investigate CE in construction, such as Gasparri et al. (2022), Malabi Eberhardt et al. (2020), and Sala Benites et al. (2023). However, unlike those studies, this research uniquely uses keyword co-occurrence analysis to inform the operational development of a façade-specific framework. It links thematic clusters directly to design strategies, lifecycle stages, and KPIs.

Beyond thematic trends, the scientometric analysis also revealed the evolution of publication activity and key sources of publications within this field. The number of publications on CFD-F and KPIs at the micro-level (components, parts, materials) remains limited. Minimal activity occurred before the Paris Agreement at COP21 in 2015 (UNFCCC, 2015). From 2016 to 2017, the number of publications grew steadily, peaking at 28 in 2022. Notable growth occurred between 2017 and 2022, as shown in Fig. 4. A slight decline followed in 2023, with only 16 publications due to data limitations until June 2023.

Fig. 5 shows the distribution of published articles across various journals. It highlights the primary sources driving research in this field. The Journal of Cleaner Production leads with about 21 articles. Sustainability follows with around 17. The IOP Conference Series: Earth and Environmental Science ranks next with approximately nine articles, reflecting its role in disseminating environmental sciences research. Other significant journals include the Journal of Building Engineering and Resources, Conservation and Recycling, each contributing multiple articles. Journals such as Building and Environment, Energies, and Sustainable Production and Consumption are also key, highlighting the interdisciplinary nature of CE and sustainable construction research.

3.2. Systematic review results

The systematic review results are organised around five CFD-F lifecycle stages. These stages were derived through a structured categorisation process. Each stage is analysed to identify specific CFD-F design strategies and KPIs aligned with circularity principles. Appendix 1 presents the Circular Framework, including Design Strategies, Actions, and Sources, providing a detailed summary of the design strategies. Appendix 2 provides the KPIs, Indicators, CE Strategies, Methods, Quantitative Metrics, and Sources. This includes a comprehensive table of KPIs, indicators, CE strategies, methods, and quantitative metrics, along with references. Together, these appendices provide a foundational reference for assessing and tracking CE performance.

3.2.1. Material input (As manufactured)

The first stage in the CFD-F lifecycle, Material Input (as Manufactured), focuses on using materials efficiently to reduce raw resource consumption. It also prioritises materials that can return to the environment without harm. This stage supports the narrowing loop principle by promoting optimisation and sustainable sourcing. The KPIs introduced here apply to materials and provide quantitative ways to assess circularity performance. Fig. 6 visualises the relevant design strategies, KPIs, and metrics. All design strategies are summarised in Appendix 1 with their associated "Design for" actions. KPIs are detailed in Appendix 2, including indicators, CE alignment, quantitative metrics, and validation examples.

3.2.1.1. Circular façade (CF) design strategies for material input (As manufactured). This stage is guided by two key CFD-F design strategies that apply to materials. Both support long-term environmental and economic benefits. They reduce virgin input and increase regenerative sourcing. Examples from built projects are referenced in Appendix 1.

- Design for materials optimisation: This approach selects materials that meet performance requirements with minimal virgin content. It promotes lightweight, practical design using reused and recycled inputs. This reduces resource demand and waste. It is particularly relevant for façades, where high-performance materials such as recycled aluminium or reclaimed glazing increase efficiency without compromising quality. Validation examples include the Modern Methods of Construction (UK) and the Swansea Building Schools project in Wales, UK. Full source details are in Appendix 1, Row 1.
- Design for biological materials: This strategy focuses on biodegradable or renewable sources, such as timber, straw, or plant-based composites. The aim is to replace non-regenerative inputs with naturally decomposing materials that do not harm the environment. It encourages ecological integration and regenerative sourcing.

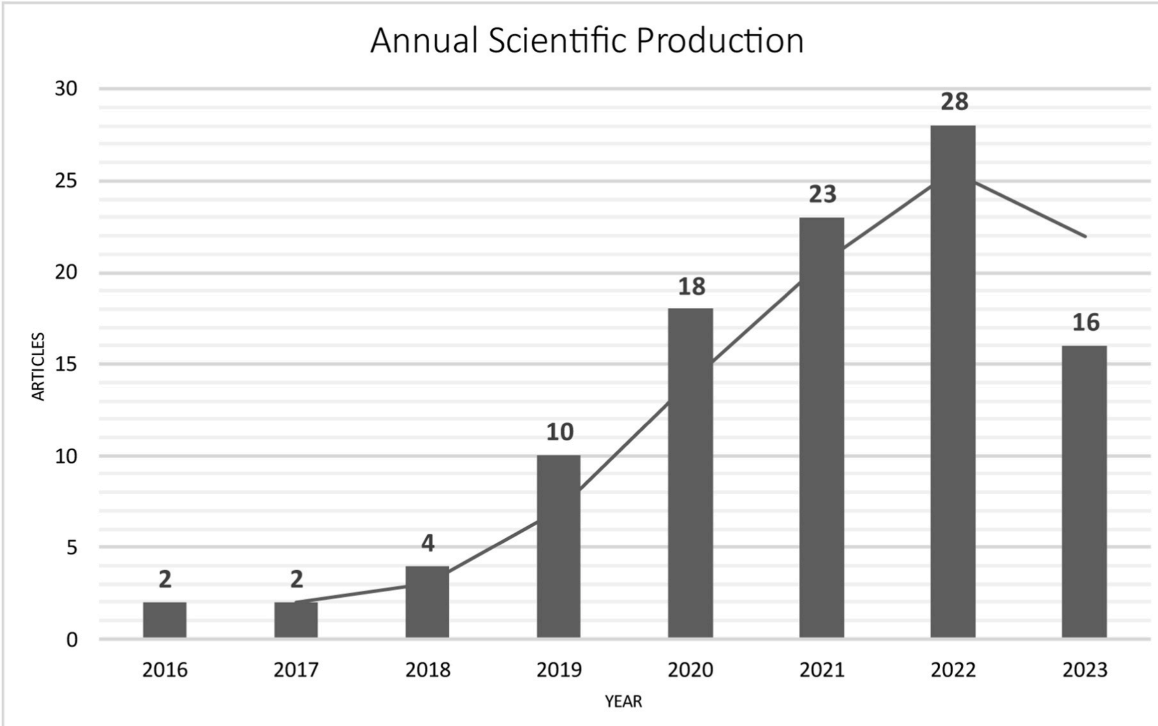


Fig. 4. Most relevant sources.

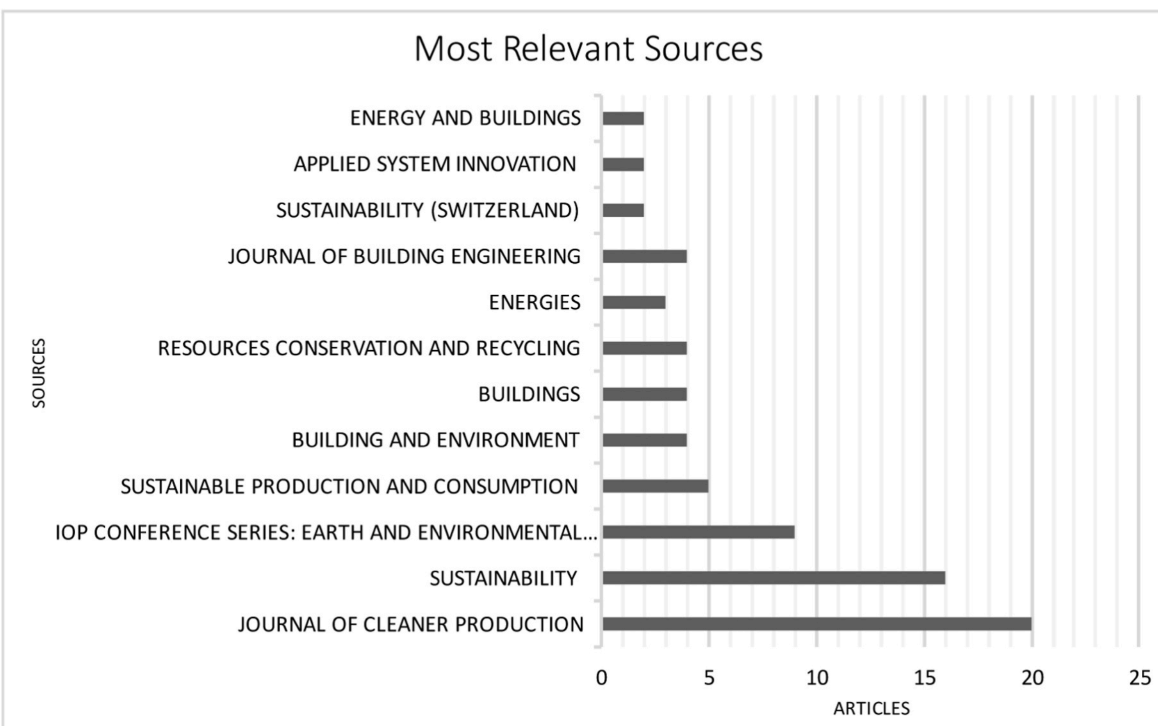


Fig. 5. Annual scientific production.

Examples include The Green House in Utrecht (Netherlands) and the Netherlands Pavilion at Expo 2020 in Dubai (UAE). Full source details are in Appendix 1, Row 2**.**

3.2.1.2. Key performance indicators (KPIs) for material input (As manufactured). The KPIs in this stage measure resource origin, regenerative sourcing, and circularity performance. They apply to materials and align with the narrowing loop principle of CE strategies. References to validation studies and ISO/Level(s) frameworks are provided in Appendix 2.1 and 2.1.1.

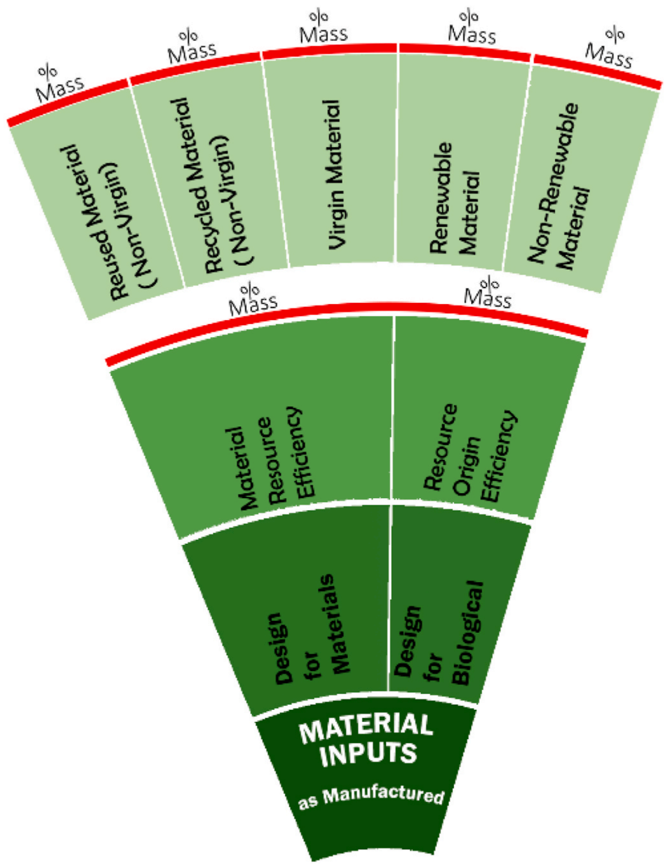


Fig. 6. Circular façade material input stage with design strategies, KPIs, and metrics.

- Material resource efficiency (assesses the design for optimisation of the material, applicable to materials): This KPI measures the proportion of non-virgin materials—reused or recycled—that enter the system. It utilises the Material Flow Analysis (MFA) method, using mass or percentage as a metric. Higher shares of reused or recycled inputs indicate greater circularity. Validation references include the Building Circularity Indicators (BCI) framework, the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation, and EU pilot building projects. Full source details are in Appendix 2.1, Row 1.

- Resource origin efficiency (assesses the origin of renewable vs. non-renewable materials, applicable to materials): This KPI evaluates the percentage of renewable input materials compared with non-renewable materials. It forms part of the MCI method and uses mass or percentage as a metric. Higher renewable content shows stronger alignment with the narrowing loop principle. The KPI is consistent with ISO 59020 and applied in MFA-driven CE assessments. Full source details are in Appendix 2.1, Row 4.

3.2.2. Material input (As installed)

The second stage of the CFD-F lifecycle emphasises the selection and integration of materials and components during façade design and assembly. It uses pre-manufactured and reusable elements to reduce site waste. These elements also enable future disassembly. This phase provides critical insights into resource optimisation, assembly efficiency, and sustainability practices during installation. Fig. 7 visualises the relevant design strategies, KPIs, and associated metrics. All design strategies are summarised in Appendix 1. The KPIs are detailed in Appendix 2.2.

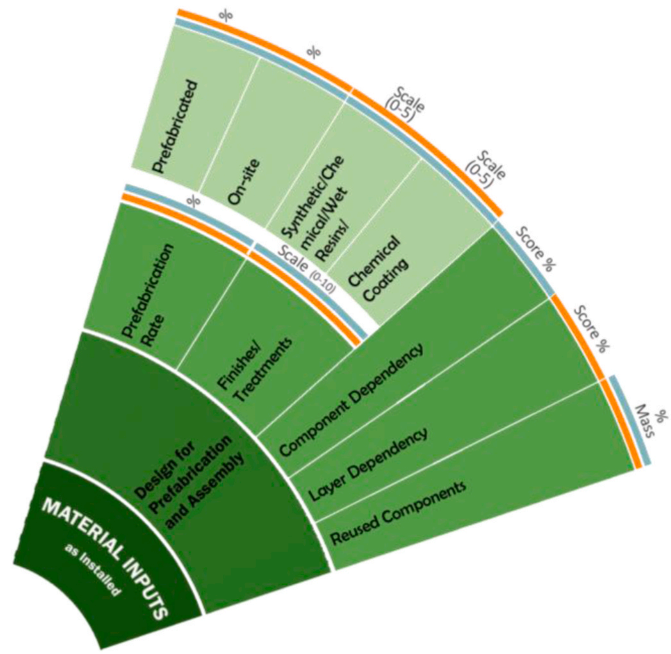


Fig. 7. Circular façade material input as installed stage with design strategies, KPIs, and metrics.

3.2.2.1. CF design strategies for material input (As installed). The CFD-F strategies in this stage guide the selection, sourcing, and installation:

- Design for Prefabrication and Assembly (components and parts): This strategy promotes modular, off-site manufactured panels. It reduces on-site construction time, emissions, and waste. It also supports the incorporation of reused elements from other projects without requiring refurbishment. The strategy aligns with CE principles of narrowing and closing loops by improving material efficiency and enabling recirculation through cleaner assembly processes. Real-world applications include the Green House in Utrecht (Netherlands) and modular schools in Amsterdam (Netherlands). Both projects used prefabricated units with low installation impact. Full source details are in Appendix 1, Row 3.

3.2.2.2. KPIs for material input (As installed). The KPIs in this stage evaluate the effectiveness of design strategies, monitor the sustainable use of materials, and assess the interdependence of façade components. Details are provided in Appendix 2.2 and 2.2.1.

- Component dependency (applicable to components): This KPI evaluates interdependence between adjacent components. A lower dependency score means components can be maintained or replaced individually. This improves flexibility and maintenance efficiency. It is assessed as a percentage based on the interaction levels of its components. Validation came from modular refurbishment case studies with varying levels of disassembly complexity. Full source details are in Appendix 2.2, Row 4.
- Layer dependency (applicable to components, parts, and materials): This KPI assesses the interconnection among material layers and parts. High-layer dependency improves maintenance by enabling access to specific layers without dismantling the entire assembly. It is calculated as a percentage using the Circular Construction Evaluation Framework (CCEF) method. Validation was based on real-life façade renovation systems that assessed layer interactions and reversibility. Full source details are in Appendix 2.2, Row 5.
- Reused components (applicable to components and parts): This KPI measures the percentage of components or parts reintroduced into

the cycle without repair or remanufacturing. Higher reuse reduces demand for new materials and promotes resource efficiency. It is measured in mass or percentage. Validation was derived from LCA-based studies that modelled reuse scenarios to assess carbon savings and service life extensions. Full source details are in Appendix 2.2, Row 6.

- Finishes/treatments (applicable to components and parts): This KPI monitors the environmental impact of component finishes and treatments. It evaluates how adhesives or coatings affect recyclability and the potential for disassembly. Minimal or eco-friendly finishes enhance material recovery and support reuse and recycling. The KPI is assessed using the CCEF method, with results expressed as a percentage. Validation was derived from four real-life façade renovation systems that applied circularity indicators to assess the ease of disassembly and environmental performance of finish strategies. Full source details are in Appendix 2.2, Row 7.

3.2.3. Lifespan and In-use performance

The third stage in the CFD-F lifecycle is Lifespan and In-Use Performance. It focuses on designing façade systems that remain functional, flexible, and efficient over an extended period of use. This stage supports the slowing loop principle by increasing durability, enabling ease of maintenance, and accommodating upgrades to prolong service life. The KPIs introduced here apply to materials, parts, and components. They provide metrics to evaluate performance, longevity, and maintainability. Fig. 8 visualises the relevant design strategies. Appendix 1 outlines each design strategy and its associated "Design for" action. All KPIs are further detailed in Appendix 2.3.

3.2.3.1. CF design strategies for Lifespan and In-use performance. This stage is guided by six CFD-F strategies applicable across all product levels. These strategies address physical durability, emotional longevity, maintenance planning, system standardisation, and future adaptability. They help extend façade performance and reduce lifecycle resource demands. Examples from built projects are referenced in Appendix 1.

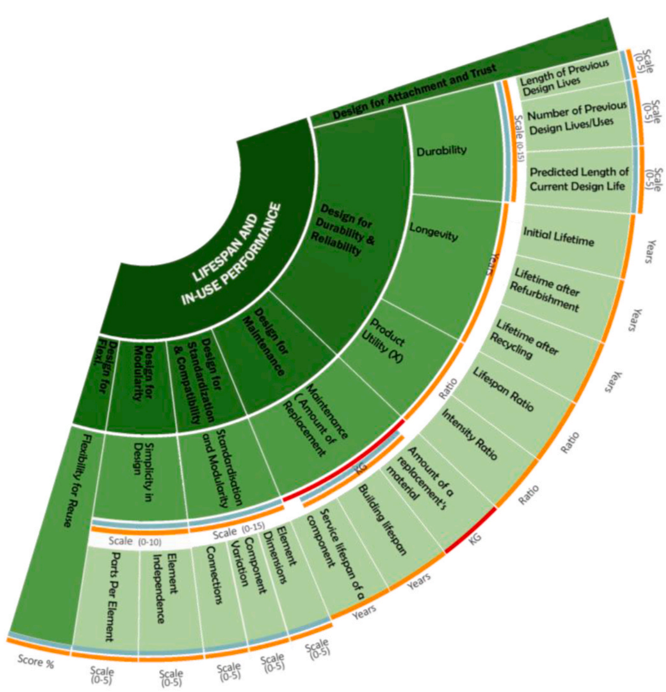


Fig. 8. Circular façade lifespan and in-use performance stage with design strategies, KPIs, and metrics.

- Design for attachment and trust: This strategy encourages emotional and aesthetic connections between users and the façade. Approaches include adopting timeless aesthetics, using meaningful design, and providing transparency of material choices. These support emotional durability and discourage premature replacement. Full source details are in Appendix 1, Row 4.
- Design for durability and reliability: This strategy focuses on selecting robust materials and construction systems that withstand wear, climate, and time. It prioritises minimal failure through weather resistance, ageing performance, and technical reliability. Examples include the Netherlands Pavilion at Expo 2020 in Dubai (UAE) and The Green House in Utrecht (Netherlands). Full source details are in Appendix 1, Row 5.
- Design for maintenance: This strategy prioritises easy access for regular cleaning, repairs, or replacements. It ensures the façade continues to function properly and extends its service life without frequent overhauls. Examples include Biosintrum in Oosterwolde (Netherlands) and the Gemeente Amsterdam building in Amsterdam (Netherlands). Full source details are in Appendix 1, Row 6.
- Design for standardisation and compatibility: This strategy uses standardised components that ensure compatibility with different systems. It allows easier installation and future upgrades. It also enhances flexibility, enabling modifications without extensive redesign. Examples include the Rogers Stirk Harbour + Partners prototype for the London Design Festival (United Kingdom). Full source details are in Appendix 1, Row 7.
- Design for modularity: This strategy emphasises independent, smaller modules to allow easy replacement or upgrading without affecting other components. It improves maintenance and flexibility. It also supports closing the loop by enabling the reuse of components and parts through disassembly. An example is Legal & General Modular Homes in Sherburn-in-Elmet (United Kingdom). Full source details are in Appendix 1, Row 8.
- Design for flexibility and upgradability: This strategy creates façades that can adapt to future changes. Future needs can be met through straightforward replacement or upgrading of materials and technology. Examples include DIRTT Project Case Studies in Canada and the United States. Full source details are in Appendix 1, Row 9.

3.2.3.2. KPIs for Lifespan and In-use performance. The KPIs in this stage assess long-term service potential, resilience to degradation, and system adaptability. They apply to materials, parts, and components, supporting the slowing loop principle of circular design. References are provided in Appendix 2.3, 2.3.1, and 2.3.2.

- Durability (focuses on design for durability and reliability, applicable to components and parts): This KPI measures a component or part's expected lifespan and reuse history. Indicators include previous design lives, duration of prior use, and predicted lifetime in a new application. It is scored using the CCEF method and presented as a cumulative score. Higher scores indicate robust components that can function over multiple cycles. Validation examples include structural reuse case studies. Full source details are in Appendix 2.3, Row 4.
- Product utility (focuses on design for durability and reliability, applicable to components): This KPI evaluates how intensively and efficiently a component is used during its service life. It combines the lifespan ratio (actual to potential use) and the intensity of use (frequency or load). It is calculated as a ratio using the MCI methodology. Higher utility scores indicate improved material productivity and a reduced environmental impact. Applications include the Environmental Assessment SYstem (EASY) Framework and the Corte Palazzo renovation project in Milan (Italy). Full source details are in Appendix 2.3, Row 1.

- Longevity (focuses on design for durability and reliability, applicable to components): This KPI measures how long a material remains in use. It considers initial lifespan, possible extension through refurbishment, and post-recycling use. Each stage is expressed in years, providing a detailed view of material retention over time. Validation comes from refurbishment pilots and façade renovation projects. Full source details are in Appendix 2.3, Row 12.
- Maintenance (amount of replacement material) (focuses on design for maintenance, applicable to materials): This KPI quantifies the mass of replacement material required over the façade's operational life. It links to façade and building service lifespans, helping assess repair frequency and efficiency. Lower replacement mass indicates better maintainability and resource conservation. It is supported by a systematic review of 65 LCA-based maintenance studies. Full source details are in Appendix 2.3, Row 8.
- Standardisation and modularity (focuses on design for standardisation and compatibility and design for modularity, applicable to components and parts): This KPI uses the CCEF method to assess uniformity in design and component compatibility. Indicators include element dimensions, component variation, and connection consistency. Higher scores indicate systems that are easier to disassemble, upgrade, or replace. Validation comes from industrialised construction case studies. Full source details are in Appendix 2.3, Row 16.
- Simplicity in design (focuses on design for standardisation and compatibility and design for modularity, applicable to components and parts): This KPI measures design complexity based on the number of parts per element and the independence of elements. It is scored using the CCEF method (out of 10). Simpler, more modular designs score higher because they are easier to maintain and reuse. Examples are drawn from modular renovation projects and Case Validation – 4 Buildings. Full source details are in Appendix 2.3, Row 20.
- Flexibility for reuse (focuses on design for flexibility and upgradability, applicable to components and parts): This KPI evaluates how well systems or components can be adapted for future reuse. It considers form, connection reversibility, and integration potential. Higher scores indicate systems that support disassembly and reconfiguration. Validation comes from façade pilot project assessments. Full source details are in Appendix 2.3, Row 23.

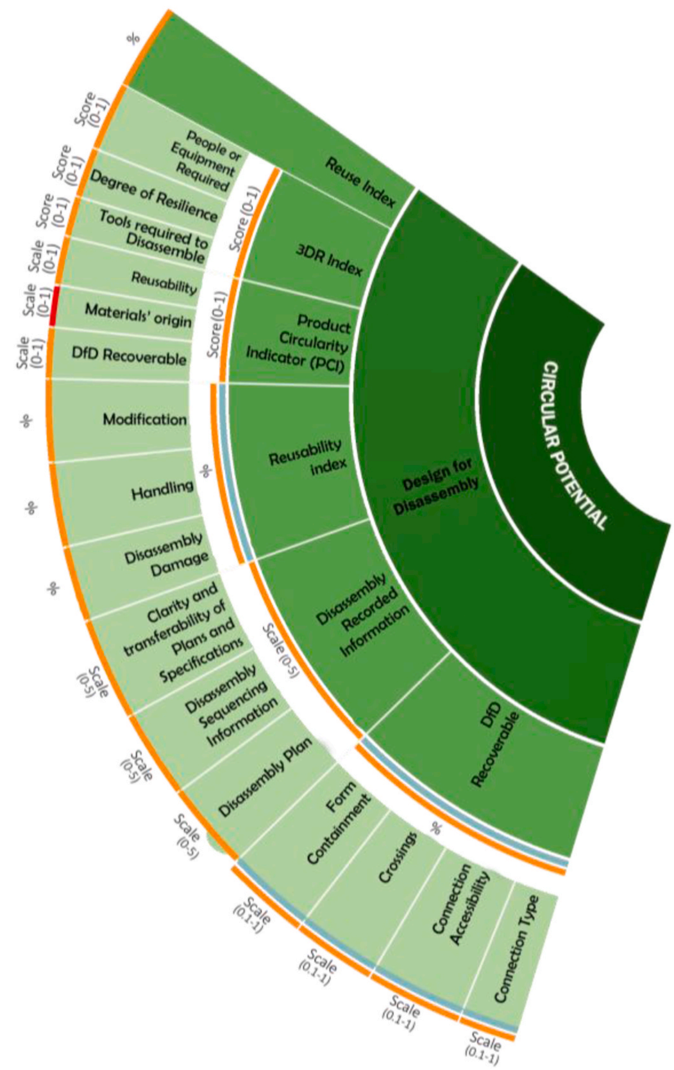


Fig. 9. Circular façade potential stage with design strategies, KPIs, and metrics.

3.2.4. *Circular potential (As installed)*

The fourth stage in the CFD-F lifecycle, Circular Potential (as Installed), focuses on designing façade systems to preserve material value at the end of life. This stage supports the closing and slowing loop principles by ensuring components and parts can be easily recovered, reused, or recycled. These measures extend their lifecycle. The aim is to maximise circularity before materials exit the system. Fig. 9 visualises the relevant design strategies. Appendix 1 outlines each design strategy and its associated "Design for" action. All KPIs are detailed in Appendix 2.4.

3.2.4.1. CF design strategies for circular potential. This stage is supported by a key CFD-F design strategy that applies to components and parts. It enhances circular potential by prioritising reversible assemblies and maintaining documentation to enable future disassembly and reuse. This strategy directly contributes to slowing and closing material loops, aligning with the end-of-life stage of the façade lifecycle. Examples from real-world applications are referenced in Appendix 1.

- Design for disassembly: This strategy enables the non-destructive removal of components and panels, supporting their reuse or recycling. It uses modular assemblies, dry mechanical joints, accessible fasteners, and reduced crossings between components. The strategy contributes to slowing loops by supporting extended use. It also supports closing loops by enabling recirculation at the end of life. Examples include Circle House in Aarhus (Denmark), Venlo City Hall in Venlo (Netherlands), and the Arup Circular Building in London (United Kingdom). Full source details are provided in Appendix 1, Row 10.

3.2.4.2. KPIs for circular potential. The KPIs in this stage assess recoverability, readiness for reuse, and the quality of documentation. They apply to materials, parts, and components. Together, they support the circular economy's principle of a closed loop. References to validation studies and benchmarking tools (e.g., ISO 59020, BCI) are noted in Appendix 2.4, 2.4.1, and 2.4.2.

- DfD recoverable (applicable to components and parts): This KPI measures the ability of components to be disassembled and recovered without damage. It uses mass or percentage as a metric. Indicators include the type of connection (mechanical fasteners are preferred), connection accessibility (non-destructive access), crossings (with minimal intersections), and form containment (ease of handling). High recoverability indicates stronger alignment with CE strategies. Validated in the Circular Biobased Construction Industry (CBCI) Living Lab in Ghent (Belgium) and across eight demonstrator projects in Belgium, the Netherlands, and France. Full source details are in Appendix 2.4, Row 1.

- Disassembly recorded information (applicable to components): This KPI assesses the presence and quality of disassembly documentation using the CCEF method with a scoring metric. Indicators include a disassembly plan, step-by-step sequencing, and transferability to other projects. Well-documented processes facilitate safe and efficient recovery. Validated through four pilot projects. Full source details are in Appendix 2.4, Row 6.
- Reuse Index (applicable to components): This KPI evaluates the potential to extend component lifespan based on its ability to be reused with minimal adaptation. It reflects the effectiveness of modularity and robustness strategies. Higher values indicate longer reuse cycles and better lifecycle performance. Applied across comparative case studies on structural reuse. Full source details are in Appendix 2.4, Row 18.
- Reusability index (applicable to components): This KPI measures the potential for reusing components after disassembly, expressed as a percentage. It considers three indicators: disassembly damage (the risk of breakage during removal), handling durability (the ability to withstand transport and storage), and modification requirements (the adjustments needed for reuse). Validated using 63 CE metric mappings. Full source details are in Appendix 2.4, Row 19.
- Product circularity indicator (PCI) (applicable to components): This KPI, developed using the BCI method, evaluates circularity based on disassemblability, material origin, and end-of-life potential. Higher PCI values reflect a better circular design. It supports consistent CE measurement across lifecycle stages. Case studies include Italian steel-frame systems in Milan (Italy) and façade benchmarking pilots in Brussels (Belgium). Full source details are in Appendix 2.4, Row 14.
- Three-Dimensional Recovery (3DR) index (applicable to components and parts): This KPI quantifies circular potential by integrating three sub-indices: disassemblability (ease of separation), deconstructability (reusability of whole systems), and resilience (capacity for multiple use cycles). It is measured as a composite score. Higher values indicate stronger retention of end-of-life value. Validated through the Legacy Living Lab in Perth (Australia) and other pilot projects across Australia. Full source details are in Appendix 2.4, Row 10.

3.2.5. Material Output and Recirculation

The final stage in the CFD-F lifecycle, Material Output and Recirculation, focuses on enabling components, parts, and materials to retain value at end-of-life. This stage supports the closing loop principle by maximising reuse, recyclability, and recoverability. These actions help reduce landfill waste and improve resource efficiency. Fig. 10 visualises the relevant design strategies, KPIs, and their metrics. Appendix 1 outlines each design strategy and its associated "Design for" action. All KPIs are detailed in Appendix 2.5, 2.5.1, and 2.5.2.

3.2.5.1. CF design strategies for Material Output and Recirculation. The following CFD-F strategies apply to materials, parts, and components, aiming to retain value at the end of life through circular reintegration. These design strategies contribute to the output lifecycle stage and align with the closing loop. Examples from real-world façade systems are referenced in Appendix 1.

- Design for reuse: Select components and materials that can be directly recovered and reintegrated into new façade systems without reprocessing. Reused components are typically reintroduced at the material input (installed stage). Reused materials enter the material input (manufactured stage). This strategy supports long-term resource conservation and reduces environmental impacts. Examples include the Velodrome in London (UK) and the Quay Quarter Tower in Sydney (Australia). Full details are in Appendix 1, Row 11.

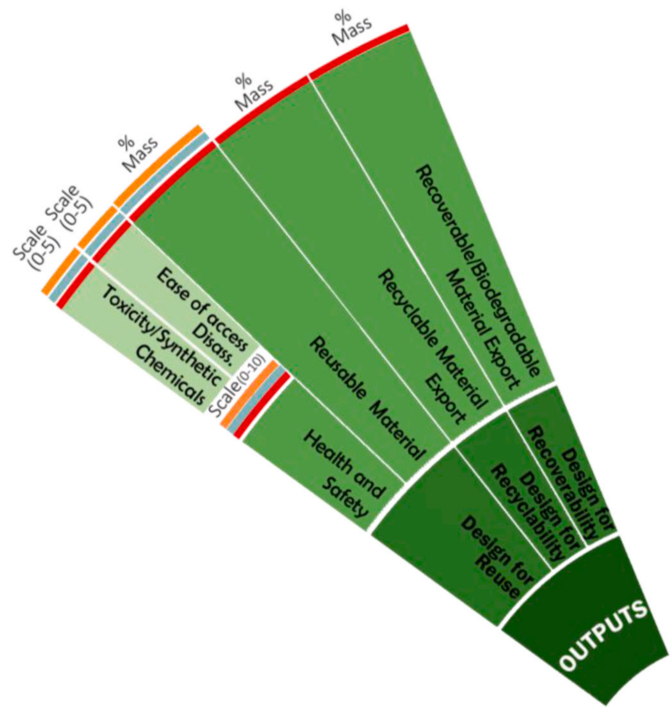


Fig. 10. Circular façade output and recirculation stage with design strategies, KPIs, and metrics.

- Design for recyclability: Select materials compatible with standard recycling processes, such as aluminium, steel, and glass. Ensure materials can be effectively separated, processed, and returned into new manufacturing cycles. Examples include the ORTUS Learning and Events Centre in London (UK) and the Enterprise Centre in Norwich (UK). Full details are in Appendix 1, Row 12.
- Design for recoverability: Where reuse or recycling is not feasible, ensure residual value through energy recovery (e.g., incineration with energy capture) or biodegradation. This reduces environmental burden at end-of-life. Example: One Market Plaza in San Francisco (USA). Full details are in Appendix 1, Row 13.

3.2.5.2. KPIs for Material Output and Recirculation. This stage introduces KPIs that assess material value retention at end-of-life through reuse, recycling, and recovery. These KPIs support the closing loop principle and apply to components, parts, and materials. All metrics are linked to Appendix 2.5, specifically sections 2.5.1 and 2.5.2.

- Reusable material (focuses on design for reuse, applicable to components, parts, and materials): Measures the total mass of materials and components that can be directly reused without significant refurbishment. Based on MFA, it is quantified using kilograms or as a percentage of total façade mass. Higher values indicate more substantial potential for reuse and extended product lifecycles. Validation comes from the Circular Kitchen & Façade Case Study in Delft (Netherlands). Full details are in Appendix 2.5, Row 4.
- Health and safety (focuses on design for reuse, applicable to components, parts, and materials): Measures the presence of hazardous substances and safe-to-disassemble finishes, using the CCEF method. It includes two indicators: (1) Toxicity/Synthetic Chemicals assesses hazardous substances (e.g., adhesives, coatings, sealants) that may pose risks during disassembly. (2) Ease of Access for Construction and Disassembly evaluates whether materials can be removed without damaging surrounding components. Higher scores reflect safer, more circular materials. Referenced in ISO 59020 and

validated in four façade pilot studies. Full details are in Appendix 2.5, Row 11.

- Recyclable materials (focuses on design for recyclability, applicable to materials): Quantifies the share of material mass that can enter established recycling streams, measured via MFA. It evaluates system performance in diverting waste and closing material loops. This KPI is especially relevant for aluminium, glass, and steel. Validation comes from the Circular Kitchen in Delft (Netherlands) and a façade pilot, aligning with Level(s) indicators. Full details are in Appendix 2.5, Row 4.
- Recoverable materials (focuses on design for recoverability, applicable to materials): Measures the volume of materials suitable for energy recovery or biodegradation where reuse or recycling is not viable. It uses mass or percentage metrics and supports decision-making for end-of-life options with the least environmental impact. Validation comes from Circular Façade Case Studies and ISO/Level (s) recovery criteria. Full details are in Appendix 2.5, Row 4.

3.3. Definition of circular façade

The concept of a circular façade is shaped by insights drawn from existing definitions of circularity and refined through the strategic design actions and Key Performance Indicators (KPIs) established in this study. A circular façade applies circular economy principles across all lifecycle stages, from material sourcing and manufacturing to use, disassembly, and recirculation. It aims to narrow resource loops in the material input stages by prioritising low-impact, reusable, and recycled materials (Cartwright et al., 2021; Geissdoerfer et al., 2017). During the in-use phase, it supports slowing loops through strategies that improve durability, ease of maintenance, standardisation, modularity, and design flexibility, ensuring components can be serviced, upgraded, or reused without complete replacement (Geissdoerfer et al., 2017; Ronholt et al., 2019). At the end-of-life, circular façades are designed for disassembly, recovery, reuse, and recycling, enabling materials and components to circulate into future systems and reduce waste (EMF, 2015; Geissdoerfer et al., 2017). This definition is operationalised through the CFD Framework, which links each lifecycle stage to design strategies and KPIs for measurable performance evaluation.

4. Discussion

This study synthesises insights from existing literature. It introduces a novel design framework that integrates circular economy (CE) principles into façade design for the construction sector. The proposed framework defines 13 design strategies and 25 key performance indicators (KPIs), systematically structured across five circular lifecycle stages. This structured approach provides a clear pathway for embedding circularity into the early design phases. It promotes sustainability, enhances resource efficiency, and supports innovation in façade system development.

4.1. Structure of the Circular Façade Design Framework

The CFD-F was developed through a thematic synthesis of 122 studies identified in the systematic review. Using the coding categories (principles, lifecycle stages, strategies, and KPIs), recurring patterns and conceptual linkages were identified and structured into the framework. This process ensured that the framework reflects evidence from the literature rather than being developed arbitrarily. The CFD-F integrates circular economy (CE) principles into façade systems through 13 design strategies and 25 KPIs distributed across five lifecycle stages. These stages are aligned with the CE principles of narrowing, slowing, and closing loops, and are supported by quantitative indicators to assess design performance. Fig. 11 presents the overall structure of the framework, which includes six essential elements:

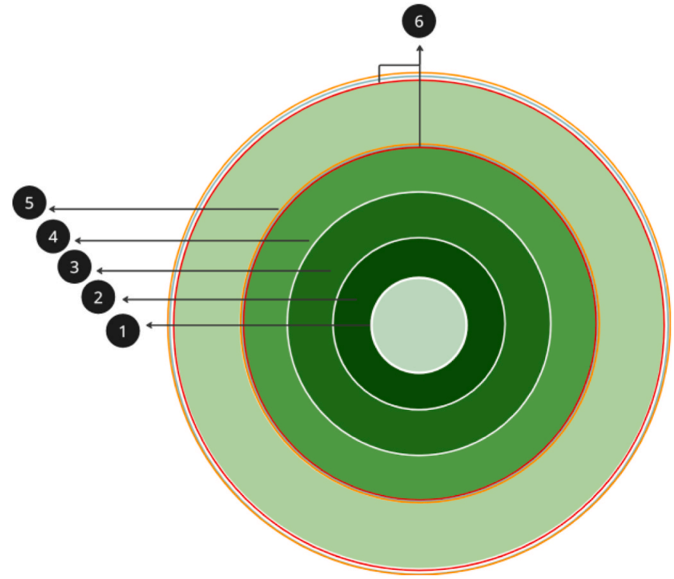


Fig. 11. Structure of the circular façade design framework.

1. Circularity Principle: At the centre of the framework are the three CE strategies described in Section 1:
   - Narrowing loops.
   - Slowing loops.
   - Closing loops.
2. Circular Design Lifecycle Stages: The framework is organised into five lifecycle stages that allow CE principles to be applied at different moments in the façade lifecycle:
   - Material inputs (as manufactured)
   - Material inputs (as installed)
   - Lifespan and in-use performance
   - Circular potential (before end-of-life)
   - Output and recirculation.
3. Circular Façade (CF) Design Strategies: Thirteen strategies are mapped across the lifecycle stages. Each is linked to CE principles and product levels, guiding the achievement of circularity. Built examples are provided in Appendix 1, which also includes built examples for each strategy. How can you achieve the CF goal through design?
4. KPIs: Each lifecycle stage is supported by KPIs that measure adoption and effectiveness. These KPIs use quantitative metrics such as mass, lifetime, or percentage. How do we measure adoption performance?
5. Indicators: Cross-referenced with validation sources and examples (Appendix 2). Formulas, scales (e.g., 0–15, ratio-based), and scoring criteria support the evaluation of performance. Façade product levels organise indicators to align with the colour-coded structure in Point 6 and Fig. 11.
6. Façade Levels: Design strategies and KPIs are applied across three façade-specific product levels, clarifying the priority aspects at each level and supporting tailored design and evaluation:
   - Component (orange)
   - Part (turquoise)
   - Material (red)

The graphical representation of the CFD-F (Fig. 12) is a novel contribution. It visualises design strategies and KPIs across interconnected lifecycle stages. This diagram helps practitioners and researchers align design decisions with CE principles, offering a structured tool for implementation in façade projects. The CFD-F is intended for architects, façade engineers, and sustainability consultants. While familiarity with lifecycle stages and CE principles is helpful, the Excel-based scoring table in Appendix 3 enables application even without

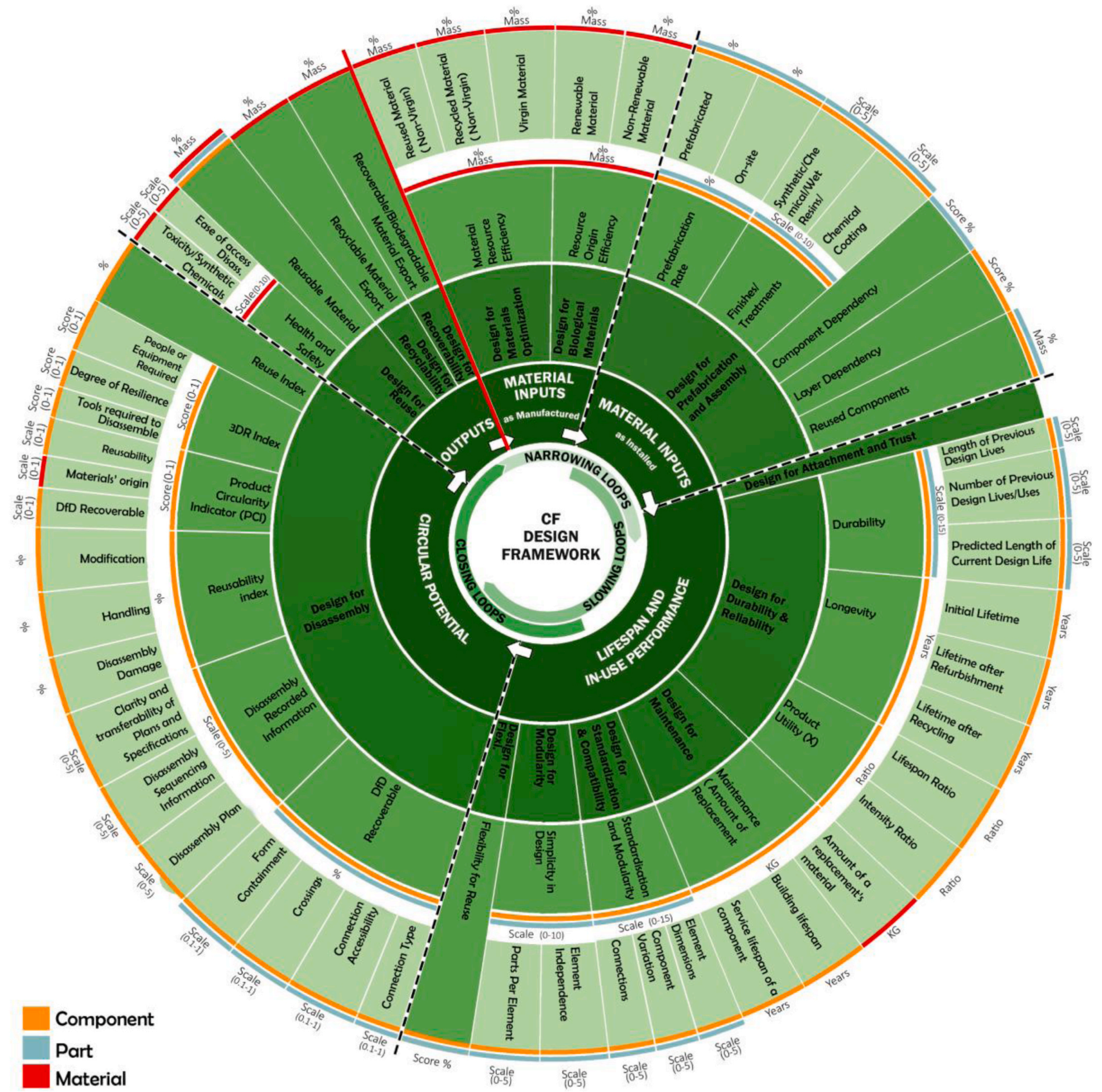


Fig. 12. Circular façade design (CFD) strategies and KPIs framework.

prior expertise. The strength of the CFD-F lies in integrating the three CE principles with design strategies across circular lifecycle stages. This directly addresses the study's initial research question by providing a framework that is façade-specific, measurable, and application-ready for linking CE strategies with quantifiable performance outcomes. Successful implementation relies on the overlap and integration of CE principles. Resource efficiency (narrowing loops) reduces virgin material use by reintroducing parts and materials from previous cycles through reuse and recycling (closing). The durability of components, parts, and materials extends their service life, supporting recirculation into another cycle at the end of life (or slowing). It also reduces demand by lowering the need for replacement and maintenance. Together, these strategies provide a comprehensive pathway for achieving the objectives of the circular economy.

4.1.1. Product levels and interface typology evaluation criteria

Fig. 13 illustrates the hierarchy of product layers and interface types relevant to façade design (Klein, 2013). The model is structured across three product levels—materials, parts, and components. Each level is linked to specific connection interfaces, ranging from adhesives and mechanical fixings at the material level to complex inter-component assemblies at the building scale (Klein, 2013; van Stijn and Gruis, 2020). This typology enables designers to organise façade elements systematically and identify where circularity interventions, such as modularity or reversibility, can be most effectively applied.

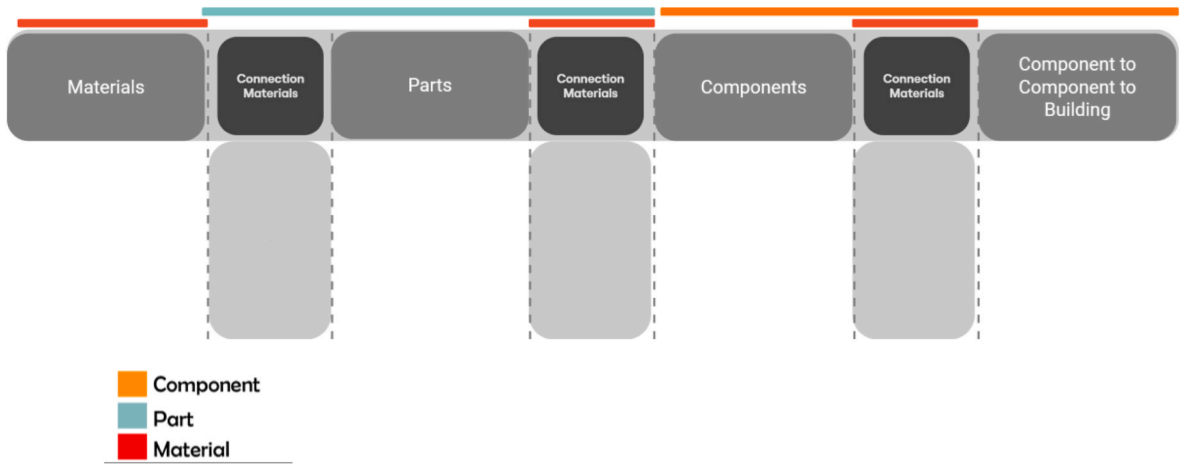


Fig. 13. Hierarchy of product layers and interface types model.

- Components(orange): Self-contained systems such as unitised panels or ventilation cassettes. These can be removed, upgraded, or reused independently of the broader façade structure.
- Parts (turquoise): Intermediate assemblies combining multiple materials (e.g., insulated glazing units with glass, spacers, and sealants). These often serve specific technical or performance functions.
- Materials (red): Base elements such as aluminium profiles, timber, or glass. At this level, circularity strategies focus on the origin of resources (renewable vs. non-renewable), efficiency, and recyclability.
- Connection (interfaces): Represented as "connection materials," including screws, clips, and adhesives. These are critical to disassembly, modularity, and the potential for reuse. Their location and reversibility strongly influence the circular performance of a façade.

The colour-coded bands in Fig. 13 align directly with the KPIs mapped in Fig. 12 (CFD-F). Together, the two figures provide a visual guide for interpreting which KPIs apply to which façade product level:

- KPIs targeting materials reference the red segment and focus on inputs (e.g., recycled content).
- KPIs applied to parts correspond to the turquoise section, often addressing inter-layer dependencies or disassembly potential.
- KPIs at the component level are linked with the orange segment and evaluate reusability, modularity, or disassembly.

This typology clarifies how each KPI is anchored to a specific layer or assembly within the façade system. It also simplifies practical implementation by guiding designers and assessors in applying KPIs in the appropriate context. This improves accuracy and supports early design decisions.

4.2. Application case study: Unitised wall system

This case study provides a step-by-step application of the CFD-F, illustrating its practical use by architects and façade engineers. It demonstrates the framework's usability across lifecycle stages, product levels, and KPIs, addressing the need for practical applicability. The objective is not only to present performance outcomes but also to show how designers and practitioners can apply the CFD-F to structure a circularity assessment. This includes its five lifecycle stages, product levels, connection interfaces, design strategies, and Key Performance Indicators (KPIs). The approach supports both practitioners and researchers in operationalising circularity across façade systems. It also aligns with the circular economy (CE) principles of narrowing, slowing, and closing loops.

The system analysed is a non-structural unitised curtain wall façade. It does not contribute to the building's primary load-bearing structure. These façades consist of fully framed, factory-manufactured glazed units designed for rapid on-site installation. After delivery, the units are offloaded from trucks, flat-stacked, and hoisted floor by floor using cranes. This streamlined process reflects contemporary construction practices, helping to reduce on-site waste, time, and emissions.

The case study focuses on a spandrel-free, fully transparent unitised system. While the façade has a design service life of 40 years, this analysis assumes a 15-year building lifespan. This aligns with the CFD-F's focus on short-to medium-term reuse scenarios. Table 5 outlines the system's configuration, mass, and lifespan assumptions. Fig. 14 maps product levels, connection interface types, material lifespans, and mass distribution. These are key elements for effectively applying the CFD-F and interpreting results across the system's lifecycle stages. In summary, the case study demonstrates how the CFD-F can inform both evaluation and decision-making in façade design, providing a structured framework for assessing circularity in real-world applications.

4.2.1. Evaluation criteria

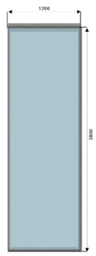
This evaluation applies the CFD-F to assess the circularity performance of the unitised curtain wall system. It is structured around the circular economy (CE) principles of narrowing, slowing, and closing loops. These principles are implemented through the framework's five lifecycle stages, each supported by specific design strategies and performance KPIs. The assessment covers twelve design strategies from the CFD-F, applied across relevant façade product levels. Each strategy is evaluated against its associated KPIs, as defined in Section 3.2. The formulas, indicators, and scoring criteria used for this evaluation are detailed in Appendix 2.

The Design for Attachment and Trust strategy was excluded because it addresses subjective user perceptions—such as emotional durability, meaningful design, and aesthetic preference—that cannot be measured using the quantitative KPIs defined in the CFD-F. While this strategy is valuable for long-term engagement and user perception, it does not provide material traceability or quantifiable metrics for performance-based assessment. In summary, the evaluation employs a structured and KPI-driven approach to assess circularity, while acknowledging the limitations of strategies that rely on qualitative measures.

4.2.2. Results of the analysis

Fig. 15 presents the circularity assessment results of the unitised curtain wall system. The evaluation follows the CFD-F's five lifecycle stages and aligns outcomes with the CE principles of narrowing, slowing, and closing loops. Each result is based on KPIs introduced in Section 3.2, calculated using the formulas and criteria in Appendix 2. An Excel-based scoring table (Appendix 3) records these results and generates visual

Table 5
Overview of the façade system: Materials, parts, component mass, expected lifespan, and material sources.



Materials	Mass	Virgin Material %	Recycled Material %	Lifespan	Source
Aluminium Mullion	38 kg	40 %	60 %	60 Years	(Azari-N and Kim, 2012; Dixit, 2019)
Laminated Glass	170 kg	100 %	0 %	60 Years	(Azari-N and Kim, 2012; Dixit, 2019)
Screw	1 kg	100 %	0 %	100 Years	(Dixit, 2019; Robati et al., 2019)
Sealant (silicone)	5 kg	100 %	0 %	25 Years	(Dixit, 2019; Robati et al., 2019)
Aluminium Spacebar	5 kg	100 %	0 %	60 Years	(Dixit, 2019; Robati et al., 2019)
Silicone Gasket	6 kg	100 %	0 %	30 Years	(Azari-N and Kim, 2012; Dixit, 2019)
Lift Lug and Anchor	5 kg	100 %	0 %	60 Years	(Azari-N and Kim, 2012; Dixit, 2019)
Parts					
Frame				60 Years	(Azari-N and Kim, 2012; Dixit, 2019)
Insulating Glass Units				25 Years	(Dixit, 2019; Robati et al., 2019)
Components					
Unitised Curtain Wall				25 Years	(Dixit, 2019; Robati et al., 2019)

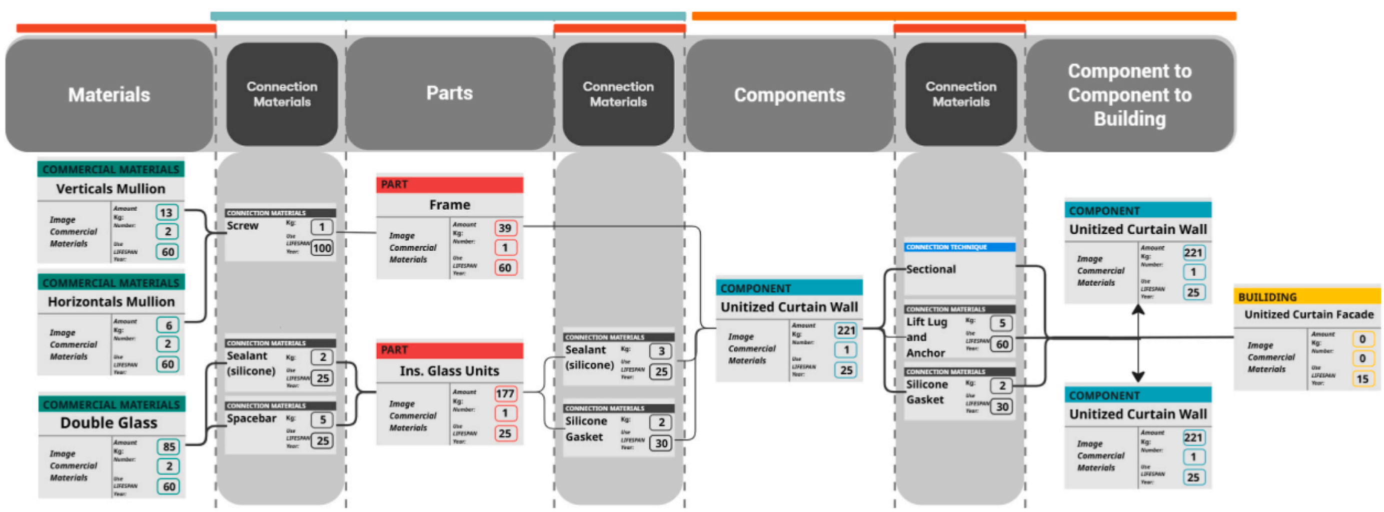


Fig. 14. Façade system product levels, interface types, lifespan considerations, mass distribution, and connection methods.

outputs. Designers can input KPI scores, track performance across stages, and link results to façade product levels and connection types, as shown in Fig. 14.

Material Inputs (as Manufactured): For Design for Biological Materials, the Resource Origin Efficiency KPI showed a low score due to reliance on non-renewable inputs. Only 10 % of materials—mainly recycled aluminium mullions—were circular. This indicates limited success in Material Resource Efficiency. These results suggest clear opportunities to increase recycled content and introduce renewable materials at the manufacturing stage. Overall, this stage aligns with narrowing loop objectives and corresponds to the material level (red zone in Fig. 15).

Material Inputs (as Installed): The Design for Prefabrication and Assembly strategy achieved complete prefabrication (100 %), which enabled rapid and low-waste installation. Performance varied across KPIs. UCW achieved 80 % reusability through connector retention, while the frame reached 40 % due to sequential disassembly requirements. IGUs performed poorly, with only 20 % reusability, because adhesives compromised their reusability. Layer Dependency was relatively high at 80 % for UCW and frames, which used bolts and screws, but lower for IGUs due to the use of sealants. No components were reused, and Finishes/Treatments scored 0/10 due to the use of adhesives and chemical coatings. These results highlight a trade-off between aesthetics and circularity. KPIs in this stage relate mainly to the component and part levels (orange and turquoise in Fig. 15), supporting both narrowing and closing loops.

Lifespan and In-Use Performance: For Design for Durability and Reliability, KPI scores differed across elements. Components scored 4/15, the frame 8/15, and IGUs 6/15, indicating varied resilience. Despite a modest Product Utility score of 0.45, the system met the 15-year requirement. Longevity KPIs revealed greater potential: the frame could last up to 180 years, IGUs up to 50 years, and the curtain wall 50 years if the sealant were replaced. The Maintenance KPI showed no replacements were needed during the 15-year life. Standardisation and Modularity scored 14/15, indicating high modularity. Simplicity in Design scored 6/10, showing functionality but not optimisation. Flexibility for Reuse demonstrated strong results, with 100 % reuse potential; however, adaptability was limited to 40 % for wider reapplication. Together, these results support slowing loops by extending service life and reducing the frequency of replacements.

Circular Potential (as Installed): The Design for Disassembly Recoverable KPI reached 85 %, reflecting strong disassembly potential, although IGU elements limited performance. Documentation for sequencing was moderate: structured information exists, but additional detail would make it more accessible to unfamiliar users. The Reusability Index demonstrated strong potential, with components that were resistant to damage and easy to modify. The Product Circularity Indicator (PCI) scored 0.88, indicating high suitability for end-of-life reuse. These outcomes align closely with the closing loop principle and are linked to components and parts (orange and turquoise in Fig. 15).

Material Output and Recirculation: The Reusable Material KPI showed that 230 kg of components could be reused after demolition, with an additional 10 years of usability beyond the building's 15-year life. Because reuse was prioritised, Recyclable Material and

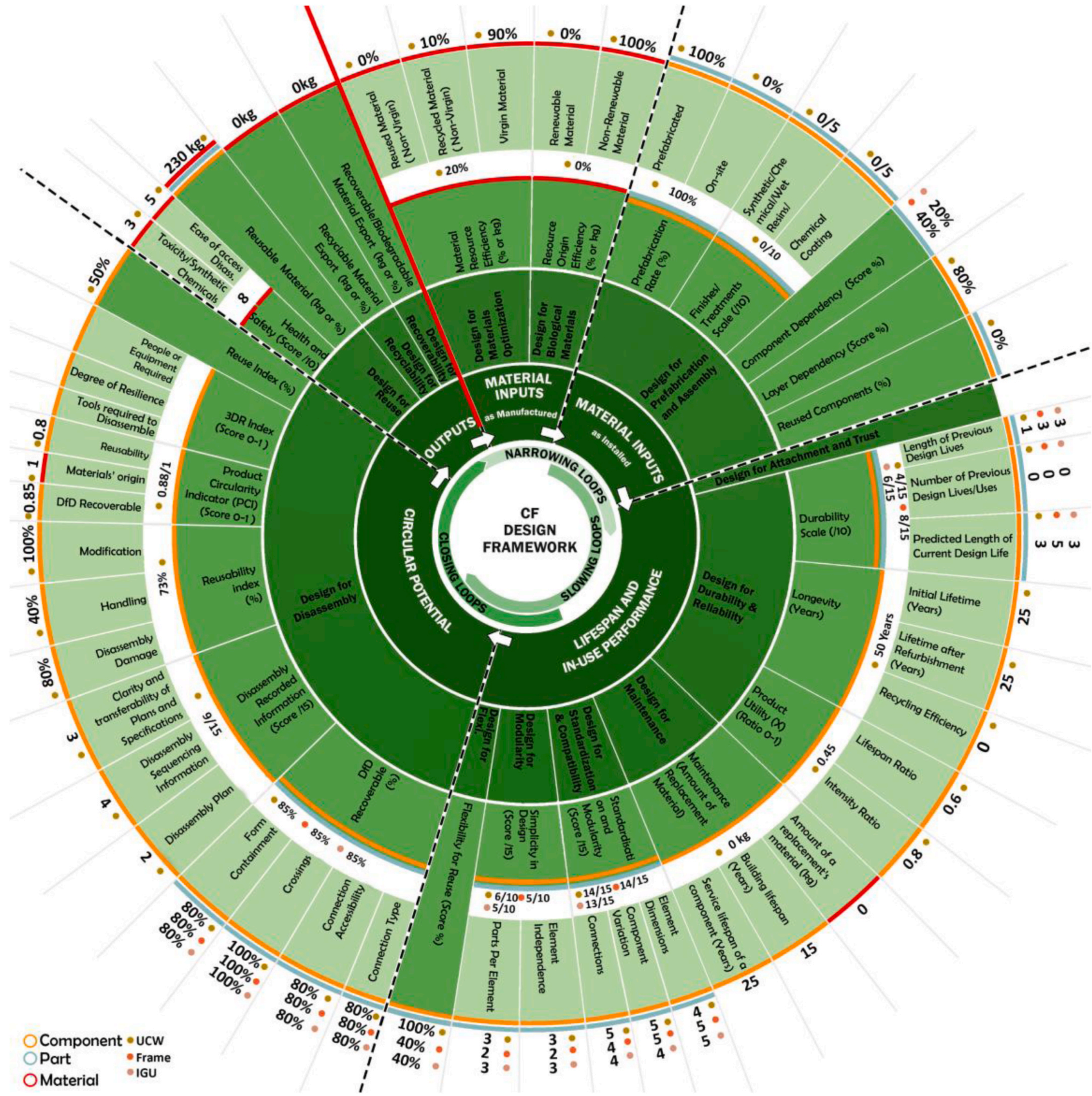


Fig. 15. Unitised curtain wall circularity assessment results.

Recoverable Material KPIs were not applicable. Health and Safety scored 8/10. The Toxicity/Synthetic Chemicals sub-indicator scored 3, showing moderate use of synthetic substances, while Ease of Access for Disassembly scored 5, showing high accessibility with minimal damage during removal. These findings confirm the effectiveness of output strategies under the closing loop principle, particularly at the material and part levels.

Summary of Circularity Loop Alignment:

- Narrowing loop: Partially addressed. While prefabrication improved resource efficiency, the system relied heavily on non-renewable materials with low recycled content.
- Slowing loop: Moderately aligned. The system met the functional 15-year service life, with high durability for the frame and strong modularity.
- Closing loop: Strongly aligned. High disassembly potential, reuse capability, and minimal waste generation support closed-loop circularity.

4.3. Limitations and future application of the CFD-F

One of the main objectives of this case study was to demonstrate the application of the CFD-F. It also showed how the framework can support practitioners in guiding design decisions and evaluating façade systems. Future work should apply the CFD-F to a wider range of façade typologies to test its adaptability and strengthen its robustness across different contexts. To support practical use and broader industry adoption, supplementary materials, such as instructional guides and training videos, will be developed during the validation workshops.

The analysis revealed important limitations, particularly in the availability and specificity of material data. Information such as recycled content, reuse status, and material origin was often incomplete or missing. This limited the accuracy of several KPIs, including:

- Resource origin efficiency
- Material resource efficiency
- Product utility
- Reusability index
- Recoverable material potential

Integration with Life Cycle Assessment (LCA) databases such as OneClick LCA or Ecoinvent could enhance data quality and enable more reliable benchmarking. In parallel, Building Information Modelling (BIM) offers substantial potential to map product levels—materials, parts, and components—and connection interfaces. BIM integration would also support early-stage application of strategies such as disassembly, modularity, maintenance, and standardisation. Together, these enhancements could transform the CFD-F into a practical decision-support tool, enabling designers to test scenarios and evaluate circularity trade-offs in real-time.

Future validation work will explore additional areas to improve usability. These include testing a tiered KPI system (essential vs. advanced) to simplify the application process for early-stage design teams, particularly those with limited expertise in circularity. Further efforts will examine how the CFD-F can be embedded within digital design workflows, including links to material passports and structured BIM integration. While this study focused on environmental performance, future research may also integrate economic considerations, such as lifecycle costing, to improve commercial feasibility. To ensure regional relevance, validation case studies will address regulatory, climatic, and material availability differences across geographic contexts, guided by practitioner input.

In terms of generalisability, the CFD-F was developed from a synthesis of international literature rather than tailored to a specific region. Its applicability, therefore, remains constrained by local factors such as climate, regulation, and material supply. Future research should test the CFD-F with different façade typologies in specific contexts, considering variations in climate, regulation, and material supply. Because this study relied on published literature, there is also a risk of publication bias: innovative or successful cases are more often reported, while less effective or failed practices may be underrepresented. This bias may have influenced the conceptual mapping and highlights the need for empirical validation to balance the literature base.

Beyond academic and design applications, the CFD-F has the potential to inform policy, certification, and standardisation. Current green building certification systems, such as LEED, BREEAM, and DGNB, already incorporate elements of CE, but they often emphasise energy and waste reduction rather than façade-specific circularity (Amarasinghe et al., 2024; Wong et al., 2024). By providing façade-oriented KPIs and strategies, the CFD-F can complement these schemes, particularly DGNB, which balances environmental, social, and economic dimensions (Chegut et al., 2019; Jeleniewicz et al., 2025). In this way, the CFD-F could help standardize circular façade metrics, support the expansion of certification criteria, and guide the development of regulatory benchmarks.

Finally, several implementation challenges remain. Resistance to change within the construction industry is common, driven by conservatism, knowledge gaps, perceived economic risks, and technical or regulatory barriers (Amarasinghe et al., 2024; Ericsson et al., 2024; Herranz-Pascual et al., 2024). Small firms may lack the resources to manage the complexity of CE implementation across fragmented supply chains (Hossain et al., 2020). The absence of strong regulatory incentives, clear targets, and financial support also continues to hinder adoption (Bertozzi, 2022; Eikelenboom et al., 2024). Overcoming these barriers will require systemic action, including targeted education, financial incentives, stronger regulations, and cultural change across the sector.

5. Conclusion

This study addressed the challenge of rising embodied carbon in façade systems—an unintended consequence of advances in energy efficiency. Traditional cradle-to-grave approaches have led to increased waste and resource consumption. At the same time, the application of circular economy (CE) principles in façade design remains limited and underdeveloped. To address this gap, a comprehensive Circular Façade Design framework (CFD-F) was developed, drawing upon elements of previously published methods and frameworks. It defines 13 façade-specific design strategies and 25 Key Performance Indicators (KPIs). These are structured across five lifecycle stages and aligned with the CE principles of narrowing, slowing, and closing loops. Applied through a unitised curtain wall case study, the CFD-F demonstrated its ability to identify strengths, performance gaps, and opportunities. Results showed partial alignment with resource efficiency (narrowing), improved durability and reduced maintenance (slowing), and strong outcomes in reuse and end-of-life recovery (closing). This confirms its potential to support low-waste, circular façade solutions in practice.

For academia, this study advances theoretical development by presenting the first façade-specific circularity framework derived from a systematic synthesis of 122 studies. It also introduces a novel graphical representation that maps strategies and KPIs across lifecycle stages, alongside a refined definition of the circular façade grounded in CE literature. For practice, the CFD-F provides architects, engineers, and façade designers with a structured tool—supported by KPIs, visual maps, and an Excel-based scoring system—that can be applied from early design phases to evaluate and enhance circularity.

Beyond research and practice, the CFD-F can also inform policy, certification, and standardisation. It can complement green building certifications such as LEED, BREEAM, and DGNB by providing façade-specific circularity metrics. In doing so, it contributes to standardizing CE indicators in the built environment. This supports regulatory and industry initiatives aimed at reducing embodied carbon and improving material efficiency in construction.

Data gaps remain in material origins and reuse potential. The reliance on literature-based synthesis introduces risks of publication bias, where innovative or successful cases are overrepresented. The CFD-F also remains, at this stage, a theoretical construct without empirical validation. Future research should:

- Integrate BIM and LCA tools to improve usability and enable automated evaluation of multiple scenarios.
- Apply the framework across diverse façade typologies and regional contexts to test adaptability and generalisability.
- Explore a tiered KPI structure (essential vs. advanced) to balance accessibility and depth for practitioners.
- Validate the framework through case studies, workshops, and pilot projects with industry stakeholders.

Together, these next steps will ensure that the CFD-F evolves into a robust, practical decision-support tool. Wider adoption could accelerate the shift toward performance-based circular design, aligning façade practice with climate goals, supporting certification and regulatory frameworks, and improving material resilience in the built environment.

CRediT authorship contribution statement

Hamad Alabdulrazzaq: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Eugenia Gasparri:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Arianna Brambilla:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Shady Attia:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147140.

Appendix 1. Circular Façade Design Framework (CFD-F) Strategies

No.	Circular Façade Design Strategies	Action Design for -	Practice-Based Validation Examples	Source
1	**Design for Materials Optimisation**	Maximise the use of reused materials. Design with recycled materials. Reduce the use of virgin and non-renewable materials. Reduce the use of carbon-intensive materials. Ensure that materials are used in their optimal applications to avoid waste and enhance efficiency. Identify the benefits of reusing materials and reduce material waste through LCA Ensure materials' suitability for reuse, refurbishment, repair, and recycling. Use material-efficient design techniques by refusing redundant components and unnecessary features.	A Temporary District Court in Amsterdam (Desirée Bernhardt, G-05), Swansea, UK (Roberts et al., 2023), Modern Methods of Construction in Schools, Australia (NSW Guidelines, G-06)	(Caldas et al., 2022; Council, 2019; Desirée Bernhardt and Roos, 2021; López Ruiz et al., 2020; Office of Energy and Climate Change, 2023; Orsini and Marrone, 2019; Roberts et al., 2023)
2	**Design for Biological Materials**	Utilize Bio-Based, Reusable, and Non-Toxic Materials Select Low-Impact and Non-Hazardous Materials Promote Biodegradability Obtain an inventory of all ingredients used within the façade Set Measurable Targets for Low-Impact Materials	The Green House, Utrecht (G-05), Biosintrum, Oosterwolde (G-05), Netherlands Pavilion, Expo 2020 Dubai (G-05), de Graaf and Schuitemaker (2022)	(Council, 2019; de Graaf and Schuitemaker, 2022; Desirée Bernhardt and Roos, 2021; Office of Energy and Climate Change, 2023; Rahla et al., 2021a; Roberts et al., 2023)
3	**Design for Prefabrication and Assembly**	Design components with standardized dimensions to facilitate ease of prefabrication and assembly. Ensure that prefabricated units are designed for efficient transportation Design for easy connection and integration of modular elements Reduce and Standardize Fasteners and Connections Avoid Using Dissimilar Components Avoid Using Fragile Components Incorporate the Assembly Method in the Design Replace Manual Methods with Automated/ Robotic Assembly	The Circular Design of Buildings (Copper8, 2021), DfD Building in Swansea, UK (Roberts et al., 2023, 77), Case Studies on Modular Prefabrication (Copper8, 2021)	(Benachio et al., 2020; Caldas et al., 2022; Council, 2019; Desirée Bernhardt and Roos, 2021; López Ruiz et al., 2020; Office of Energy and Climate Change, 2023; Roberts et al., 2023)
4	**Design for Attachment and Trust**	Create Timeless Aesthetics Design for Pleasurable Experiences Meaningful Design Emotional Durability customization or made-to-measure products Transparency By making it clear how a product was made and the environmental impacts of each choice		(Bocken et al., 2016; Moreno et al., 2016)
5	**Design for Durability & Reliability**	Choose materials that can withstand typical wear and tear Opt for materials and systems that require minimal maintenance and repair Design for Physical Durability can withstand various environmental conditions Develop a Maintenance Strategy (a clear maintenance plan) Future-proof the Design by selecting materials and strategies that allow the structure or product to endure evolving conditions or new requirements.	Digital Twins/Smart Maintenance Pilots (Çetin et al., 2022, 166), Circular Retrofit Case Studies (WorldGBC, G-01), Expo 2020 Netherlands Pavilion (G-05), Biosintrum, Oosterwolde (G-05), The Green House, Utrecht (Copper8, 2021), Leppington and Edmondson Commuter Car Parks, Australia (NSW Guidelines, G-06)	(Council, 2019; Council, 2023; Desirée Bernhardt and Roos, 2021; Kayaçetin et al., 2022; Moffatt and Russell, 2001; Office of Energy and Climate Change, 2023)

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No.	Circular Façade Design Strategies	Action Design for -	Practice-Based Validation Examples	Source
		Design for Reliability they can function as intended over their entire lifespan without failure when properly maintained. Improve Internal Characteristics		
6	**Design for Maintenance**	Repairing Defects and Regular Maintenance Ease of Maintenance and Repair includes using modular components that can be easily replaced or upgraded without requiring specialized skills or tools. Extend the service life of construction components by ensuring they are designed for long-term use and regular maintenance Focus on upgrading, repairing, and maintaining products while they are still in use to avoid early disposal Plan for a product-life extension by making buildings and products adaptable and maintainable.	The Green House, Utrecht (Copper8, 2021), Biosintrum, Oosterwolde (Copper8, 2021), NSW Circular Design Guidelines (2023, G-06)	(Achterberg et al., 2016; Bocken et al., 2016; Desirée Bernhardt and Roos, 2021; Office of Energy and Climate Change, 2023; Sáez-de-Guinoa et al., 2022)
7	Design for Standardisation & Compatibility	Ensure reusability and reconfiguration, using standardized dimensions to recombine components efficiently. Employ simple geometric designs and standardized connection points for components. Create parts or interfaces compatible with other products or systems, allowing for easier integration, modification, and reuse.	Rogers Stirk Harbour + Partners prototype for London Design Festival 2016, Laing O'Rourke Explore Industrial Park (G-02), Legal & General Modular Homes (G-02), Circle House (G-02), WWF-UK Living Planet Centre (G-02), Sky Central Project (G-02)	(Antonini et al., 2020; Bocken et al., 2016; Council, 2019, 2023)
8	**Design for Modularity**	use prefabricated modules that are manufactured off-site and assembled on-site. Standardizing connections between modules or components facilitates easier interchangeability and adaptability. Design modular products to be compatible with other products or systems. Standardized building parts are to be easily maintained, disassembled, relocated, or refurbished for reuse.	Modular Wall System Case Study (Roberts et al., 2023, 77), Modern Methods of Construction in Schools, Australia (NSW Guidelines, G-06), Legal & General Modular Homes – Practical Example (G-02)	(Benachio et al., 2020; Council, 2019; Council, 2023; Machado and Morioka, 2021; Office of Energy and Climate Change, 2023; Roberts et al., 2023)
9	**Design for Flexibility and Upgradability**	Design buildings to balance current needs with future changes by allowing for frequent reconfiguration of non-structural parts. Design buildings that can be easily adapted, refurbished, or transformed to meet future user needs Consider timeless designs and high-quality materials that allow the product to last longer through upgrades or repairs. Incorporate features that allow products to be easily updated or adapted to new technologies or conditions Select durable materials that support the long-term use of the product and facilitate upgrades without needing complete replacement.	Modular Student Complex Case Study (Copper8, 2021) Sky Central Case Study (G-02), DIRTT Project Case Studies – Flexible Interior Systems (G-02)	(R. Askar et al., 2022; Bocken et al., 2016; Council, 2019; Desirée Bernhardt and Roos, 2021; Hasman, 2023; Mhatre et al., 2021; Munaro et al., 2022; Office of Energy and Climate Change, 2023)
10	**Design for Disassembly**	Reversible connections and materials that can be recovered without damaging other components. Ensure that building elements can be disassembled without damaging each other by using modular designs and reversible connections. Consider the end-of-life stage of materials and components during the initial design phase. ease of access to these connections to enable quick and efficient disassembly. Develop Disassembly Plan Integrate Environmental and Health Considerations Use Dry, Mechanical Connections Use prefabricated components	GREENBIZZ, Brussels (architectesassoc+, 2016, G-03), Circle House, Denmark (G-02), The Arup Circular Building (G-02), Venlo City Hall (G-02), District Court of Amsterdam (G-02), Derwent London's 25 Saville Row (G-02), Pyörre House, Finland (G-01), Käinga Ora – Homes and Communities (G-01), Het Diekmann Vocational School, The Netherlands (G-06)	(Antonini et al., 2020; R. Askar et al., 2022; Council, 2019; Council, 2023; Galle et al., 2019; Lei et al., 2021; Moffatt and Russell, 2001; Munaro et al., 2022; Office of Energy and Climate Change, 2023)
11	**Design for Reuse**	Plan for Deconstruction Use mechanical fasteners such as screws and bolts instead of sealants and adhesives. Use materials that are safe and healthy for reuse easily repaired, remanufactured, or recycled, ensuring reduced consumption of new resources.	WWF Living Planet Centre (G-02), The Velodrome, London (G-02), Quay Quarter Tower, Australia (NSW Guidelines, G-06)	(Council, 2019; Mhatre et al., 2021; Office of Energy and Climate Change, 2023; Sáez-de-Guinoa et al., 2022)

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No.	Circular Façade Design Strategies	Action Design for -	Practice-Based Validation Examples	Source
		Modular and Standard Components Durable Materials Plan for safe movement of workers during repair, dismantling or retrofitting processes designing for standardized material sizes, modular components, and easily disassembled building parts.		
12	**Design for Recyclability**	Work collaboratively across the value chain to improve recycling infrastructure and technologies. Closed loop recycling reprocessing materials so they can replace virgin materials without degradation, creating a continuous loop of reuse. Open loop recycling reprocessing materials that can be used in different industries or products, often requiring some addition of virgin materials to meet quality standards. design products with materials that can be efficiently processed through available recycling systems easy to disassemble so that the materials can be separated and recycled without excessive processing	ORTUS Learning and Events Centre (G-02), The Enterprise Centre (G-02), Huckletree Office Space (G-02)	(Council, 2019; Council, 2023; Desirée Bernhardt and Roos, 2021; Galle et al., 2019a,b; Office of Energy and Climate Change, 2023; Rahla et al., 2021a, 2021b; Sáez-de-Guinoa et al., 2022)
13	Design for Recoverability	Energy recovery should only be considered after all other circular economy strategies focusing on technologies like waste-to-energy conversion that minimise environmental impact. Ensure that materials and components used in buildings or products can be converted to energy if needed	One Market Plaza, United States of America (NSW Guidelines, G-06)	(Desirée Bernhardt and Roos, 2021; Office of Energy and Climate Change, 2023; Rahla et al., 2021a, 2021b)

Appendix 2. Overview of Methods and Validation

Appendix 2.1, Material Input (As Manufactured) - Overview of Methods and Validation

No.	KPIs	Indicators	CE Principle	Method	Quantitative Metric	Validation	Source
1	**The amount of Virgin Material**		**1**	**MCI, BCI/ PBCI model**	**Mass**	Applied in eight EU buildings using process-based LCA and detailed material inventories. Virgin input was explicitly tracked to assess circular performance.	(Cottafava and Ritzen, 2021; Dodd et al., 2017; International Organization forS, 2024; Khadim et al., 2022; Kristensen and Mosgaard, 2020; Mazzoli et al., 2022; Saidani et al., 2019; Shevchenko and Cluzel, 2023)
1.1		Reused Material	1	MCI, CPD Toolkit:	Fractions or %	Frameworks such as BCI and MCI integrate reused content into circularity scores, reported per product or building layer.	
1.2		Recycled Material	1	MCI, CPD Toolkit:	Fractions or %	A review of 30+ micro-level indicators shows that recycled content is among the most commonly used metrics across CE assessment tools.	
2	**Total Material Import**		**1**	**MFA**	**Mass**	Multiple case studies demonstrate that total material flows are directly linked to circular performance; import tracking enhances LCA and CE transparency.	(Andrade et al., 2019; Bilal et al., 2020; Cottafava and Ritzen, 2021; Dodd et al., 2017; International Organization forS, 2024; Malabi Eberhardt et al., 2021; Malabi Eberhardt et al., 2020; van Stijn et al., 2022; van Stijn and Gruis, 2020; Wouterszoon Jansen et al., 2022)
2.1		Virgin Material Import	1	MFA	Mass	LCA-based validation includes virgin and non-virgin material flows; tested on eight EU demonstrator buildings.	
2.2		Non-Virgin Material Import	1	MFA	Mass	Circular building components are evaluated using allocation models that support reuse and recycling across multiple life cycles.	
2.3		Renewable Material Import	1	MFA	Mass	Pilot studies in reversible construction systems; emphasis placed on renewability and regional sourcing.	
2.4		Non-Renewable Material Import	1	MFA	Mass		

* Resources flow: [1] Design for resource efficiency, [2] Design for Long Life Use of Products, [3] Design for Extending Product Life, [4] Design for Multiple Cycles.

Appendix 2.1.1 Material Input (As Manufactured) - KPI Calculation Formulas and Parameters

No.	KPIs	Formula	Parameters	Source
1	The amount of Virgin Material	$V = M\,(1 - FR - FU)$	F R represents the fraction of feedstock derived from recycled sources. Fu, represents the fraction from reused sources. M mass of virgin material	Mazzoli et al. (2022)
1.1	Fractions Reused Material	$Fu = \frac{Amount\ of\ Reused\ Material}{Total\ Amount\ of\ Material}$		
1.2	Fractions Recycled Material	$Fr = \frac{Amount\ of\ \text{recycled}\ Material}{Total\ Amount\ of\ Material}$		

Appendix 2.2.1 Material Input (As Installed) - KPI Rating Scales and Indicator Scores

No.	KPIs/Indicator	Rating Scale	Score	Source
2	**Component Dependency**			Gulck et al. (2021)
		Completely Independent	100 %	
		Remove connectors to sperate (materials and connectors remain intact)	60–80 %	
		Sequential disassembly: disconnect all to disconnect one	40–50 %	
		Destroy connectors to separate	10–20 %	
		Completely dependent	0 %	
3	**Layer Dependency**			Gulck et al. (2021)
		Dry Connection: Dry connection, Click connection, Velcro connection, and Magnetic connection.	100 %	
		Connection with Added Elements: Bolt and nut connection, Spring connection, Corner connection, and Screw connection.	80 %	
		Direct Integrated Connection: Peg connection and Nail connection.	40 %	
		Soft Chemical Connection: Sealant connection and Foam Connection (PUR)	20 %	
		Hard Chemical: Glue connection, Cement-bound connection, and Chemical anchor	0 %	
5.1	**Synthetic/Chemical/Wet Resins/ Adhesives**			Dams et al. (2021)
		YES	0	
		NO	5	
5.2	**Chemical Coating**			Dams et al. (2021)
		YES	0	
		NO	5	

Appendix 2.2 Material Input (As Installed) - Overview of Methods and Validation

No.	KPIs	Indicators	CE Principle	Method	Quantitative Metric	Validation	Source
1	**Prefabrication Rate**		**1,2**	**DfMA**	**%**	The Green House, Utrecht: Modular prefabricated timber panels were used for fast construction and full disassembly. The building was completed in just three months, demonstrating practical application of circular design.	(de Graaf and Schuitemaker, 2022; Ronholt et al., 2019)
1.1		Prefabricated	1.2		%		
1.2		On-site	1.2		%	Precast vs. Cast-in-Situ (Comparative LCA Case Study)	
2	**Component Dependency**		**2,3**	**Circularity Indicators**	**Score%**	Four real-life façade renovation systems were tested using circularity indicators. The case studies focused on disassembly, material layering, and reversibility scoring.	Gulck et al. (2021)
3	**Layer Dependency**		**2,3**	**Circularity Indicators**	**Score%**	Component and layer dependency indicators were applied in actual renovation projects.	Gulck et al. (2021)
4	**Reused Components**		**1**	**MFA**	**Mass or %**	Three different scenarios were modelled to assess reuse crediting for structural systems. The LCA showed carbon savings based on disassembly potential and remaining service life.	(Joensuu et al., 2022; Kim and Kim, 2020)
5	**Finishes/ Treatments**		**3,4**	**CCEF**	**% or Score/10**	Four real-life façade renovation systems were tested using circularity indicators.	(Dams et al., 2021; Khadim et al., 2022)
5.1		Synthetic/ Chemical/Wet Resins/Adhesives	3, 4	CCEF	Yes (Score 0) No (Score 5)		
5.2		Chemical Coating	3, 4	CCEF	Yes (Score 0) No (Score 5)		

* Resources flow: [1] Design for resource efficiency, [2] Design for Long Life Use of Products, [3] Design for Extending Product Life, [4] Design for Multiple Cycles.

Appendix 2.3 Lifespan and In-Use Performance - Overview of Methods and Validation

No.	KPIs	Indicators	CE Principle	Method	Quantitative Metric	Validation	Source
1	**Product Utility (X)**		**2,3**	**MCI**	**Ratio**	Used in the EASY framework and compared to OneClick LCA. Applied to the Corte Palazzo deep renovation pilot project in Italy to benchmark circular performance.	(Askar et al., 2022; Cottafava and Ritzen, 2021; Mazzoli et al., 2022)
1.1		Lifespan Ratio	2	MCI	Ratio		
1.2		Intensity Ratio	2, 3	MCI	Ratio		
2	**Durability**			**CCEF**	**% Or Score/ 15**	Component Case Study: Component-level reuse scenarios tested in LCA models using three allocation strategies. Demonstrated carbon and material savings for reused structural elements	(Dams et al., 2021; Malabi Eberhardt et al., 2020, 2021; van Stijn et al., 2020, 2022)
2.1		Number of Previous Design Lives/Uses	1,2	CCEF	Scale (0–5)	Practice-Based Scoring – Evaluated Across Four Buildings	
2.2		Length of Previous Design Lives		CCEF	Scale (0–5)		
2.3		Predicted Length of Current Design Life		CCEF	Scale (0–5)		
3	**Maintenance**		**3**	**LCA**	**Mass**	Systematic Review – 65 LCA-Based Studies	Lei et al. (2021)
3.1		Amount of a replacement material	3		Mass		
3.2		Building lifespan	3		Year		
3.3		Service lifespan of a component	3		Year		
4	**Longevity**		**3**	**Circularity Indicators**	**Year**	Circularity indicators applied to four façade renovation systems	(R. Askar et al., 2022; R. Askar et al., 2022;Gulck et al., 2021; Kristensen and Mosgaard, 2020; Parchomenko et al., 2019)
4.1		Initial Lifetime	3		Year		
4.2		Building lifespan	3		Year		
4.3		Lifetime after Recycling	3		Year		
5	**Standardisation and Modularity**		**3**	**CCEF**	**% or Score/ 15**	Applied Case Validation – 4 Buildings	(Dams et al., 2021; Khadim et al., 2022)
5.1		Element Dimension		CCEF	Scale (0–5)		
5.2		Component Variation		CCEF	Scale (0–5)		
5.3		Connection		CCEF	Scale (0–5)		
6	**Simplicity in Design**			**CCEF**	**% or Score/ 10**	Applied Case Validation – 4 Buildings	Dams et al. (2021)
6.1		Element Independence		CCEF	Scale (0–5)	12.24	
6.1		Part Per Element		CCEF	Scale (0–5)		
7	**Flexibility for Reuse**		**4**	**Circularity Indicators**	**Score %**	Circularity indicators applied to four façade renovation systems	Gulck et al. (2021)

* Resources flow: [1] Design for resource efficiency, [2] Design for Long Life Use of Products, [3] Design for Extending Product Life, [4] Design for Multiple Cycles.

Appendix 2.3.1 Lifespan and In-Use Performance - KPI Calculation Formulas and Parameters

No.	KPIs	Formula	Parameters	Source
1	**Product Utility (X)**	X = *M* (Lifespan Ratio) *(Intensity Ratio)		(Cottafava and Ritzen, 2021; Mazzoli et al., 2022)
1.1	Lifespan Ratio	$L = \frac{L}{Lav}$	L lifetime L_av industry average	(Cottafava and Ritzen, 2021; Mazzoli et al., 2022)
1.2	Intensity Ratio	$U = \frac{U}{Uav}$	U number of functional units achieved during the use of product. U_av use of an industry average product of similar type	(Cottafava and Ritzen, 2021; Mazzoli et al., 2022)
4	**Longevity**	$\boldsymbol{longevity = LA + LB + LC}$	LA Initial lifetime LB lifetime after Refurbishment LC lifetime after Recycling	(R. Askar et al., 2022)

Appendix 2.3.2 Lifespan and In-Use Performance - KPI Rating Scales and Indicator Scores

No.	KPIs/Indicator	Rating Scale	Score	Source
2.1	**Number of Previous Design Lives/Uses**			Dams et al. (2021)
		Virgin materials	0	
		Minimal reclaimed or recycled material	1	
		Little reclaimed or recycled material	2	
		Some reclaimed or recycled material	3	
		Significant use of reclaimed or recycled material	4	
		Extensive use of reclaimed or recycled materials	5	
2.2	**Length of Previous Design Lives**			Dams et al. (2021)
		Zero Year	0	
		10 Years	1	
		20 Years	2	
		30 Years	3	
		40 Years	4	
		50 Years	5	
2.3	**Predicted Length of Current Design Life**			Dams et al. (2021)
		Zero Year	0	
		10 Years	1	
		20 Years	2	
		30 Years	3	
		40 Years	4	
		50 Years	5	
5.1	**Element Dimensions**			Dams et al. (2021)
		Highly complex or customized design with sequential construction required	0	
		Complex design with varying elements requiring sequential construction	1	
		Moderately complex design with variability in parts and sequential construction required	2	
		Some simplicity in design, moderate variability in elements	3	
		Simplicity and/or standardisation in design, moderate component variation	4	
		Standardisation and modularity in design with minimal variation in components	5	
5.2	**Component Variation**			Dams et al. (2021)
		Highly complex or customized design with sequential construction required	0	
		Complex design with varying elements requiring sequential construction	1	
		Moderately complex design with variability in parts and sequential construction required	2	
		Some simplicity in design, moderate variability in elements	3	
		Simplicity and/or standardisation in design, moderate component variation	4	
		Standardisation and modularity in design with minimal variation in components	5	
5.3	**Connections**			Dams et al. (2021)
		Highly complex or customized design with sequential construction required	0	
		Complex design with varying elements requiring sequential construction	1	
		Moderately complex design with variability in parts and sequential construction required	2	
		Some simplicity in design, moderate variability in elements	3	
		Simplicity and/or standardisation in design, moderate component variation	4	
		Standardisation and modularity in design with minimal variation in components	5	
6.1	**Element** Independence			Dams et al. (2021)
		Sequential construction required	0	
		Complex design with varying elements that require sequential construction	1	
		Moderately complex design with part variability and sequential construction required	2	
		Some design simplicity, moderate element variability, and some potential for parallel construction	3	
		Potential for parallel construction	4	
		Complete independence with potential for parallel construction	5	
6.2	**Parts Per Element**			Dams et al. (2021)
		More than 5 parts	0	
		5 Parts	1	
		4 Parts	2	
		3 parts	3	
		2 parts	4	
		One Part	5	
7	**Flexibility for Reuse**			Gulck et al. (2021)
		Easily adaptable How labour-intensive are actions	100 %	
		Flexible because of small dimensions, but hard or impossible to adapt E.g. bricks, small tiles …	50–60 %	
		Adaptable by more complex/specialized actions How specialized are the used machines	40 %	
		Reuse not possible	0–20 %	

Appendix 2.4 Circular Potential (As Installed) - Overview of Methods and Validation

No.	KPIs	Indicators	CE Principle	Method	Quantitative Metric	Validation	Source
1	**DfD Recoverable**		**3,4**	**DfD**	**%**	Case Study – 8 European Demonstrators, Case Study – 9 Structural PDs, CBCI Living Lab	(Cottafava and Ritzen, 2021; Kayaçetin et al., 2022)
1.1		Types of Connection	3,4		Scale (0.1–1)		
1.2		Connection Accessibility	3,4		Scale (0.1–1)		

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No.	KPIs	Indicators	CE Principle	Method	Quantitative Metric	Validation	Source
1.3		Crossings	3,4		Scale (0.1–1)		
1.4		Form Containment	3,4		Scale (0.1–1)		
2	**Disassembly Recorded Information**		3,4	**CCEF**	**% or Score/ 15**	Case Study – 4 Pilot Buildings	(Dams et al., 2021; Khadim et al., 2022)
2.1		Disassembly Plan (Drawing and Specifications)	3,4	CCEF	Scale (0–5)		
2.2		Disassembly Sequencing Information	3,4	CCEF	Scale (0–5)		
2.3		Clarity and transferability of Plans and Specifications	3,4	CCEF	Scale (0–5)		
3	**3DR**		**3,4**	**3DR index**	**Score (0–1)**	Case Study – Legacy Living Lab, Australia	(Kristensen and Mosgaard, 2020; O'Grady et al., 2021)
3.1		Disassemlability Index (DI)	3,4	3DR index	Score (0–1)		
3.2		Deconstructability Index (DE)	3,4	3DR index	Score (0–1)		
3.3		Resilience Index (R)	3,4	3DR index	Score (0–1)		
4	**Product Circularity Indicator (PCI)**			**BCI, PCI**	**Score (0–1)**	Case Study – Steel-Frame Buildings in Italy	(Cottafava and Ritzen, 2021; Khadim et al., 2022; Mazzoli et al., 2022)
4.1		Disassembly Capability	3,4	BCI	Score (0–1)		
4.2		Materials Origin (MO)	1	BCI	Score (0–1)		
4.3		Reusability (RU)	4	BCI	Score (0–1)		
5	**Reuse Index**		**3,4**	**CE Metrics**	**%**	Indicator Mapping – Meta-Analysis of 63 CE Metrics	(Askar et al., 2022; de Pauw et al., 2022; Parchomenko et al., 2019)
6	**Reusability Index**		**4**	**PROGRESS Pro**	**%**	Case Study – Selective Demolition of Steel Buildings	Melella et al. (2021)
6.1		Disassembly Damage	4		%		
6.2		Handling	4		%		
6.3		Modification	4		%		

* Resources flow: [1] Design for resource efficiency, [2] Design for Long Life Use of Products, [3] Design for Extending Product Life, [4] Design for Multiple Cycles.

Appendix 2.4.1 Circular Potential (As Installed) - KPI Calculation Formulas and Parameters

No.	KPIs	Formula	Parameters	Source
5	**Reusability index**	$RI = \sum Recovery\ Potential\ X\ Weights$	Recovery Potential (7.1, 7.2, 7.3) Weights DD = 0.5, H = 0.25, M = 0.25	Melella et al. (2021)

Appendix 2.4.2 Circular Potential (As Installed) - KPI Rating Scales and Indicator Scores

No.	KPIs/Indicator	Rating Scale	Score	Source
1.1	**Parts Per Element**			Cottafava and Ritzen (2021)
		Dry Connection: Dry connection, Click connection, Velcro connection, and Magnetic connection.	1	
		Connection with Added Elements: Bolt and nut connection, Spring connection, Corner connection, and Screw connection.	0.8	
		Direct Integrated Connection: Peg connection and Nail connection.	0.6	
		Soft Chemical Connection: Sealant connection and Foam Connection (PUR)	0.2	
		Hard Chemical: Glue connection, Cement-bound connection, and Chemical anchor	0.1	
1.2	Connection Accessibility			Cottafava and Ritzen (2021)
		Freely Accessible	1	
		Accessibility with additional actions that do not cause damage	0.8	
		Accessibility with additional actions with reparable damage	0.4	
		Not accessible irreparable damage to objects	0.1	
1.3	**Crossings**			Cottafava and Ritzen (2021)
		Modular zoning of objects	1	
		Crossings between one or more objects	0.4	
		Full integration of objects	0.1	
1.4	**Form Containment**			Cottafava and Ritzen (2021)
		Open, no inclusions	1	
		Overlaps on one side	0.8	
		Closed on one side	0.2	
		Closed on several sides	0.1	
2.1	**Disassembly Plan (Drawing and Specifications)**			Dams et al. (2021)
		No Disassembly Plan	0	
		Minimal Consideration for Disassembly in Design and Plans	1	

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No.	KPIs/Indicator	Rating Scale	Score	Source
		Some Considerations for Disassembly	2	
		Clear Disassembly Plans	3	
		A Reasonably Comprehensive Disassembly Plan	4	
		Clear Disassembly Plan	5	
2.2	**Disassembly Sequencing Information**			Dams et al. (2021)
		No Disassembly Sequence	0	
		Minimal Consideration for Disassembly	1	
		Some Considerations for Disassembly	2	
		Moderately Detailed	3	
		Reasonably Comprehensive Disassembly And Sequence	4	
		Sequence Prepared During the Design Stage	5	
2.3	**Clarity and transferability of Plans and Specifications**			Dams et al. (2021)
		Incomplete Or Unclear	0	
		Minimal Consideration for Disassembly	1	
		Some Considerations for Disassembly	2	
		Clear Disassembly Plans	3	
		Reasonably Comprehensive Disassembly Plan and Sequence	4	
		Clear Specifications	5	
3.1	**Tools required to disassemble its components DIt, DEt**			(Kristensen and Mosgaard, 2020; O'Grady et al., 2021)
		No tool	1	
		Hand tool	0.9	
		Power tool	0.8	
		Gas/pneumatic tool	0.5	
		Hydraulic equipment	0.2	
3.2	**People or equipment required to move components DIm, DEm**			(Kristensen and Mosgaard, 2020; O'Grady et al., 2021)
		One person: <20 kg	1	
		Two people: <42 kg	0.9	
		Hand trolley: <50 kg	0.7	
		Forklift: <2000 kg	0.4	
		Crane: >2000 kg	0.1	
3.3	**Degree of resilience of a part, component or material**			(Kristensen and Mosgaard, 2020; O'Grady et al., 2021)
		Reusable an infinite number of times	1	
		Reusable up to three times	0.9	
		Reusable only once	0.7	
		Recyclable	0.6	
		Downcyclable	0.2	
		Disposable	0	
4.2	**Materials' origin (MO)**			(Cottafava and Ritzen, 2021; Khadim et al., 2022; Mazzoli et al., 2022)
		In-use	1	
		Locally repaired, reused materials	0.8	
		Refurbished, remanufactured, recycled materials	0.6	
		Biobased virgin materials	0.4	
		Non-biobased virgin materials	0.1	
4.3	Reusability (RU)			(Cottafava and Ritzen, 2021; Khadim et al., 2022; Mazzoli et al., 2022)
		Repairable	1	
		Reusable	0.8	
		Refurbishable	0.6	
		Recyclable	0.4	
		Not recoverable	0.1	
6.1	Disassembly Damage			Melella et al. (2021)
		"Welded" system Welds	40 %	
		"Dry" system, Clamping technique Nails, rivets	60 %	
		"Dry" system clamping Technique Hard to access bolts, screws	80 %	
		"Dry" system, clamping and interlocking technique Bolts, snap joints, simple overlap	100 %	
6.2	Handling			(Askar et al., 2022; Melella et al., 2021)
		Fragile elements	0–20 %	
		Mobile crane Elements length greater than 12.00 m	40 %	
		Mobile crane Elements length less than 12.00 m	60 %	
		Lift equipment (telescopic handler, metal baskets)	80 %	
		Manual	100 %	
6.3	Modification			(Melella et al., 2021; Parchomenko et al., 2019)
		Complete regeneration or non-reusability	0–20 %	
		Removal of welded parts (plates) or Imperfections generated by the plasma cutting process	40 %	
		Removal of perforated parts caused by bolted or screwed connections	60 %	
		Removal of surface imperfections, parts damaged during disassembly or transport	80 %	
		Cleaning and refurbishment of the corrosion protection system	100 %	

Appendix 2.5 Material Output and Recirculation - Overview of Methods and Validation

No.	KPIs	Indicators	CE Principle	Method	Quantitative Metric	Validation	Source
1	**The amount of unrecoverable waste (W)**		**4**	**MCI**	**Mass**	Real-world applications through eight European building case studies.	(R. Askar et al., 2022; Cottafava and Ritzen, 2021; Dodd et al., 2017; International Organization forS, 2024; Khadim et al., 2022; Kristensen and Mosgaard, 2020; Saidani et al., 2019)
1.1		Waste from the linear flow		MCI	Mass		
1.2		Waste from the recovery process	4	MCI	Mass		
2	**Material Consumption**		4	MFA	**Mass or %**	Case Study – Circular Kitchen & Façade, Netherlands	(Dodd et al., 2017; Elia et al., 2017; International Organization forS, 2024; Malabi Eberhardt et al., 2021; Parchomenko et al., 2019; van Stijn et al., 2022; Wouterszoon Jansen et al., 2022)
2.1		Reusable Material Export	4	MFA, CPD Toolkit	Mass or %		
2.3		Recyclable Material Export	4	MFA, CPD Toolkit	Mass or %		
2.4		Recoverable/ Biodegradable Material Export	4	MFA	Mass or %		
2.5		Disposed Material	4	MFA	Mass or %		
3	**Material that cannot be recovered**		**4**	**Waste Ordinance**	**%**	Case Study – Steel-Frame Buildings, Italy	Melella et al. (2021)
4	**End-of-life pathways**		**4**		**letters**	Case Study – BNB Pilot Projects, Germany	(Khadim et al., 2022; Nemeth et al., 2022)
5	**Health and Safety**		**3,4**	**CCEF**	**% or Score/ 10**	Material Health Assessment – Product-Level Certifications, Case Study – 4 Pilot Buildings	(R. Askar et al., 2022; Council, 2019; Dams et al., 2021)
5.1		Toxicity/Synthetic Chemicals	3,4	CCEF	Scale (0–5)		
5.2		Ease of access Construction and Disassembly	3,4	CCEF	Scale (0–5)		

* Resources flow: [1] Design for resource efficiency, [2] Design for Long Life Use of Products, [3] Design for Extending Product Life, [4] Design for Multiple Cycles.

Appendix 2.5.1 Material Output and Recirculation - KPI Calculation Formulas and Parameters

No.	KPIs	Formula	Parameters	Source
1	**The amount of unrecoverable waste (W)**	$Wj = W0j + Wfj$	Recovery Potential (7.1, 7.2, 7.3) Weights DD = 0.5, H = 0.25, M = 0.25	(Cottafava and Ritzen, 2021; Dodd et al., 2017)
3	**Material that cannot be recovered**	$\%\,Material\ that\ cannot\ be\ recovered = 100\% - \%Reusability\ index$		(Melella et al., 2021; Parchomenko et al., 2019)

Appendix 2.5.2 Material Output and Recirculation - KPI Rating Scales and Indicator Scores

No.	KPIs/Indicator	Rating Scale	Score	Source
4.3	**Toxicity/Synthetic Chemicals**			Dams et al. (2021)
		Very high use of synthetic chemicals, resins, finishes and treatments.	0	
		High use of synthetic chemicals, resins, finishes and treatments.	1	
		Significant use of synthetic chemicals, resins, finishes and treatments.	2	
		Moderate use of synthetic chemicals, resins, finishes and treatments	3	
		Little use of synthetic chemicals, resins, finishes and treatments.	4	
		No synthetic chemicals, resins, finishes or treatments.	5	
5.1	**Ease of access Construction and Disassembly**			Dams et al. (2021)
		no accessibility or disassembly without significant damage to surrounding materials	0	
		limited accessibility or scope for disassembly without significant damage to surrounding materials	1	
		limited accessibility or scope for disassembly without some damage to surrounding materials	2	
		reasonably accessible, scope for disassembly with minor damage to surrounding materials	3	
		mostly accessible, disassembly possible with only very minor damage to surrounding materials	4	
		full accessibility with minimal work and scope for full disassembly with no damage to surrounding materials	5	
4	**End-of-life pathways** **Reuse (Product/Element)**		A+++	Nemeth et al. (2022)

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No.	KPIs/Indicator	Rating Scale	Score	Source
	RC Recycling (Materials)	Closed Circuit feedstock Recycling	A++	
		Mechanical Recycling without Processing Effort	A+	
		Mechanical Recycling with Processing Effort	A	
	Recovery	Backfilling	B	
		Energy Recovery (Low-Pollution)		
	Landfill	Landfill without Processing effort	C	
		Energy disposal (Average Pollution content)		
	Landfill	Landfill with Processing effort	D	
		Energy disposal pollutant content)		

Appendix 3. Application Case Study: Unitised Wall System

CE Principle				Circular lifecycle stages	Circular Façade Design Strategies	KPIs	Indicators	Metric	Components	Parts		Materials					
1	2	3	4						UCW	Frame	IGU	Aluminium	Silicone Gasket	Laminated Glass	Spacebar	Silicone Sealants	
				Material Inputs (as manufactured)	Design for Biological Materials	Resource Origin Efficiency		%or Kg	0%	0%	0%	0%	0%	0%	0%	0%	
							Renewable Material (Appx. 2.1.1)	%or Kg	0%	0%	0%	0%	0%	0%	0%	0%	
							Non-Renewable Material (Appx. 2.1.1)	%or Kg	100%	100%	100%	100%	100%	100%	100%	100%	
					Design for Materials Optimization	Material Resource Efficiency		%or Kg	10%	35%	0%	40%	0%	0%	0%	0%	
							Reused Material (Non-Virgin) (Appx. 2.1.1)	%or Kg	0%	0%	0%	0%	0%	0%	0%	0%	
							Recycled Material (Non-Virgin) (Appx. 2.1.1)	%or Kg	10%	35%	0%	40%	0%	0%	0%	0%	
							Virgin Material (Appx. 2.1.1)	%or Kg	90%	65%	100%	60%	100%	100%	100%	100%	
				Material Inputs (as installed)	Design for Prefabrication and Assembly	Prefabrication Rate		%	100%	100%	100%						
							Prefabricated	%	100%	100%	100%						
							On-site	%	0%	0%	0%						
						Component Dependency	(Appx. 2.2.1)	Score %		40%	20%						
						Layer Dependency	(Appx. 2.2.1)	Score %	80%								
						Reused Components		%or kg	0%	0%	0%						
						Finishes/Treatments		/10	0	0	0						
							Synthetic/Chemical/Wet Resins/ Adhesives (Appx. 2.2.1)	/5	0	0	0						
							Chemical Coating (Appx. 2.2.1)	/5	0	0	0						
				Lifespan and In-Use Performance	Design for Durability & Reliability	Durability		/15	4/15	8	6						
							Number of Previous Design Lives/Uses (Appx. 2.3.2)	/5	1	3	3						
							Length of Previous Design Lives (Appx. 2.3.2)	/5	0	0	0						
							Predicted Length of Current Design Life (Appx. 2.3.2)	/5	3	5	3						
						Product Utility (X)	Appx. 2.3.1	Scale 0-1	0.45								
							Lifespan Ratio (Appx. 2.3.1)	Ratio	0.6								
							Lifetime	Years	15								
							Lifetime industry average.	Years	25								
							Intensity Ratio (Appx. 2.3.1)	Ratio	0.8								
							Number of functional units achieved during the use of a product	Years	25								
							Average use of an industry-average product of similar type.	Years	30								
						Longevity	(Appx. 2.3.1)	Years	50	180	25	180	30	30	120	25	
							Initial Lifetime	Years	25	60	25	60	30	30	60	25	
							Lifetime after Refurbishment	Years	25	60	0	60	0	0	0	0	
							Lifetime after Recycling	Years	0	60	0	60	0	0	60	0	

CE Principle (1, 2, 3, 4)	Circular lifecycle stages	Circular Façade Design Strategies	KPIs	Indicators	Metric	Components: UCW	Parts: Frame	Parts: IGU	Materials: Aluminium	Materials: Silicone Gasket	Materials: Laminated Glass	Materials: Spacebar	Materials: Silicone Sealants
	Lifespan and In-Use Performance	Design for Maintenance	Maintenance (Amount of Replacement Material)		Kg or %	0	0	0	0	0	0	0	0
				Amount of a replacement's material	Kg	0	0	0	0	00	0	0	0
				Building lifespan	Years	15	15	15	15	15	15	15	15
				Service lifespan of a component	Years	25	60	25	60	30	30	60	25
		Design for Standardisation & Compatibility	Standardisation and Modularity		/15	14	14	13					
				Element Dimensions (Appx. 2.3.1)	/5	4	5	5					
				Component Variation (Appx. 2.3.1)	/5	5	5	4					
				Connections (Appx. 2.3.1)	/5	5	4	4					
		Design for Modularity	Simplicity in Design		/10	6	5	5					
				Element Independence (Appx. 2.3.1)	/5	3	2	2					
				Parts Per Element (Appx. 2.3.1)	/5	3	3	3					
		Design for Flexibility and Upgradability	Flexibility for Reuse	(Appx. 2.3.1)	Score %	100&	40%	40%					
	Circular Potential (as installed)	Design for Disassembly	DfD Recoverable		%	85%	50%	20%					
				Connection Type (Appx. 2.4.2)	%	80%	80%	20%					
				Connection Accessibility (Appx. 2.4.2)	%	80%	80%	10%					
				Crossings (Appx. 2.4.2)	%	100%	40%	40%					
				Form Containment (Appx. 2.4.2)	%	80%	10%	10%					
			Disassembly Recorded Information		/15	9							
				Disassembly Plan (Drawing and Specifications) (Appx. 2.4.2)	/5	2							
				Disassembly Sequencing Information (Appx. 2.4.2)	/5	4							
				Clarity and transferability of Plans and Specifications (Appx. 2.4.2)	/5	3							
			Reuse Index	(Appx. 2.4.2)	%	50%							
				Number of use periods		2							
			Reusability index	(Appx. 2.4.2)	%	73%							
				Disassembly Damage (Appx. 2.4.2)	%	80%							
				Handling (Appx. 2.4.2)	%	40%							
				Modification (Appx. 2.4.2)	%	100%							
			Product Circularity Indicator (PCI)	(Appx. 2.4.2)	0-1 score	0.88							
				DfD Recoverable (Appx. 2.4.2)	0-1 score	0.85							
				Materials' origin (MO) (Appx. 2.4.2)	0-1 score	1							
				Reusability (RU) (Appx. 2.4.2)	0-1 score	0.8							
			3DR Index										
				Tools required to disassemble its components DIt, Det	0.2-1 score	0.9							
				People or equipment required to move components DIm, Dem	0.1-1 score	0.4							
				Degree of resilience of a part, component or material	0-1 score	0.9							
				Weight of component	Kg	230							
				Total weight of the building	Kg	6900							
				total number of components	Nu.	30							
				total number of components in the building	M	1							

CE Principle (1, 2, 3, 4)	Circular lifecycle stages	Circular Façade Design Strategies	KPIs	Indicators	Metric	Components: UCW	Parts: Frame	Parts: IGU	Materials: Aluminium	Materials: Silicone Gasket	Materials: Laminated Glass	Materials: Spacebar	Materials: Silicone Sealants
	Materials Output and Recirculation	Design for Reuse	Reusable Material Export		Kg or %	230 kg Reused	-	-	-	-	-	-	-
			Health and Safety		/10	8	3	0	**8**	**0**	**3**	**0**	**0**
				Toxicity/Synthetic Chemicals (Appx. 2.5.2)	/5	3	0	0	5	0	0	0	0
				Ease of access Construction and Disassembly (Appx. 2.5.2)	/5	5	3	0	3	0	3	0	0
		Design for Recyclability	Recyclable Material Export		Kg or %				0	0	0	0	0
		Design for Recoverability	Recoverable/Biodegradable Material Export		Kg or %				0	0	0	0	0
			Decrease unrecoverable waste (W)	(Appx. 2.5.1)	Kg				0	0	0	0	0
				Waste from the linear flow	Kg				0	0	0	0	0
				Waste from the recovery process	Kg				0	0	0	0	0
			End-of-life pathways	(Appx. 2.5.2)	Letter	A+++			A+++	A+++	A+++	A+++	A+++

. (*continued*).

Data availability

Data will be made available on request.

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