Data-Driven Workflow Framework for Façade Retrofit Processes based on Circular Economy Principles

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Abstract

Over 85% of Europe's existing building stock fails to meet current energy-efficiency standards, underscoring the urgent need for large-scale retrofits. In line with EU climate objectives to accelerate the renovation wave and reduce embodied carbon emissions, façade retrofit offers significant potential to lower operational energy and resource demand, aligning with Circular Economy (CE) principles. However, the implementation of CE strategies is limited by fragmented practices, insufficiently documented product data, and the lack of standardised integration within design workflows.

This research presents a framework that embeds CE-relevant Key Performance Indicators (KPIs) as guidelines for product selection, data structuring, and environmental performance evaluation. The framework links a Material Database (MDB) for structured product data management with a Façade Configurator (FC) as a digital, simulation-based design support tool. The MDB aligns with EU data requirements and extends the Digital Product Passport (DPP) concept by capturing detailed circularity-related information. Environmental impact criteria include Global Warming Potential (GWP), Primary Energy Demand from Non-Renewable Resources (PENRE), Recycling Content (RC), and the use of Renewable Resources (RR). Applied to real-world façade retrofit case studies, the proposed framework enhances early-phase environmental assessment and supports informed, circular design decisions.

Keywords

Façade retrofit, material database, workflow management, digital services, information management, façade configurator

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1 INTRODUCTION

Today, over 85% of Europe's building stock does not meet energy-efficiency standards (European Commission, 2020), even though the building sector is one of the largest energy consumers, accounting for 40% of total energy demand and 36% of greenhouse gas emissions in Europe (EUROSTAT, 2023). The construction sector remains heavily reliant on the extraction of natural resources, operating within a predominantly linear "take-make-dispose" economic model (Ellen MacArthur Foundation, 2014), thereby exacerbating resource depletion and environmental degradation.

Retrofitting existing building stock with prefabricated façade assemblies appears to be a key strategy for transitioning toward a Circular Economy (CE), as it significantly reduces resource consumption and emissions compared to new construction. At the same time, façade retrofitting approaches can reduce operational energy demand by 15% to 20% (Nagel et al., 2024).

Despite these benefits, the annual renovation rate in the EU is only 0.2%, falling significantly short of the 3% target required by 2030 to align with climate objectives (Atanasiu et al., 2011). At the same time, the implementation of CE principles is progressing slowly due to challenges such as the complexity and fragmentation of the construction industry's value chain (Rohde & Lützkendorf, 2011), a lack of collaborative structures (Ghinoi, Silvestri & Steiner, 2020; Pomponi & Moncaster, 2016), insufficient data transparency throughout the building lifecycle (Ma & Jørgensen, 2025), the competitiveness of recycled versus primary resources (EEA, 2026), limited cultural acceptance (Ranasinghe et al., 2024), and regulatory hurdles (Global ABC, 2024).

Although previous studies (Marques & Salgado, 2007; Albayati & Kadhim, 2023) have demonstrated that material selection has significant potential to influence environmental impacts, architects—who play a central role in material selection and construction methodologies—often face challenges in making environmentally responsible design choices (Li, 2020), for example when prioritising and weighting relevant assessment criteria (Akadiri, Olomolaiye, & Chinyio, 2013; Li, 2020).

These challenges primarily arise from (1) the absence of well-defined guidelines for integrating CE strategies into design (Mirzaie, Thuring, & Allacker, 2020), (2) the lack of systematic integration of frameworks for assessing design decisions based on CE principles, and (3) the inadequate availability and structuring of CE-relevant building product information. In façade retrofitting projects, these challenges are amplified by the predominance of Engineer-to-Order systems (Montali et al., 2017) and the increasing range of façade-related requirements, which together render façade design highly interdisciplinary and complicate the integration of CE principles.

Although the European Commission's Level(s) framework (European Commission, 2019) introduces indicators related to circularity, its flexibility results in a lack of precision in assessing circularity and the availability of product data. The European Union (EU) has recognised these challenges related to missing environmental data by introducing the Digital Product Passport (DPP) (European Council, 2024). However, no specific instructions on data formats and methodologies are provided to ensure integration with other digital systems used in the construction sector, such as BIM (Construction Products Europe, 2025). Currently, DPPs primarily serve as passive repositories of CE-related data rather than as active tools to guide planners' design decisions.

Although private-sector tools such as Madaster generate Material Passports (MPs) from BIM models via Industry Foundation Classes (IFC) or spreadsheet uploads, they do not actively guide architects toward circular design solutions (Druijff, 2019).

The integration of DPPs into design workflows remains limited due to the current lack of a binding legal mandate and regulatory clarity. At the data level, the current IFC schema provides limited support for representing CE-related attributes and often requires project-specific extensions, hindering interoperability and scalability (Tomczak et al., 2024). To sum up, circular KPIs, BIM-based environmental design assessment, and DPPs currently form parallel but weakly connected systems, limiting transparency, comparability, and traceability across the building lifecycle.

As a result, companies lack both an obligation and clearly defined datasets—many of which are still under standardisation—to share CE-relevant information (European Union, 2024).

Architects, clients, and other stakeholders still base their decisions on conventional priorities, such as aesthetics, cost (Lützkendorf, 2019; Meex, 2018), or material availability (Yildiz, 2025). Consequently, established planning tools and routines continue to dominate design practice.

Effective adoption of CE strategies requires structured data exchange across products (Kedir et al., 2024; Heinrich & Lang, 2019), for example, through DPPs, as well as guided stakeholder engagement through workflow mapping and clearly defined guidelines. Such frameworks support informed design decision-making based on KPIs (Acharya, Boyd & Finch, 2018) and enable seamless integration into the design process through digital simulation tools.

Central to the proposed framework is a Material Database (MDB), which follows the DPP approach. The MDB enables transparent access to CE-related product information throughout the presented design workflow and is actively integrated into the design through a digital tool. This integration allows for continuous assessment of environmental impacts during early-stage decision-making. A digital Façade Configurator (FC) retrieves data from the MDB and generates alternative façade assembly configurations based on KPIs aligned with CE principles. The FC is compatible with IFC, rendering the proposed framework adaptable to other façade retrofit projects.

By being directly linked to the IFC model of a real case study comprising four demonstration buildings, the framework supports informed, performance-driven decision-making. It strengthens the systematic integration of circularity and environmental performance while storing data on products' circularity performance via an MDB following the EU's DPP approach.

2 METHOD

This research is structured into two key stages, as shown in Figure 1.

The first part of the research focuses on creating a workflow for façade retrofitting based on a case study approach, grounded in a real-world façade retrofit scenario (AEGIR, 2025). It involves the development of a prefabricated façade retrofit system applied to four demonstration buildings listed in Table 1. This part of the research includes analysing and mapping the workflow of the case study's design process, with a focus on digital services for environmental simulation. The results are presented in Section 3.1.

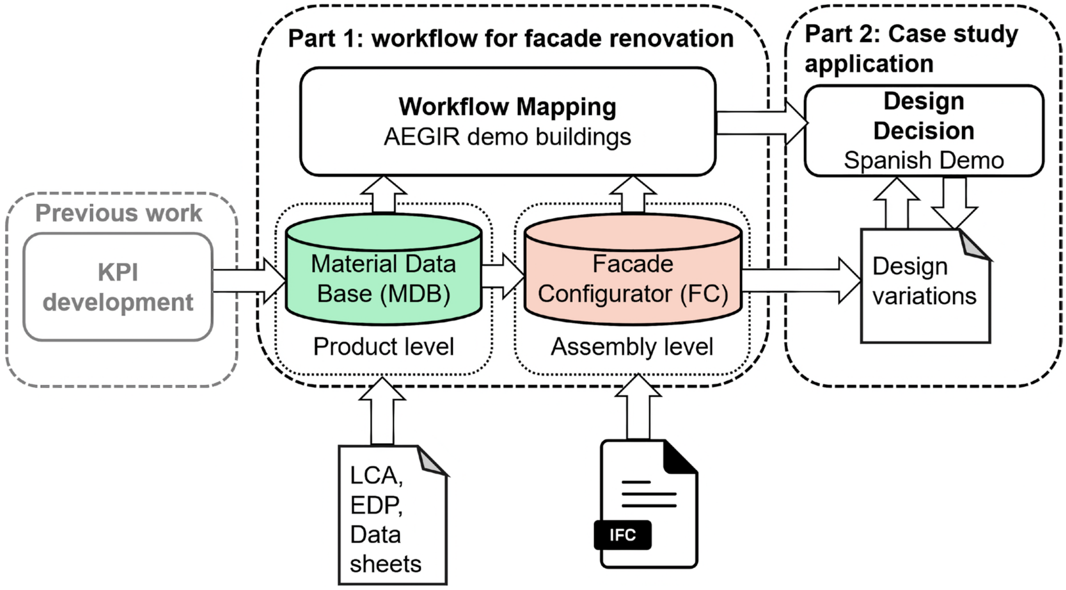


FIG. 1 Schematic graph of the research methodology

TABLE 1 Four AEGIR demo buildings

Quantitative KPI	Demo 1	Demo 2	Demo 3	Demo 4
Photo				
Location	Denmark	Spain	France	Romania
Description	Social housing	Educational building	Residential home for elderly people	Residential building

The second part of the research focuses on applying the proposed framework to one building within the project as a case study; the results are presented in Section 3.2.

2.1 PART I. CREATION OF A WORKFLOW FOR FAÇADE RETROFIT

2.1.1 Data Collection and Workflow Mapping

Data collection was conducted during a research exchange with leading partners from the four demonstration buildings in 2024, focusing on the design process to narrow the research scope. Interviews and workshops were used to gather information. Four semi-structured interviews (May-July 2024, ~6 h total) were conducted with demonstration site owners, representing private individuals (Romanian demo), corporate entities (Danish demo), and public authorities (Spanish and French demos). These discussions examined CE approaches and challenges, forming the basis for refining the design process map.

In addition, four workshops (~20 h total) were organised with key stakeholders (approximately five participants per demonstration building), including architects, structural engineers, contractors, manufacturers, and digital experts. The goal was to analyse the design process, add or redefine CE-relevant information, and determine strategies for data exchange through a World Café approach (Brown & Isaacs, 2005). Participants were selected based on their expertise and involvement within the project consortium, ensuring in-depth process knowledge but potentially introducing bias by primarily reflecting the consortium's internal perspectives. This limitation was addressed by structuring the discussions around predefined themes and focusing on process-related challenges rather than individual project positions.

Details on the interviews and workshops are available upon request.

2.1.2 Workflow mapping

A BPMN methodology was employed to systematically map design workflows, providing a structured representation of stakeholder interactions and key points for CE-relevant data generation, exchange, and utilisation. The results of one case study workflow are shown in Figure 8 (Section 3.1). BPMN was originally developed by the Object Management Group and standardised in 2011 (ISO/IEC 19510, 2013).

The methodology organises stakeholders in horizontal swimlanes, delineating their activities as tasks (see Figure 2), while the relevance of each building design stage (RIBA, 2020) is represented in vertical columns (Object Management Group, 2025; Kossak et al., 2014). The lowest row of the process map illustrates data files (e.g., EPD, IFC) as data objects and digital tools (e.g., MDB, FC) as data stores, as illustrated in Figure 2.

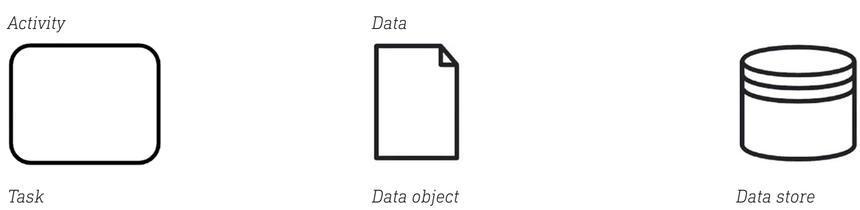


FIG. 2 BPMN symbols of activities and data exchange formats

TABLE 2 Qualitative and quantitative KPIs and their source (1) LCA, (2) Level(s) framework, (3) C2C, (4) R-Strategies

Quantitative KPI	Qualitative KPI
GWP (1,2)	Demountability (2)
RC (1,3)	Durability (2)
PENRE (1)	Compostability (3)
Hazardous substances (1,3)	Modularity (3)
Purity (3)	Low-Tec (3)
Materials for reuse/recycling (1,2)	Bill of Quantities (BoQ) (2)
RR (4)	Financial concept (3,4)
	Local material (3)

2.1.3 Selection of Key Performance Indicators

In the framework of the research, KPIs were derived from established methodologies such as LCA (ISO, 2006), Level(s) (European Commission, 2019), and common CE definitions such as Cradle-to-Cradle (C2C) (Braungart & McDonough, 2002) and the R-strategy approach (Reike, Vermeulen & Witjes, 2018), presented in previous publications (Zabek et al., 2023, 2024, 2025) and summarised in Table 2. While quantitative KPIs enable the assessment of design decisions, qualitative KPIs effectively guide design decisions. The selected KPIs in this research prioritise the assessment of Global Warming Potential (GWP), the share of Recycled Content (RC), Primary Energy Non-Renewable (PENRE), and the share of Renewable Resources (RR). This limitation provides measurable insights into carbon emissions, energy use, and resource utilisation associated with material choices, thereby establishing a robust framework based on CE principles.

2.1.4 Material Data Base (MDB) Development

The MDB is designed to store key data on product components intended for façade retrofit, such as insulation, cladding, structural elements, fixing elements, waterproofing foils, boards, windows, energy systems, shading devices, painting, and ventilation systems. It records product-specific data in accordance with the DPP approach, including manufacturer information, product designation, dimensions, size, and physical properties. These general data were obtained from product data sheets or provided directly by manufacturers upon request.

In addition to these general parameters, CE-related data based on predefined KPIs (Section 2.1.3) has been sourced from specific EPDs or LCA studies, such as those found in Ökobaudat (German Federal Ministry for Housing, Urban Development and Building, 2023), ecoinvent (Wernet et al., 2016), INIES (INIES, 2024), IBU data (Institut Bauen und Umwelt e.V., 2025), and Environdec (International EPD System, 2025). The GWP data is limited to LCA modules A1-A3, as outlined in EN 15804:2012 + A2:2020. Data on product-specific references are available upon request.

The functional unit is defined at the product level and expressed as a unitary reference (per kilogram/area/volume, depending on the product type), enabling consistent data normalisation. The FC (see Section 2.1.5) converts the normalised data of individual components to a mass-based reference using component material densities. Some components (e.g., photovoltaic panels or gaskets) have fixed dimensions, while others (e.g., metallic profiles or insulation materials) vary according to the overall dimensions of the AEGIR module. The reference time at the assembly level is 50 years; however, depending on product specifications, shorter lifespans have been considered.

Initially stored in a structured spreadsheet file (the dataset and its relation to the KPIs are presented in the appendix, Table 6), the data were converted into a dedicated ontology and stored in a triple-store database using scripts and imported as Resource Description Framework (RDF) (RDF Working Group, 2014). SPARQL Protocol (Harris & Seaborne, 2013) and RDF Query Language queries were used to harmonise data directly within the database. The MDB ontology builds on existing standards, notably ISO 23386 for the definition of product property dictionaries and the Building Product Ontology (Wagner et al., 2019) for the standardised description of building products, both adapted to the project's specific requirements.

The MDB introduces the concept of "Product Quantity," which describes the amount of a specific product used within an assembly. The ontology structures data as Products, each with associated Properties, composed of multiple Product Quantities. Finally, a dedicated frontend user interface was developed to enable the creation, modification, and deletion of Properties, Products, and AEGIR Modules.

2.1.5 Integration of MDB into digital services

To maximise the effectiveness of the MDB during the design phase, it is embedded within a Common Data Environment (CDE) (see Figure 3). This integrated digital infrastructure serves as a centralised repository for project information, ensuring data interoperability, consistency, and accessibility among all project stakeholders.

The MDB is not conceived as an isolated tool; rather, its value emerges through integration with a suite of specialised digital services. Using standardised material descriptions, the MDB supplies essential input data to the Digital Twin (DT), the FC, multiple performance simulation tools (including energy demand, solar energy production, and indoor air quality), as well as KPI management services.

The simulation phase used to evaluate design alternatives with respect to CE performance is described through four development steps, as illustrated in Figure 3.

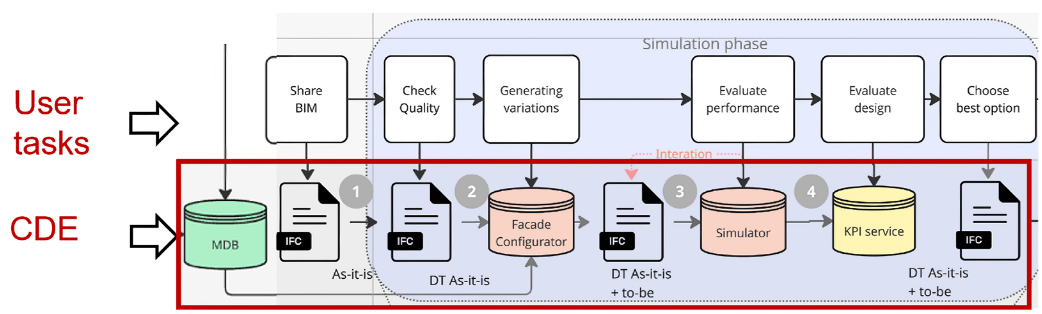


FIG. 3 Detailed Workflow of Common Data Environment (CDE) and user tasks during simulation phase, including integration of MDB into FC (extracted from the Design Process Map of Figure 8 in Section 3.1.)

As a first step, the IFC file of the BIM model representing the existing building ("as-is") is uploaded to the DT. The model is refined until it meets the quality standards required for digital services (e.g., thermal simulation or solar potential services). Upon verification, the BIM model becomes available for additional digital services, including the FC.

As a second step, the BIM-based FC serves as the primary entry point to the digital services, generating a range of retrofit alternatives while calculating material-related quantitative KPIs retrieved from the MDB and integrating with additional digital services (e.g., energy performance, solar potential) for further KPI assessments.

Figure 4 shows an overview of the FC logic with (1) four module families (MF1 = opaque, MF2 = embedded windows, MF3 = modules for corners, and MF4 = modules with PV panels included) and (2) the rules used to internally configure each module, in this case MF1. Each MF has minimum and maximum allowable width (W) and height (H) constraints that reflect construction and transportation requirements. Based on these parameters, the number and spatial arrangement of internal profiles are automatically determined. The FC workflow is as follows (3): the user uploads the as-is IFC model (B) into the web-based application and generates multiple retrofit alternatives, resulting in a set of IFC models (A) that serve as input for other services, including performance simulations and the KPI service. The selected FC alternative is subsequently transferred to the DT environment for integration with digital services and tools. The DT is not used for design modification or alternative analysis; instead, it represents and operates exclusively on the final selected solution for visualisation and service deployment.

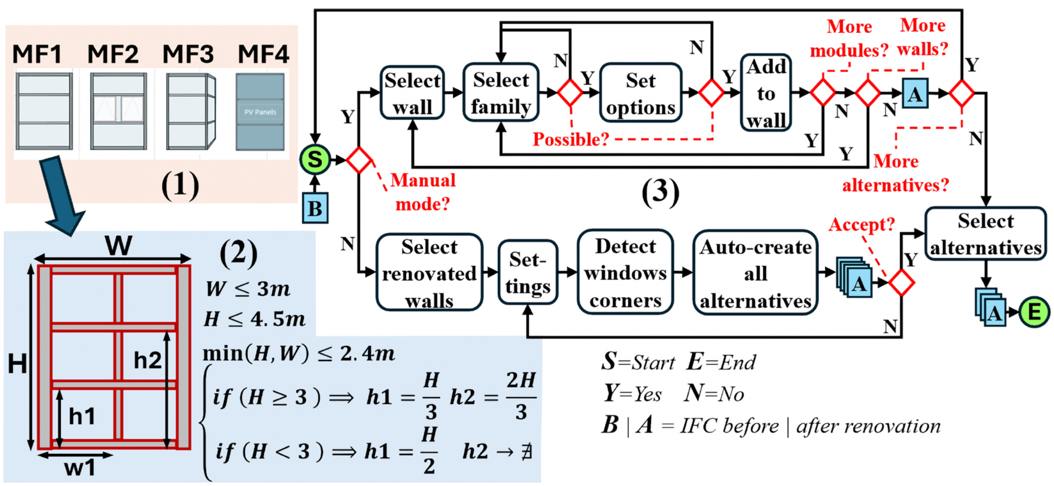


FIG. 4 Workflow inside the FC and rules to configure each module family

The only requirement for the IFC input file is that external walls are modelled as IfcWall entities with the IsExternal = TRUE property; no other objects can be edited. Two operating modes are available:

- Manual mode: Users manually select walls and assign suitable module families. Automated validation prevents incompatible or dimensionally invalid configurations before generating the output IFC.
- Automated mode: The FC automatically generates a set of valid retrofit variants after the user selects the façade areas to be renovated. Users may constrain the solution space by specifying initial parameters such as module families or dimensions.

Figure 5 illustrates the creation of a façade module instance.

(1) The FC connects to the MDB via an Application Programming Interface (CSTB, 2025) to retrieve the module hierarchy and available material variants. In this example, MF1 consists of an insulation layer (I1: cellulose, I2: wood fibre), metallic profiles (P1: aluminium, P2: steel), and a cladding layer (C1: ceramic tile, C2: composite wood). MF1 excludes windows (MF2) and PV elements (MF4).

(2-4) An instance of MF1 is generated based on the dimensions of a specific wall and selected material options. Multiple modules are combined to cover the façade, with partial visualisation enabling inspection of internal layers and profiles. Figure 5 shows an individual module (2), the assembled wall (3), and a detailed view (4).

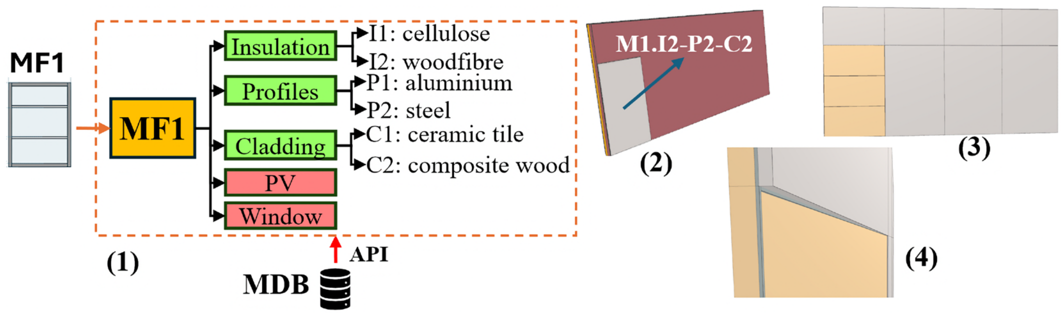


FIG. 5 Creation of module instances from MDB

Figure 6 shows the mapping conventions used in IFC to create the module. The whole module is represented by an IfcElementAssembly, and the internal decomposition into products is materialised through an IfcRelAggregates relationship. The colour coding shows which IFC class has been used for each product (insulation, profiles, etc.). In some cases, the classes can be too generic, and further detailing is done using predefined types (shown in blue uppercase).

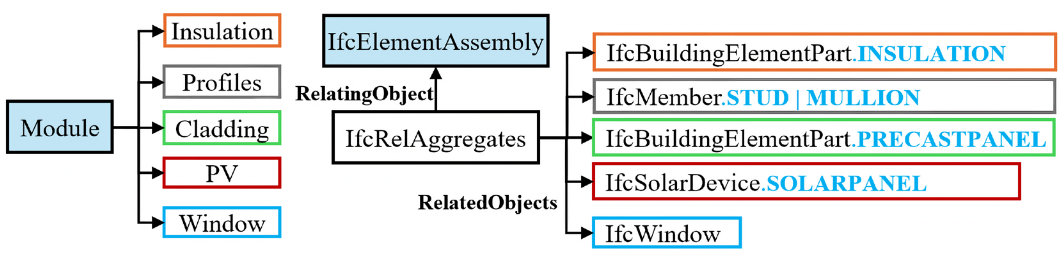


FIG. 6 Mapping the hierarchy represented in the MDB into the IFC schema

For each product, the base quantities are internally calculated: volume for all products, additionally area and thickness for 2D layered products (e.g., insulation, cladding), and length for linearly extruded ones (e.g., profiles). These values are assigned to the associated property set in IFC4 (e.g., Qto_MemberBaseQuantities for profiles). The rules depicted in Figure 4 (2) determine the dimensions of each subcomponent as a function of the whole module's W and H. These values are also used to create the IFC geometry using IfcExtrudedAreaSolid representation.

The FC retrieves from the MDB the material content of each component and its circularity data (GWP, RC, PENRE, RR) per kg or m^3, which are converted to absolute values using the component's volume (and density if the value is provided per kg). These values are then aggregated into the module and finally into the building.

To demonstrate the FC's capabilities, Section 3.2 presents three variations of cladding products applied to one specific case study.

As a third step of the simulation phase, selected design alternatives undergo environmental, structural, and economic assessments. The KPI management service, integrated into the platform, acts as a centralised dashboard aggregating data from interconnected services, including the FC, performance simulation tools (e.g., energy demand, solar potential, indoor air quality), and the DT. Deployed within the DT, the service generates dashboards with static KPIs (e.g., CO_2 footprint, circularity, material data) and dynamic KPIs, linking monitored and simulated performance data to installed façade components. This enables holistic comparison of design alternatives and supports iterative optimisation until predefined circularity targets are met. The DT functions as the integrative platform connecting all project data, including 3D building geometry (architecture, HVAC, PV, façade systems), material information, Bills of Quantities (BoQ), costs, maintenance and dismantling instructions, End-of-Life scenarios, and dynamic data from sensors and simulation outputs.

In the fourth step of the simulation phase, users can assess and validate the most promising design alternative before advancing to the preliminary design phase using the KPI service. Results derived from the simulator service are visualised on a high-level dashboard, offering stakeholders an intuitive representation of the environmental impacts.

2.2 PART II. CASE STUDY FOR VALIDATING THE PROPOSED FRAMEWORK

To validate the proposed framework, a detailed examination of design decisions and the integration of the FC was conducted for a specific case study within the AEGIR project. The decision-making process has been documented by the authors, as they have been part of the project team. The validation of the decision-making process focuses on the product selection of the cladding materials.

The selected case study (Figure 7) focuses on the retrofit of a public school building for infant and primary education located in Malgrat de Mar, Spain. This case study presents distinct challenges and opportunities compared to the other three demonstration sites, particularly in its approach to incorporating reused and bio-based materials.

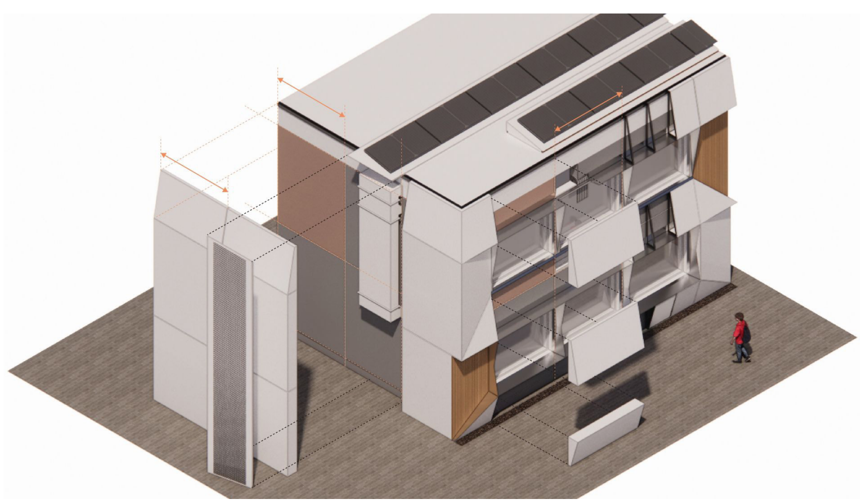


FIG. 7 Design for façade retrofit of the case study building in Malgrat de Mar, Spain. Source: UNS

3 RESULTS

3.1 PART I. WORKFLOW OF THE AEGIR DEMO BUILDINGS

The research methodology follows a case study approach embedded within a real-world façade retrofit scenario (AEGIR, 2025). The workflow of the façade retrofit is presented in the following sections, explicitly highlighting stakeholder involvement.

Across the four AEGIR demo buildings, data exchange mechanisms were inherently multidisciplinary, involving structural, ventilation, and electrical engineers, architects, panel manufacturers, among others, as illustrated by the BPMN (described in Section 2.1.2) in Figure 8.

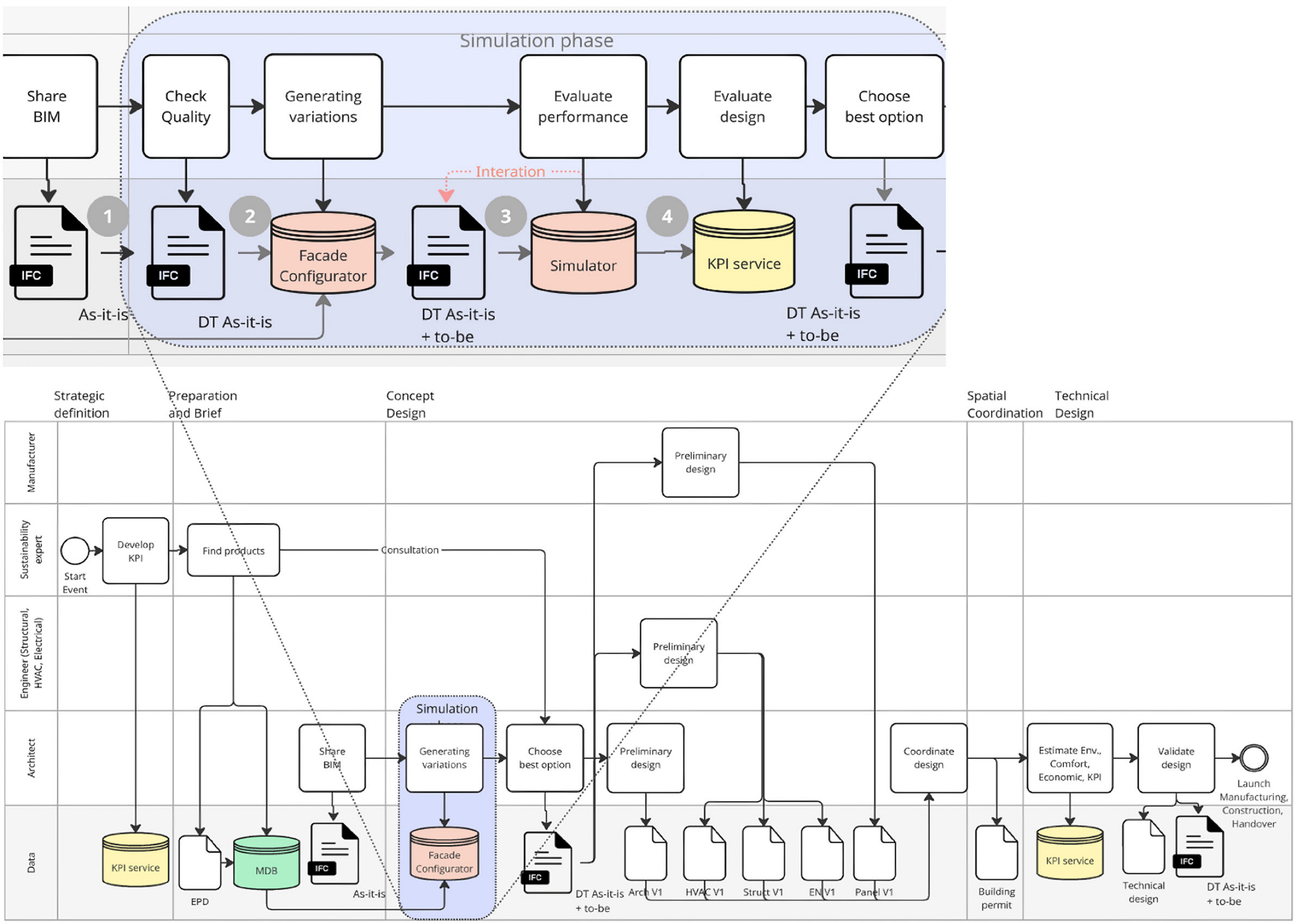


FIG. 8 Design Process Map of a circular façade retrofit process

CE objectives were systematically integrated into the design workflow, with KPIs (presented in Section 2.1.3) established *a* priori by sustainability experts to guide material and product selection. The sustainability experts used these KPIs to determine the required data for inclusion in the MDB (see Table 2). Additionally, they influenced early-stage design decisions, for example, product selection, through direct consultation with architects. Structural engineers concurrently ensured material integrity, for example, of the timber frame in the French demo and the bio-composite frame in the Spanish demo, optimising the trade-off between resource efficiency and structural performance.

Sustainability experts conducted environmental impact evaluations of selected materials by incorporating design decisions into the FC, delivering targeted recommendations—such as using insulation materials with high RC—to architects through individualised consultations. Meanwhile, energy engineers optimised building systems to minimise energy consumption while maximising operational efficiency through the integration of PV panels into the façade system.

The architect served as the central coordinator, synthesising multidisciplinary design inputs. Key responsibilities included the retrieval and federation of heterogeneous design documents, as well as the quantitative assessment of design variations across environmental, thermal comfort, economic, and KPI-based parameters.

3.2 PART II. APPLICATION OF DIGITAL SERVICES IN THE CASE STUDY OF A SCHOOL BUILDING IN SPAIN

3.2.1 Design decisions for product selection

The Spanish demonstration building is characterised by the early involvement of sustainability experts and close collaboration with the building owner. From the initial design stages, environmental KPIs (Section 2.1.3) were introduced, while the client prioritised the use of renewable and reused materials. Cladding products meeting both client preferences and the proposed KPI thresholds (low GWP and PENRE, high RC and RR) were selected as design alternatives, including post-consumer wood (reclaimed from building demolition, pallets, or mussel farms), harvested wood (virgin timber), and biobased composite products (see Table 2), where at least one material is derived from renewable biological resources.

These options were evaluated based on product-specific criteria such as cost, durability, availability, and composition, and were subsequently selected in the FC to generate alternative assembly designs, including all components required for a full façade retrofit. The assessment results are presented in Section 3.2.2, Table 4.

In line with the client's preference, reclaimed timber was proposed as a cladding option. Locally available sources—both post-consumer wood and harvested wood from regional forests—were identified and assessed for feasibility.

TABLE 3 Selected cladding material of reclaimed timber, virgin timber, and biobased composite products regarding product-specific criteria. All data sourced from manufacturers

	Product	Price	Durability (CEN, 1995)	Availability	Composition	Reference
Reclaimed wood	Reclaimed sweet chestnut (Castanea sativa) from building demolition	~800 €/m³	0-5 years (class 5)	limited	100 % reclaimed	Hnos. Castaño-a (2024)
	Reclaimed pallets (pine or poplar)	~1200 €/m³	0-5 years (class 5)	Available within 1 year	100 % reclaimed	Hnos. Castaño-b (2024)
	Reclaimed Southern blue gum (Eucalyptus globulus) from mussel farms	900 - 1800 €/m³	5-15 years (class 3)	Available within 1 year	100 % reclaimed	HVS (2024)
Locally sourced wood	Sweet chestnut	~800-1000 €/m³	15-25 years (class 2)	Available	100 % virgin	Sierolam (2024)
	Oak (Quercus robur)	~2000 €/m3	15-25 years (class 2)	Available	100 % virgin	Gamiz (2024)
	Douglas fir (Pseudotsuga menziessii)	~600 €/m³	5-15 years (class 3)	Available	100 % virgin	Sebastia (2024)
Biobased composite from raw and secondary resources	Bio-composite 1	80 -100 €/m²	50 years (class 1)	Available	40 % shredded Dutch poplar trees, 60 % minerals	Kerloc, (2025)
	Bio-composite 2	75-80 €/m²	50 years (class 1)	Available	60 % from paper waste	Trespa, (2025)
	Bio-composite 3	180 – 250 €/m²	50 years (class 1)	Available	100 % from residual waste	Nabasco (2025)

Reclaimed timber from demolition (commonly pine or oak) typically originates from structural elements and requires further processing for use as cladding. Pallet wood offers more standardised dimensions but is limited in length and often requires preservative treatment due to its low natural durability according to EN 350 (CEN, 1995) (e.g., pine, poplar), as shown in Table 3. Timber recovered from aquaculture infrastructure (Eucalyptus globulus), such as mussel farming platforms, shows moderate natural durability and, in some cases, dimensions suitable for direct reuse as cladding, making it the preferred reclaimed material. Overall, the feasibility of reclaimed timber depends heavily on regional availability.

Due to uncertainties in reclaimed timber supply, virgin timber cladding planks were evaluated as an alternative. Species with moderate to high natural durability were assessed. Oak and sweet chestnut exhibited higher durability (HVS, personal communication, March 2024) than Douglas fir (Table 3). Thermal modification was also considered to improve durability and reduce aesthetic and dimensional instabilities caused by weathering. Ultimately, oak was selected as a durable and renewable cladding option that balances performance and sustainability objectives.

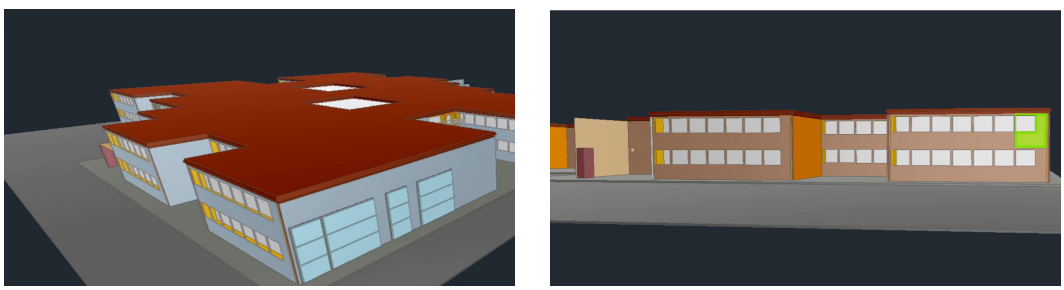
Due to the expected colour changes in timber caused by weather exposure, biobased composite products were evaluated as an alternative cladding solution. These materials, composed of renewable and recycled constituents, offer reduced environmental impact and potential for closed-loop recycling, with reported service lifespans of up to 50 years. Among the assessed products, a bio-composite with a high paper content (bio-composite 2) was selected based on its availability in the Spanish market and its competitive cost (Trespa, personal communication, March 2024).

The environmental performance of cladding solutions based on reclaimed timber from mussel farming platforms, virgin oak, and bio-composite 2 was subsequently evaluated using the FC. Results are presented in the following section.

3.3 SIMULATION PHASE OF QUANTITATIVE KPIS

To assess the environmental performance of the three selected cladding products — (1) reclaimed wood, (2) timber, and (3) bio-composite product —a detailed analysis was carried out using FC. With this tool, users can select cladding materials integrated into a predefined module design, which is then automatically applied in BIM. The environmental impact of each variation is evaluated based on (1) GWP, (2) PENRE, (3) RC and (4) RR.

The methodology underlying this process is explained in Section 2.1.5. Data sources are presented in Section 2.1.4. Figure 9 shows screenshots of the FC applied to the case study.



a b

FIG. 9 Application of FC to the case study. a: design process. b: final result with a sample module selected in green.

The final results are shown in Table 4, with three design options (MF1, MF2, and MF3) revealing significant differences in terms of GWP, PENRE, RC, and the share of RR.

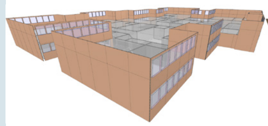
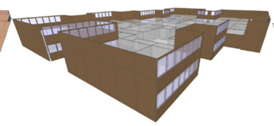
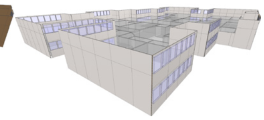
MF1, using reclaimed timber (eucalyptus) as cladding, demonstrated a considerably lower GWP of 9,156 kg CO_2 eq. and the lowest PENRE at 2,796,903 MJ. It also achieved the highest RC (68.98%), indicating a substantial contribution to circular resource use; its share of RR (40.48%) remained moderate.

MF2, composed of virgin timber cladding (oak), achieved a net negative GWP of −2,110 kg CO_2 eq., attributed to carbon sequestration during the wood's lifecycle. It recorded a PENRE of 2,814,422 MJ and the highest RR proportion (52.27%), with a moderate RC of 22.85%.

MF3, composed of a bio-composite cladding material (product 2), exhibited the highest GWP at 22,652 kg CO_2 eq. and the highest PENRE value of 3,151,453 MJ. Despite its relatively high RR share (37.62%), it had the lowest RC percentage (19.74%) among the three variants.

These results suggest that reclaimed wood (MF1) optimally balances environmental impact with high circularity potential, while conventional wood (MF2) offers the lowest climate impact due to its biogenic carbon storage. In contrast, the bio-composite solution (MF3) currently demonstrates the highest environmental burdens across most indicators.

TABLE 4 Final results of the environmental impact of AEGIR module families (MF) with preselected cladding materials generated by FC

AEGIR Module name	MF 1	MF 2	MF 3
Image			
Design specifications	Cladding material: Reclaimed timber (Eucalyptus globulus)	Cladding material: virgin timber (oak)	Cladding material: Bio-composite 2
Façade area (m2)	1169.34	1169.34	1169.34
GFA - Gross Floor Area (m2)	1234.80	1234.80	1234.80
GWP (Kg CO2 eq.)	9 156	-2 110	22 652
PENRE (MJ)	2 796 903	2 814 422	3.151.453
RC (kg %)	68,98	22,85	19,74
RR (kg %)	40,48	52,27	37,62

4 DISCUSSION

The presented workflow integrates CE principles through KPIs embedded in an MDB and an FC. Although these KPIs are derived from established and standardised methodologies that follow the DPP concept, they remain inherently incomplete and lack prioritisation. They should therefore be interpreted as flexible design guidelines rather than prescriptive metrics. In the current implementation, only quantitative KPIs are incorporated into the FC, while qualitative aspects—such as disassembly potential, reuse capacity, and product-specific constraints including cost and availability—remain relevant and should be considered when assessing circularity across the building life cycle.

The case study highlights that design decisions are strongly influenced by project-specific constraints, including budget limitations, timeframes, and client or architect preferences. This was evident in the Spanish demonstration building, where the final selection of cladding materials was primarily driven by client preferences, making it difficult to quantify the influence of simulation-based results. While the FC enables early-stage estimation of environmental impacts, results may vary depending on the selected KPIs and are not location-specific.

Differences in KPI rankings further emphasise the importance of adopting a holistic life cycle perspective. In the presented case, the selected façade solution combined materials with high performance in terms of recyclability and resource recovery, while alternatives performed better in terms of GWP. This divergence illustrates that focusing on a single indicator can lead to suboptimal decisions. In particular, biogenic materials may show favourable results in early life cycle stages (A1-A3), while potential carbon releases at the EoL stage are not fully captured. Consequently, evaluations require expert supervision.

The FC should therefore be understood primarily as an early-stage decision-support tool. Subsequent design phases must incorporate more detailed environmental assessments. Furthermore, the MDB currently contains only a limited number of products and includes only project-relevant reused materials, despite their potential for reducing resource consumption and

CO_2 emissions. This limitation is largely due to insufficient digital infrastructure and the dynamic availability of such materials.

The effective implementation of the workflow depends on several prerequisites: an accurate geometric representation of existing façades (e.g., via Scan-to-BIM processes), structured and hierarchical material data enriched with circularity KPIs, and a parametric tool capable of generating façade configurations, calculating material quantities, and ensuring interoperability with downstream applications. Its broader applicability depends on data quality, expert input, further validation across additional case studies, and practitioners' willingness to adopt the FC.

5 CONCLUSION

This research developed and validated a data-driven workflow framework for façade retrofit processes that systematically integrates CE principles into architectural design. By linking an MDB with a digital FC, the study demonstrates how structured product data and CE-relevant KPIs can be embedded into a digital design environment to support performance-based decision-making in early project stages.

The results confirm that the proposed framework addresses key barriers in current façade retrofit practice, particularly the fragmentation and limited availability of structured product data and the lack of integration of CE principles into design workflows. While the EU is advancing the implementation of DPPs, it has not yet clearly defined which information should be systematically stored or how such data should be structured and used within design processes. In this context, the MDB represents one possible approach to organising CE-relevant product information during the design phase.

Through the MDB, product-specific information aligned with the DPP concept becomes accessible within the design process. The FC operationalises this data by generating and evaluating alternative façade configurations based on quantitative KPIs, including GWP, PENRE, RC, and RR, enabling continuous environmental assessment and comparison between design options.

The application of the framework to a real-world case study demonstrates its practical relevance. The FC successfully generated multiple façade alternatives and quantified their environmental performance, revealing significant differences between material choices. Reclaimed timber showed strong performance in terms of circularity (high RC and low PENRE), while virgin timber achieved the lowest GWP due to biogenic carbon storage. In contrast, the evaluated bio-composite solution exhibited comparatively higher environmental impacts across most indicators. These findings highlight that no single material solution performs best across all KPIs, reinforcing the need for multi-criteria evaluation and a holistic life cycle perspective.

At the workflow level, the study emphasises the importance of interdisciplinary collaboration and structured data exchange. The BPMN-based process mapping illustrates how sustainability experts, architects, and engineers interact, with KPIs guiding material selection and design development. The architect plays a central coordinating role, synthesising inputs from various disciplines, while the integration of digital services within a CDE ensures data consistency and interoperability. Overall, the proposed framework helps bridge the gap between CE principles, digital product data, and architectural design workflows, supporting more circular façade retrofit practices.

5.1 FUTURE DEVELOPMENT

Future research should focus on expanding the MDB-FC system to incorporate building-level material specifications, comprehensive lifecycle performance indicators, and smart readiness metrics in machine-readable formats aligned with emerging EU standards. At present, the FC operates as an additional tool alongside established design environments commonly used by architects. However, the introduction of new digital tools may be perceived as an additional burden within already time-constrained design processes. Therefore, future developments should prioritise the seamless integration of the FC into existing workflows, particularly within BIM environments, to enhance usability and industry adoption.

Standardisation efforts should align with existing CEN/CENELEC specifications (e.g., EN 15804) and be coordinated with ongoing initiatives. Key priorities for further development include:

1. the adoption of standardised data templates for material characterisation;
2. the integration of structured datasets into digital design and assessment tools using open standards (e.g., IFC, gbXML); and
3. the piloting and validation of digital tool protocols.

By combining structured material data, interoperable digital workflows, and holistic LCA approaches, the proposed framework provides a replicable foundation for enabling environmentally informed decision-making in early-stage façade retrofit design.

6 GLOSSARY

TABLE 5 Glossary

Abbreviation	Full name
BIM	Building Information Modelling
BoQ	Bill of Quantities
BPMN	Business Process Model and Notation
C2C	Cradle to Cradle
CDE	Common Data Environment
CE	Circular Economy
CO_2	Carbon Dioxide
CPR	Construction Products Regulation
DPP	Digital Product Passport
DT	Digital Twin
EoL	End-of-Life
EU	European Union
Eq	Equivalent
EPD	Environmental Product Declaration
FC	Façade Configurator
gbXML	Green Building eXtensible Markup Language
GWP	Global Warming Potential
H	height
IFC	Industry Foundation Classes
Kg	Kilogram
LCA	Life Cycle Assessment
MDB	Materials Database
MF	Module Family
MP	Material Passport
mm	Millimeter
PENRE	Primary Energy Demand from Non-Renewable Resources
PV	Photovoltaic
RDF	Resource Description Framework
RIBA	Royal Institute of British Architects
KPI	Key Performance Indicator
RC	Secondary Material Content (Recycled Content)
RR	Renewable Resources Content
W	Width

7 APPENDIX

TABLE 6 MDB Data link to KPIs

KPI	Data
General	Name of component
	Developer/manufacturer
	Pictures
	Characteristics
	Short description (max 500 characters)
	Density (kg/m3)
	Thickness (mm)
GWP (CO2 eq.)	CO2 (eq/kg)
	Available Certificates (e.g., EPD) and their source
PENRE	MJ
Use of renewable resources RR (kg)	Amount of renewable/ primary material (%/kg)
Use of recycled material RC (kg)	Amount of reused/ recycled/ primary material (%/kg)
Use of reused material (kg)	Amount of reused/ recycled/ primary material (%/kg)
Hazardous substances (HWD) (kg)	Hazardous substance
Materials for recycling or reuse (kg)	Materials for reuse/recycling) (benchmarked according to levels framework)
	Recycling system (description)
	Expected material flow represented as waste categories according to European Commission
	Weight (kg)
	Size (mm x mm)
Durability/Lifespan/Maintenance/ Warranty (years)	Maintenance
	Expected lifespan (years)
	Material performance (e.g. thermal conductivity, energy performance)
BoQ	URL
	ID/GUI number
Demountability, reversibility (type of installation)	Demountability
Financial concept for multiple life circles (Take-back system or leasing)	Value (Euro/m2)
	Financial concept
Modularity	Modularity
	Size (mm x mm)
Local Material	Production site
	Locally sourced materials.
Low-Tech	Low-Tech approach
Material purity	Main material
	Product composition in kg %
Compostability	Compostability

8 DECLARATIONS

Declaration of competing interests

All authors disclose any financial and personal relationships with other people or organisations that could inappropriately influence or bias this work.

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Declaration of generative AI in scientific writing

During the preparation of this work, the authors used ChatGPT in the writing process in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

Acharya, D., Boyd, R., & Finch, O. (2018). *First steps towards a circular built environment.* Arup; Ellen MacArthur Foundation.

AEGIR. (2025). *Developing modular, renewable & industrialised building envelopes for low energy renovation.* https://aegirproject.eu/project/

Akadiri, P. O., Olomolaiye, P. O., & Chinyio, E. A. (2013). Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Automation in Construction*, *30*, 113–125. https://doi.org/10.1016/j.autcon.2012.10.004

Albayati, M., & Kadhim, A. (2023). Sustainable materials selection in building construction: A systematic literature review. *International Journal of Sustainable Engineering*, *16*(2), 106–119.

Atanasiu, B., et al. (2011). *Europe's buildings under the microscope.* Building Performance Institute Europe. https://www.bpie.eu/wp-content/uploads/2015/10/HR_EU_B_under_microscope_study.pdf

Braungart, M., & McDonough, W. (2002). *Cradle to cradle: Remaking the way we make things.* North Point Press.

Brown, J., & Isaacs, D. (2005). *The world café: Shaping our futures through conversations that matter.*

European Committee for Standardization. (1995). *EN 350-2:1995: Durability of wood and wood-based products — Natural durability of solid wood — Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe.*

Construction Products Europe. (2025). *Navigating the construction products regulation: A guide for manufacturers.* Construction Products Europe AISBL. https://www.construction-products.eu/publications/cpr-a-guide-for-manufacturers_navigating-the-construction-products-regulation-2/

CSTB. (2025). *AEGIR assemblies API.* https://cesium.cstb.fr/aegir/docs#/

Druijff, B. (2019). *BIM-based material passport in Madaster during the operational and maintenance phase of a building* [Master's thesis, University of Twente].

Ellen MacArthur Foundation. (2014). *Towards the circular economy: Accelerating the scale-up across global supply chains.* https://emf.thirdlight.com/link/t4gb0fs4knot-n8nz6f/@/preview/1?o

European Commission. (2019). *Level(s): Taking action on the total impact of the construction sector.* Publications Office of the European Union. https://ec.europa.eu/environment/eussd/pdf/LEVELS_REPORT_en.pdf

European Commission. (2020). *A renovation wave for Europe: Greening our buildings, creating jobs, improving lives* (COM(2020) 662). https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

European Council. (2024). *Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011.* https://eur-lex.europa.eu/eli/reg/2024/3110/oj/eng

European Environment Agency. (2022). *Investigating Europe's secondary raw material markets* (EEA Report No. 12). https://www.eea.europa.eu/en/analysis/publications/investigating-europes-secondary-raw-material

European Environmental Agency EEA. (2026). *Unlocking the circular economy: investment needs, barriers and enabling conditions.* Publications Office of the European Union. https://doi.org/10.2800/5422329

European Union. (2024). *Regulation (EU) 2024/1781 establishing a framework for ecodesign requirements for sustainable products (Ecodesign for Sustainable Products Regulation).* Official Journal of the European Union.

Eurostat. (2023). *Generation of waste by economic activity.* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation

Gamiz. (2024). *Boards and planks: Product information.* https://www.grupogamiz.com/en/products/boards-planks/

German Federal Ministry for Housing, Urban Development and Building. (2023). *Ökobaudat: The German database for life cycle assessment data in the construction sector.* https://www.oekobaudat.de

Ghinoi, S., Silvestri, F., & Steiner, B. (2020). The role of local stakeholders in disseminating knowledge for supporting the circular economy: A network analysis approach. *Ecological Economics*, *169*, Article 106446. https://doi.org/10.1016/j.ecolecon.2019.106446

Global Alliance for Buildings and Construction. (2024). *Building materials and climate: (Re-)use of secondary materials* (Section 3.6). https://globalabc.org/buildingmaterialsandclimate/chapter-3-avoid/3-6-re-use-of-secondary-materials.html

Harris, S., & Seaborne, A. (2013). *SPARQL 1.1 query language* (W3C Recommendation). World Wide Web Consortium. https://www.w3.org/TR/sparql11-query/

Heinrich, M., & Lang, W. (2019). *Materials passports: Best practice innovative solutions for a transition to a circular economy in the built environment.*

Hnos. Castaño. (2024). *Reclaimed materials: Product information.* https://www.hermanoscastano.es/material-de-derribo/

HVS. (2024). *Recycled timber products.* https://www.hijosdevicentesuarez.es/innovaciones-madera-outes.aspx#reciclada

INIES. (2024). *Les données environnementales et sanitaires de référence pour le bâtiment.* https://base-inies.fr/tableau-de-bord

Institut Bauen und Umwelt e.V. (2025). *IBU.data.* https://ibu-epd.com/en/ibu-data-start/

International EPD System. (2025). *Environdec.* https://www.environdec.com/home

International Organization for Standardization. (2006). *ISO 14044:2006 — Environmental management — Life cycle assessment — Requirements and guidelines.* https://www.iso.org/standard/38498.html

International Organization for Standardization & International Electrotechnical Commission. (2013). *Information technology — Object Management Group business process model and notation (BPMN)* (ISO/IEC Standard No. 19510:2013). https://www.iso.org/standard/62652.html

Kedir, F., Hall, D. M., Brantvall, S., Lessing, J., Hollberg, A., & Soman, R. K. (2023). Circular information flows in industrialised housing construction: The case of a multi-family housing product platform in Sweden. *Construction Innovation. 24*(5), 1354-1379. https://www.emerald.com/insight/content/doi/10.1108/CI-08-2022-0199/full/html

Kerloc. (2026). *Durability, availability, and composition data.* https://martensgroep.eu/nl/producten/gevelbekleding/productinformatie

Kossak, F., Illibauer, C., Geist, V., Kubovy, J., Natschläger, C., Ziebermayr, T., ... & Schewe, K. D. (2014). *A rigorous semantics for BPMN 2.0 process diagrams.* Springer. https://books.google.de/books?id=M1eEBgAAQBAJ

Li, S. (2020). Sustainable material selection in architectural design. *Proceedings of the International Conference on Sustainable Architecture*, 1–8.

Lützkendorf, T. (2019). Product data and building assessment: Flow of information. *IOP Conference Series: Earth and Environmental Science*, *225*, Article 012038.

Ma, Z. G., & Jørgensen, B. N. (2025). Federated data spaces for digital continuity in the building lifecycle: Accelerating the mission of energy informatics. *Energy Informatics*, *8*, Article 144. https://doi.org/10.1186/s42162-025-00610-9

Marques, F. M., & Salgado, M. S. (2007). The building material selection importance at the building design process for its sustainability. *CIB World Building Congress.*

Meex, E. (2018.) *Early design support for material related environmental impact assessment of dwellings.* http://hdl.handle.net/1942/27512

Mirzaie, S., Thuring, M., & Allacker, K. (2020). End-of-life modelling of buildings to support more informed decisions towards achieving circular economy targets. *International Journal of Life Cycle Assessment*, *25*(11), 2122–2139. https://doi.org/10.1007/S11367-020-01807-8

Montali, J., Overend, M., Pelken, P. M., & Michele, S. (2017). Towards façades as make-to-order products: The role of knowledge-based-engineering to support design. *Journal of Façade Design and Engineering*, *5*(2), 101–112. https://doi.org/10.7480/jfde.2017.2.1744

Nagel, R., Kaldenhoff, M., Glander, I., Preuße, B., Bartel, M., Ederer, L., & Kniza, B. (2024). *Baukultur Bericht: Neue Umbaukultur 2024/25.* Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen. https://www.bundesstiftung-baukultur.de/fileadmin/files/BKB-24/Baukulturbericht_202425_Infrastrukturen.pdf

Nabasco. (2026). *Durability and composition data.* https://www.npsp.nl/en/material/nabasco-8010

Pomponi, F., & Moncaster, A. (2016). *Circular economy research in the built environment: A theoretical contribution.* International Conference on Sustainable Ecological Engineering Design for Society.

Ranasinghe, N., Domingo, N., & Kahandawa, R. (2024). Enhancing building material circularity: A systematic review on prerequisites, obstacles, and the critical role of data traceability. *Journal of Building Engineering*, *98*, Article 111136. https://doi.org/10.1016/j.jobe.2024.111136

RDF Working Group. (2014). *Resource Description Framework (RDF).* World Wide Web Consortium. https://www.w3.org/RDF/

Reike, D., Vermeulen, W., & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? Exploring controversies in the conceptualisation of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264.

RIBA. (2020). *RIBA plan of work 2020 overview.* Royal Institute of British Architects. https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work

Rohde, C., & Lützkendorf, T. (2011). *Projekt objektINFO: Analyse der Informationsbedürfnisse ausgewählter Akteursgruppen zu Objektinformationen im Lebenszyklus von Gebäuden als Voraussetzung für die Entwicklung einer Bauwerks-Informations-Systematik (BIS).*

Sebastiá. (2024). *Douglas fir planks and their use in façades* [Catalog]. https://sebastia.eu/wp-content/uploads/2024/08/Cataleg_facanes_en_fusta.pdf

Sierolam. (2024). *Wooden cladding from sweet chestnut, Spain.* https://www.sierolam.com/tarimas/fachada-de-madera/

Object Management Group. (2025). *BPMN: Business process model and notation.* https://www.omg.org/spec/BPMN

Tomczak, A., Benghi, C., van Berlo, L., & Hjelseth, E. (2024). Requiring circularity data in BIM with information delivery specification. *Circular Economy*, *1*(2). https://doi.org/10.55845/REJY5239

Trespa. (2026). *Durability, availability, and composition data.* https://www.trespa.com/Trespa-meteon

Wagner, A., Moeller, L., Leifgen, C., & Eller, C. (2019). *BPO: Building product ontology.* https://annawagner.github.io/bpo/

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Yildiz, S. (2025). Rating the importance of material selection and sustainability criteria in building material selection. *[journal title not provided]*. https://doi.org/10.36922/dp.4491

Zabek, M., Konstantinou, T., & Klein, T. (2023). *D2.3 Sustainable requirements* (Version 01) [Report]. Zenodo. https://doi.org/10.5281/zenodo.8239083

Zabek, M., Konstantinou, T., & Gálvez-Matos, J. L. (2024). Circularity potential of building products: Material flow analysis of façade building components. In *Book of proceedings of the 37th PLEA Conference* (pp. 1213–1218). https://doi.org/10.37190/PLEA_2024

Zabek, M., Gálvez-Matos, J. L., & Konstantinou, T. (2025). Carbon flow analysis: A novel approach for circularity evaluation of façade components. *Cleaner Environmental Systems*, *19*, Article 100361. https://doi.org/10.1016/j.cesys.2025.100361