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Carbon flow analysis: A novel approach for circularity evaluation of façade components

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ABSTRACT

The transition towards a circular economy in the built environment requires robust methodologies to evaluate carbon and material flows at the component level. This paper introduces Carbon Flow Analysis (CFA), an innovative approach that integrates Material Flow Analysis and Life Cycle Assessment to facilitate environmental decision- making for façade renovations. CFA systematically maps embodied carbon and material inputs within façade components, offering a transparent assessment of their circularity potential. The study further refines the selection process through a contextualization framework, which contrasts CFA results against environmental performance ranges derived from Environmental Product Declarations (EPDs) and environmental databanks. Findings demonstrate the variable role of secondary materials in reducing carbon emissions, due to the large variability of impact across materials and components. While CFA provides actionable insights into material selection for façade components, the study highlights the need for standardized circularity indicators and reliable databanks to enhance decision-making in architectural design. By combining quantitative carbon tracking with performance- based contextualization, this research contributes to the development of practical guidelines for achieving carbon-neutral façade renovations.

1. Introduction

The transition to a climate-neutral built environment is critical for Europe to achieve its ambitious environmental objectives, particularly in reducing energy and resource consumption. Europe is striving to become climate-neutral by 2050 while implementing a Circular Economy (CE) (European Commission, 2020), aiming to reduce CO_2 emissions and waste production, particularly in the construction sector, which remains a significant source of energy consumption and greenhouse gas emissions (EUROSTAT, 2023). The construction sector is responsible for around 40 % of the European Union's (EU) total energy use and 36 % of its greenhouse gas emissions while the built environment consumes about 50 % of all extracted materials and generates 37 % of EU's total waste (EUROSTAT, 2023). This trend is expected to continue with a global total increase of resource extraction by almost 60 % until 2060 (WBSCD, 2024).

The challenge today lies in aligning construction practices with CE principles (European Commission, 2020) and effectively measuring progress toward reducing waste and emissions across the entire lifecycle of a building. In this regard, renovation, which extends a building's lifespan, aligns with CE principles targeting narrow material loops (Stahel, 1994). As newly built facades account for 10 %–22 % of total embodied carbon emissions (LETI, 2020, Kitayama et al., 2024), façade renovation becomes a critical focus for reducing the environmental impact of the construction sector.

However, scaling facade renovations to include advanced technologies, such as prefabricated systems could inadvertently increase cost due to additional equipment (Horbach and Rammer, 2020), resulting in an increase of carbon emissions and resource consumption unless managed with a holistic, circular approach.

Despite the increased research on carbon reduction strategies for buildings, including circularity (Alaux et al., 2024), stakeholders involved in the design phase of a building typically do not account for End-of-Life (EoL) considerations for building systems (Hartwell and Overend, 2024) although this phase has the highest potential to cut down emissions and reduce waste production (Zabek, 2023).

In this context, product selection plays a critical role in determining the future reusability, resource efficiency, and environmental impact of materials and components (Akadiri et al., 2013; Godfaurd et al., 2005; Marques and Salgado, 2007). Environmentally responsible product selection relies on comprehensive data collection at the component and material scale across multiple functional levels. As identified by

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Luscuere and Mulhall (2018) these levels encompass the building, system, product, component, and material scales. This multi-level approach facilitates the standardization of information and reduces ambiguities in the assessment process (CB23, 2020; Kedir et al., 2023).

Yet, architects, who significantly shape material choices and construction methods, face difficulties in making environmentally responsible decisions (Meex, 2018). This is largely due to the absence of clear guidelines for implementing CE strategies and the lack of harmonized benchmarks (Mirzaie et al., 2020).

It is now common to integrate different methods and data sources, such as Material Flow Analysis (MFA) for quantifying stocks and tracking material flows entering or leaving the building stock (Deetman et al., 2020) or Life Cycle Assessment (LCA) to calculate the associated environmental impacts (Heeren et al., 2013) to get a holistic view on the circularity potential of components (Alaux et al., 2024). However, these methodologies have limitations to which extent they depict carbon emissions and material flows (Zhang et al., 2021). For example, Environmental Product Declarations (EPDs) which are based on LCA, do not consistently indicate which materials contribute most to environmental impact of components, hindering efforts to optimize material use and reduce the prevalence of high-carbon materials. Additionally, while the European Commission's Level(s) framework (European Commission, 2019) provides indicators for material efficiency and circularity, its approach is flexible enough to lack specificity for evaluating circularity – i.e. there is no set of prescribed indicators for circularity.

Consequently, architects, building owners, and other decision-makers continue to prioritize traditional criteria such as aesthetics, cost (Lützkendorf, 2019; Meex, 2018) or availability of materials (Yildiz, 2025) rather than using metrics that reflect the content of secondary materials or embodied carbon emissions. This research aims to address this gap by developing a method to contextualize metrics that integrate material input flows with carbon emissions to support material selection towards more circular solutions.

Therefore, the primary objective of this work is to develop a comprehensive methodology to support product selection in façade renovation, ensuring alignment with CE principles (*Research Question 1: How can a methodology be developed to* support *façade product selection in alignment with CE principles?*). This involves the creation of a guideline based on Key Performance Indicators (KPIs) derived from established CE assessment methodologies to steer decision-making, and built to ensure harmonization with current trends in the measurement of circularity. These KPIs will help to provide architects and other stakeholders with a practical guideline for selecting and applying components that contribute to carbon neutral facade renovation, targeting near-zero emissions during a building's operational phase and providing contextual benchmarks to optimize circularity during building design.

The environmental performance of major components groups used in facade renovation was assessed through each component embodied carbon and material composition, including the content of secondary (recycled) materials. (*Research Question 2: How do different façade components perform in terms of embodied carbon and material circularity?*) This components-specific analysis offers detailed insight into both the environmental impact and resource efficiency of different façade materials and components. This innovative approach was employed to update existing MFA and LCA methodologies by incorporating carbon flow tracing into components evaluation, which was named Carbon Flow Analysis (CFA). To strengthen CFA's practical relevance, results were systematically compared across various building products. While CFA identifies key contributors to mass and carbon flows, a contextualization framework extends this insight by introducing comparative value ranges. (*Research Question 3: How can contextual benchmarks* support *environmental performance analysis of façade components?*). This helps assess environmental performance among components with similar materials and supports performance analysis of more complex, multi-material components.

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2. Method

The first part of the paper presents a systematic component selection methodology based on a KPI-driven (chapter 2.2.) CFA of main façade components (selection criteria outlined in Chapter 2.1.) as shown in Fig. 1. Part 1 in this figure involves the development of the CFA, informed by material composition, with results shown in chapter 3. In part 2, a structured material databank and classification system was developed, following the method described in section 2.3.3. To compare the CFA outcomes across different components, the research contextualized the performance results using the databank to provide ranges for carbon and resource flows, with findings detailed in Chapter 4. A critical discussion of the approach's limitations is provided in Chapter 5, followed by conclusions in Chapter 6.

2.1. Target building component groups

The research methodology is structured around a case study approach, grounded in a real-world facade renovation scenario (AEGIR, 2025). As part of this study, a prefabricated facade system, integrating both passive and active components, was developed. A picture of the AEGIR façade system is shown in Fig. 2.

The primary objective is to identify the key component groups within the industrialized building envelope required for façade renovation, with a specific focus on achieving net-zero carbon emissions. The analysis will concentrate on commercial building components for façade renovation such as insulation, glazing, window frames, sealants and cladding (Konstantinou, 2014). Additional products may be required based on the operational energy goals, such as energy independence, near-zero energy buildings (NZEB), zero energy buildings (ZEB), or even energy-positive buildings (EPB) (Kaewunruen et al., 2024). In this context, building components can be further classified into active components (e.g., energy generation systems) and passive components (e.g., insulation). In this research, active components such as photovoltaic panels and energy storage systems are excluded from the analysis due to the existence of extensive data available on their environmental performance (Kourkoumpas et al., 2018; Li et al., 2023; Peters et al., 2017). Ventilation systems are also excluded due to their variable complexity and the heterogeneity of regulatory and normative

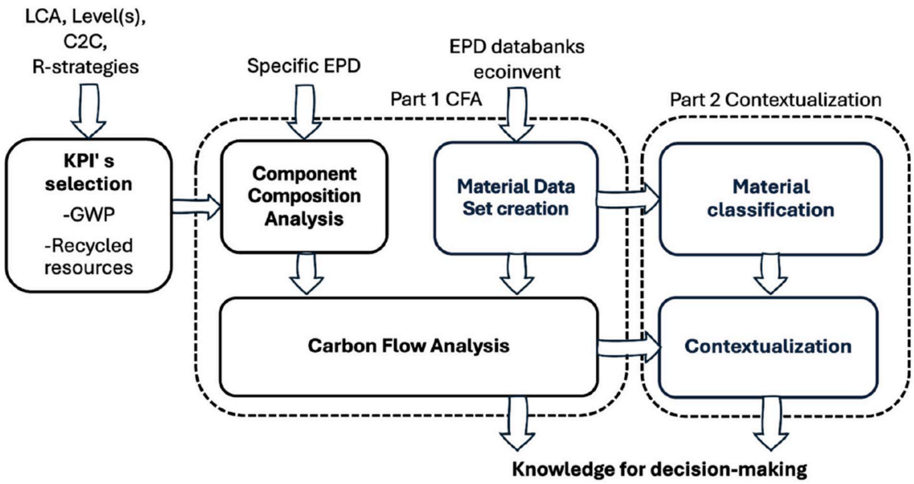


Fig. 1. Carbon Flow Analysis methodological framework.

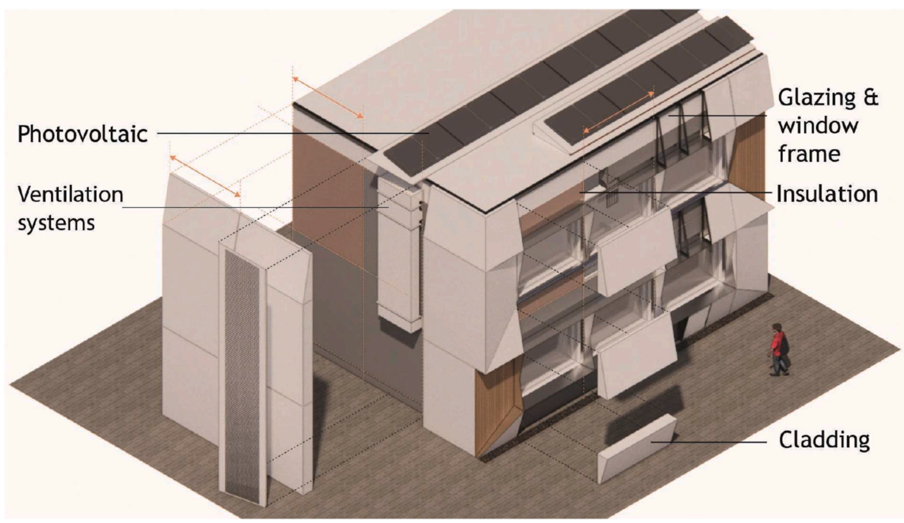


Fig. 2. AEGIR façade system. Image courtesy of AEGIR project partner UNStudio.

frameworks governing their energy and environmental performance during operation, which makes isolated benchmarking challenging. However, following the method from this work, a material-level aggregation approach could be considered to approximate their embodied impacts and circularity potential in a case-by-case basis. Hence, this work focuses on the following passive building components required for a nearly zero energy performance: *insulation, cladding, glazing* and *window frames*. The detailed component selection is presented in Table 1. Although the list is far from being comprehensive, these components include enough elements essential to the functionality of the façade, which can be removed and assessed individually (European Commission, 2020). The application of this method at the component level will enable the identification of carbon sinks and carbon hotspots in components, supporting further data analysis and component selection process.

Table 1
Key Passive facade renovation components.

Component group	Component Name
Insulation	Fabric
	Wood fiber
	Stone mineral wool
	Glass Mineral wool
	XPS
	PET
	Cellulose
Cladding	Timber
	Aluminum sheet
	Recycled Aluminum sheet
	Bio composite panel
	Steel Sheet
	Steel sheet
	RC Steel sheet
	Concrete unreinforced concrete C20/25
	RC concrete
Windows double-glazing single-sash tilt & turn	Wood/aluminum
	PVC
	Aluminum

2.2. Key Performance Indicators selection

In the context of accelerating the transition towards a CE in the construction sector, the development and application of specific circularity indicators has become a central focus, specifically when it comes to the practical application of both policy and research objectives. For example, the European Commission's Level(s) framework (Joint Research Centre, 2023) stands out as a reference methodology for evaluating sustainability performance in buildings in Europe, particularly through its life-cycle-based indicators. These include metrics for global warming potential (GWP), resource efficiency, and EoL recyclability. Built almost entirely based on Level(s), the Green Taxonomy criteria for CE objectives (European Commission, 2023) establish technical thresholds for construction and renovation activities, such as achieving a minimum of 70–90 % reuse or recycling rates for non-hazardous construction waste, and incorporating secondary raw materials within defined material categories (e.g., concrete, metals, plastics, etc) for which KPIs require extensive data management practices from building design and construction.

Further methodological implications of circularity indicators are provided by Brincat et al. (2023), who proposed a multi-level indicator system applicable at the product, building, organizational, and urban levels. Their approach emphasizes that many circularity KPIs—such as recycled content, modularity, and durability—can be derived from shared data sources like EPDs and bills of quantities. Complementary perspectives on the operationalization of these concepts are found in standardized documents like EN 15804 (CEN, 2012), which guides life cycle assessments of construction products, ISO 59020 (ISO, 2024), which standardizes the approach to the assessment of circularity performance, and CSTB's Ecoscale (CSTB, 2023), which offers qualitative assessments for demountability and product lifespan. At building level, the practical implementation of the material circularity index (Goddin et al., 2019) for buildings is implemented by Madaster in its software platform (Dervishaj and Gudmundsson, 2024). Other complementary approaches modify this indicator to include energy flows, such as the building circularity index, which provides a solid foundation for circularity measurements of buildings (Khadim et al., 2023). There is, however, the need for harmonization and standardization of circularity assessment of buildings and how these can help the transition to a CE (dos Santos Gonçalves, 2025).

In the framework of our research (AEGIR, 2025), in order to ensure a high level of harmonization and standardization, KPIs were derived from well established methodologies like LCA (ISO, 2006), the European Level(s) framework (European Commission, 2019) and common CE definitions (Braungart and Mc Donough, 2002; Reike et al., 2018), supported by previous findings (Zabek et al., 2023, 2024). These KPIs are organized into quantitative and qualitative categories (see Table 2), to guide design decisions effectively.

- Quantitative KPIs — particularly GWP and the share of reused and recycled materials — are prioritized in this study. GWP data can be sourced from LCA studies or EPDs, offering measurable insights into carbon impacts. The share of reused and recycled materials supports circularity by tracking the reduction of primary resource consumption. Together, these indicators form the foundation of the CFA, enabling a clear assessment of component-level environmental performance.
- Qualitative KPIs, such as modularity, provide essential design guidance but require more flexible, non-standardized evaluation methods. While not used as formal assessment criteria in this study, they serve as valuable guidelines to help planners design assemblies aligned with circularity principles.

Table 2
Qualitative and quantitative KPIs.

Quantitative KPI	KPI source	Qualitative KPI	KPI source
GWP	LCA, Level(s)	Demountability	Level(s)
Renewable resources	LCA, C2C	Durability	LCA
Recycled material	R-Strategy, LCA	Modularity	C2C
Reused material	R-Strategy, LCA	Low-Tec	C2C
Hazardous substances	C2C, LCA	Bill of quantities	Level(s)
Purity	C2C	Financial concept	C2C
Materials for reuse/recycling	LCA	Local material	R-Strategy
		Compostability	C2C

This structured approach ensures that carbon impact and material circularity remain central to the evaluation process, empowering architects and manufacturers to make data-driven, sustainable design decisions.

Table 2 shows the classification of these KPIs along with their respective sources, which include LCA methodologies (ISO, 2006), the European Level(s) framework (European Commission, 2019) and established CE principles such as Cradle to Cradle (C2C) (Braungart and Mc Donough, 2002) and the R-Strategies (Reike et al., 2018).

2.3. Part 1 carbon flow analysis

To assess the carbon flows of key passive facade renovation components (Table 1), the research will develop a novel approach grounded in MFA. MFA is a standardized method for quantifying material movements within defined systems (Ayres and Kneese, 1969) and commonly applied in tracking national material flows, waste management, and recycling systems (Gao & You, 2018). By leveraging MFA, this study aims to map carbon flows measured in terms of GWP (kg CO_2 eq./m^2) in a carbon flow analysis, CFA, and material masses in kg to provide manufacturers and architects with a more transparent analysis within specific components, enhancing clarity in component composition and hence material selection process. While the method does not constitute a full LCA (as standardized in EN15804 or EN 15978) it supports early decisions by addressing the lack of material-level breakdown in standard product data. However, it may involve uncertainties, primarily related to transport impacts, which are not included and requires the designer to consider material supply chains.

Carbon flows will be visualized using Sankey diagrams (Schmidt, 2008). On the left side of the diagram, the composition of the component is represented in terms of its cradle-to-gate GWP (kg CO_2 eq/m^2), illustrating the carbon contribution of each material. Materials with a negative CO_2 impact are positioned below the zero line. On the right side, the component's composition is displayed in terms of mass (kg/m^2 %). To further differentiate material composition, a vertical classification is introduced at both ends of the diagram, distinguishing between primary raw materials (PR) and recycled resources (RC). Only post-consumer recycling was considered as RC. Data is taken from the specific component EPDs.

2.3.1. Component composition Analysis (CCA)

As a first step, the amount of material stored in a component is determined in weight (kg).

Data is given in % of the total mass of the component. The weight of Material X is determined by:

$$W_X = \rho \times t \times C$$

Where:

- W_X = Weight of material X (kg)
- ρ = Component Density (kg/m^3)
- t = Component Thickness (m)
- C = Component Composition (%)

Data for the Component Composition Analysis is taken from manufacturer-provided information through EPDs or other sources of LCA data.

2.3.2. Carbon Flow Analysis (CFA)

To quantify the contribution of each material to the total GWP of the component, the mass of each material stored within the component was multiplied by its corresponding GWP. The total GWP of the component is presented as the sum of the GWP contributions of its constituent materials.

Step 1: Calculate the GWP of each material in the component.

For Material X:

$$GWP_X \text{ per } m^2 = (\rho_X \times t_X \times C_X) \times GWP_x \text{ per kg}$$

2.3.2.1. *Substituting the giving values.*

- GWP_X = GWP of Material X (kg CO_2 eq.)
- ρ_X = Density of Material X (kg/m^3)
- t_X = Thickness of Material X (m)
- C_X = Composition of Material X (w/w)
- GWP_X per kg = GWP of Material X per kg (kg CO_2 eq./kg)

Step 2: Sum the GWP of all materials to get the total component GWP:

Component GWP:

$$\sum_{i=1}^{n} GWP\ i$$

It is important to note that the total GWP does not correspond to the GWP reported in the specific EPD of the component. This discrepancy arises due to variations in data sources, as the GWP values for individual materials originate from different references explained in the following section. Results are presented in chapter 3 and the Supplementary Material S1.

2.3.3. *Material Data Set creation*

The required data (density, composition, thickness) for component composition analysis is sourced from specific EPDs or LCA studies, such as those found in German Ökobaudat (German Federal Ministry for Housing, 2023) ecoinvent (Wernet et al., 2016), INIES (INIES, 2024), IBU data (IBU, 2024), and Environdec (International EPD System, 2024). The GWP data for individual materials was obtained from those EPD databanks and compiled together with the data on component composition within a structured Material Data Set.

To obtain a comprehensive dataset on the environmental impact of building components, a final material databank containing 600 entries was compiled from those identified sources. This dataset was utilized for subsequent application in CFA and contextualization, facilitating the extraction of data on the GWP of materials and the proportion of recycled content in the production phase. The criteria for inclusion in the databank were as follows:

1. **Material-level focus:** The databank was developed at the material level, meaning complex components containing more than one significant material were usually excluded, although complex components such as windows were maintained for reference (components listed in Table 1).
2. **Primary data sources:** Since most EPDs rely on ecoinvent (Wernet et al., 2016) as the primary source for life cycle inventory data, basic material production data from *ecoinvent* was included. However, the main source for the databank was Ökobaudat (Dräger et al., 2022; German Federal Ministry for Housing, 2023) chosen for its higher data quality requirements.
3. **Supplementary data sources:** Alternative databanks were incorporated to fill gaps for specific materials. For example, stainless steel components are underrepresented in both Ökobaudat and ecoinvent, so additional sources such as INIES (INIES, 2024) and the International EPD System (International EPD System, 2024) were used.

The GWP data is limited to LCA modules A1-A3, as outlined in EN 15804:2012 + A2:2020 (CEN, 2012), which measures carbon emissions in kg CO_2 equivalents only for the production phase. This exclusion of later lifecycle phases aims to prevent environmental burdens related to specific building applications but related to input material flows, with circularity being addressed in subsequent phases through the quantification of primary and secondary raw materials.

2.4. *Part 2 contextualization*

Circularity assessment indicators, as reported in section 2.2., are mostly based on mass flows and are thus expected to depend on the material composition basis. For instance, the recycled content of a component is the sum of the recycled content of its individual materials. The same applies to recyclability, compostability, or renewable materials content, while embodied carbon footprint can be approximated by summing individual contributions from subcomponents or materials. This ***scaling*** approach is termed in the literature the "nano-level" in circularity assessment and offers the advantage of generating a relevant context without exhaustive market research, e.g. as publicly available information for novel multi-component approaches is limited. Scaling from the material level to product, subcomponent, component, and assembly levels is particularly useful for indicators derived from MFA (Khadim et al., 2022).

Once the data on the environmental impact of components was collected and compiled in a Material Data Set, the next step involved classifying each material data, using the material categories defined in the components' dataset from the CCA (chapter 2.3.1).

After completing the databank, it was used for circularity-based *contextualization*. This analytical approach was designed to assess circularity performance when designing building components or selecting construction materials. It can establish typical performance levels based on existing data, providing context for individual values that would otherwise lack meaningful reference points.

While the databank could serve as a basis for establishing performance benchmarks, a comprehensive review of all reported performance data was not conducted. Therefore, instead of defining fixed benchmarks, the focus was on identifying performance ranges, helping to determine the expected environmental performance of similar components and avoiding the proposal of non-representative threshold values.

3. Carbon flow analysis

This section presents the CFA of the insulation components presented in Table 1. The results for cladding and window components are shown in the Supplementary Material S1.

To ensure comparability, components of varying thicknesses but equivalent thermal resistance of 1 m^2 K/W were analyzed. The calculation methodology of the component thickness is outlined in the first chapter of the Supplementary Material S1. To illustrate the calculation process of the CFA analysis, the calculation steps for a fabric-based insulation are presented as an example below.

For Material A (Cotton):

$$GWP_A = \rho_A \times t_A \times \frac{C_A}{100} \times GWP \text{ per } kg_A$$

$$GWP_A = 45 \times 0.034 \times \frac{80}{100} \times 0.011$$

GWPA = 0.013kg CO2eq/m2

For Material B (Phenolic resin):

$$GWP_B = GWP_B = \rho_B \times t_B \times \frac{C_B}{100} \times GWP \text{ per kgB}$$

$$GWP_B = 45 \text{ x } 0.034 \text{ x } \frac{20}{100} \text{ x } 3.57$$

GWPB = 1.09 kg CO2 eq/m2

Total GWP of the component:

Total GWP Component = $GWP_A + GWP_B$

Total GWP Component = 0.013 + 1.09

Total GWP Component = 1.1 kg CO_2eq/m^2

Data sources:

Component Density (ρ) [kg/m^3] = Specific component EPD

Component Composition (C) [%] = Specific component EPD

Component Thickness (t) [m] = Specific component EPD

Material GWP [kg CO_2 eq/m^2] = Material databanks

The CFA of the fabric insulation is depicted in a Sankrey diagram in Fig. 3 and the corresponding Material Dataset in Table 3.

Additional results for the insulation material are presented in Table 4 or in the Supplementary Material S1.

The Sankey diagram in Fig. 3 illustrates that phenolic resin accounts for 20 % of the mass but contributes significantly to the total CO_2 emissions (GWP) of the fabric insulation with 99 %. This indicates that, although recycled cotton constitutes a larger portion of the mass (80 %), it only accounts to 1 % of the total CO_2 emission, suggesting that the use of recycled content leads to reduced CO_2 emissions.

Similar results are found in the incorporation of secondary raw materials in other insulation. For example, the use of aluminum waste and slag in glass wool (Table 4), recycled paper in cellulose insulation and recycled PET in PET fiber insulation, leads to lower carbon emissions. Certain additives made of primary resources—including binders in Stone mineral insulation, boric acid in Cellulose insulation, PMDI in wood fiber insulation, and polyester fibers in PET fiber insulation contribute disproportionately to CO_2 emissions compared to their mass. The biggest benefits in carbon reduction could be achieved through the utilization of renewable materials, like wood fibers in the wood fiber insulation.

These results correlate with findings in other component groups. For instance, the use of recycled materials leads to significant carbon emission reductions in other components, such as steel and aluminum cladding sheets in Supplementary Material Table 1 chapter 7.2. or aluminum windows in Supplementary Material Table 2 in chapter 7.2. with CO_2 reductions of up to 82 %, and aluminum cladding sheets, with reductions of up to 67 %. However, the utilization of recycled materials in other applications, such as recycled aggregates in concrete production

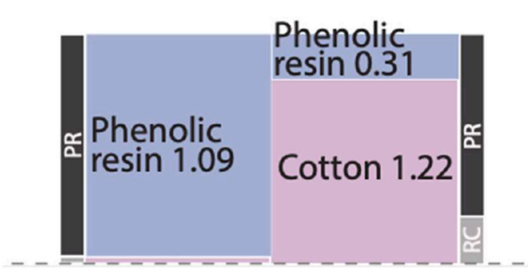


Fig. 3. Sankey diagram of fabric insulation.

(Supplementary Material Table 1), does not have a significant impact on carbon emissions. The highest share of carbon emissions in concrete is attributed to cement, which, despite comprising only 10 % of the total material weight, accounts for 93 % of the total GWP.

These findings highlight the complex interplay between material composition and environmental impact, underlining that simply increasing the proportion of recycled or renewable materials does not always guarantee a reduction in CO_2 emissions.

In Supplementary Material S1, chapter 3, the material dataset is shown of the remaining components such as cladding and windows.

4. CFA results contextualization

This section presents a comparative analysis of the CFA results from the preceding section against established performance ranges derived from the databank built from EPDs and environmental data repositories. By contrasting CFA outcomes against these reference data, the analysis provides a clearer understanding of how different building components perform in terms of mass and carbon flows. This systematic comparison helps contextualize the results within industry standards, facilitating more informed decision-making in circular design and material selection. Fig. 4 shows the results of the contextualization approach for the carbon footprint and Fig. 5 shows the recycled content of the insulation component analyzed in the previous section. The boxplots in the figure represent the observed variability of the data distribution of values for a given category, i.e. the carbon footprint and the recycled content, across different components of the 600 data points samples taken from EPDs, as described in chapter 2.3.3. and listed in the Material Databank in the Supplementary Material S2. This type of visualization highlights the variability of KPIs for each component while providing a reference space for single carbon flow or recycled material values. To clarify, each box shows the median (central line), interquartile range, IQR, as the space between the first quartile and the third quartile Q1–Q3, also defined as the central space where the 50 % central values are placed. The whiskers extend to 1.5 × IQR by definition. In this particular case, outliers are excluded to improve clarity, although they are usually shown in this type of charts. The inverted yellow triangle with a black border represents the reported values from the previous section.

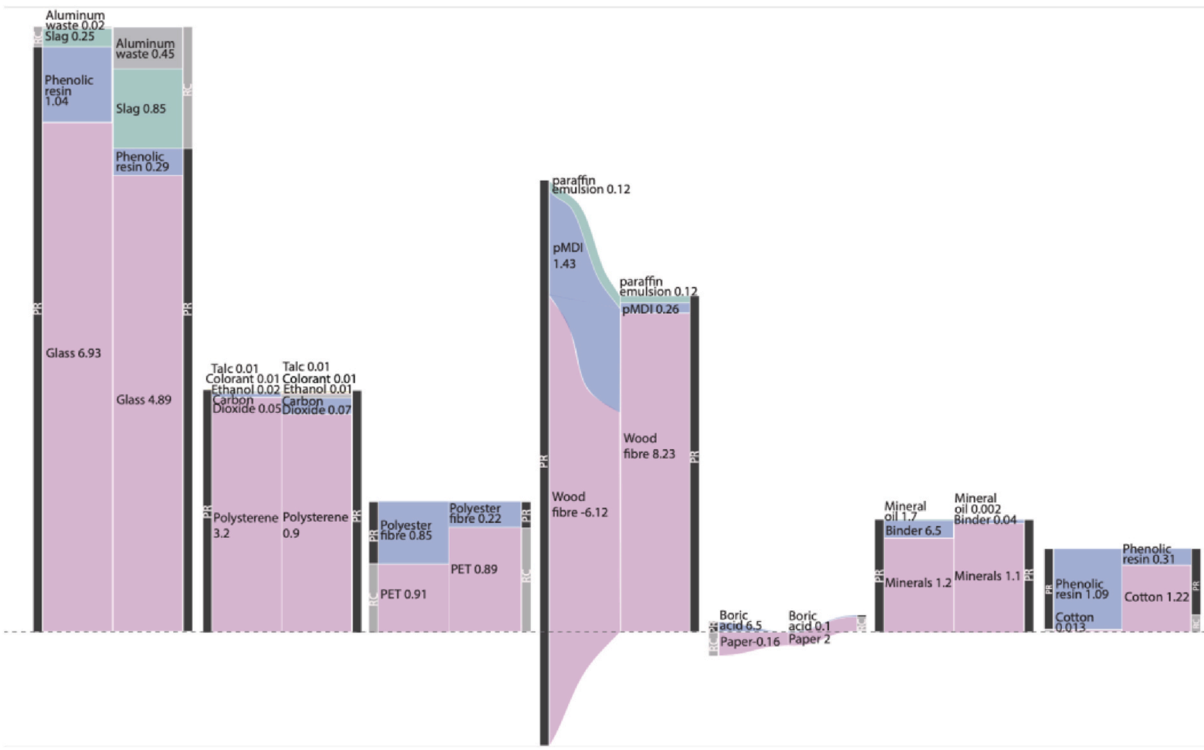
As observed, there is a wide variation of carbon footprint (Fig. 4) values for different insulation components, highlighting differences in environmental impact. In the case of wood fiber and cellulose, the chart shows negative carbon footprints, indicating they act as carbon sinks, likely due to their biogenic carbon storage. However, this only covers the production stages (modules A1 – A3 of standard EN 15804); such negativity of footprint would be compensated in the EoL options from the EPDs. Fabric insulation exhibits the highest variability in carbon footprint, suggesting differences in e.g. material sourcing, processing methods or content of recycled material as shown in the results of the CFA the recycled cotton reduces significantly to the carbon footprint of the component. The content of recycled cotton varies between 70 and 90 % according to the manufacturer (Geopannel, 2021). XPS has the highest median carbon footprint, making it probably the least environmentally friendly among the analyzed components, after glass wool. The yellow triangles, representing the components analyzed in the CFA of the previous section, show that some components (e.g., wood fiber, cellulose) perform better than the median, while others (e.g., XPS) have higher-than-average emissions.

When looking at the recycled content in Fig. 5, cellulose insulation contains the highest recycled content, consistently close to more than 80 %, making it a potentially highly circular component. Fabric insulation exhibits a null percentage of recycled content, which contrasts with the selected material (represented by the yellow triangle), where 80 % of its composition consists of recycled fabric. However, this substantial incorporation of recycled resources does not translate into a total lower carbon footprint. This substantial incorporation of recycled resources does not necessarily result in a lower total carbon footprint. As seen in

Table 3
Material dataset fabric insultation.

Component	Material	Composition [kg %]	Component Thickness [m]	Component Density [kg/m^3]	Material Weight [kg/m^2]	Material RC content [kg %]	Material GWP [kg CO_2 eq./m^2]	Total Component GWP [kg CO_2 eq./m^2]
Fabric insulation	Cotton	80	0.034	45	1.22	100	0.013	1.1
	Phenolic resin	20			0.31	0	1.09	

Table 4
Compiled CFA of insulation components.



Sankey Diagrams for Insulation Components

Component	GWP (kg CO_2/m^2)	Mass (kg/m^2)	Recycled content (kg %)
Glass Mineral wool	8.24	1.11	65
XPS	3.26	0.99	5
PET	1.77	1.11	80
Wood fibre	−4.57	8.66	0
Cellulose	−0.19	2.1	95
Stone mineral wool	1.54	1.11	3
Fabric	1.1	1.53	80

the results of the CFA, the use of cotton significantly reduces the total carbon footprint, making phenolic resin the largest contributor. The selected component demonstrates environmental performance below the median. This indicates that other components could potentially be produced using alternative binders. In the case of the cellulose, PET, or fabric, where recycled cotton constitutes a significant portion of the material's mass, the associated CO_2 emissions are notably higher or perform comparable to components made of little recycled materials such as stone mineral wool or XPS. These components have a relatively low amount of recycled content (selected stone mineral wool component performing below the average) but show similar carbon footprint as components made with high recycled material content. These results indicate their reliance on primary raw materials. Generally, the yellow triangles show that the analyzed products in the CFA generally align with or exceed the median recycled content for their respective classification, except the fabric insulation.

The boxplots for cladding components and windows are shown in the Supplementary Material S1, chapter 4, and arrive at similar conclusions. For cladding components, the carbon footprint varies significantly depending on the material type. Some recycled materials such as recycled steel and recycled aluminum exhibit notably lower carbon footprints compared to their virgin counterparts, following results from CFA. However, this is not the case for recycled concrete, whose footprint is in range with non-recycled concrete. As derived from the CFA, cement mainly contributes to the carbon footprint and not the aggregates regardless of its material source. Aluminum has the highest median and variability in carbon footprint, suggesting a strong dependence on production methods and energy sources. In terms of recycled content, recycled aluminum, recycled concrete and recycled steel show the highest percentages, reinforcing their contribution to circularity.

For windows, the carbon footprint distribution reveals that aluminum windows have the highest impact illustrated in the Supplementary Material S1, chapter 4, with a wide range of values extending beyond 300 kg CO_2eq/m^2. In comparison, PVC and wood/aluminum

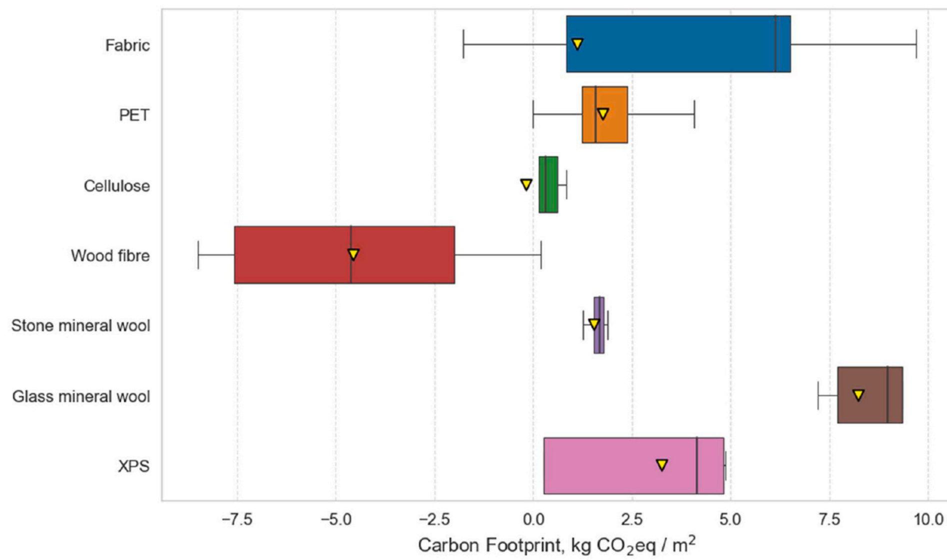


Fig. 4. Boxplot of the distribution of carbon footprint values for 1 square meter of insulation materials at a thermal resistance of 1 m^2K/W. Yellow triangles indicate the value for the products analyzed in the CFA.

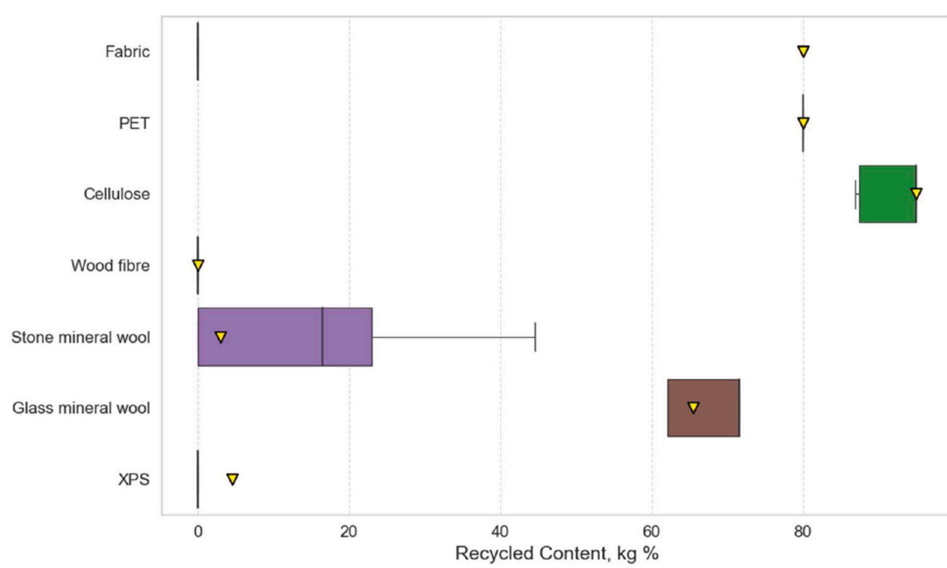


Fig. 5. Boxplot of the distribution of recycled content values for 1 square meter of insulation materials at a thermal resistance of 1 m^2K/W. Yellow triangles indicate the value for the products analyzed in the CFA.

composite windows show significantly lower emissions, with wood/aluminum windows having the lowest median value, probably because of lower densities of materials. Regarding recycled content, all window types display relatively low values, with aluminum windows having the widest variability due to the potential recycled content of aluminum-based frames. Overall, aluminum windows have the highest variability, but sustainable alternatives seem available in the market.

5. Discussion

The developed KPIs were derived from established methodologies and strategies on the CE. Each model and methodology have their own focus, leading to the prioritization of indicators and principles in this research. However, it is important to acknowledge that these indicators may be incomplete for some aspects and lack prioritization themselves. They should be viewed as design guidelines with flexibility in their application. A quantifiable approach becomes necessary when clearer variables are needed to make decisions, which typically occurs at certain stages of the design phase. From a methodological perspective, the data sources for GWP correspond to the A1–A3 modules (i.e., cradle-to-gate) as reported in representative EPDs of the material category under study. The contribution of different materials aggregated into a single product (e.g., multilayer panels or the use of adhesives) does not account for the environmental impacts associated with component assembly or transport to the assembly site, resulting in the omission of impacts such as those from transportation and on-site integration. Assembly-related impacts are equivalent to the A5 module in the case of prefabricated façades and generally represent less than 10 % of the total GWP and tend to be consistent across material categories. However, the exclusion of transport impacts may become significant in scenarios involving long transport distances—an aspect where other circularity indicators, such as "local material," gain relevance within the CFA methodology. As previously noted, the context in which the CFA is applied is critical to understanding the validity and limitations of the results.

The product selection phase is one such moment where quantifiable variables are crucial. Unfortunately, architects often do not utilize assessment methods such as MFA, LCA nor CFA to evaluate their decisions, due to missing data for making informed decisions or missing knowledge about how to interpret data and apply methodologies.

Furthermore, this research does not target architects and manufacturers for the direct application of this method. Instead, it aims to emphasize foundational assumptions and propose a novel approach to design components and select materials. The approach advocates for decision-making to be guided by the assessment of embodied carbon flows. For instance, recycling products are fundamental aspects of a CE, yet their application is not always beneficial in reducing their environmental impact as shown for example in the recycled concrete component. Even more beneficial for a CE is the reuse of components, as reuse often requires fewer resources than recycling since materials remain in their original form. However, common methodologies such as MFA are not able to precisely capture the benefit of incorporating reused and recycled materials and must be complemented with LCA-based indicators. Additionally, methodologies like LCA often fall short in recognizing the benefits of reusability and recyclability at the EoL, especially the standardized approach through EPDs, which implement the polluter-pays principle (CEN, 2012). Component-based contribution analysis in construction EPDs is currently limited due to a lack of detailed composition data (Chàfer et al., 2021).

In addition, the method does not provide insight into future material flows. Indicators related to EoL performance—such as recyclability, potential for disassembly, or durability—remain difficult to quantify due to a lack of standardized methods and the inherent uncertainty in projecting future scenarios. Although data on secondary raw materials inputs is mostly available and is assumed from the EPD data as such, but it is not sufficient to reliably estimate future reuse or recovery. Moreover, the polluter-pays principle used in EPDs excludes the environmental benefits of what happens beyond the product's first life. For these reasons, future material flows were not addressed in this work, to ensure alignment with current data practices and maintain methodological consistency.

Uncertainties arise from factors such as component connectivity and evolving recycling technologies for future material streams. To mitigate these uncertainties, a clearer understanding of the components context and connectivity is essential. Typically, this assessment is conducted at a later stage through assembly-level analysis, providing more detailed insights into the product's lifecycle and EoL scenarios. However, a comprehensive CE perspective encompasses both EoL and design phases and should be included in the assessment of a component's performance. Nevertheless, the proposed CFA demonstrates significant adaptability, enabling the mapping of carbon and mass flows across different contexts. This flexibility enhances its value in evaluating the circularity of building components. But, this approach relies on a robust and reliable KPI databank, as the two primary indicators assessed in this study require well-defined reference values. Furthermore, to gain a comprehensive understanding of a component's circularity performance, a performance-based contextualization remains essential, ensuring that CFA results are interpreted within a meaningful comparative framework. The main goal of such contextualization is to support the design process by incorporating circularity aspects, which involves the evaluation of ranges of quantitative KPIs, as demonstrated in Chapter 4.

Nevertheless, this research represents only part of the overall picture and has certain limitations. Some KPIs cannot be fully contextualized, as only two or three performance levels can be defined. For instance, hazardousness is categorized into only two levels—e.g. hazardous and non-hazardous—but it may significantly impact other metrics, influences decision-making, and has important safety and cost implications. Other KPIs, while quantifiable—such as circularity scores, demountability, and repairability—are not well-suited yet for direct numerical evaluation. Their definitions are still evolving, they are applied in case-specific contexts, or they have not been widely implemented to allow for meaningful comparisons. The vast implementation of EPDs allows benchmarking exercises, but such EPDs are still to evolve in order to incorporate further informative indicators that can help design decisions over other circularity indicators, such as modularity, demountability, recyclability, etc. Additionally, comparing GWP values from different environmental data sources is generally not advisable, as variations in standards or product category rules can limit the reliability of such assessments. Factors such as biogenic carbon flow considerations and the scope of market analysis can further affect comparability, since biogenic carbon flows usually need to be assumed to return to the atmosphere at the EoL stage of components according to standards. However, current building LCA methodologies allow the use of EPDs based on different standards, meaning that co-design practices can also benefit from utilizing multiple EPD databanks to inform decision-making.

Future work could expand the approach by (i) integrating more advanced indicators for repairability, demountability, and durability once reliable benchmarks are available, (ii) extending the CFA beyond the production stage (A1–A3) to include use-phase and EoL scenarios, (iii) strengthening harmonization between EPD datasets to improve cross-comparability, and (iv) multivariable contextualization is also possible within the framework of the developed methodology when two or more circularity KPIs need to be optimized in an eco-design approach (Fig. 6). For example, as observed in our work, the reduction of embodied carbon footprint is not necessarily correlated with a decrease in the recycled content of a material. To support decision-making in such cases, a 2D diagram mapping recycled content against GWP could help visualize trade-offs and guide optimization strategies (Giama and Papadopoulos, 2020).

6. Conclusion

The successful implementation of a CE in the built environment requires holistic methods and KPIs that assess circularity at both material and component levels. Early design decisions, particularly regarding material selection, play a crucial role in shaping EoL scenarios. To support this process, the presented KPIs aim to guide architects, designers, and manufacturers in making informed, circular choices from the outset.

Simultaneously, the urgency to measure and mitigate the environmental impact of design decisions continues to grow. Yet, a significant barrier remains: the lack of a user-friendly, comprehensive evaluation method for assessing circularity potential. Existing methodologies, such as LCA and MFA, exhibit limitations in accurately representing carbon emissions and material flows. For example, EPDs, which rely on LCA data, often fail to consistently identify which materials contribute most significantly to a component's overall environmental impact. In addition, a major limitation lies in the difficulty of obtaining accurate and reliable data for the life cycle inventory—particularly for complex materials and products. To address these challenges, a methodology called Carbon Flow Analysis (CFA) was developed. CFA maps carbon flows — including primary and secondary materials — alongside CO_2 emissions, offering a clearer representation of environmental performance. This enhanced visualization supports manufacturers in optimizing components and supports architects to make environmentally conscious material selections.

Results show that using secondary resources, especially metals, reduces carbon emissions in the same component group. However, recycled materials do not always guarantee lower emissions — for example, recycled aggregates in concrete have almost no influence on emissions. Interpreting CFA results requires expertise due to a lack of comparison within component categories. To tackle this, a contextualization approach was developed to compare performance within the same component group. This is applied to quantitative KPIs like GWP and recycled content, emphasizing the need to assess component groups for low-energy façades individually — direct comparisons are often

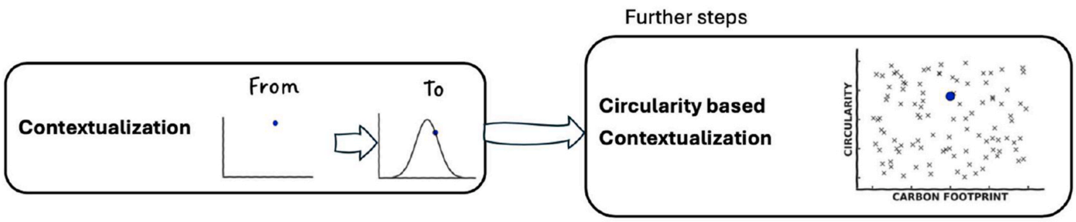


Fig. 6. Concept of multivariable circularity-based contextualization.

impractical due to varying performance metrics.

For example, innovative insulation panels made from recycled cotton or PET may show high secondary resource content, but their CO_2 emissions may still align with conventional mineral wool. Future recycling potential is also essential, though systems for compostable materials remain underdeveloped. Additionally, fire retardants often limit reuse, highlighting the need to incorporate health-related KPIs addressing hazardous substances alongside carbon and resource metrics. A combined analytical and qualitative approach — using CFA and the proposed KPIs — offers a comprehensive evaluation of circular building components.

However, practical material selection is often constrained by regulations, economics, and structural requirements. Despite these limitations, architects can still optimize component choices based on environmental performance indicators. For instance, when fire safety regulations prevent replacing mineral-based insulation with bio-based alternatives, architects can prioritize options with lower embodied carbon or higher recycled content. Similarly, when aluminum is necessary for durability and corrosion resistance, choosing recycled aluminum over virgin material significantly reduces the environmental footprint. This highlights the importance of robust methodologies and accessible databanks to support decision-making, enabling architects to balance regulatory constraints with CE principles — ensuring more sustainable, informed design choices.

CRediT authorship contribution statement

Magdalena Zabek: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jose-Luis Galvez-Martos:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Thaleia Konstantinou:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Magdalena Zabek reports was provided by Delft University of Technology. Magdalena Zabek reports a relationship with Delft University of Technology that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2025.100361.

Data availability

Data will be made available on request.

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Glossary

AEGIR: Digital and physical incremental renovation packages/systems enhancing environmental and energetic behavior and use of resources (project title)
CB23: Platform CB'23 (Guide for Passports for the Construction Sector)
C2C: Cradle to Cradle
CFA: Carbon Flow Analysis
CE: Circular Economy
CSTB: Centre Scientifique et Technique du Bâtiment
EoL: End-of-Life
EPD: Environmental Product Declaration
EU: European Union
GWP: Global Warming Potential
ISO: International Organization for Standardization
IBU: Institut Bauen und Umwelt e.V.
INIES: French environmental and health database for construction products
KPI: Key Performance Indicator
LCA: Life Cycle Assessment
MFA: Material Flow Analysis
ÖKOBAUDAT: German national database for construction LCA data
PET: Polyethylene Terephthalate
PVC: Polyvinyl Chloride
RC: Recycled Content
XPS: Extruded Polystyrene