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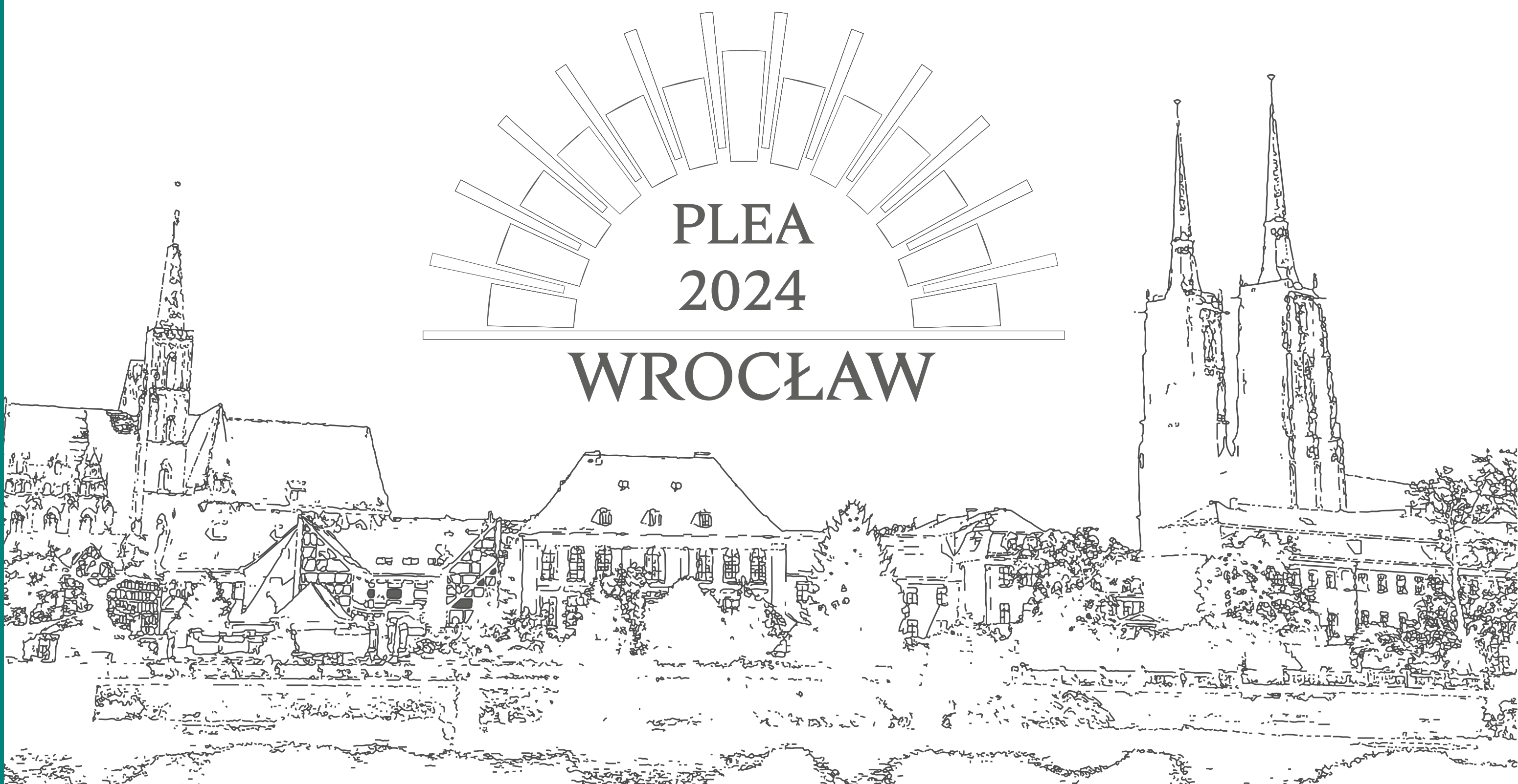

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Circularity potential of building products

Material Flow Analysis of façade building components

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ABSTRACT: The construction industry, accounting for a significant portion of energy consumption and greenhouse gas emissions, is pivotal in achieving Europe's ambitious climate neutrality goal by 2050. Circular Economy (CE) principles and the renovation of existing buildings are identified as promising strategies to reduce raw material and energy consumption. However, the lack of knowledge and guidelines for effective CE design and construction in the built environment, along with heterogeneous metrics and standards, pose challenges. The research outlines an investigation study aimed at developing Key Performance Indicators (KPIs) for evaluating building products based on CE principles, focusing on façade renovation. The study emphasizes the need for a holistic approach, considering both material input and output flows, and introduces qualitative and quantitative KPIs addressing aspects such as recyclability, modularity, and local materials. The research proposes established frameworks like Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and the Level(s) framework, but recognizes their limitations in assessing circularity comprehensively. The methodology involves a comprehensive analysis of material streams and circularity potential for nine components crucial to achieving a net-zero façade renovation. Results from the material flow analysis demonstrate the environmental impact of selected building products, such as insulation panels and photovoltaic panels. The research underscores the importance of informed design choices, leveraging adaptable KPIs, and visualizing resource flows to enhance decision-making for sustainable construction practices aligned with CE principles.
KEYWORDS: Circularity, Material Flow Analysis (MFA), Façade Renovation, Life Cycle Assessment (LCA), Key Performance Indicators (KPI)

1. INTRODUCTION

The construction industry plays a key role in influencing responsible and sustainable production and consumption of resources as it significantly contributes to energy use and greenhouse gas emissions, accounting for approximately 40% of the EU's energy usage and 36% of its greenhouse gas emissions. The built environment is also major consumer of extracted materials (50% by mass) and is responsible for generating 37% of the total waste in Europe [1].

Europe's ambitious goal is to achieve climate neutrality by 2050 requires significant decarbonization efforts and a reduction in raw materials and energy consumption. In this context, a calculation of life-cycle Global Warming Potential (GWP) will be obligatory [2] from 2027 on. Adopting Circular Economy (CE) principles and renovating existing buildings is a promising approach to meet this target. The mandatory inclusion of Life Cycle Assessment (LCA) and a recycling quota for building products has the potential to drive a significant influence toward the conservation and maintenance of the current building inventory [3].

Today, over 85% of Europe's existing buildings lacks energy efficiency standards [4]. Achieving net-zero energy buildings involves on-site generation of energy from clean, renewable resources, equaling the total energy consumed on-site. This necessitates deep renovation, capable of reducing energy consumption by 60% to 90%.[5]. However, the annual rate of deep building renovations in the EU falls far short of the recommended target. To address this, the European Commission initiated the Renovation Wave in 2020, aiming to double the annual rate of energy-based building renovations by 2030 [4]. In the context of upscaling facade renovation that incorporates various technologies, higher amounts of material will be required. This demand for resources makes it imperative that the early design phases for the renovation products and systems incorporate CE design objectives, considering end-of-life scenarios, as these activities significantly affect resource utilization, environmental impact [6] and embodied energy demand.

Up to now, the focus of sustainable development has been directed towards the energy consumption incurred during the operational phase of buildings [7] leading to missing knowledge and guidelines supporting effective design and construction for a CE [8]. Moreover, assessing the impact of the design decision on the environmental impact is currently hindered by heterogeneity in metrics and standards [9] and missing user friendly guidelines. Besides, existing methods like LCA, Material Flow Analysis (MFA) or the European Commission's Level(s) framework [10] have limitations in evaluating circularity.

1.1 Objectives

This research belongs to the Horizon Europe project "Digital and physical incremental renovation packages/systems enhancing environmental and energetic behavior and use of resources", AEGIR [11], which focuses on implementing CE practices in the built environment by strategically selecting building materials and components during the early stages of the renovation process. The aim is to establish a closed-loop system throughout the façade renovation value chain. To this end, the first step is to develop Key Performance Indicators (KPIs) for supporting the design process in line with CE principles. This involves defining a comprehensive CE concept, reviewing common circularity measurement approaches, and presenting a practical method for validating building products in terms of material flows and use of secondary raw materials. KPIs shall be derived from methodologies assessing the environmental impact of materials and construction methods, contributing to a more sustainable decision-making process in façade renovation solutions. The overarching aim is to provide KPIs that function as a structured framework for directing decision-making procedures during the design phase. This process is complemented by the application of a standardized methodology at the product level to assess environmental impact and raw material utilization. The application of a standardized methodology during product selection, coupled with the integration of a comprehensive framework throughout the entire design process, is anticipated to generate a solution in line CE.

The research specifically applies this concept to a net-zero façade renovation solution, representing an innovative, modular, renewable, and industrialized building envelope for low-energy renovation. The research supports decision-making in product selection process of four façade renovation solutions by analyzing five building product groups specialized for achieving net-zero solutions. The objective is to comprehensively grasp the composition of two representative products of two selected groups and identify the associated material flows. This analysis is crucial for formulating strategies to establish closed-loop re-use systems for products that aim to achieve a net-zero façade renovation, such as PV panels, insulation, ventilation, windows, and energy storage batteries.

2. METHODS

This research focuses on implementing CE strategies by supporting the development of an industrialized building envelope solution for low-energy renovation by a holistic analysis of the material streams and circularity potential of construction products. To achieve this, KPIs based on the CE concept will be developed in section 3. In section 3.1 a review on the most common methods to assess circularity will be presented supporting the development of the KPIs. In section 3.2, the level of functionality to assess material streams will be defined, enabling the selection of an appropriate method for evaluating each product and its environmental impact in part 4. In this part results from the MFA will be presented and conclusions will be presented in part 5.

2.1 Review of sustainability frameworks

Standardized methods that measure the resource consumption and future waste streams of building products have been developed in the past such as LCA (ISO 14040:2006/14044:2006 and EN 15804) or Level(s) methodology [12], supported by programs and guidelines, such as the EU Action Plan for a Circular Economy [13] or the Green Taxonomy [14].

The definition of indicators within Level(s) remains adaptable, particularly in terms of methodology. An example of this is evident in the use of Level(s) 2.4, focusing on design for deconstruction. While Level(s) outlines a calculation workflow for the circularity score, certain aspects, such as the circularity coefficient assigned to specific building components, are left open, based on the "best possible outcome" of the component. Determining such characteristics involves expert judgment and additional considerations.

Material Flow Analysis (MFA) is another key method for quantifying the movement of materials within defined systems, including flows and stocks. It is essential in understanding the bio-physical aspects of human activities at various scales. Initially introduced in 1969 [15], MFA is now commonly used to track national material flows and plan waste management and recycling systems [16]. It complements other industrial ecology methodologies like LCA and input-output models [17], although they differ in objectives, level of functionality, and data requirements.

The LCA and MFA represent the most frequently used methodologies. However, there are many more circularity metrics that have been developed by companies, governments, and academics in the recent past. However, these metrics frequently exhibit contradictions in both their form and content, leading to confusion and misunderstandings regarding the CE concept. Additionally, there is a growing number of frameworks, creating an excess of indicators aimed at measuring resource efficiency and assessing circularity performance [18].

2.2 Material Flow Analysis

To determine the raw material composition of a building component, the product substance is categorized into two main types i) primary and ii) secondary raw material. Primary raw material includes renewable and non-renewable materials. Secondary material includes reused and recycled material.

Furthermore, material streams are categorized into material in- and output streams. Material Input refers to the resources used to produce a component. Material output refers to resources being available after the End-of-Life (EoL) phase of products and can be categorized into three categories: i) transformation into other products, ii) disposal in landfills and iii) returning to the product's own material cycle as secondary material.

Material flows can be quantified by measuring mass or other indicators such as GWP. In this research GWP is utilized to assess the environmental impact of components during their production phase (LCA module A1-A3 as per EN 15804 definitions) in terms of CO2 equivalent. Data is sourced from the German Ökobaudat.de or available EPDs. The proportions of primary and secondary resources within the product are determined based on mass (kg) in percentage. The system is visually presented within a Sankey diagram.

This research concentrates on existing recycling methods and does not predict future material output flows. Uncertainty arises from the unknown connecting joint to the façade module. Further specific details can be evaluated through an assembly-level analysis.

3. RESULTS

LCA incorporates various indicators quantifying the potential environmental impact of a product or a service during different life cycle stages (module A-C in EN 15804). Within the Level(s) framework, several indicators correspond to the ones developed in the LCA such as:

- Global Warming Potential (GWP)
- Construction & demolition waste and materials (Hazardous substances)
- Durability.

Besides, indicators within the scope of EN 15804-based LCA that directly contribute to a CE are:

- Use of renewable resources
- Use of recycled material
- Use of reused material
- Materials for recycling or reuse.

The Level(s) methodology, introduced by the EU, goes far beyond those circularity evaluation practices. It can be used to report on and improve the performance of new-build and major renovation projects [12]. This framework comprises an extra range of indicators and standardized metrics to assess the sustainability performance of buildings in addition to LCA, of which we chose:

- Bill of quantities
- Design for adaptability and deconstruction.

While existing methods like LCA and the Level(s) framework are valuable for assessing the environmental impact of building products, there is a need for additional indicators that align with the holistic approach of the CE. The following aspects take a broader perspective and draw inspiration from two core concepts of the CE: the R-Strategies (Reduce, Reuse, Recycle) embedded in the Waste Directive [19] and the Cradle-to-Cradle concept [20]:

- Financial concept for multiple life circles [21].
- Modularity [22]
- Local Material [19]
- Low-Tech [20]
- Purity [20]
- Compostability [20].

Many of the above present KPIs are widely employed in the environmental assessment of specific objectives within various policies and regulatory frameworks. Such as the Environmental Product Declaration (EPD) by EN 15804 (CEN, 2012), providing a consistent and recognized methodology for evaluating the environmental performance of construction materials.

Similarly, aspects such as the bill of quantities, the ease of demountability, and other indicators pertaining to end-of-life (EoL) stages of construction products are integrated into the technical criteria of the Green Taxonomy, especially within the "Transition to a Circular Economy" aspect. Compliance with specific threshold values related to these indicators is typically required to access green financing instruments.

A comprehensive perspective on CE considers both the EoL phase and the manufacturing/extraction phase. Nevertheless, indicators that focus on future material output at the EoL are predominantly quantitative, making them challenging to benchmark, particularly in terms of disassembly or durability.

The presented KPIs are organized according to their qualitative or quantitative characteristics and their emphasis on either the material in- or output flow. These are outlined in table 1, which also includes their respective sources. This approach aims to provide a more comprehensive and nuanced guideline for the building product selection process.

Table 1: Qualitative (Ql) and quantitative (Qn) KPIs addressing material in- and output flows based on (1) LCA, (2) Level(s) or (3) CE definition

Input	Output
GWP (1,2) Ql	Demountability (2,3) Qn
Renewable resources (1) Ql	Durability (1) Qn
Recycled material (1) Ql	Modularity (3) Qn
Reused material (1) Ql	Low-Tec (3) Qn
Local material (3) Qn	Bill of quantities (2) Qn

	Financial concept (3) Qn Hazardous substances (1,3) Ql Materials for reuse/recycling (2,3) Qn Purity (3) Qn Compostability (3) Qn

3.1 Assessing Circularity Across Multiple Scales

Each of the mentioned methodologies has its limitations when it comes to assessing circular performance characteristics on various scales. It is recognized that sustainable manufacturing is comprised of three core levels: [23] "building, assembly, component". Each of these levels has its own distinct characteristics and limitations. As the selection of an appropriate component assumes to have a critical role in the environmental impact of a building [24], a common method specifically tailored for assessing the circularity of components will be selected. Table 2 shows instruments that assess circularity in relation to the level of functionality.

Table 2: directly (x) and indirectly (/) related frameworks to assess different level of functionalities

Instrument	Component	Assembly	Building
LCA	x	x	x
EPD	x	-	-
Level(s)	-	/	x
MFA	x	x	x

While LCA and EPDs are primarily utilized as an assessment tool at the component level, it has the flexibility to transition to a macro-level perspective when facilitating decisions on a larger scale. This includes supporting macro-level considerations concerning national policies or sector strategies related to technologies, services, or a collection of products. Nevertheless, it's crucial to note that LCA is not suitable for evaluating the overall performance of the global economy. In such cases, alternative tools like MFA would be more fitting and effective as it even goes beyond building level [18].

When considering priorities for circularity assessment, whether from a regulatory or strategic perspective, it is essential to emphasize that the analysis should always include a holistic view on all represented level of functionalities. In addition, qualitative KPIs, as for now, lack translation into quantitative analysis, introducing uncertainties. The choice of the circularity assessment framework should align with business, commercial, reputational, or regulatory priorities. For instance, if a construction product's commercialization strategy is to demonstrate compliance with specific indicators within Level(s) under the green taxonomy, the assessment should be conducted within the Level(s) methodological framework. However, if the emphasis lies on the utilization of secondary materials and the visualization of material streams, opting for a MFA proves to be the more fitting choice.

The MFA applied in this research assesses the material input (KPI Recycled/reused material) using GWP as an indicator at component level and will be used to critically evaluate the circularity of nine building products that are essential for the achievement of a circular facade renovation solution. The term component is defined as part of an assembly that is required for functionality, performs a unique and necessary function in the operation of the assembly, is removed in one piece and is indivisible for the use of the overall assembly [25].

3.2 Material Flow Analysis of insulation

Displayed are the outcomes of four selected components, encompassing both active (such as PV panels) and passive (like insulation) characteristics (figure 1).

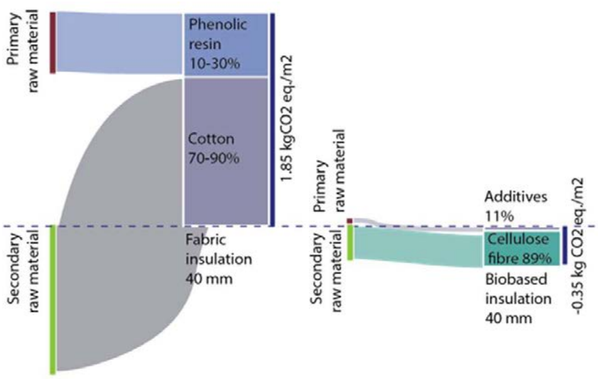

Figure 1: Material Flow Analysis of fabric (Product A) and biobased insulation (Product B)

The insulation panels are characterized using secondary materials (Product A: recycled cotton) and renewable materials (Product B: cellulose). Both products exhibit similar characteristics in terms of thermal conductivity (A 0.034 W/mK and B 0.041 W/mK) density (A 50/60 kg/m^3 and B 45 kg/m^3) and thickness (A/B 40 mm). Over a life span of 50 years Product A emits CO_2 emissions (1.85 kg CO_2/m^2) during product phase whereas Product B captures carbon emissions (-0.35 kg CO_2/m^2) due to the use of renewable material. Both have a high amount of secondary material, as 89% of Product B uses waste from paper production and Product A up to 90 % waste from textile production and 10 % of primary material (phenolic resin). Reuse and recycling options are restricted by the presence of fire-retardant substances like boron salt, which poses health risks. Consequently, owing to the absence of recycling systems, insulation is primarily disposed of in landfills or incinerated.

3.3 Photovoltaic (PV) Panels

The analyzed PV panels (**Error! Reference source not found.**) are a standard PV panel (PV1) and a flexible thin film PV panel (PV2) which are specialized for façade application. PV1 is a standardized roof panel that has been adapted for use as a façade module in the case study, eliminating the need for a specialized and typically more expensive module. Both products encompass a series of production stages which result in high amount of CO2 emission for PV1 (68.9 kgCO2eq./m^2), PV2 emits up to 80 % less CO2 emissions (14 kg CO2eq./m^2) over a lifespan of 30 years. However, its power rate is 7 times less (63,1 Wp/m2 compared to a standard PV1 (212,8Wp/m^2). Both mainly consists of glass (up to 76-88%) and aluminum (7-8%) which accounts mostly for the CO2 emissions. According to manufacturer data, PV2 is composed of nanoscale carbon-based (organic) molecules that facilitate the production of thin products. Compared to a standard PV which typically has a thickness of between 200 and 300 µm, PV2 typically has a thickness of anywhere from a few nanometers to tens of micrometers which results in lower energy efficiency [26].

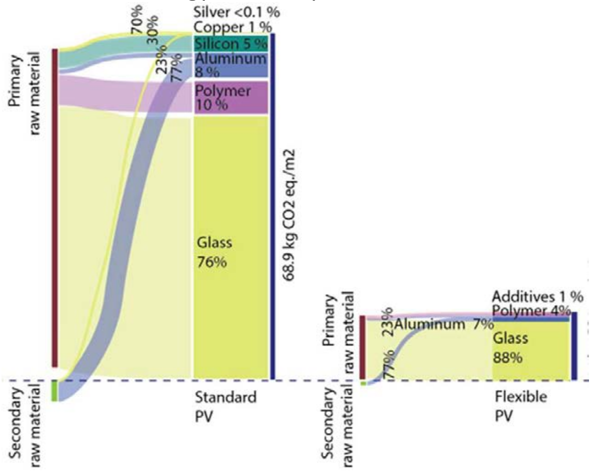

Figure 2: Material Flow Analysis of standard (PV1) and flexible (PV2) PV panels

Thin film technologies require less material overall compared to crystalline silicon. Flexible PV panels contain about 88-89% glass, 7% aluminum, 4% polymer with less than 1% semiconductor material (indium, gallium, selenium) and other metals (e.g. copper) [27]. Approximately 80 percent of a solar panel's weight comprises energy-intensive materials like aluminum and glass, posing recycling challenges due to the difficulty of separating glass from silicon, and the remaining 20 percent can be challenging to recover. However, materials like copper, plastics (including cables and junction boxes), and silver can be efficiently repurposed with careful separation, necessitating time and expertise to prevent contamination and safely dismantle the panels into raw components [28].

4. CONCLUSION

Currently, the use of methodologies that assess the use of secondary resources in the built environment is a novel area in architectural discourse. Yet, a comprehensive, user-friendly method that holistically assesses the circularity potential of products is lacking. This necessitates architects and manufacturers to make informed design choices during early stages based on holistic KPIs. The presented KPIs act as a guide during the design phase of a façade renovation project. Nevertheless, a comprehensive method to assess the circularity of products is necessarily which also includes additional information about parameter such as costs.

A pivotal element for comprehending circularity involves the visualization of resource flows. Displaying the utilization of primary and secondary material flows, alongside CO_2 emissions, using MFA as a standardized method supports the decision-making process and contributes to the preservation of natural resources for future generations. However, characterization of MFA requires expertise and further deliberation. In addition, the decision-making process needs further support by a variety of more indicators, especially focusing on the future material output. For example, flexible photovoltaic (PV) panels, in addition to the implemented MFA demonstrating low embodied carbon emissions, it is crucial to consider indicators like health related KPIs (hazardous substances) and other KPIs such as recyclability and reusability that provide insights into future material output flows. Therefore, this study introduced holistic KPIs that can guide the design process towards a circular solution. Future research could focus on the development of a tool that incorporates all presented KPI's and facilitates comparisons between products and includes additional parameters, such as cost.

Thus far, a combination of analytical assessments using standardized methods like MFA, alongside qualitative approaches represented by the KPIs identified in this research, is recommended for achieving a solution of a circular building component. This integrated approach enables a more thorough evaluation, considering both quantitative and qualitative aspects, leading to informed decision-making in sustainable construction practices.

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