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Defining a Framework for Holistic Life Cycle Assessment of Building Components

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***Abstract*—**In response to the building and construction sectors accounting for a third of all energy demand and emissions, the European Union has placed new laws and regulations in the construction sector that emphasize material circularity, energy efficiency, biodiversity, and social impact. Existing design tools assess sustainability in early-stage design for products or buildings; however, there is no standardized methodology for measuring the circularity performance of building components. Existing assessment methods for building components focus primarily on carbon footprint but lack the comprehensive analysis required to design for circularity. The research conducted in this paper covers the parameters needed to assess sustainability in the design process of architectural products such as doors, windows, and facades. It maps a framework for a tool that assists designers with real-time sustainability metrics. Considering the life cycle of building components such as façades, windows, and doors involves the life cycle stages applied to product design and many of the methods used in the life cycle analysis of buildings. The current industry standards of sustainability assessment for metal building components follow cradle-to-grave life cycle assessment (LCA), track Global Warming Potential (GWP), and document the parameters used for an Environmental Product Declaration (EPD). Expanding on the MCI with additional indicators such as the Water Circularity Index (WCI), the Energy Circularity Index (ECI), the Social Circularity Index (SCI), Life Cycle Economic Value (EV), and calculating biodiversity risk and uncertainty, the assessment methodology of an architectural product's impact can be targeted more specifically based on product requirements, performance, and lifespan. Broadening the scope of LCA calculation for products to incorporate aspects of building design allows product designers to account for the disassembly of architectural components. For example, the MCI for architectural products such as windows and facades is typically low due to the impact of glass, as 70% of glass ends up in landfills due to damage in the disassembly process. The low MCI can be combatted by expanding beyond cradle-to-grave assessment and focusing the design process on disassembly, recycling, and repurposing with the help of real-time assessment tools. Design for Disassembly and Urban Mining has been integrated within the construction field on small scales as project-based exercises, not addressing the entire supply chain of architectural products. By adopting more comprehensive sustainability metrics and incorporating uncertainty calculations, the sustainability assessment of building components can be more accurately assessed with decarbonization and disassembly in mind, addressing the large-scale commercial markets within construction, some of the most significant contributors to climate change.

***Keywords*—**Architectural products, early-stage design, life cycle assessment, material circularity indicator.

I. Introduction

THE research conducted in this paper covers the parameters required to assess sustainability in the design process of architectural products and the construction of a tool that assists designers with real-time sustainability calculations. A multidimensional approach is taken to address design for circularity in architectural components by combining the metrics and calculations of LCA and Circularity Indicators with the design guidelines and principles of design for disassembly. Targeting a broad range of users such as designers, assessment metrics, and strategies must be accessible to users of varying expertise. This paper covers the research of Design for Disassembly, Urban Mining, Circularity Indicators, and existing LCA tools for designers. The paper then outlines the selected methodology for creating a tool to assist designers of architectural components in designing for circularity.

II. Life Cycle Assessment

Circularity aims to use materials as long as possible, using the fewest natural resources to create products and waste the least amount possible, recovering everything possible for future products. Circularity considers material choice, product design, and end-of-life conditions like reuse, recyclability, and energy capture.

In calculating carbon emissions, the terminology 'scopes 1, 2 and 3' is used to distinguish emissions originating directly from production or more indirectly through other actors. Scope 1 refers to the direct transmissions of an organization. Scope 2 includes all emissions of the energy used by a company in operations and production. Scope 3 encompasses all other indirect emissions within the life cycle that fall outside of scopes 1 and 2. Scope 3 may entail use and disposal emissions and is the most difficult to account for in calculations, especially for products such as architectural components, which do not have a consistent life cycle [1].

LCA examines the environmental impacts of a process, service, or product across the stages of its lifespan, from first impacts through the supply chain to its end-of-life. First impacts of LCA include sourcing of raw materials, manufacturing, fabrication, transportation, and construction, leading to the use stages. Use impacts cover all operability and maintenance until the end of life. End-of-life impacts can be waste/disposal, energy recapturing, recycling, or reuse. The scope of an LCA ranges from Gate-to-gate assessment (partial LCA that looks at one value on the supply chain) to Cradle-to-gate assessment (resource extraction to factory gate), to Cradle-to-grave assessment (resource extraction to disposal), and finally to Cradle-to-cradle assessment (resource extraction to recycling)

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[2].

LCA is used to inform decision-making, to compare different materials, practices, and products, to inform product design, for marketing, and for policy. An EPD uses LCA to provide standardized and verified reports of the impacts of a product. With external validation, the data are presented across the life cycle stages in the declaration. In the context of EPDs and LCAs, uncertainty refers to the areas of unknown data in the LCA calculation. In EPDs, there is manufacturer uncertainty (industry-wide), product uncertainty (across the product line), plant uncertainty (in cases with multiple production facilities), supply chain uncertainty (using the average background lifecycle inventory data), batch uncertainty (minor batch-to-batch variations), and basic uncertainty, which is 3% for all EPDs, independent of their accuracy or precision. In LCAs, uncertainty relates to input parameters, model uncertainty, real-world translation, environmental uncertainty, and more. Quantifying these uncertainties is crucial for enhancing the robustness and reliability of LCA results [3].

LCA tracks the use of natural resources. The International Resource Panel states that 90% of the world's biodiversity loss is attributed to the extraction and processing of these resources. While tracking biodiversity in LCA is a challenge, the European Union has outlined a comprehensive biodiversity strategy with the Circular Economy concept. By merging and maximizing the utility of natural resources, the overall demand for them is lessened [20]. In early design, biodiversity depletion risk can be assessed using the following LCA parameters: total renewable energy used as raw materials and energy carriers (PERT), total non-renewable energy used as raw materials and energy carriers (PENRT), use of net fresh water (FW), and global warming potential (GWP).

III. Design for Disassembly and Urban Mining

A. Design for Disassembly

Throughout the design process of products and buildings, Level-of-Detail (LOD) is assessed in categories. The most rudimentary level is LoD 100, with model elements represented schematically. The most refined LoD is 500, where information is obtained through field verification. Multi-LoD principles must be followed to generate a disassembly model by existing guidelines (e.g., BIMForum and AIA definitions) for building design. LoD 500 is required for building elements to determine realistic disassembly sequences according to the structural and thermal conditions of and between building elements. Due to the LoD needed for building structures and components and a lack of efficient methods for assessing disassembly parameters, current building information models do not support selective disassembly planning.

Sequential Disassembly Planning for Buildings contains three required parameters: the Deconstruction Method Parameter, the Deconstruction Cost Parameter, and the Deconstruction Life Cycle Assessment. The Deconstruction method parameter indicates the type of deconstruction method, such as selective demolition, destructive disassembly, or complete disassembly. The Deconstruction LCA indicates the net environmental impact associated with each element of the model and its associated deconstruction method [4].

BIM elements such as objects and blocks are currently designed to interact with other BIM elements without the incorporation of disassembly criteria. Disassembly criteria currently rely on detailed manual inspection. From the perspective of early design, disassembly can be incorporated seamlessly and efficiently. Planning for disassembly from the smallest building components can save labor hours further down in the design process and improve the accuracy and predictability of disassembly projects. With disassembly metrics structured into BIM elements, the design for disassembly of building design will be significantly more refined and meet disassembly and construction standards.

B. Urban Mining

Urban mining is reevaluating waste material from a structure and repurposing it for new construction. By 'mining' these materials from structures that have reached the end of their lifetimes, the necessity to extract new resources can be bypassed, creating a closed loop. At one point, all recovered materials in the Urban Mine are sourced from conventional mining. Urban Mining is the cycling of essentially what would otherwise be end-of-life products; thus, the urban landscape becomes the mine. Similar to conventional mining, materials are separated into classes based on element concentration and other factors. Material reutilization is part of Cradle-to-Cradle assessment, with broad cycling categories that help assess potential cycling pathways and act as guides in the early design stages to meet cyclability and disassembly requirements [21]. Categories include waste/landfill, recoverable energy, recycling, remanufacturing/repair, refurbishing, and reuse [5].

C. Existing Initiatives of Architectural Component Reuse

Several existing circularity initiatives within the building components sector are included in this research. Rewindo, Concular, and Saint-Gobain structure urban mining and recycling into their product development strategy.

Rewindo, headquartered in Cologne, Germany, specializes in the advanced recycling of PVC materials. The company meticulously oversees the proper disposal of windows, shutters, and doors by collaborating with state-of-the-art partners. Working with Schüco Polymer, used PVC windows are collected from residential buildings, dismantled, sorted, and recycled. This approach contributes to a notable reduction in CO_2 emissions and aligns with efforts to curtail energy consumption. The recycled PVC-U, a byproduct of this environmentally responsible procedure, is utilized on the inner core of new window profiles. Notably, the recyclability of PVC in windows extends up to seven cycles before disposal [6].

Concular, also in Germany, offers portfolio analysis, strategy development, and practical recommendations to assist in circular construction and sustainable real estate solutions. Concular optimizes compliance with ESG and EU taxonomy standards by actively closing material cycles, reducing CO_2 emissions, and waste planning, conversion, and dismantling. For example, when an old building is ready for demolition, Concular may create proposals to reuse the building components in new projects. Concular also utilizes digital solutions to achieve certifications for its clients, such as DGNB, BREEAM, GRESB, and CRREM [7].

Saint-Gobain, based in France, recently introduced the product Cool-lite ORAE, incorporating 64% to 100% recycled float glass; it is the lowest carbon glass on the market. This pioneering glass product presents a remarkable environmental advantage, boasting a 42% reduction in CO_2 emissions compared to the European industry standard of 6.64 kg CO_2 per square meter [8].

IV. Current Cyclability Standards and Practices for Architectural Components

When an architectural element such as a façade, door, or window completes its life cycle, the current standard best-case scenario is to remove it and send it to a recycling plant. The members of the architectural products undergo systematic shredding and sorting at the few recycling plants that support it. For Cradle-to-Cradle, it is necessary to prove the existing partnership and process of this recycling to obtain the certification; it is not enough to prove that the product is theoretically recyclable. Aluminum recyclability generally operates at an efficiency of 95%. Plastics are extracted with 95% efficiency and either incinerated for energy generation or recycled, depending on their chemical content [18]. Thermoplastic-based components can be recycled, but thermoset-based components must be incinerated due to the permanent chemical bond. Currently, gaskets are almost entirely incinerated, but there are efforts to incorporate recycled content into new gaskets while maintaining performance requirements. Glass often breaks or fractures during this process, with approximately 70% damage post-extraction. In the case of broken glass, it can only be used as float glass or sent to landfill. Glass is crushed, melted, and recycled. In more detail, according to the Product Category Rule BS EN 17213:2020, the prescribed maximum recycling rate for glass is 30%. To allocate a recycling rate exceeding this threshold to glass, it is imperative to generate an EPD substantiating that a superior recyclability rate has been attained for the specific product in question [9].

To boost recyclability and reduce the energy demand needed in the recycling process, a gap in the methodology remains: strategies and standards for designing products that require less energy in the end-of-life stages. Recycling is associated with substantial energy costs and the production of carbon dioxide. In addition to sourcing energy at recycling plants from renewable sources, introducing design philosophies centered around disassembly proves to be a strategic approach that aligns the design process more closely with the inner circles of the Material Circularity Indicator (MCI) diagram [10].

In the schematic of the circular economy from the Ellen Macarthur Foundation (Fig. 1), the inner circles of the supply chain keep the products, components, and materials in their cycle as long as possible. Greater circularity is achieved by repair, maintenance, reuse, refurbishment, remanufacture, and recycling. Products must be designed for durability, reuse, remanufacturing, and/or recycling. It is important to note that in a circular economy, non-renewable resources are avoided as much as possible, and the use of renewable energy is strongly encouraged [10].

These circular practices aim to capture additional value (extended life) from their products and materials and mitigate business risks from material price volatility and supply.

V. Existing LCA Design Tools: Precedents and Case Studies

A. One Click LCA®

One Click LCA® is an LCA platform developed for Revit®, Rhino®, and Excel®. With material benchmarking using extensive material databases, One Click LCA® generates diagrams of material comparisons and EPD results. One Click LCA® has multiple software available for different users and project types. According to the website, services offered through One Click LCA®, the "world's largest construction environmental database," ranges from design and construction LCA, embodied carbon calculation and optimization, costing, EPD generators, GSG reporting, and climate strategy GHG reduction [11].

B. Sphera®

Sphera®, named the leader in Carbon Management Software, provides Environmental, Social and Governance (ESG) performance software, ESG risk management software, data, and consulting services. Sphera® structures ESG solutions using 13,000 datasets with scalable solutions based on requirements from stakeholders such as B2B, B2C, investors, and governments. Based on LCA methodology following 14040 and 14044 standards, Product Carbon Footprints (PCFs) quantify greenhouse gas emissions. Additionally, Sphera® calculates Social LCAs, Life Cycle Costing, and water footprints and performs comparative studies between multiple LCAs [12].

C. MI:Product Intelligence™ and MI:BoM Analyzer™

The MI:Product Intelligence™ online tool, using the Circularity Indicators of the Ellen Macarthur Foundation, was developed by Granta Design for commercial use. The tool analyzes environmental risks within the supply chain using a Bill of Materials (BoM) and the Granta MI database, which contains extensive material data. BoMs can be imported or created using the Circularity Indicators tool and MI:BoM Analyzer ™ or CAD, with outputs of a circularity report and risk analysis [10].

D. The Circular Design Guide

The Circular Design Guide was created by the Ellen MacArthur Foundation and IDEO. The guide is a collection of sources to assist a broad spectrum of users in circular thinking and design. The guide contains content on methods, including learning, planning, and reflecting activities. For example, the Product Redesign Workshop explores safe and circular material selection. It includes a Safe & Circular Product Redesign Worksheet, Safe & Circular Strategy Cards, Safe & Circular

Product Redesign Presentation, and Safe & Circular Material Choices Series. Users learn about material screening and selection in this activity, with additional resources and topics linked to explore further [13].

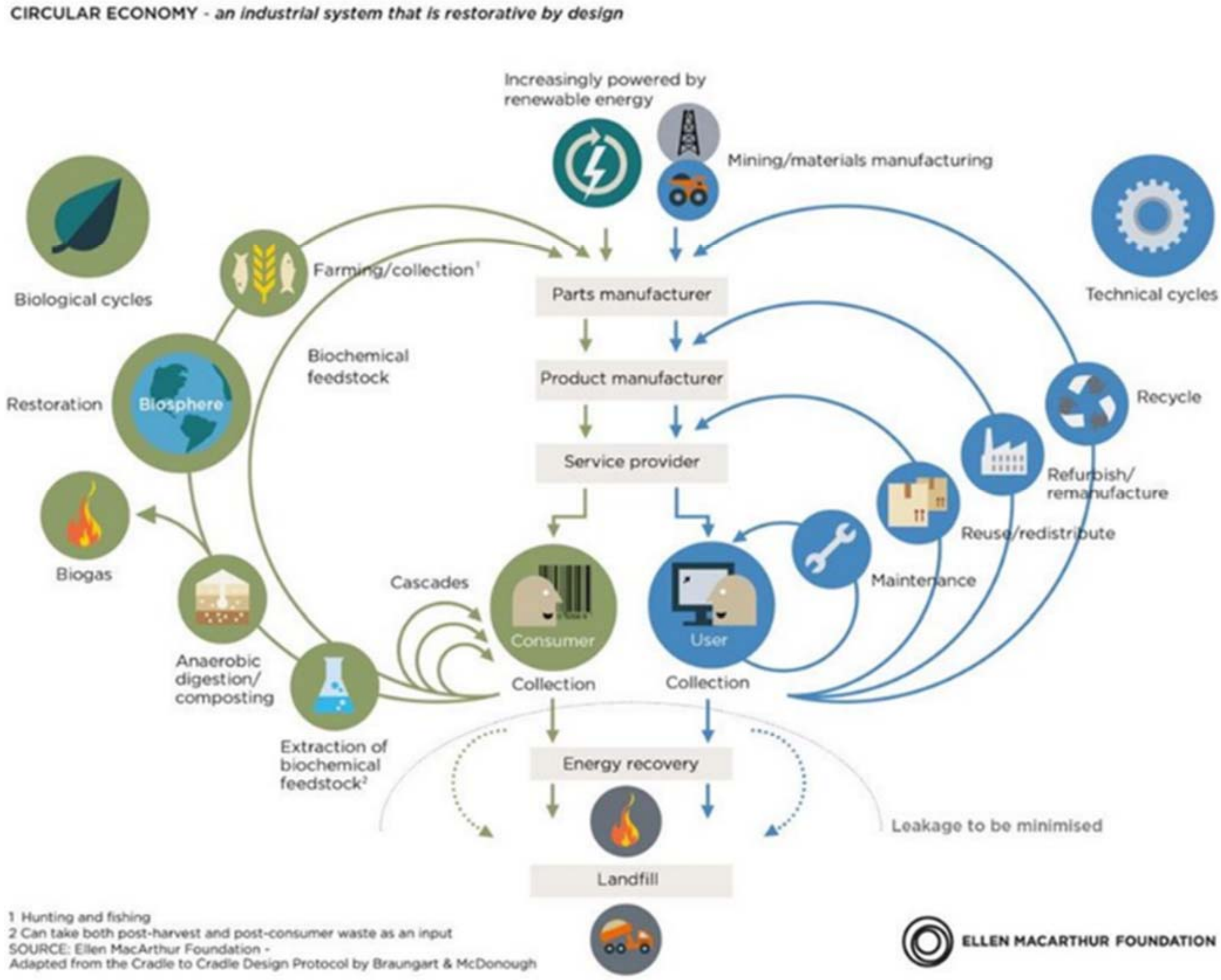

Fig. 1 Material Circularity Indicator concept and architecture [10]

E. Makersite

Makersite Add-on for Autodesk® Fusion 360™ is a plug-in for Fusion 360™. It generates a BoM and calculates CO_2 in addition to cost estimates, compliance, and risk. Makersite provides suggested material alternatives and visual representations of LCA data. Makersite assesses designs across the supply chain incorporating scopes 1-3. Blind spots are filled by combining primary and third-party data [14].

F. The BHoM LCA Toolkit

Buro Happold developed the Buildings and Habitats object Model (BHoM) with a user interface in Grasshopper®, Dynamo, and Excel®. The LCA toolkit was added in 2020. The LCA toolkit is structured from the highest level, from scope to objects, materials, and detailed datasets. It is highly versatile and can specify the scope of data, allowing users to create a very detailed inquiry or one at a high level without the need for extensive knowledge of LCA [15].

G.Bombyx

The Grasshopper® 3D plug-in Bombyx was developed to be used at ETH Zurich by architecture and engineering students. The tool is designed with two approaches to LCA: top-down and bottom-up. Building elements are separated by layer; preset materials and preset building components are available. The top-down approach focuses on high-level building design decisions such as dimensions and the main structural system. The bottom-up approach requires more LCA knowledge but offers a much) more detailed analysis from assigning materials to geometry [15].

H.Tortuga

Tortuga, another LCA Grasshopper® plug-in, was developed by Thumfart M. and operates from the material level. Predefined material data can be assigned to modeled volumes, surfaces, and curves. Components of multiple materials can be combined into one greater design, such as a block or family in BIM software. The analysis can be customized based on specific LCA modules, and results show total calculations for all materials combined [15].

I. Tally®

Kieran Timberlake developed the Tally® LCA App for Autodesk® Revit® in partnership with Autodesk® and Sphera® to create a plug-in for Revit®. Embodied carbon is calculated for building design in Revit® based on real-time modeling and a robust database of materials and objects with LCA data. Embodied energy calculations are done for the building's impact on land, water, and air. Tally® also offers comparative analysis for different design options based on embodied energy calculations. Using the E3 tool for calculating uncertainty, the design and LCA calculation aspects are approximated for an informed estimate. In addition to the LCA calculation outputs across the whole supply chain, Tally® produces a BoM [16].

J. Summary of Precedents and Case Studies

Current software and platforms on the market included in this research focus on gathering dynamic client data on products and materials to generate sustainability and circularity analytics. This information is used to advise clients of the material content and respective circularity and sustainability data. Software such as One Click LCA, MI:Product Intelligence ™, MI:BoM Analyzer ™, and Sphera® expand with recommendations for material selection and supply chain risks and recommendations. Software such as Tally goes a step further by including these sustainability metrics in the metadata of BIM objects, giving clients an option for a more informed decision regarding product selection. Platforms such as the Circularity Design Guide fill the gaps in quantitative data with learning materials on circular thinking and circular design. This paper argues that combining robust life cycle and circularity analysis with design manuals and guidebooks provides designers with the resources necessary for the circular design of architectural products.

VI. The MCI and Other Indexes

A. The Material Circularity Indicator

The methodology developed by the Ellen McArthur Foundation, the MCI, quantifies the minimization of linear material flow and maximization of restorative flow for all component materials in a product. To be classified as a completely circular material, it must be sourced from recycled or reused sources, made from safe materials, and have the capacity to be recycled or reused after the product's lifecycle.

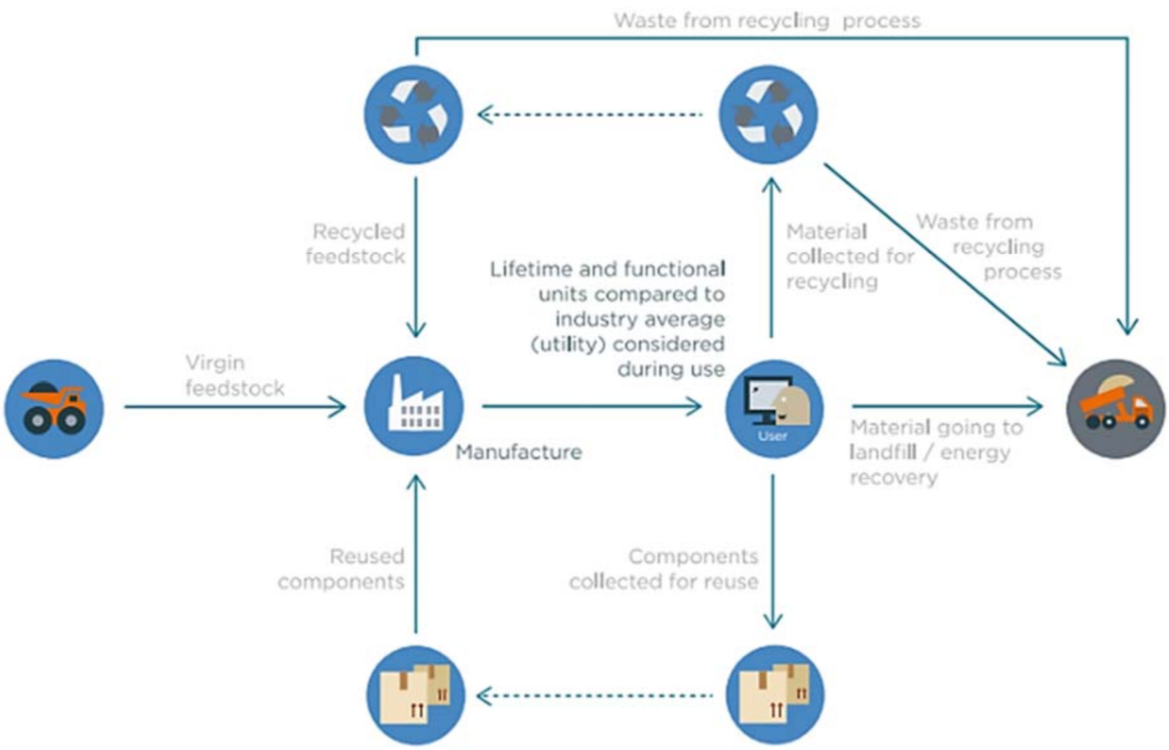

Fig. 2 MCI material flow [10]

The MCI assesses the duration and intensity of a product's usage compared to an industry-standard average product. In more detail, three pivotal product characteristics influence the MCI: the mass (V) of virgin materials employed in manufacturing, the mass (W) of unrecoverable waste associated with the product, and the utility factor (X), which encompasses the length and intensity of the product's utilization. To be classified as a completely circular material, it must be sourced from recycled or reused sources, capable of being recycled or reused after the product's lifecycle, and safe for the environment and people. The MCI extends beyond initial product assessment to reuse, remanufacturing, and recycling. A higher MCI score indicates the products and materials remain in circulation longer. The MCI incorporates six principles to quantify the sustainability and circularity of a product:

- The first MCI principle considers the sourcing of biological materials.
- The second MCI principle considers the sourcing of feedstock.
- The third MCI principle considers the product's longevity, incorporating factors such as durability, redistribution, and reuse.
- The fourth MCI principle emphasizes the reuse of components after the product's initial lifespan.
- The fifth MCI principle focuses on maximizing product utilization through sharing and reservice.
- The sixth MCI principle emphasizes preserving biological materials in an uncontaminated state and ensuring their biological accessibility.

A 100% circularity implies total repurposing upon completing a lifecycle, as the reuse of product components significantly improves embedded energy compared to recycling. The MCI has a significantly higher potential if reuse and future life cycles are planned for in the earliest design stages [10].

Fraction of feedstock from virgin sources:

$$V = M \cdot (1 - F_R - F_U - F_S) \quad (1)$$

Fraction of feedstock from virgin sources:

$$W_0 = M \cdot (1 - C_R - C_U - C_C - C_E) \quad (2)$$

Waste generated in the recycling process:

$$W_C = M \cdot (1 - E_C) \cdot C_R \quad (3)$$

Waste generated to produce any recycled content used as feedstock:

$$W_F = \frac{(M \cdot (1 - E_F) \cdot F_R)}{E_F} \quad (4)$$

Overall amount of unrecoverable waste:

$$W = W_0 + \frac{(W_F + W_C)}{2} \quad (5)$$

Utility:

$$X = \left(\frac{L}{L_{av}} \cdot \frac{U}{U_{av}}\right) \quad (6)$$

Function of Utility:

$$F(X) = \frac{0.9}{X} \quad (7)$$

Material Circularity Index:

$$MCI = 1 - LFI \cdot F(X) \quad (8)$$

B. The Energy Circularity Index

The energy circularity is measured as the kWhPE ratio of renewable energy used over the total embodied energy. Renewable energy may be sourced from on-site generation or energy savings.

In computing the ECI, requisite data are sourced from an EPD or alternative reputable outlets like LCA software. The initial step involves extracting information on renewable energy utilization from pollution control parameters. The cumulative deployment of renewable energy is denoted as PERT, signifying the total consumption of renewable primary energy resources, measured in Mega Joules. PERT serves as the numerator in the calculation. The denominator, PENRT, is also discerned from pollution control parameters, representing the total utilization of non-renewable primary energy resources. The ECI is determined by dividing the total consumption of renewable energy (PERT) by the overall energy consumption, represented by the sum of PERT and PENRT. Products or materials manufactured with a higher proportion of renewable energy are inclined to exhibit a comparatively diminished environmental impact when assessed through the lens of the ECI [17].

$$ECI[\%] = \frac{(CE_{A1-3} + CE_{A3-5} + CE_B + CE_C)}{(E_{th}+E_e)_{A1-3} + (E_{th}+E_e)_{A3-5} + (E_{th}+E_e)_B + (E_{th}+E_e)_C} \quad (1)$$

C. The Water Circularity Index

Water circularity is measured as the ratio, in m^3, of circularly sourced water over the total amount of water used. Circularly sourced water can be sourced locally, and cycled water may refer to grey water, rainwater, or black water. In the computation of the WCI for a material or product, essential data must be acquired from an EPD or an LCA, requiring a thorough analysis of the supply chain. The supply chain data do not need to be provided by the designer, but access to an LCA database or EPD is. Water originating from recycled sources is outlined in section D and is represented as a negative value. The cumulative water usage, excluding recycled sources, is determined by aggregating values from sections A-C, clearly delineated in tables featured in an EPD or an LCA. The WCI is then derived by dividing the volume of water from recycled sources by the total water consumption. Notably, a higher WCI in the manufacturing process of a product or material signifies a greater reliance on recycled water sources. This, in turn, translates to a reduction in overall water consumption, thereby positively contributing to a diminished environmental impact [17].

$$WCI[\%] = \frac{CW_{A1-3} + CW_{A4-5} + CW_B + CW_C\,[m^3]}{W_{A1-3} + W_{A4-5} + W_B + W_C\,[m^3]} \quad (2)$$

D. Life Cycle Economic Value

The life cycle economic value is measured as the initial investment minus the operation cost plus the total revenue. It is designed to reflect circularity similarly to the other indexes, portraying the economic viability of the product over time.

Extensive knowledge of a product's business model is necessary for EV calculation and cannot be sourced from an

LCA database. Total revenue also cannot be predicted during early design. This information may be sourced internally in a company and used as an assessment or comparison tool for existing projects [17].

$$EV = -CAPEX - OPEX + REVENUES \qquad (3)$$

E. The Social Circularity Index

Social circularity is measured as the ratio of social impacts engaged with over the total amount of possible social impacts to engage with. Potential social impacts can be found in the Cradle-to-Cradle Social Fairness Categories at the Product stage, the Construction Process stage, the Use stage, and the End-of-Life stage [17].

$$SCI[\%] = \frac{SI_{A1-3} + SI_{A4-5} + SI_{B1} + SI_{B2-5} + SI_C}{N_{A1-3} + N_{A4-5} + N_{B1} + N_{B2-5} + N_C} \qquad (4)$$

VII. Methodology

Environmental impact factors of materials are analyzed by obtaining data from EPDs and LCAs. As an architectural products company, the primary focus is on specific materials such as metals, glasses, plastics, and polymers. Performance indexes of such materials are calculated based on their weight. The provided data in EPDs and LCAs are typically in terms of a given quantity of material, expressed, for example, as kg CO_2e/kg of material. The sustainability design tool offers designers data on how chosen materials perform compared to alternatives, how early designs compare to each other, and how designs compare to industry standards. Metrics such as the MCI, WCI, ECI, SCI, Life Cycle Economic Value, and Pollution Control factors (such as GWP and other relevant indicators) are displayed in real-time. The tool identifies materials with the highest environmental impact throughout the design process and suggests alternative options. A window displaying infographics about the chosen material assists designers in visualizing each environmental impact category by comparing them to everyday life scenarios.

VIII. Workflow and Integration

A. Material Data Sourcing

Material data are imported from Sphera or another LCA software or database. Sphera is used in this case because it contains extensive data on the environmental impacts of many materials related to architectural components such as facades. All inputs for the circularity indicators can be sourced from Sphera® or similar LCA database software. Eleven material parameters must be obtained to find the MCI:

- The mass of the finished product (M)
- The fraction of feedstock from recycled sources (V)
- The fraction of mass from reused sources (Fu)
- The fraction of mass from sustained production (Fs)
- The fraction of mass of product collected for recycling (Cr)
- The fraction of mass of product for component reuse (Cu)
- Fraction of mass collected for composting (Cc)
- Fraction of mass of biological materials from sustained production being used for energy recovery (Ce)
- Efficiency of the recycling processed used for recycling the product at the end of its used (Ec)
- Efficiency of recycling feedstock (Ef)
- Utility across the lifespan (X)

While LCA does not contain material data necessary for the MCI calculation such as recycled content, robust material databases such as Sphera® contain the necessary data. When assessing a single material, the factors with the most impact on the MCI are the fraction of feedstock from recycled sources, a fraction of mass from reused sources, and the efficiency of recycling feedstock. For example, the MCI of aluminum with 40% recycled content is 70%. In comparison, the MCI of aluminum with 80% recycled content is 87% [19].

B. Assigning Materials

Similarly to Bombyx and Tortuga, predetermined LCA data are linked to the BIM software's extrusions and other closed volumes. As designs are scaled 1:1, the associated weight of the material is assigned to the volume, and calculations can be run throughout the design process. To avoid unnecessary buffering time throughout the process, the calculations are only run when a "Compute" command is run.

Data are associated with 1 kg of material. When the material is assigned to volume in BIM software, the environmental impacts are calculated with the accurate weight of the material. As multiple volumes in a product are linked to multiple materials, calculations can be done separately by material or component or the whole design. Calculations of indexes can be done per material (as Sphera® and other databases provide this ability) and for the entire designed solution.

C. Contextualization and Comparison

Expert knowledge of LCA data and EPD results is not guaranteed in addressing a broad user group such as product designers. Designers may be trained in aesthetics, structural engineering, material conservation, or other broad or narrow focus areas. Whether the user has detailed knowledge of LCA and EPD data, all users should be able to view and understand the circularity outputs to the degree necessary for their inquiry. For this reason, circularity outputs should include a range from a cursory overview to a detailed evaluation of the results. Cursory overviews of the results include circularity indicators with graphic representations and contextualization for understanding the data. Contextualization involves real-world frames of reference to put the results into a different perspective. For example, the GWP can be given as a result in kg CO_2e and the number of flights between two cities. The use of net fresh water can be given as the result in meters cubes and the number of baths equivalent. The energy consumption can be given as the result of megajoules and the number of electric car charges, and so on. These comparisons enable users to better understand LCA analysis outputs through real-world examples. In addition to contextual references, the ability to compare results to other designs is also necessary. For designers and clients, it is necessary to consider results relative to existing designs, alternative designs, certification standards (Cradle-to-Cradle, LEED, BREEAM, etc.), industry standards, and national or global standards. Optimal solutions may vary for different users, some may optimize for lowest CO_2, others for lowest use of natural resources, others for lowest cost, and so on. In these circumstances, solutions come with trade-offs; while a solution may be optimal for one specific parameter, it may be a significant sacrifice in another. Making these data available and legible to users empowers them to make informed decisions throughout the design process. Collectively, these comparisons are helpful to different user groups regarding material selection, design configuration, and the overall investment in new products.

D.Design Principles for Circularity

In addition to metric tools such as circularity indicators, the most impactful design choice is to design with disassembly in mind. In architectural components, this refers to all system subcomponents planned in a hierarchy or working steps of connecting units to come apart during demolition. All subcomponents inherently have a connection to their adjacent subcomponents. These connection types can be sorted into categories: permanent and detachable. Each connection type, clipped, rolled, welded, bolted, glued, etc., is either a connection that is fixed and cannot be undone during demolition or can be disconnected so the components can be refurbished or reused. For example, gaskets can be rolled into profiles permanently or fit into grooves from which they can later be removed. The connection type used in a design has typically been chosen based on criteria such as structural capacity, thermal and acoustic performance, and industry knowledge. By adding the factors of material reutilization and disassembly into this decision process, designers have significantly more control of the end-of-life of a design from the earliest stages.

Following an approach similar to the Circularity Design Guide [13], small-scale and large-scale design principles addressing reusability and material selection can be made available through curated learning materials. The accessibility of this knowledge can be demonstrated in solutions such as catalogs of legible connection-type diagrams with tags such as "permanent" and "detachable." For a design tool, these guides can be in the form of an additional ribbon on the user interface with the ability to expand and learn more and the option to tag parts of the design with connection-type labels.

IX. Outputs

The tool's outputs can vary based on user needs and project scope. All LCA data in preliminary LCA, MCI, ECI, SCI, EV, and WCI will be generated as data (spreadsheet or PDF), visualizations (annotated graphs), and real-world contextualization of the calculation. Comparison outputs between material choices and between multiple designs configured in the tool would also be available for export in PDF or images. Lastly, the export of the 3D model will be available with all generated LCA metadata to be imported to Building Information Modeling (BIM) software and building LCA databases (such as Tally for Revit®) to be used as ready-made blocks or families for building design. Users such as architects and interior designers could optimize the selection of architecture products such as windows, facades, and doors based on climate, site, and context.

X.Conclusion

Combining the quantitative data of LCA calculation and circularity indicators with the qualitative data of design for circularity principles allows for a methodology to conduct LCA in the early design of architectural components and access to disassembly strategies. While LCA s for products and buildings separately are widely researched and developed, assessing the circularity of architectural products does not yet have a standardized or widely researched methodology. Currently, for both products and buildings, the process to assess environmental damage is through an LCA before production, and/or for EPD after production. This paper proposes an approach where the MCI, ECI, WCI, SCI, and EV are displayed in pre-production. The small-scale design aspects of structural and resilient products and the life cycle stages of buildings must be addressed for architectural product design. This research proposes a methodology to increase the circularity of new designs from the earliest stages and significantly impact the carbon footprint in the construction sector.

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