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Circular Economy Maturity: How Circular are our Construction Products?

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Abstract. The concept of circular economy (CE) has gained momentum in the construction industry to mitigate the effects of climate change and decouple economic growth from environmental impact. There is a growing body of research related to the circularity of specific construction materials, as well as to the entire building. However, there remains a lack of understanding at the construction product level, and this lack of transparency prevents informed decisions when choosing which products to use in projects and how those products support the CE. A maturity assessment is one methodology that can provide insights for both product decisionmakers and product suppliers. Maturity assessments are a way to evaluate the level of development or progress towards a certain goal, whether at the organization, project, or product level. This paper proposes a conceptual framework to assess construction product system circularity maturity. Through a systematic literature review, the authors analyze existing CE maturity assessments and CE indicators for construction products to develop the framework. The functional unit is defined as a construction product, which is defined as an integrated system with multiple materials (i.e. a prefabricated wall system). This research finds that while there are many CE assessment frameworks for the construction sector, these must be translated into a construction product context, which requires a tailored subset of circularity indicators and maturity levels. The paper proposes construction product maturity levels ranging from "initial" to "optimizing" for key circularity indicators at the construction product level, including, material procurement, manufacturing, product use phase, and end-of-life. This conceptual framework serves as a practical tool for decisionmakers and as an educational tool for suppliers on how to support the CE in construction.

Keywords: Circular Economy, Maturity Assessment, Construction, Indicators, Construction Products

1. Introduction

Globally, the construction industry is responsible for 40% of generated waste, 40% of material resource use and 37% of energy-related carbon emissions [1]. In Europe, the construction

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industry accounts for 50% of raw materials extraction, 36% of generated solid waste, and 40% of greenhouse gas emissions [2]. This significant environmental impact is predicted to worsen without intervention, with 300 million new houses needed globally by 2030 [1]. To mitigate these effects, the concept of circular economy (CE) has gained popularity. CE can be defined as an economy that is "restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times" [4]. For the construction sector to transition to a CE, considerations on how to refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover building materials must be made [4].

Standardization is increasingly cited as enabling the abovementioned strategies to keep materials in use for as long as possible [6]. There are assessments at the material level, the building level, and the organization level (see Section 2.2). However, to date, there has been little standardization in the assessment of CE in the construction industry. There is an assessment gap at the construction product level, whose scope is neither as narrow as individual materials, nor as broad as a whole building. For construction product decisionmakers and construction product suppliers, this level of guidance and benchmarking is essential for continued improvement with respect to CE, and without it, industry is unable to fully understand how the use of each product impacts the overall circularity of a building. Furthermore, these assessments typically measure point-in-time performance, which does not provide clear guidance on a pathway to increased circularity. The main barrier this research aims to address is a lack of standardized implementation methods, which leads to industry fragmentation [9].

Maturity assessments are one method to standardize performance while also providing a clear pathway to improvement. Maturity assessments analyze the competency, capability, or level of sophistication of a selected domain based on a comprehensive set of criteria to assist organizations, products, or projects in maintaining competitive advantage [7].

Through a systematic literature review, this paper aims to answer the following research question:

How can a circular economy maturity assessment for construction products be conceptualized?

2. Background

2.1. Construction Products

This research focuses on the construction product functional unit of analysis. A construction product is defined as a complex system comprised of a set of subcomponents and materials. For example, a prefabricated wall system or packaged water heating unit qualify as a construction product. This definition excludes products that do not combine multiple materials or subcomponents. For example, a brick is a standalone product, however it is not a system of interdependent subcomponents, and therefore would not qualify as a construction product under the definition used in this paper. Construction products are also different from construction materials, which are typically just one uniform material such as drywall, wood, or tile.

2.2. Circular Economy in the Construction Industry

Although the level of awareness in the construction sector about CE is widespread [7], many barriers contribute to the delayed adoption of CE practices in the sector. As previously stated, the main barrier this research aims to address is a lack of implementation methods, which leads to industry fragmentation [9]. Currently, there is a lack of well-developed and standardized indicators [3], which is significant because standardized indicators can enable systematic adoption, decision-making, and reporting. Moreover, standard indicators for CE can enable the industry to track its maturity, (ie. how closed a loop is and what actions are necessary to fully close the loop) [10]. There is a clear need for standardized assessment using circularity indicators to track circularity in the construction sector. This research aims to address this gap through the development of a conceptual framework for a CE maturity assessment for construction products.

2.3. Existing Circular Economy Assessments in Construction

A review of existing CE assessments for construction yielded 14 assessments from academia and industry that are designed to assess various parts of CE, as illustrated in Appendix A. Six assessments were developed by industry and the remaining eight were developed by academia. Of the assessments developed by industry, two are geared towards the construction industry overall, while the remaining four are non-specific to industry but intended for product manufacturer use. The two assessments for the construction industry are designed to be used on a whole-building level and give results on an absolute impact scale for all systems in the building (EU Level(s) and Platform CB '23 Guide). The remaining industry assessments use the product as the unit of analysis and provide results or ratings based on a level scale or percentage scale. All industry assessments apart from Cradle-to-Cradle structure their assessments by lifecycle stage of the analysis unit. No industry assessments provide a maturity rating or maturity scale.

None of the academic assessments have products as their unit of analysis and focus instead on the construction sector or construction companies at the project or company level. Three assessments incorporate maturity ratings into their methodology; however, one relates only to leadership maturity, which was not relevant for the construction product. The academic assessments focus less on analysis unit lifecycle and more on CE impact categories and strategies. Rating output is much more varied for the academic assessments as well, ranging from an absolute score, weighted average, and benchmarking relative to a set landscape or average.

Overall, the assessments identified do not typically include detailed advice or guidance on how to improve circularity for the given analysis unit, i.e. building, construction site, or construction product. They also do not consider the nuances of construction product circularity specifically or provide standardized analysis categories and outputs. Given these findings, there is a gap in how construction products support CE and how circularity of construction products should be assessed over time.

Maturity assessments are used to measure the current maturity level of a certain organizational aspect, project, or product in a meaningful way, thereby "enabling stakeholders to clearly identify strengths and improvement points, and accordingly prioritize what to do in order to reach higher maturity levels" [11]. This concept was first popularized by Philip B. Crosby's Quality Management Maturity Grid (QMMG) [12], which laid out a five-level maturity map for the software industry. This paper uses the Capability Maturity Model (CMM) to assess maturity, which is similar in structure to the QMMG and is widely used across industries. The CMM was created to score potential software suppliers to US government grants on a maturity scale with five levels and assumes that companies with higher maturity will have a higher rate of success. Each level describes the typical supplier mode of operation at that maturity level. Figure 1 illustrates the CMM's five maturity levels with a brief description.

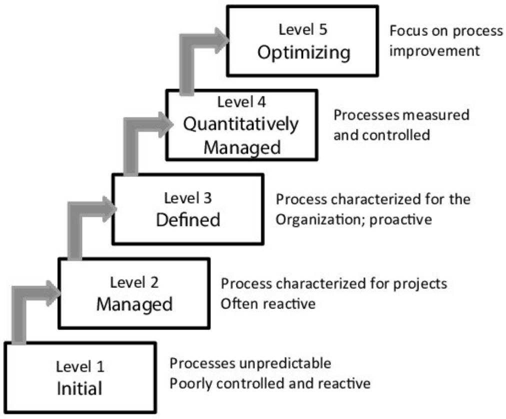

Figure 1: Summary Capability Maturity Model from Capability Maturity Model Integration [12]

3. Methodology

This paper develops a conceptual framework based on a systematic review process, following the three steps suggested by de Almeida Biochini et al. (2017) [13]: Data search, data analysis, and data reporting. This systematic review process provides the empirical evidence necessary to formulate the conceptual research and framework to answer the research question. Conceptual research relies on this empirical evidence to pull together a model that integrates findings related to the research question across literature [14].

(1) Data Search: To capture a full picture of potentially relevant research on circularity maturity assessments for construction products, the authors identified three main areas of interest, as reflected in Figure 2, which were subsequently translated into three search strings and corresponding inclusion criteria (Appendix B). Although the research focus is on maturity, the word "readiness" was also included in the search strings to broaden the search and ensure the inclusion of potentially relevant literature.

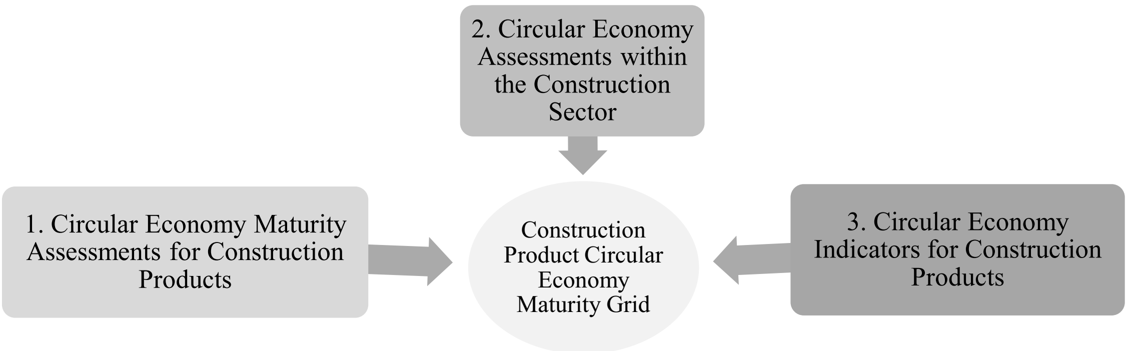

Figure 2: Research Areas for Systematic Literature Review

Concurrently, the authors undertook desk research, to collect non-academic industry literature relating to the three research areas. The authors also contacted design and construction CE professionals to source industry-focused materials connecting maturity assessments, construction products, and CE. This was done to enable triangulation by involving recent industry thinking into the review.

The result of this initial data collection process was a total of 172 articles from the search strings and an additional 12 academic articles and 20 non-academic articles from the industry outreach process. The content sourced from professional networks was first reviewed to determine a fit for the research, which resulted in most of the content being filtered out. All articles and documents were then reviewed and eliminated based on title, abstract, and full text. The same inclusion process was undertaken for the industry-sourced articles. Appendix B presents the final search strings and inclusion criteria used. By the end of the process, a total of 20 articles remained, comprising three, nine, and eight academic articles respectively for each search string and an additional 6 non-academic articles, as shown in Table 1.

Table 1: Summary of Documents included in Integrative Literature Review

	Search String 1 CE Product Maturity		**Search String 2 CE Assessments**		**Search String 3 CE Indicators**	
	Academic	Non-Academic	Academic	Non-Academic	Academic	Non-Academic
Starting Number from SCOPUS	16	-	32		124	
Documents from Outreach	0	-	1	3	1	3
Total	**16**	**-**	**33**	**3**	**125**	**3**
Filtered by Title & Abstract	3	-	14	3	55	3
Filtered by Full Text	3	-	9	3	8	3

(2) Data Analysis: Subsequently, these articles were coded into strategies, indicators, and maturity levels using Atlas.ti for data extraction and further analysis. Atlas.ti is a program developed by Scientific Software Development GmbH that supports qualitative research through coding, tagging, and annotating of text-based documents. The authors uploaded all documents that were deemed suitable for a full text review into Atlas.ti for coding. Strategy and indicator categories were developed deductively through the coding process, where when a topic such as "design for disassembly" was mentioned across at least two papers, codes would be established to connect those topics between papers. Maturity levels came from the CMM and maturity levels relating to indicators were also coded and later associated with the CMM maturity levels. In this process, the papers were further filtered to ensure that all papers and codes referred to the functional unit of construction products. Papers and codes related to business models, organizational operations, and entire buildings were eliminated. Ultimately, the authors identified 45 CE indicators and 18 CE strategies for construction product circularity. From there, the authors were able to extract this data into Microsoft Excel to analyze the outputs.

(3) Data Reporting: To structure the following report, the sourced data from coding was synthesized, contextualized, and integrated to compile the analysis in a structured way (Section 4). For the reporting, frequencies of indicators and strategies were tracked and similar and overlapping indicators and strategies were merged. To build the framework (Section 5) indicators and strategies were matched with one another, while most indicators were mapped below strategies. Indicators that could not be mapped below an existing strategy were grouped and four novel strategies were introduced (indicated with * in the framework, Appendix G).

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4. Literature Review Findings

4.1. Circular Economy Indicators in Construction

The review of academic and non-academic literature yielded 45 indicators that target construction products. 66% of which are mentioned only in academic articles, 23% are mentioned only in non-academic articles, and 11% appeared in both, illustrating the more detailed nature of the academic analysis of CE, whereas industry documents simplified and synthesized more categories. Figure 3 shows the most frequently occurring indicators across the literature. Five of these six indicators refer to material use and reuse in various ways, indicating the importance of closing the loop on material cycles, both through the incorporation of reused or recycled materials, and through the consideration of end-of-life scenarios in product design. “Renewable electric energy consumption,” which refers to the energy type used in manufacturing processes, is the indicator that does not fit this trend, and was only mentioned in academic literature. “Amount of secondary material – from reuse” was only identified in non-academic literature. All other indicators in Figure 3 were referenced by both types of literature.

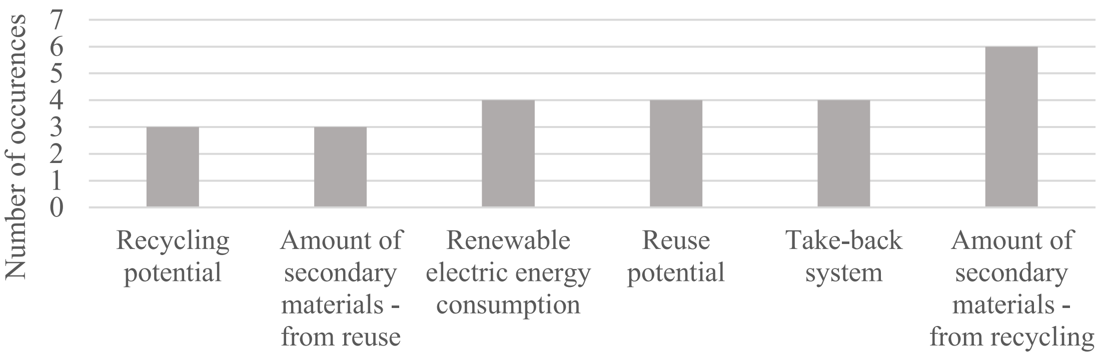

Figure 3: Number of occurrences for the most mentioned indicators

Figure 4 illustrates how the remaining indicators occur only once or twice, with 64% of the indicators mentioned once and 21% of the indicators mentioned twice. 51% of the total indicators are mentioned once and in academic papers only, whereas 13% of indicators are mentioned once and in non-academic papers only. The indicators mentioned once in academic literature correspond to the 68% of the total indicators mentioned in academic literature, while the indicators mentioned once in non-academic literature correspond to the 40% of the total indicators mentioned in non-academic literature. This diversity and expansiveness in CE indicators is indicative of the lack of standardization in CE assessment processes detailed in the background of this paper. Most of the indicators mentioned three, four or six times occur in both academic and non-academic. The complete list of indicators and their frequency in literature can be found in Appendix E.

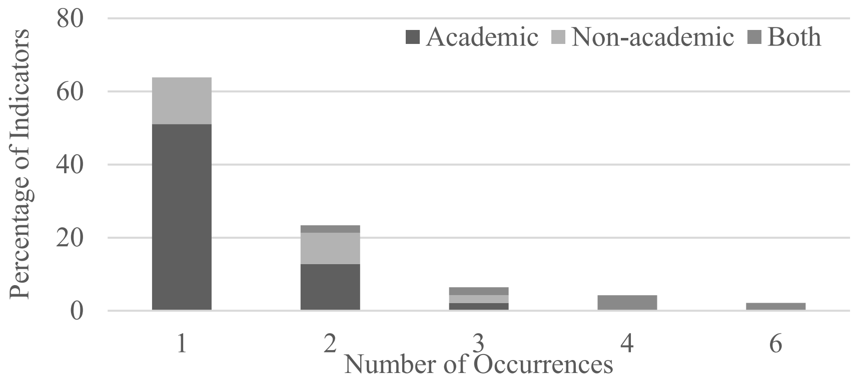

Figure 4: Percentage of Indicators by Frequency of Occurrence

Indicators mentioned multiple times often have different measurement methods, and not all indicators present a measurement method, which again illustrates the lack of standardization in assessing CE. 10 indicators (21%), mentioned in academic articles, remain undefined in their measurement methodology. Partly, this is due to the inaccessibility of background materials. A list of all indicators and their measurement methods can be found in Appendix C.

4.1.1. Circularity Topics Covered by Indicators. All indicators measure product circularity performance. 31% of the indicators measure materials' circularity performance, 15% measure value chain performance, followed by 10% that measure business model performance and 10% that measure manufacturing or production performance (Figure 5). The indicators measuring materials' performance are evenly distributed between academic articles and non-academic articles, which underlines the significance of materials in CE performance. Indicators targeting business model performance, value chain performance or production performance were mentioned in academic literature only. The indicators addressing business model performance and value chain performance followed qualitative methods, while those addressing material performance and production performance are both qualitative and quantitative.

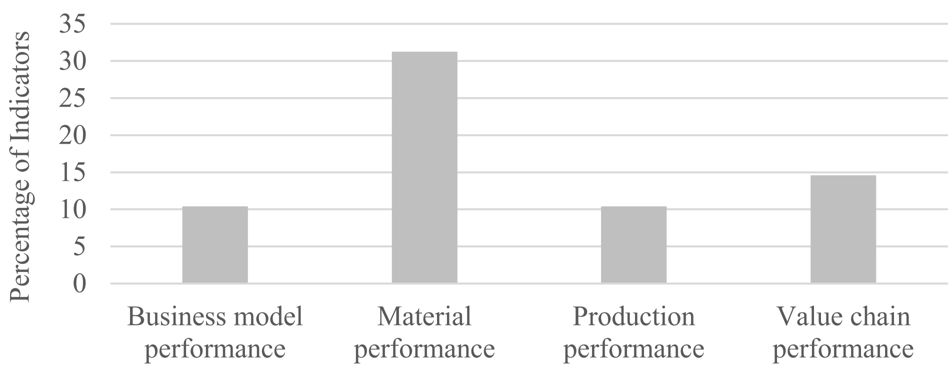

Figure 5: Percentage of indicators identified for each scope within product circularity performance

4.1.2 Type, Structure, Input, and Output. More than half (52%) of the methods are qualitative, 31% are quantitative, and 17% are semi-qualitative (i.e. maturity dimension is based on numeric ranges from a quantitative calculation), again underscoring the difficulty and lack of development in measuring CE in a standardized, quantitative manner. Almost all the qualitative methods were found in academic literature, while quantitative methods were found in non-academic literature. Few indicators (8%) are structured in the form of a questionnaire, the remainder is structured according to mathematical formulas (27%) or by maturity levels (60%). The questionnaires range typically from one to five questions referring to qualitative indicators, and the possible answers are usually yes or no. The methods structured as mathematical formulas are simple and consider input flow percentages such as material flows and return percentages of the measured target. Mathematically formulated indicators were mainly identified through non-academic articles. Most indicators are structured according to maturity levels and were identified in only two articles [15][16]. They are generally qualitative with few exceptions, and the outputs are points or weights. Only 8% of indicators consider inputs as absolute numerical values, and these are typically indicators associated with the longevity of products.

4.2. Circular Economy Strategies in Construction

The review extracted 14 CE strategies from literature and an additional four emerged from indicators that did not fall into the strategies identified in literature ("Design for Circularity," "Design for End-of-Use or End-of-Life," "Energy Use," and "Value Chain"). Almost all strategies were identified in both types of literature except for "Water and wastewater efficiency," which occurred once in academic literature perhaps due to its lack of connection to typical CE scope, and "Design for maintenance," which occurred five times in academic literature, perhaps due this being an emerging topic for CE performance. The distribution of the strategies by the number of occurrences in articles is shown in Figure 6. Two-thirds of the strategies occur between five and seven times in literature, indicating agreement across sources of strategy importance. The strategies that occur two times in both academic and non-academic articles are "Design with LCA" and "Non-toxic materials use". The most frequently mentioned strategies with eight occurrences are "Design for disassembly" and "Design for durability". The complete list of identified strategies and their definitions can be found in Appendix D.

With a few exceptions, the strategies target material use in products and product design. 33% of the strategies address the material composition of a product, 47% address product design and the remaining 20% of the strategies address water efficiency, use of renewable energy and traceability of products or materials. The strategies regarding materials, energy, and water inputs were categorized in the procurement and manufacturing stages of the product life cycle, whereas the strategies regarding product design were categorized in the use and end-of-life stages.

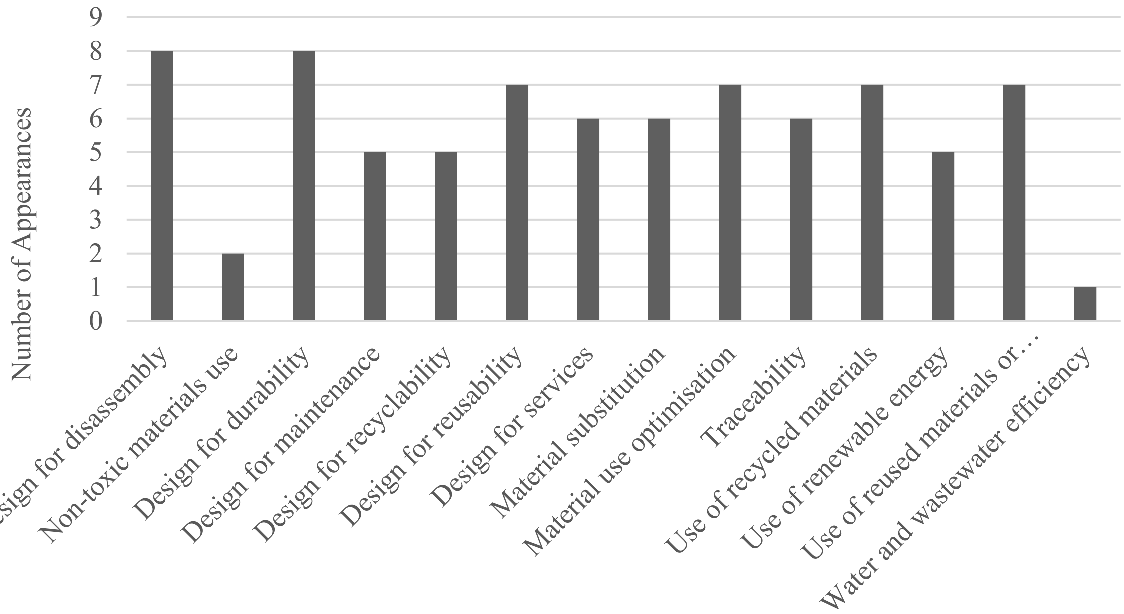

Figure 6: Strategy occurrence frequency from the literature review

4.3. Circular Economy Maturity Levels

The review identified 29 indicators with defined maturity levels. Only two articles presented maturity levels for these indicators, which were the LCA-C2C-PBSCI framework [15] and the Circularity Assessment Tool (CAT2022) for construction projects in developing economies [16]. The indicator maturity levels range from two to five, are mainly qualitative, and are evenly distributed between business performance, value chain performance and production performance scopes.

16 of the 31 indicators presented in the LCA-C2C-PBSCI framework were relevant and included maturity levels. The excluded indicators were discarded due to their economic, legislative or policy background, or were CE enablers at an organizational level rather than product level. The authors of the framework formulated the indicators based on systematic literature review and they recognize the need to further reiterate indicators' formulation by involving industry experts [15].

The other 13 indicators with maturity levels from the CAT2022 were selected for their connection to construction products. These indicators' maturity levels were identified through systematic literature review by the CAT2022 developers. If indicators' maturity levels were not defined by literature, the authors of CAT2022 proposed their own.

5. Conceptual Framework: Assessment of Circularity Maturity of Construction Products

The conceptual framework for a maturity assessment for the circularity of construction products mirrors the structure of other CE assessments through its structure based on typical lifecycle stages for construction products: material procurement, manufacturing, product use, and end-of-life. This was done to assist future users apply the framework according to the development stage that they are trying to assess, and hopefully enable the supply chain to evaluate the entire lifecycle circularity of the product. The framework includes 18 strategies are assigned according to these lifecycle stages and contain 45 indicators (Table 2). Most of the proposed strategies and indicators were mentioned in both academic and non-academic literature. Some indicators, however, only appeared in academic literature, while others appeared only in non-academic literature. Strategies and indicators that were referenced more than once were prioritized, assuming that the number of references corresponds to industry and academic agreement that such strategies and indicators are significant to CE performance.

Table 2: Simplified Overview of Stages, Strategies, and Indicators

Life Cycle Stage (4)	Strategy (18)	Indicator (45)
Material Procurement	**Non-toxic Material Use**	Material Toxicology
		Hazardous Waste
	Material Substitution	Amount of Non-renewable or Unsustainably Produced Renewable Materials
		Amount of sustainably produced renewable materials
		Use of secondary materials
	Use of Recycled Materials	Amount of Secondary Materials from Recycling
		Quality of Materials from Recycling
	Use of Reused Materials	Amount of Secondary Materials from Reuse
	Value Chain*	Material Provenience
		Procurement Routes
		Actors Involved in Partnerships
		Collaborations Extensiveness
Manufacturing	**Material Use Optimization**	Material Consumption
		Solid Waste Generated
		Raw Materials Saved
	Energy Use*	Renewable Electric Energy Consumption
		Electric Energy Consumption
	Water and Wastewater Efficiency	Water Stewardship
		Water Consumption
	Traceability	Material Passport
		Availability of a Complete Bill of Solid Waste for Manufacturing
		Availability of Complete BoM & Product Substances
		Material Database
Product Use	**Design for Maintenance**	Repairability Potential
		Design for Maintenance
		Product Lifetime Extension Initiatives
	Design for Durability	Product Service Life Potential
		Material Longevity
	Design for Services	After Sales Service
		Product-As-A-Service

End-of-Life	**Design for Disassembly**	Design for Disassembly
		Connection Accessibility
		Connection Type
	Design for Circularity*	CE Strategies Incorporated
		Design in Accordance with CE Principles
	Design for Recyclability	Recycling Potential
	Design for Reusability	Reuse Potential
	Design for End-of-Use/ End-of-Life*	Realistic End-of-life Scenarios Developed
		Quantity of Materials Going to Landfill
		Quantity of Materials for Energy Generation
		Recovery Potential
		Upcycling Potential
		Design for Nutrient Cycling System
		Waste Collection
		Take-Back System

* Strategies emerged from indicators

To measure circularity maturity, the framework is further expanded by maturity levels for each indicator as defined by the literature review and the CMM. This was done to standardize the assessment process and illustrate potential further development pathways towards CE performance. In its current form, the conceptual framework only reflects the maturity levels sourced from literature (Appendix G, Appendix H), which were found for 29 of the 45 indicators. The remaining 16 indicators lack the definition of maturity levels completely, and 21 of the 29 indicators with specified maturity levels are incomplete, with less than five levels specified. In these cases, the authors assigned the three to four identified maturity levels to the five-level CMM. For example, an indicator with three maturity levels would be assigned at Level 1, Level 3, and Level 5 to represent the lowest, middle, and highest maturity levels identified by the literature. Indicators with four maturity levels were assigned to levels 1, 2, 4, and 5.

Additionally, some maturity levels sourced from literature do not strictly follow the CMM maturity definitions. Some indicators, such as "end-of-life scenarios developed," are simply a yes or no answer, which does not give any indication of maturity or implementation guidance. These binary maturity levels need further adaptation and integration into the CMM framework. Other maturity levels are presented as a percentage of adoption (i.e. "Amount of sustainably produced renewable materials"), which does not explicitly refer to the maturity level definitions. These percentages can, however, be seen as a proxy for the level of adoption and process integration, and the overall trajectory represented by the identified maturity indicators follow the progression set forth by the CMM. For example, if a product uses 100% sustainably produced renewable materials, this indicates the highest level of maturity ("optimizing") where the company has established sophisticated means and methods to use renewable materials.

5.1. Implications for Theory
The conceptual framework was created using insights from academic and non-academic literature. Through merging and synchronization, the framework has been streamlined and simplified. There is emphasis on closing the material loop throughout the framework, with a

significant number of indicators and strategies focusing on "design for X" (maintenance, durability, services, disassembly, circularity, recyclability, reusability), at end-of-life and the use of secondary materials. This trend intuitively makes sense given the material intensiveness of construction products and the need to connect supply and demand to achieve circularity. However, it is worth noting that the mapping of strategies to lifecycles stages is not always mutually exclusive. For example, strategies made in the design phase do not show their effect until the use phase and at the end-of-life, where maintenance, repair, service, disassembly, circulation, recycling, and reuse take place. If the conceptual framework was formulated to target specific stakeholders involved in different lifecycle stages, it might create additional value to group the strategies differently and in a more detailed way, for instance, grouping all strategies that relate to an architect's responsibility together.

It is also worth highlighting two strategies that came up indirectly in the literature but were not mentioned explicitly: Standardization and Modularization. Both are integrated into strategies such as use of reused materials, use of recycled materials, traceability, and all "design for X" strategies (maintenance, durability, services, disassembly, circularity, recyclability, reusability), which comprises a significant portion of the conceptual framework. Standardization and modularization might serve as necessary enablers of the framework and deserve further investigation.

Overall, there is an adequate amount of maturity literature and assessments targeting whole buildings and organizations. Maturity assessments for construction products are not sufficiently developed, thus this paper aimed at closing this gap. The conceptual framework does not only present a first step to conceptualizing circularity maturity on a construction product level, but also showcases the need to investigate the integration of circularity across various functional units, such as the organizational-, building-, and construction product level.

5.2. Implications for Industry

With the aim to create an applicable tool for industry, this conceptual framework provides a structured approach for practitioners to identify the most relevant areas for construction products to comply with the dominant definition of circularity. It will also provide an outlook and guidance on how products should mature to support circularity. This conceptual framework is thus a useful support for product manufacturers on the supply side, but also for the demand side, for developers, architects, and contractors to assess the circularity of the products they source and use.

There are several implications for industry in terms of the strategies and indicators. Since a portion of the indicators were sourced from academic literature, there is a need to test and revise those indicators based on lessons learned in the field. Qualitative indicators from academia might also need quantitative metrics assigned to them for industry use. There are also several indicators, such as the use of renewable energy in manufacturing, that appear in academic literature only, and there might be a need to explore why industry did not address those topics. Additionally, standardization and modularization do not only have theoretical but also practical implications, as both strategies have the potential to unlock additional circularity, especially in combination with practices such as industrialized and offsite construction.

To evaluate the comprehensiveness of the conceptual framework, we use the hierarchy framework by Saidini (2017) [10] which tests the following five levels (Figure 7): 1) connection to sustainable development pillars, 2) intuitiveness of the user interface, 3) adaptability and flexibility of the framework, 4) how integrated and operational, and 5) how systemic the framework is.

Applying the hierarchy of requirements to our conceptual framework makes clear, that this research paper fulfills levels 1 and 5 of the pyramid (marked in green): It reflects a clear connection to sustainable development pillars and mostly recognizes the systemic character of a construction product by considering all life-stages, and the different looping strategies (from recycling to reuse). The three levels in between, however, are still in need of further development and will be further evaluated in the following section (Section 6).

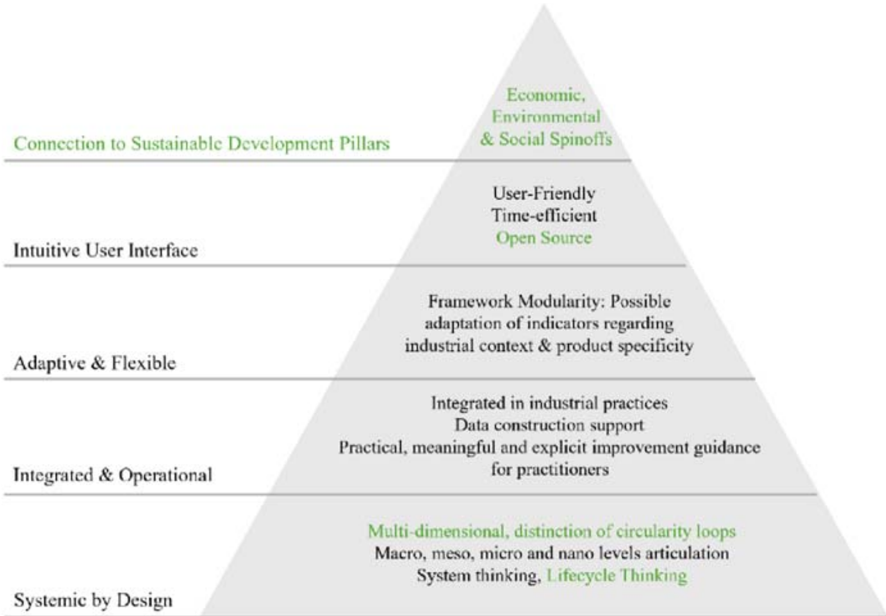

Figure 7: Hierarchy of Requirements for Product Circularity Measurement Framework, adapted from [10].

6. Conclusions, Limitations, and Further Research

The authors of this paper answered the research question ("How can a circular economy maturity assessment for construction products be conceptualized?") through a systematic literature review that resulted in a conceptual maturity assessment framework. As mentioned, the conceptual framework presents a first development step. The framework does not include economic or business model considerations, as this was not the primary focus. Nevertheless, those are important aspects to product design and development that need investigation in future research. These aspects might also be important if this framework is integrated into other functional unit assessments (ie. At the whole building or organization level). Furthermore, because this field of CE is relatively new, the landscape of CE maturity assessments, strategies, and indicators is constantly evolving. Thus, the review might need an update as literature and practical implementation progress. The literature review was also restricted to the construction sector, however, indicators from other sectors applied to the product level could be relevant to consider. Future iterations of the framework might also consider how standardization and modularity influence construction product circularity.

Finally, after testing the conceptual framework against the product circularity measurement framework, the need for several levels of additional development became visible:

(2) Intuitiveness of the User Interface: The conceptual framework needs adaptation to the five levels as defined in the CMM (Figure 7) to increase usability and evaluation of overall circularity maturity. The maturity levels must also be completed and reworked to ensure each indicator has 5 maturity levels defined with adequate description to guide users to act. To ensure comparability, the framework needs to be expanded with a clear and transparent evaluation scheme that connects the maturity levels of the indicators with the final output. This output must also be defined based on a roll-up of the results from each lifecycle phase. This will, in turn, give users of the assessment an idea of where the product is located on the maturity scale and how the construction product must change to increase circular economy maturity.

(3) Adaptability and Flexibility: Since the framework was conceptualized for the construction sector, there is no need for modularization of the assessment based on sector/industry. However, depending on the construction product, the assessment might need to be adapted to the specific context, so that, e.g., volumetric systems are evaluated differently than heating, ventilation, and air conditioning, and systems. This can be done by weighing more relevant areas of the assessment more heavily than less relevant areas. The conceptual framework could also benefit from the inclusion of key stakeholders in each lifecycle stage, strategy, and indicator. In this way, the stakeholders (architects, developers, product manufacturers, demolishers, etc.) immediately know where they can have the biggest possible impact on a construction product, or whom to involve in the conversation when making construction products more circular.

(4) Integrated and Operational: To integrate this assessment framework into industrial practices, this framework necessitates feedback from industry through interviews, testing, and workshops so that the best ways to assess products can be identified. Additionally, case studies of multiple different construction products would yield insights into how well the framework reflects the real circularity of construction products, and how well the framework guides practitioners in creating increasingly circular construction products.

The authors hope that this conceptual framework will serve as a useful step in standardizing how industry and academia measure construction product circularity. The proposed conceptual framework is a novel contribution to CE assessment due to its unit of analysis and summarizes CE literature across academia and industry to create a holistic view of construction product circularity. Future developments will ensure that the content is useful to practitioners who would like to integrate the maturity assessment into their workflows.

Appendix A: Review of Existing CE Assessments in the AEC Sector

	Doc. 4	Doc. 5	Doc. 6	Doc. 9	Doc. 11	Doc. 12	Doc. 15
Assessment Name	RISE Framework	LCA-C2C-PBSCI	Circularity Assessment Tool (CAT2022)	Evolutionary Leadership Model for CE in Construction Companies	Circular Economy Framework for Construction	Level(s)	Circular Economy Measurement Scale for Building Industry
Assessment Developer	Ecole Polytechnique Federale de Lausanne	University of Hong Kong, City University of Hong Kong	Nazarbayev University, Ara Institute of Canterbury	Bydgoszcz University of Science and Technology, University of Jaén	University of London	EU	University of Jaen, University of Granada, University of Science and Technology in Bydgoszcz
Sector	Construction and demolition	Construction	Construction projects (developing economies)	Construction management	Construction	Construction	Construction companies
Audience	Construction companies	Environmental analysts	Construction company employees	Construction managers and leaders	General construction sector	Buidling owners	Construction professionals
Assessment type	Framework	Quantitative and qualitative analysis	Maturity Assessment	Leadership maturity assessment	Quantitative analysis based on LCA, LCC, and waste indexing calculator	Quantitative analysis	Weighting assessment with max weighting of 15% per category
Assessment scope	Waste management practices and larger waste	Whole building or building systems	Whole building	Management and culture through building lifecycle	5 phases of construction	Building lifecycle	Design through construction

	management ecosystem						
# of categories	4	7	5	None	5	5	7
Category Details	Research and realize, Implement, Support, Enable	Environmental, Technical, Social, Innovation, Economic, Legislative, Business	Waste transformation, material use, maximizing the lifespan of a building, circular business models and strategies, construction, energy and environment		Production, Consumption/ Operation, Waste Management, Recovery/ Circularity, and Innovation	material volume, embodied carbon, cost per lifecycle stage	Resource Management: 3Rs (Reduce, Reuse, and Recycle), Efficient Management of Energy, Water, and Materials; Environmental impact: Emissions and Waste generated; and, Indicator of transition to the CE
Maturity levels	None	5	3	3	None	None	None
Maturity level details		Indicator-specific	Legislative, Market, and Technological maturity	Evolution, euphoria, harmony			
Rating output	None; positioning within CE landscape for all companies contributing to CE	Systemic circularity recommendations	Qualitative fulfillment score above or below average	Ranking of leadership in one of the three maturity levels	Absolute impact	Absolute impact, optional reporting for bill of materials, lifecycle scenarios, reliability, and LCA	Weighted score out of 100%

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^ Maturity dimensions ^

	Doc. 16	**Doc.17**	**Doc. 21**	**Doc. 22**	**Doc. 23**	**Doc. 24**	**Doc. 25**
Assessment Name	New Material Flow Model for Building Circularity	Social Impact Assessment for Circular Construction	Platform CB´23 Guide	Cradle to Cradle	Material Circularity Index (MCI)	Circular Economy Toolkit (CET)	Circular Economy Indicator Prototype (CEIP)
Assessment Developer	Eindhovn University of Technology	Ghent University Department of Engineering	Central Government Real Estate Agency and Rijkswaterstaat , supported by De Bouwcampus and NEN	Cradle to Cradle Products Innovation Institute	Ellen MacArthur Foundation	Accenture; Cambridge University	Griffiths and Cayzer
Sector	AEC Sector	Construction	AEC sector	Consumer products, including construction materials	Non-specific	Non-specific	Non-specific
Audience	AEC Sector	Construction professionals	AEC sector	Consumers/ customers	Product manufacturers	Product manufacturers, consumers, and retailers	Product manufacturers
Assessment type	Quantitative analysis	Weighting assessment with quantitative indicators	Weighting assessment with quantitative indicators	Benchmarking assessment	Material modelling tool	Circularity calculator	Product performance evaluation questionnaire
Assessment scope	Whole building	Whole building	Whole building	Product-level	Product to company level	Product-level	Product-level

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# of categories	4 building layers and 4 building circularity cycles	4 stakeholder categories with 13 total impact categories	4 categories with 18 subcategories	5	8	7 categories with 33 questions total	5 categories with 15 questions total
Category Details	Building, system, material, component; biological, technical, economic, and social cycles	stakeholders - worker, local community, society, consumer; impact categories - (see paper)	quantity of material used, quantity of materials available for next cycle, quantity of materials lost, influence on quality of the environment	material health, material reutilization, renewable energy & carbon management, water stewardship, and social fairness.	Feedstock: % reused, % recycled, % recycling efficiency; Destination after use: % reused, % recycled, % recycling efficiency; Lifespan; Functional Units	Categories relate to lifecycle stages	design or redesign; manufacturing; commercialisation; usage; and end-of-life
Maturity levels	None	None	None	None	None	None, however results to note improvement potential	None
Maturity level details							
Rating output	Absolute impact	Weighted score out of 100	Absolute score	Bronze, Silver, Gold Platinum	Weighted score from 0-1	3 levels of improvement potential in each category	% score with radar diagram for each lifecycle stage
					^ Product-focused assessments ^		

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Appendix B: Search String and Inclusion Criteria SCOPUS

Research Area	Search String	Inclusion Criteria
1	CE Maturity Assessments for Construction Products: “circular economy” AND “construction” OR “building” AND “maturity” OR “readiness” AND “product”	The included articles must relate to the construction sector, construction products, and present CE maturity or readiness assessment frameworks with CE indicators.
2	CE Maturity for Construction Sector: “circular economy” AND “construction” OR “building” AND “maturity” OR “readiness”	The included articles must relate to the construction sector and present CE maturity or readiness assessment frameworks.
3	CE Indicators for Construction Products: “circular economy” AND “construction” OR “building” AND “indicator” OR “dimension” OR “KPI” OR “index”	The included articles must relate to the construction sector and present CE indicators at the construction product functional level.

Appendix C: Indicator Characteristics Description

Scope	Business model performance	In CE, adopting certain typologies of business models enhance circular performance. In these cases, products and business models are designed in accordance. Thus, although the indicators refer to products, some of them measure the business performance as well.
	Material performance	Materials are part of products and their choice and circular performance play a fundamental role in products' performance.
	Product performance	Some circular implementations focus directly on products, for example circular product design strategies.
	Production performance	Circular strategies can be applied at the production level, for example by adopting technologies that reduce material losses.
	Value chain performance	In order to enhance products' circularity, value chains might need to be entirely redesigned in order for example to develop a take-back system for the product.
Type	Academic	Indicators developed in academy through systematic literature review.
	Non-academic	Indicators developed in industry-by-industry experts.
	Qualitative	The indicators' method is qualitative.
	Quantitative	The indicators' method is quantitative.
Structure	1 - 5 questions	The assessment is performed through one or multiple questions.
	Mathematical formula	The indicator presents a mathematical formula.
	Maturity levels	The indicator is structured in maturity levels.
Input	% flow	The indicator requires in input a flow percentage, usually material, electric energy, or water.
	Multiple choice	The indicator requires the choice of an answer.
	Numerical value	The indicator requires in input a numerical value.
Output	%	The output of the indicator is a percentage.
	Numerical value	The output of the indicator is a numerical value.
	Points	The indicator assigns different points to different answers or values.
	Weights	The indicator assigns different weights to different answers or values.
	Yes/No answer	The output of the indicator is a Yes/No answer.
Level	Micro	The intended application of the indicator is at product level.
	Meso	The intended application of the indicator is at industrial park level.
	Macro	The intended application is at regional or national level.

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Appendix D: Strategies and Definitions

Design for disassembly	Construction products are manufactured in a way to facilitate easy access to components. This strategy aims to enable reuse, recycling, and ease of maintenance.
Design for durability	This strategy involves utilising high-quality, durable components and materials with a focus on extending products lifespan and reduce the need for replacements. Repairability of construction products is also essential to this approach.
Design for maintenance	Products are manufactured in a way to facilitate easy access to components. This strategy aims to maximize the use of the product by extending its lifespan.
Design for recyclability	The strategy ensures that materials can be efficiently reclaimed and recycled at the end of their life cycle. This is achieved by incorporating materials easy to recycle such as wood, metal, bricks, concrete, and sandstone. An example are modular elements that simplify deconstruction, and the materials can be recycled up to 90%.
Design for reusability	This strategy ensures that materials can be efficiently reclaimed and reused at the end of their life cycle. It is achieved by incorporating materials and components that maintain their quality and functionality. An example are prefabricated elements that ensure ease of reclamation, reusability, and recyclability.
Design for services	The strategy implies that a product manufacturer is obligated to maintain the product condition during its lifetime. In the service contract concept, a material or product passport is created, and product performance is tracked all the time. Servicing is applied when the material or product starts to lose its condition, not when the situation has reached a critical limit. Services apply also at the EoL of the product, through take-back-systems for example.
Material use optimisation	The strategy involves reducing both the quantity and diversity of materials used. It is important to reduce material input, maintaining the functionality of the product without compromising its quality and minimise material losses during product manufacturing and build construction. An example are prefabricated products that contributes to minimise material lose on construction sites and reduce waste by 65-80%.
Material substitution	Material substitution involves the replacement of traditional materials with alternatives that offer specific advantages. The material substitution is based on criteria such as locality, renewability, environmental impact, quality, durability, ease of assembly/disassembly, Cradle to Cradle (C2C) certification, purity, maintenance-free properties, and the ability to retain or increase value over time. Examples include replacing concrete and metal constructions with wood.
Non-toxic Materials use	This strategy involves the use of materials and substances that are not toxic to human health or the environment. In construction products, prioritizing non-toxic substances means selecting materials that are free from hazardous chemicals or pollutants. This approach aims to create a safer and healthier built environment for occupants, construction workers, and surrounding ecosystems.
Traceability	This strategy involves the creation of databases and tools to document materials, components and products characteristics, usage history and conditions across their life cycle. This includes the implementation of material passports, products labels, etc. Standardisation and central registration of these documents in dedicated platforms are essential practices.
Use of recycled materials	This strategy involves increasing the recycled content of construction products. The provenience of materials can be from construction and demolition activities or from the manufacturing process itself. The aim is to slow and close resource loops by incorporating materials that have undergone recycling processes.
Use of renewable energy	This strategy encourages the transition to renewable energy to completely avoid the use of fossil fuels. During production, energy efficiency-driven practices should be implemented to reduce energy consumption. The use of renewable energy sources, such as solar panels, geothermal, wind, and biomass energy are a priority.
Use of reused materials	This strategy involves increasing the reused content of construction products. The provenience of materials, components or products can be from construction and demolition

	activities or from the manufacturing process itself. The aim is to slow and close resource loops.
Water and wastewater efficiency	The focus is on employing water and wastewater efficient techniques and technologies to minimize water consumption. This includes practices such as recycling water and monitoring water consume.

Appendix E: Frequency of Indicator Occurrence

	D33: Alejandrino et al., 2022	D37: Antwi-Afari et al., 2022	D17: Bilal et al., 2020	D15: Cottafava et al., 2021	D13: Heisel et al., 2020	D21: Jiménez-Rivero et al., 2016	D2: Tokazhanov et al., 2022	D:75 CIRCUIT	D82: EU Study (2022)	D:81 Platform CB'23	# Occurrences
Actors involved in partnerships											1
After sales service											1
Amount of wastewater											1
Availability of complete bill of solid waste for the manufacturing											1
Availability of complete BoM and substances for the product											1
CE strategies incorporated											1
Collaborations extensiveness											1
Design for nutrient cycling system											1
Design in accordance with CE principles											1
DfD - Connection Accessibility											1
DfD - Connection Type											1
Material database											1
Material longevity											1
Material provenience											1
Material toxicology											1
Procurement routes											1
Product as a service											1
Product lifetime extension initiatives											1
Quality of materials from recycling											1
Raw materials saved											1
Recovery potential											1
Solid waste generated											1
Upcycling potential											1
Waste collection											1
Amount of non-renewables or unsustainably produced renewables											1
Amount of primary materials											1
Hazardous waste											1
Quantity of materials for energy generation											1
Quantity of materials going to landfill											1
Repairability potential											1
Design for maintenance											2
Electric energy consumption (kWh)											2
Material consumption											2
Material passport											2
Water consumption											2
Water stewardship											2
Realistic end-of-life scenarios developed											2
Amount of secondary materials											2
Amount of sustainably produced renewable materials											2
Design for Disassembly											2
Product service life potential											2
Recycling potential											3
Amount of secondary materials - from reuse											3
Renewable electric energy consumption											4
Reuse potential											4
Take-back system											4
Amount of secondary materials - from recycling											6

Appendix F: Discarded Indicators

	D33: Alejandrino et al., 2022	D37: Antwi-Afari et al., 2022	D17: Bilal et al., 2020	D46: Chen et al., 2022	D15: Cottafava et al., 2021	D43: Dräger et al., 2022	D7: Eberhardt et al., 2022	D44: Gomes et al., 2022	D1: Gorecki, 2019	D13: Heisel et al., 2020	D21: Jiménez-Rivero et al.,	D28: Medina et al., 2021	D42: Poolsawad et al., 2023	D39: Ruokamo et al., 2023	D2: Tokazhanov et al., 2022		D:75 CIRCUIT	D82: EU Study (2023)	D77: Level(s)	D:81 Platform CB' 23	D45	# Appearances
Building Circularity Indicator																						4
Building Circularity Indicator (Simplified)																						1
Building Circularity Indicator (Verberne)																						1
Carbon emission generated (t CO2eq)																						1
CAS																						1
Circular Cost Analysis																						1
Circular Indicator																						2
Circular Indicator (construction)																						1
Circular Indicator (EoL)																						1
Circular Indicator (use)																						1
Complement of the Energy Use Intensity Index (%)																						1
Complex Cost Method																						1
Comprehensive disposal rate of dangerous waste																						1
Comprehensive utilisation rate of industrial solid waste																						1
Cost comparison between routes																						1
Dematerialisation																						1
Design 4 Adaptability																						1
Design 4 Disassembly (building)																						1
Design for Deconstruction Strategies (%)																						1
Effluents discharged (m^3)																						1
Embodied Carbon Calculator																						1
Energy-saving amount																						1
Fuel consumption (m^3)																						1
GHG emissions processign and transport																						1
Indoor air quality																						1
Initiatives for sustainable production (%)																						1
Net Annual Saving																						1
Passign rate of used materials back into the SC																						1
Payback Period																						1
Predictive Building Circularity Indicator																						4
Predictive Building Circularity Indicator (simplified version)																						1
Product Recycled																						1
Rate of carbon footprint																						1
Rate of waste emissons																						1
Recycled Content (2)																						1
Recycled solid waste (%)																						1
Recycling rate of industrial solid waste																						1
Residual value (all materials in building)																						1
Residual value (product)																						1
Residual value per unit at end-of-life																						1
Reuse Potential																						1
Reused Content																						1
Reused Content (2)																						1
Reusing rate of products/materials																						1
System Circularity Indicator (Verberne)																						4
Time outside of thermal comfort range																						1
Total amount of COD emissions																						1
Total amount of industrial solid waste disposal																						1
Total amount of SO2 emissions																						1
Total Annual Cost																						1
Total Material Arisings (whole life)																						1
Wastage Rate																						1

Appendix G: Conceptual Framework

Life Cycle Stage	Strategy	Indicator (Source)	Measure-ment	Maturity Levels				
				Level 1	Level 2	Level 3	Level 4	Level 5
Material Procure-ment	**Non-toxic Material Use** [16]	**Material Toxicology [15]**	4 levels	No knowledge on the toxicology of the materials in the product	The toxicology of some of the materials is known and communicated but not substituted		The toxicology of some of the materials of the product is known and substituted	The toxicology of the material or product is known and well-communicated. Harmful materials are also substituted for alternative ones
		Hazardous Waste [2]	% by mass					
	Material Substitution [15][3][17][2][18]	**Amount of Non-renewable or Unsustainably Produced Renewable Materials** [18][18]	% by mass	-	-	-	-	-
		Amount of sustainably produced renewable materials [18][21][18][21]	% by mass	1-5%	6-10%	11-15%	16-20%	20% or more
		Use of secondary materials [2][18]	% of total material use	-	-	-	-	-
	Use of Recycled Materials [16][3][18][22][23][2][19]	**Amount of Secondary Materials from Recycling [17][15]**	5 levels	No recycled materials are used in the new product	The product is made of > 5% of recycled materials	The product is made of > 20% of recycled materials	The product is made of > 50% of recycled materials	The product is made of > 80% of recycled materials

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	[18][21][18] [15][17][18][18][21]						
	Quality of Materials from Recycling [16][16]	3 levels	No external certification / recycling standards are not followed		No external certification / recycling standards are followed		Recycled waste quality is certified by qualified party (e.g. Global Recycled Standard, ASTM, etc.) / recycling standards are followed.
Use of Reused Materials [2][3][16][18] [19] [22][23]	**Amount of Secondary Materials from Reuse** [2][18][21]	% by mass	-	-	-	-	-
Value Chain*	**Material Provenience** [15]	3 levels	Local materials are barely considered		Local materials are considered but they are compared with others and the least costly is chosen		Local materials are used and chosen when available
	Procurement Routes [15]	3 levels	Tracing of material sources are difficult and hence, any unsustainability within the procurement route is unknown		Improved procurement routes where materials sources are known but the effects of their processes are barely considered in decision making		Enhanced CE procurement routes for intelligent resource pooling is upheld

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		Actors Involved in Partnerships [15]	3 levels	No partnership of any sort is established		Partnerships are established only at the recycling stages of the product system		Partnership is established between the processing, manufacturing, and reprocessing firms / department of a company to enhance the circularity of the product
		Collaborations Extensiveness [15]	3 levels	The business model adopted for the product is such that it can only work within the culture of the manufactured company's settings		The business model adopted for the product is such that it can work within only the manufactured country's economic and market settings		The business model adopted for the product is such that it can work within several different economic and market settings
Manufactur -ing	**Material Use Optimization** [2][3][16][17] [18][19] [22]	**Material Consumption** [15][16]	5 levels	The amount (mass) of materials used is reduced compared to similar projects within last 5 years: 1-5%	6-10%	11-15%	16-20%	20% or more
		Solid Waste Generated [17]	*	-	-	-	-	-
		Raw Materials Saved [24]	*	-	-	-	-	-

	Energy Use*	**Renewable Electric Energy Consumption** [15][17][25]	4 levels (%)	0-25% of the total consumed energy	26-50% of the total consumed energy		51-75% of the total consumed energy	76-100% of the total consumed energy
		Electric Energy Consumption [17][25]	4 levels	No efforts	Low efforts		Moderate efforts	High efforts
	Water and Wastewater Efficiency [16]	**Water Stewardship** [15][25]	4 levels	Water from the production system is not treated	Water from the production system is partially treated and let flow into nearby waterbodies		Water from the production system is treated and clean, let flow into water streams	Water from the production system is treated and clean even for drinking
		Water Consumption [17][25]	4 levels	No efforts	Low efforts		Moderate efforts	High efforts
	Traceability [15][16][17][18] [25] [26]	**Material Passport** [15][16]	4 levels	No product / material passport is available	Product / material passport is available only at the design/production stage and not linked to the product throughout its life cycle		Product / material passport for key materials or components of the product is available	Product / material passport that could enable the traceability of materials for reuse is available
		Availability of a Complete Bill of Solid Waste for Manufacturing [25]	*	-	-	-	-	-
		Availability of Complete BoM & Substances for the Product [25]	*	-	-	-	-	-

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		Material Database [15]	4 levels	No technologies are used for data linking	Enabling technologies are used to feed some generic products to a database for general processing		Enabling technologies are used to feed only key aspect of the product throughout its lifecycle for recycling at EoL	Enabling technologies are used to link data of materials / components of the product in real-time to feed the online system of the material banks and provide reliable data on imports and recycling
Product Use Phase	**Design for Maintenance** [3][16][17][18][26]	**Repairability Potential [**21]	% by mass					
		Design for Maintenance [15**]**[16]	3 levels	No contract		Maintenance during certain time period		Maintenance during whole lifetime
		Product Lifetime Extension Initiatives [17]	*	-	-	-	-	-
	Design for Durability [2][3][16][17][18][19][22][27]	**Product Service Life Potential** [2][21]	years					
		Material Longevity [16]	4 levels	no priority	low priority	moderate priority	high priority	one of the top priorities.
	Design for Services [2][3][16][17][19] [27]	**After Sales Service [**15**]**	5 levels	No after sale services of any form is considered	After sales services are not considered during design stage, but customers can return only parts of the product which are not working	After sales services are not considered during design stage, but only considered for marketing purposes	Aftersales services such as pre-installation, warranties, training, online support, upgrades etc. are available and integrated into the products	No business model is developed for the products and no collaborations could be seen between firms at the recycling stage

					within a fixed period of time after purchase		development and plan	
		Product-As-A-Service [15**]**	3 levels	No product as a service business model is considered for the product		Product as a service is not thought of at the design stage and only adopted during sales / marketing. Hence, trade-offs of adopting a particular product as a service approach may be unknown		The product is designed around its service base (i.e., user, results, or product oriented) to ensure key proof and implementation
End-of-Life	**Design for Disassembly** [2][3][17][18] [19] [26][27]	**Design for Disassembly** [2][15]	3 levels	Uncompensated transformations i.e., products which cannot be reused again because of how they were produced in the first place		Difficult transformations i.e., products may be able to be transformed, but requires more energy or means of transformation are not known yet		Compensated product transformations i.e., designing products for easy disassembly and easy return to their natural state
		Connection Accessibility [15]	4 levels	Not accessible irreparable damage to objects	Accessibility with additional actions with reparable damage		Accessibility with additional actions that do not cause damage	Freely accessible
		Connection Type [15]	5 levels	Hard chemical connection (e.g., glue, pitch, weld, cement bond,	Soft chemical connection (e.g., kit, foam etc.)	Direct integral connection (e.g., pin, nail etc.)	Connection with added elements (e.g., ferry,	Dry connections (e.g., click, magnetic, Velcro etc.)

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			chemical anchors etc.)			screw, bolt, and nut etc.)	
Design for Circularity*	**CE Strategies Incorporated** [17]	*	-	-	-	-	-
	Design in Accordance with CE Principles [25]	*	-	-	-	-	-
Design for Recyclability [2][3][16][17][18]	**Recycling Potential** [18][21][26]	% by mass	-	-	-	-	-
Design for Reusability [2][3][16][18][19] [22][27]	**Reuse Potential** [15][17][18][23]	3 levels	The company with the licensed product only has the right to reuse their materials at EoL		Reuse of materials from other licensed product have little obligation to the licensed base product company		Feasible material collateral effects which could allow reuse of the materials / components of the product in other products other than the base company should be well documented
Design for End-of-Use or End-of-Life*	**Realistic End-of-life Scenarios Developed** [2][15]	yes/no	No				Yes
	Quantity of Materials Going to Landfill [18]	% by mass	-	-	-	-	-
	Quantity of Materials for Energy Generation [18]	% by mass	-	-	-	-	-
	Recovery Potential [16]	5 levels	0-20%	21-40%	41-60%	61-80%;	81-100%.

Upcycling Potential [15]	5 levels	All the materials or components of the product will be downcycled at EoL	> 5% of the materials or components of the product will be upcycled at EoL	> 20% of the materials or components of the product will be upcycled at EoL	> 50% of the materials or components of the product will be upcycled at EoL	> 80% of the materials or components of the product will be upcycled at EoL
Design for Nutrient Cycling System [15]	3 levels	No separation of nutrients is considered except the usual sorting out of waste / impurities		Nutrient cycling is not considered in the design, but considered during the recycling process to separate biological from technical nutrients		Nutrient cycling system is integrated in the designing of the products to ensure easy separation of biological and technical nutrients of the materials / components of the product at EoL
Waste Collection [15]	4 levels	No technology whatsoever is used in the collection of waste	Only minimal technologies such as QR codes for informal waste collection and payments are employed		Advanced and digitalized waste collection is available for the sorting or collection of the materials / components of the product only	Advanced and digitalized waste collection system is available for the materials or components of the product at its EoL e.g., GPS for waste trucks tracking, QR codes for payment of waste collectors, and automated sorting out of waste

	Take-Back System [2][15][17][21]	3 levels	No take back system is available for the product	A take-back system is available, but not a full integrated EoL logistics which could get all recyclable materials / components back to the material processing firms	A take-back system comprising of EoL logistics and recycling routes of the materials / components of the building is available

*** Strategies emerged from indicators**

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Appendix H: Indicators and Maturity Levels for Conceptual Framework

Indicator (Source)	Maturity Levels				
	Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Material Toxicology	No knowledge on the toxicology of the materials in the product	The toxicology of some of the materials is known and communicated but not substituted		The toxicology of some of the materials of the product is known and substituted	The toxicology of the material or product is known and well-communicated. Harmful materials are also substituted for alternative ones
Hazardous Waste	-	-	-	-	-
Amount of Non-renewable or Unsustainably Produced Renewable Materials	-	-	-	-	-
Amount of sustainably produced renewable materials	1-5%	6-10%	11-15%	16-20%	20% or more
Use of secondary materials	-	-	-	-	-
Amount of Secondary Materials from Recycling	No recycled materials are used in the new product	The product is made of > 5% of recycled materials	The product is made of > 20% of recycled materials	The product is made of > 50% of recycled materials	The product is made of > 80% of recycled materials
Quality of Materials from Recycling	No external certification / recycling standards are not followed	-	No external certification / recycling standards are followed	-	Recycled waste quality is certified by qualified party (e.g. Global Recycled Standard, ASTM, etc.) / recycling standards are followed.
Amount of Secondary Materials from Reuse	-	-	-	-	-

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Material Provenience	Local materials are barely considered	-	Local materials are considered but they are compared with others and the least costly is chosen	-	Local materials are used and chosen when available
Procurement Routes	Tracing of material sources are difficult and hence, any unsustainability within the procurement route is unknown	-	Improved procurement routes where materials sources are known but the effects of their processes are barely considered in decision making	-	Enhanced CE procurement routes for intelligent resource pooling is upheld
Actors Involved in Partnerships	No partnership of any sort is established	-	Partnerships are established only at the recycling stages of the product system	-	Partnership is established between the processing, manufacturing, and reprocessing firms / department of a company to enhance the circularity of the product
Collaborations Extensiveness	The business model adopted for the product is such that it can only work within the culture of the manufactured company's settings	-	The business model adopted for the product is such that it can work within only the manufactured country's economic and market settings	-	The business model adopted for the product is such that it can work within several different economic and market settings
Material Consumption	The amount (mass) of materials used is reduced compared to similar projects within last 5 years: 1-5%	6-10%	11-15%	16-20%	20% or more
Solid Waste Generated	-	-	-	-	-
Raw Materials Saved	-	-	-	-	-
Renewable Electric Energy Consumption	0-25% of the total consumed energy	26-50% of the total consumed energy	-	51-75% of the total consumed energy	76-100% of the total consumed energy
Electric Energy Consumption	No efforts	Low efforts	-	Moderate efforts	High efforts

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Water Stewardship	Water from the production system is not treated	Water from the production system is partially treated and let flow into nearby waterbodies	-	Water from the production system is treated and clean, let flow into water streams	Water from the production system is treated and clean even for drinking
Water Consumption	No efforts	Low efforts	-	Moderate efforts	High efforts
Material Passport	No product / material passport is available	Product / material passport is available only at the design/production stage and not linked to the product throughout its life cycle	-	Product / material passport for key materials or components of the product is available	Product / material passport that could enable the traceability of materials for reuse is available
Availability of a Complete Bill of Solid Waste for Manufacturing	-	-	-	-	
Availability of Complete BoM & Substances for the Product	-	-	-	-	
Material Database	No technologies are used for data linking	Enabling technologies are used to feed some generic products to a database for general processing		Enabling technologies are used to feed only key aspect of the product throughout its lifecycle for recycling at EoL	Enabling technologies are used to link data of materials / components of the product in real-time to feed the online system of the material banks and provide reliable data on imports and recycling
Repairability Potential	-	-	-	-	-
Design for Maintenance	No contract		Maintenance during certain time period		Maintenance during whole lifetime
Product Lifetime Extension Initiatives	-	-	-	-	-
Product Service Life Potential	-	-	-	-	-

Material Longevity	no priority	low priority	moderate priority	high priority	one of the top priorities.
After Sales Service	No after sale services of any form is considered	After sales services are not considered during design stage, but customers can return only parts of the product which are not working within a fixed period of time after purchase	After sales services are not considered during design stage, but only considered for marketing purposes	Aftersales services such as pre-installation, warranties, training, online support, upgrades etc. are available and integrated into the products development and plan	No business model is developed for the products and no collaborations could be seen between firms at the recycling stage
Product-As-A-Service	No product as a service business model is considered for the product	-	Product as a service is not thought of at the design stage and only adopted during sales / marketing. Hence, trade-offs of adopting a particular product as a service approach may be unknown	-	The product is designed around its service base (i.e., user, results, or product oriented) to ensure key proof and implementation
Design for Disassembly	Uncompensated transformations i.e., products which cannot be reused again because of how they were produced in the first place	-	Difficult transformations i.e., products may be able to be transformed, but requires more energy or means of transformation are not known yet	-	Compensated product transformations i.e., designing products for easy disassembly and easy return to their natural state
Connection Accessibility	Not accessible irreparable damage to objects	Accessibility with additional actions with reparable damage	-	Accessibility with additional actions that do not cause damage	Freely accessible
Connection Type	Hard chemical connection (e.g., glue, pitch, weld, cement bond, chemical anchors etc.)	Soft chemical connection (e.g., kit, foam etc.)	Direct integral connection (e.g., pin, nail etc.)	Connection with added elements (e.g., ferry, screw, bolt, and nut etc.)	Dry connections (e.g., click, magnetic, Velcro etc.)
CE Strategies Incorporated	-	-	-	-	-

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Design in Accordance with CE Principles	-	-	-	-	-
*					
Recycling Potential	-	-	-	-	-
Reuse Potential	The company with the licensed product only has the right to reuse their materials at EoL		Reuse of materials from other licensed product have little obligation to the licensed base product company		Feasible material collateral effects which could allow reuse of the materials / components of the product in other products other than the base company should be well documented
Realistic End-of-life Scenarios Developed	No	-	-	-	Yes
Quantity of Materials Going to Landfill	-	-	-	-	-
Quantity of Materials for Energy Generation	-	-	-	-	-
Recovery Potential	0-20%	21-40%	41-60%	61-80%;	81-100%.
Upcycling Potential	All the materials or components of the product will be downcycled at EoL	> 5% of the materials or components of the product will be upcycled at EoL	> 20% of the materials or components of the product will be upcycled at EoL	> 50% of the materials or components of the product will be upcycled at EoL	> 80% of the materials or components of the product will be upcycled at EoL
Design for Nutrient Cycling System	No separation of nutrients is considered except the usual sorting out of waste / impurities	-	Nutrient cycling is not considered in the design, but considered during the recycling process to separate biological from technical nutrients	-	Nutrient cycling system is integrated in the designing of the products to ensure easy separation of biological and technical nutrients of the materials / components of the product at EoL

Waste Collection	No technology whatsoever is used in the collection of waste	Only minimal technologies such as QR codes for informal waste collection and payments are employed	-	Advanced and digitalized waste collection is available for the sorting or collection of the materials / components of the product only	Advanced and digitalized waste collection system is available for the materials or components of the product at its EoL e.g., GPS for waste trucks tracking, QR codes for payment of waste collectors, and automated sorting out of waste
Take-Back System	No take back system is available for the product	-	A take-back system is available, but not a full integrated EoL logistics which could get all recyclable materials / components back to the material processing firms	-	A take-back system comprising of EoL logistics and recycling routes of the materials / components of the building is available

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