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MEASURING CIRCULARITY FROM BUILDINGS TO NEIGHBOURHOODS

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Abstract. The circular economy (CE) aims to eliminate the concept of pollution and waste generation, maintain the integrity of the product over several use cycles, and focus on closing material and energy loops. Circularity metrics are relevant for monitoring, reporting and communicating CE implementation progress. Applied to buildings, these metrics deliver structured assessments through standardized indicators, which establish a common language among the agents involved, help implement strategies to assess the circular potential of technical options. Studies dealing with circularity metrics for buildings are still scarce and somewhat variable within an overall common framework. Applications to neighbourhoods are even more incipient. This study applied selected metrics to two building cases with different constructive characteristics, to improve the understanding on how information on circularity is conveyed. The selected metrics highlighted the circularity challenges for the two building designs. However, such metrics disregard the environmental impacts required to induce circular flows and loop closure. It is herein proposed that such metrics are paired with environmental performance profiles produced by e.g., life cycle assessments (LCA). The concept of "nested indicators" could be applied to neighbourhood and city scales by referring to the LCA concept of functional equivalency as the "relevance" weighting criterion.

Keywords: Circular building, indicator, metric, circularity, circular economy.

1. Introduction

The circular economy (CE) aims to eliminate the concept of pollution and waste generation so that material circulates in the economy perpetually, that is, it seeks to maintain the integrity of the product over several cycles of use and focus on the closure of material and energy cycles [1]. This helps not only in the security of material supply and sustainable consumption, but also in improving environmental and socioeconomic analyses [2].

This new economic-environmental paradigm has gained relevance in recent years [3]. Indeed, our systematic literature review (see Appendix A) confirmed that this is a trending research topic, and this will continue or intensify. It also showed that this discussion is notably Euro-centred: no article in the final sample focused on e.g., Brazil or South America. In 2015, the European Commission defined a first Action Plan that allocated more than ten billion euros, between 2016 and 2020, for the transition from the current linear model to a circular model [1]. In 2019, the "European Green Deal" was established to address the climate and environmental challenges in Europe and to separate economic growth from the use of resources. In 2020, the European Commission adopted a new action plan and the proposal for a new regulation of sustainable batteries. Finally, in 2021, the Global Alliance on Circular Economy and Resource Efficiency was launched, and several initiatives were adopted in the action plan [4]. All these measures aim to make the economy of Europe and the world adjust to protect the environment, enhancing competitiveness and circularity, and thus achieving a green future [4]. Despite the debate that has taken place over the last decade, the concept of CE is still being discussed, and remains somewhat confusing, as shown by the over 114 definitions found in a previous review [5].

CE metrics are relevant, as they serve to identify areas in which countries need to focus their efforts to boost their performance in the circular economy [6]. In addition, the EC's comprehensive performance assessment metrics and methods are critical to defining public policy. Therefore, metrics serve to monitor, report and communicate progress towards the implementation of the circular economy [7].

The EC's concepts apply to companies in all sectors [8], and therefore also to the construction industry [9, 10]. The construction sector plays a critical but also a strategic role in achieving global environmental, social and economic goals. The Paris Agreement provides for the global decarbonization of the construction sector by 2050, intending to avoid the impact of a 2 °C rise in temperature [4]. From the perspective of circularity, the sector is one of the largest consumers of resources and natural capital, with about 40 % of resource consumption and waste generation [11, 12]. Furthermore, the end-of-life destination of buildings is usually demolition and, at best, recycling the waste generated. Thus, applying CE principles to buildings allows for considerable benefits to be gained by keeping assets in circulation rather than starting a cycle from new resource extraction. For this reason, the European Commission has identified "construction and buildings" as one of the seven main product value chains in its Action Plan for the Circular Economy [13].

In this context, circularity metrics for buildings are a topic of great interest, as they allow managers to identify and control the application of CE practices in the different phases of construction projects, and with what intensity [14]. Furthermore, they implement a common language among all involved actors, which helps to assess the circularity of buildings and monitor the progress of a project according to standardized indicators [15]. Indicators and metrics are also needed to implement strategies to assess the circular potential of the technical options that can be adopted and their efficiency [2]. As circular buildings gain in reputation, the valuation model can be used as a benchmark to compare the performance of buildings based on CE [15]. The lack of indicators and metrics has prevented policymakers and stakeholders from setting verifiable recovery targets for new construction and renovation [16]. By providing a meaningful measure of key elements of circular buildings, metrics form the heart of assessment methodologies, and should objectively assess and measure the building's development towards CE and help to improve the performance of buildings, from the initial stages to the end of their useful life, closing the materials cycle [15].

Currently, the most recognized and globally adopted indicator for the built environment is the Material Circularity Indicator (MCI), also known as the theoretical indicator of circularity of the product. The MCI tool is part of a broader "Circular Indicators Project" developed by The Ellen MacArthur Foundation and ANSYS Granta [17] and evaluates the input type, output type and the technical useful life of the materials [17]. In Verberne's adaptation [18], MCI is the basis for subsequent nested calculations at product (PCI), system (SCI) and building (BCI) levels. PCI incorporates product disassembly possibilities and can be referred to as the practical "product circularity indicator".

The System Circularity Indicator (SCI) assesses the circularity of products assembled in a system based on their mass contribution, broken down into the Brand's six building layers [19]. Lastly, the Building Circularity Indicator (BCI) assesses the set of systems considering a factor for the level of importance each of them has [18]. In the past few years, some BCI improvements have been proposed. Van Vliet [20] proposed to omit the building layers in the PCI calculation; Alba Concepts developed a new BCI based on product, element (instead of "system") and building [21]; and van Schaik [22] slightly modified it to apply to building foundations.

Some buildings circularity assessments combine metrics on reversibility and durability [2], the Building Circularity Indicator (BCI), the new Predictive BCI (Predictive BCI – PBCI) [21] and the Circular Economy Key Performance Indicators of the construction industry (KPIs) to determine to what extent a company implements CE in the different construction projects phases [23]. An expanded list of indicators extracted from the systematic literature review (SLR) can be found in Table 3 (Appendix A). Despite this, there is still a lack of clear definitions to link what characterizes the circularity of buildings to circular construction technologies and to adequate indicators to measure the circular economy [2] and circularity indicators for the built environment as a whole [3]. Hence, two main research questions emerged to be addressed in this paper:

- "How clear is the message regarding environmental assessment of the materials flows involved? Which kind of information do the studied metrics convey? Do they stand-alone or should be combined to other to communicate environmental performance of buildings and the built environment?", and
- "Can they be aggregated to address larger scales?".

For this purpose, selected metrics were applied to two case studies of different material and constructive characteristics.

2. Method

The methodological approach consisted of

- a Systematic Literature Review (RSL) to identify existing metrics, as well as their structure, content, components and where they were applied; and
- the application of metrics which stood out in the SLR to two case studies; followed by an analysis of the information conveyed and its potential combination to other environmental assessment outcomes.

Material Circularity Indicator (MCI), Product Circularity Indicator (PCI), System Circularity Indicator (SCI) and Building Circularity Indicator (BCI) were hence selected for application in this study.

Two residential buildings were selected as case studies. The first case is a six-story wood-framed building, and the second building is a thirteen-story reinforced concrete structure with masonry walls. For our exploratory purposes, only the structure and envelope components were considered in the calculations. The

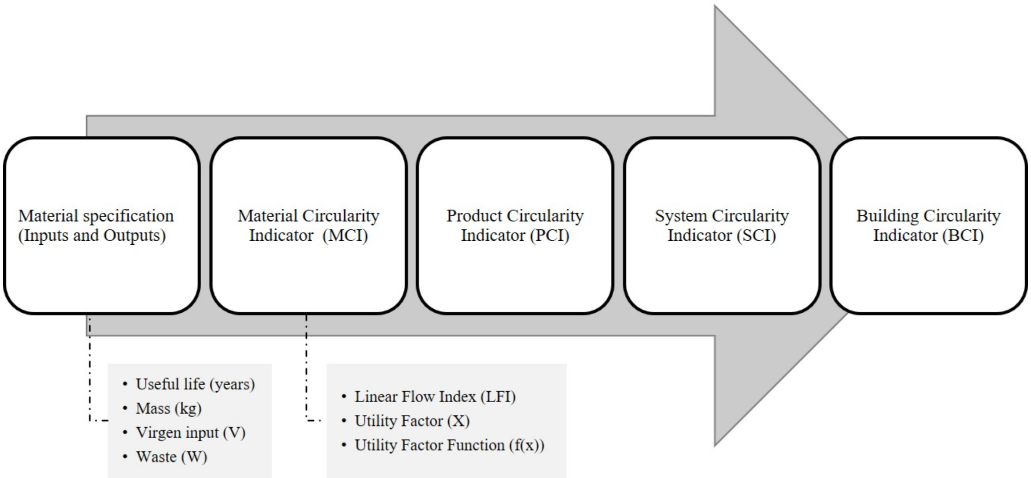

Figure 1. Circularity metrics calculation flow.

building lifespan was 50 years, and the materials service life followed the Brazilian performance standard NBR 15575:2013 [24], and the waste rate was based on Brazilian Association for Recycling of Civil Construction Waste data.

2.1. Circularity indicator calculation method

The calculations followed the steps in Figure 1, once the products and materials used in each case study, their service life, and mass (kg), virgin input (V) and waste (W) involved were determined. Calculations begin by the Linear Flow Index (LFI), the Utility Factor (X) and the Utility Factor Function, F(X). LFI and F(X) are next used to compute the Material Circularity Indicator (MCI). The MCI and the Determining Factor of Disassembly (DDF) – that is: the amount of material assembled into systems that can be disassembled – feed calculation of the Product Circularity Indicator (PCI). The MCI is also used to obtain the theoretical value for the System Circularity Indicator (SCI (t)), by considering the products' contribution to the complete system, in mass. Then, the practical value for the SCI (SCI (p)) is calculated using the PCI and the product mass. Finally, the factors accounting for system dependency/level of importance (LK_k) and SCI (theoretical and practical) are considered, to calculate the theoretical (BCI (t)) and the practical (BCI (p)) values of the Building Circularity Indicator.

To compute "X", the buildings were decomposed into six systems (layers). Table 1 is used to compute the systems lifetime (Lsys) and level of importance, a weighting factor between 0 and 1. PCI calculations need the Determining Factor of Disassembly (DDF) nof each product. For that we used Durmisevic's [25] classification into seven variables (Functional separation; Functional dependence, Technical life cycle / coordination; Geometry of product edge; Standardisation of product edge; Type of connections; Accessibility to fixings), and assigned values from zero (worst) to 1 (best) impact on disassembly. Finally, to compute the BCI (t) and BCI (p), the level of importance (LK_k) of each system is computed (Table 1).

System	Lifetime [years]	Level of importance
Site	500	0.1
Structure	100	0.2
Skin	20	0.7
Services	15	0.8
Space Plan	10	0.9
Stuff	5	1.0

Table 1. Lifetime (Lsys) in years and level of importance of each system, based on the Brand's six building layers [19].

3. Results and Discussion

The linear flow index (LFI) offers immediate insight on the potential circularity challenges – i.e., flows with LFI closer to 0, like asphalt or acrylic waterproofing, extruded polystyrene board from external walls or slabs – and accomplishments, i.e., LFI closer to 1, such as steel from window frames and softwood plywood from external walls. The MCI shows how linear a material flow is, also from 0 (linear) to 1 (circular). In Figure 1 and Figure 2, the more the red shape is open, the closer to theoretical circularity is achieved. The wood-framed building has visibly more circularity questions solved than the masonry building, particularly regarding envelope components (Figure 3).

Still, apart from the wood elements themselves, the building's structure uses several items that stress its circularity performance. The lowest result was presented by the floor mortar cement (0.95), which had the shortest estimated lifetime (13 years) within this group of systems (100 years). Materials with longer service life positively affect the utility factor (X) if it suits the system in which the material is inserted. As pointed out by Verberne [18], the ideal

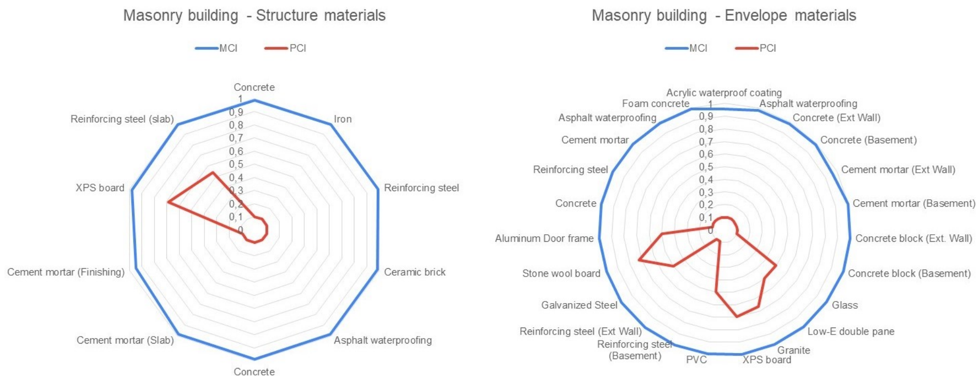

Figure 2. MCI and PCI results – Concrete-framed & masonry building.

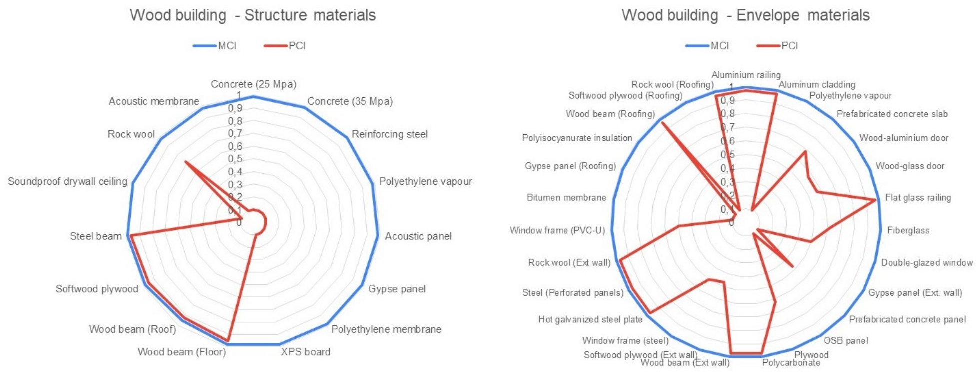

Figure 3. MCI and PCI results – Wood-framed building.

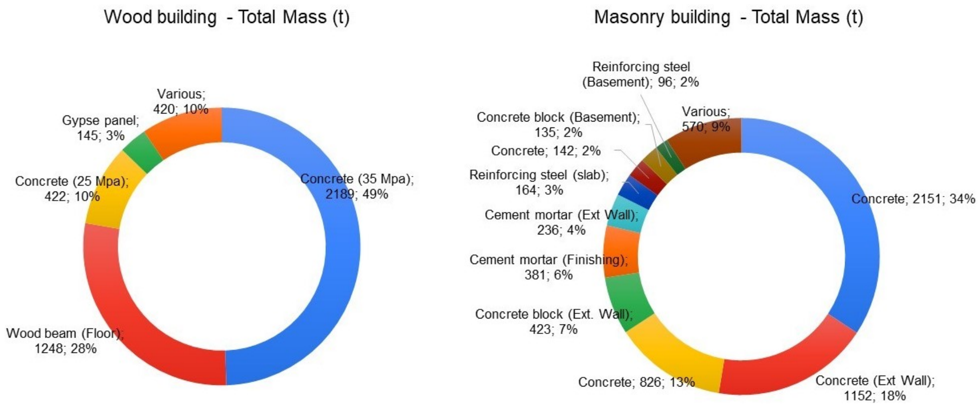

Figure 4. Mass distribution [t] for values the cases studied.

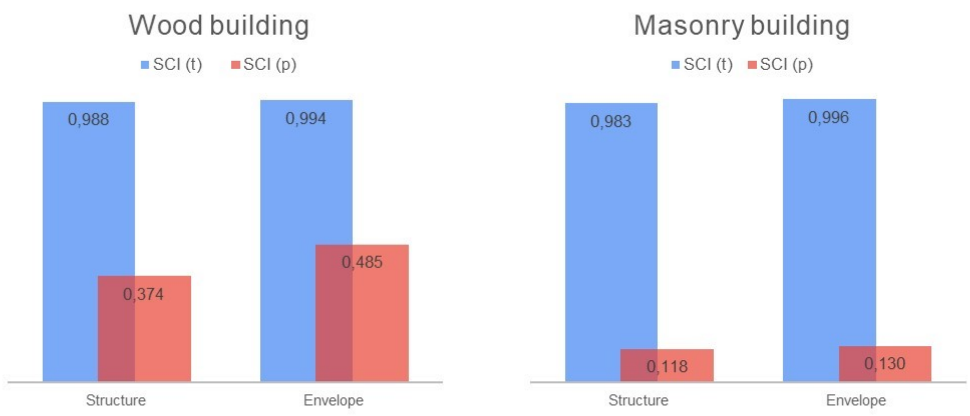

Figure 5. Mass distribution [t] for values the cases studied.

Total	Wood-framed building	Concrete-framed & masonry building
BCI (t)	0.992	0.993
BCI (p)	0.461	0.127
Disassembly potential loss	0,531	0,866

Table 2. BCI results for the cases studied.

balance between service life and reusable materials is still subject for future research.

As a product that is going to be recycled does not, by definition, mean that it remains functional and can be safely broken down, the PCI highlights those components with the greatest disassembly potential. The masonry building shows lower indicators, but still with some items that can be disaggregated from the system, mainly envelope components (e.g., stone wool board, XPS board and granite). The wood-framed building showed improved results for disassembly, both for structure (e.g., steel or wood beams) and envelope (e.g., aluminium or steel elements, rockwool and prefabricated concrete slab) components.

The SCI aggregates the MCI and PCI results, normalizing and weighting the results from the mass, to generate a single value that demonstrates a system's circularity potential. Thus, products with the largest mass contribution influence the SCI results, according to their circularity potential determined in the previous steps (MCI used in the calculation of SCI (t); PCI used in the calculation of SCI (p)). The distance between the theoretical and the practical values indicate the potential "circularity losses" created due to limited disassembly.

Even in the wood-framed building, concrete use is substantial and responds for about 62 % of the structure mass, followed by the wood beams (floor) summing up to 30 % (Figure 4). Whilst the theoretical SCI value represents a circularity stand close to ideal (MCI $\sim$1), the practical SCI value is cut by almost half due to the influence of the concrete's PCI, which is close to zero, despite the good performance of wood elements (PCI $\sim$1) (Figure 5).

The mass of the envelope elements is concentrated by the gypsum panel (34 %) and wood beams (14 %). In the concrete-framed and masonry building, concrete holds 81 % and 44 % of the structure and envelope mass, respectively (Figure 4). Concrete blocks account for 16 % of the envelope's mass. Such products have low PCI results and therefore push the practical SCI towards linearity (Figure 5).

As the BCI (Table 2) factors in the systems' importance, those with shorter lifetimes – in the case, the envelope products – weight and (negatively) influence the most. Though both buildings have similar BCI (t), the disassembly potential loss (BCI (t) – BCI (p)) is higher for the concrete-framed building (0.866) and reflects the circularity opportunities designed out for the wood-framed building.

4. Conclusions

This study's outcome made clear that – though very intuitive and crucial for societal development peacemaking with its supporting environment – circularity metrics do not convey complete environmental information. By highlighting the renewability, potential re-application and recoverability of materials, they emphasize the use phase, and do not usually consider, for example, the actual impacts to keep materials and energy in the loop. The environmental impacts / costs to reinject potentially returnable material in the industrial loops and transition to circular economy are not accounted for. Increased material and energy circularity might even enlarge life cycle impacts until the full circular economy status is reached. So, it is herein proposed that such metrics are paired with environmental performance profiles produced by e.g., life cycle assessments.

As to the second research question posed, the concept of "nested indicators" seems to also be smoothly applicable to larger – e.g., neighbourhood and city – scales. A "relevance" weighting criterion is needed and is herein proposed to refer to the life cycle assessment concept of functional equivalency. Procedures for applying LCA to neighbourhoods have already been investigated in a few studies, including by some of these authors, and can provide the basis for such extended examination.

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A. Appendix – Table 3

Identifier	Authors	Title	Year	Indicador	Description	Case study
1	Verberne, J.J.H.	Building circularity indicators an approach for measuring circularity of a building	2016	Material Circularity Indicator (MCI)	The indicator evaluates input type, output type and technical useful life of materials. Currently, the most recognized and adopted indicator globally.	Two fictitious buildings (circular and not circular).
				Product Circularity Indicator (PCI)	The indicator incorporates product disassembly possibilities and can be referred to as the practical indicator of product circularity.	
				System Circularity Indicator (SCI)	The indicator evaluates the circularity of products in a system based on their weight and making a separation based on the six layers of the system.	
				Building Circularity Indicator (BCI)	The BCI evaluation model is composed of the Material Circularity Indicator (MCI), Product Circularity Indicator (PCI), System Circularity Indicator(SCI) and, finally, the Construction Circularity Indicator (BCI). BCI evaluates the separate systems as a whole with a factor of importance level of each system.	

Identifier	Authors	Title	Year	Indicador	Description	Case study
2	Gerard Finch, Guy Marriage, Antony Pelosi, Morten Gjerde	Building envelope systems for the circular economy; Evaluation parameters, current performance and key challenges	2021	Building Circularity Indicator (BCI)	-	New Zealand Construction.
				Circular Economy Indicator (CEIP)	-	
				Circular Economy Index (CEI)	-	
				Circularity Performance Indicator (CPI)	-	
				Eco-efficient Value Ratio (EVR)	-	
				End-of-Life Recycling Rates (EoL-RRs)	-	
				Material Circularity Indicator (MCI)	-	
				Product-Level Circularity Metric (PCM)	-	
				Reuse Potential Indicator (RPI)	-	
				Resource Duration Indicator (RDI)	-	
				Recycling Indices (RIs)	-	

Identifier	Authors	Title	Year	Indicador	Description	Case study
3	Felix Heisel, Sabine Rau-Oberhube	Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster	2020	Material Circularity Indicators (MCI)	Described above.	Urban Mining Unit and Recycling (UMAR) designed and built by Werner Sobek with Dirk E. Hebel and Felix Heisel at NEST (Next Evolution of Sustainable Technologies) of Empa Dübendorf (Federal Laboratories Swiss Materials Science Technology) in Switzerland.
				Madaster Circularity Indicator	The indicator registers stocks and material flows within a circular built environment.	
				Level(s)	-	
				Circularity Indicator (CI)	The indicator evaluates each building's circularity level between 0 and 100 percent based on users.	
				CI Construction	The indicator represents the ratio of virgin materials to recycled, reused or rapidly renewable materials. It is balanced by efficiency indicators of the process of recycling prior to the construction phase and the mass of waste generated during the recycling process.	
				CI Use	The indicator represents the life expectancy of the products used, compared to the average life of products in status quo. The actual score is determined by calculating the weighted average of all products of the various layers of the system.	
				CI End of life	The indicator represents the relationship between waste and reusable and/or recyclable materials generated when a building is renovated or demolished.	
4	Kimberlee Marcellus-Zamora, Patricia Gallagher, Sabrina Spatari	Can Public Construction and Demolition Data Describe Trends in Building Material Recycling? Observations From Philadelphia	2020	Material Fraction (MF)	Individual fractions of material waste.	Municipal waste management in different economies, including the Pacific Islands and Asian Cities.
				Material Diverted (MD)	Overall deviation rate of total materials.	

Identifier	Authors	Title	Year	Indicador	Description	Case study
5	Dario Cottafava, Michiel Ritzen	Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects	2021	Material Circularity Indicator (MCI)	Described above.	Analyzed the component of buildings in Singapore. Study of case in 8 places.
				Circularity Indicators (CI)	-	
				System Circularity Indicator (SCI)	Described above	
				Environmental Product Performance Indicators (EPI)	They aim to indicate the macro, meso or micro characteristics of a product.	
				Indicador de Potencial de Recursos (RPI)	The index measures the intrinsic value of reusing a material, taking into account state of the art recycling technologies.	
				Product Circularity Indicator (PCI)	-	
				Linear Flow Index (LFI)	-	
				Indicador de Longevidade (LI)	The index indicates the total time the material is held in a product/service system.	
				Building Circularity Indicator (BCI)	Described above.	
				New Predictive BCI (PBCI)	Based on three levels, namely a Product Circularity Index (PCI), an Element Circularity Index (ECI) and a Building Circularity Index (BCI).	
6	Catherine De Wolf, Endrit Hoxha, Corentin Fivet	Comparison of environmental assessment methods when reusing building components: A case study	2020	Cut-off method	The index is used to evaluate the recycling of construction products.	Commercial building with reused components. Kopfbau Halle Building 118, which is designed with elements recovered from demolition sites.
				Recycling rate	The index encourages recycling at the end-of-life stage.	
				Ability to be dismantled or remounted	The index measures the repair and transformation required during assembly and disassembly, reuse can only happen if components can be disassembled and reassembled.	
				End-of-Life (EoL)	-	

Identifier	Authors	Title	Year	Indicador	Description	Case study
7	Muhammad Bilal, Khurram Iqbal Ahmad Khan, Muhammad Jamaluddin Thaheem, Abdur Rehman Nasir	Current state and barriers to the circular economy in the building sector: Towards a mitigation framework	2020	Comprehensive utilization rate of industrial solid waste	-	-
				Recycling rate of reclaimed wastewater	-	
				Total amount of SO2 emissions	-	
				Total amount of COD emissions	-	
				Rate of waste emissions	-	
				Total amount of wastewater discharge	-	
				Water consumption per unit product in key industrial sectors	-	
				Passing rate of used materials back into the supply chain	-	
				Comprehensive disposal rate of dangerous waste	-	
				Reusing rate of products/materials	-	
				Freshwater consumption	-	
				Energy-saving amount	-	
				Rate of carbon footprint	-	
				Availability of complete bill of materials and substances for the product	-	
				Percentage consumption of renewable or clean energy	-	
				Output of main mineral resource	-	
				Energy consumption	-	
				Total amount of industrial solid waste disposal	-	
				Recycling rate of industrial solid waste	-	
				Relative importance index (RII)	-	
				Evaluation index system for the assessment of CE at the regional level	The index contains 16 indicators classified into 4 groups. It included indicators of EC "reduce" and "recycle" principles and not the "reuse" principle.	

Identifier	Authors	Title	Year	Indicador	Description	Case study
8	Carmen Díaz-López, Manuel Carpio, María Martín-Morales, Montserrat Zamorano	Defining strategies to adopt Level(s) for bringing buildings into the circular economy. A case study of Spain	2021	Local priority index (pj)	The index allows knowing and quantifying the greater or lesser weight that experts have given to relevant factors.	The territory of Spain was selected for this study.
				Consistency Index of the matrix (CI), Random Consistency Index of the matrix (RCI)	-	
				Total priority indices	From the local priority indexes and the determined weighting coefficients, the overall priority index is calculated for each of the relevant factors.	
				Level(s)	It is a common European Union framework of essential sustainability indicators to measure the performance of buildings throughout their life cycle, enabling reduction of emissions and circular resource flows. The tool aims to unite the entire value chain of the sector around a common European language to improve the performance of a building.	

Identifier	Authors	Title	Year	Indicador	Description	Case study
9	Matan Mayer, Martin Bechthold	9. Development of policy metrics for circularity assessment in building assemblies	2018	Material Recovery Potential Index (MRPI)	The system assesses the recovery potential at both material and assembly levels through a series of categories and subcategories that is mainly based on quantitative material data.	Application in wall mounts residential outdoor.
				Unfastening Effort Index (UFI)	The index evaluates the effort of releasing widely used fasteners. Effort is defined as the level of complexity involved in accessing, unlocking, relocating and removing fasteners.	
				Time (in seconds) and cost (in €) are used as disassembly potential indicators	The index estimates the potential end-of-life disassembly product during early design phases. The disassembly potential is calculated from a time perspective and cost, using link-oriented sequence analysis.	
				Disassembly Effort Index (DEI)	The index quantifies end of life effort and disassembly cost. Disassembly effort and cost is measured through time, tools, fastening, access, instruction, danger and force considered.	
				Discrete index scores	The index considers three main life stages: Disposal, disassembly and recovery, which includes recycling or remanufacturing.	
				Connection index	The index takes into account separation damage, type of tool required for disassembly and disassembly time.	
				Access index	The index considers the correlation between disassembly sequence and product life expectancy, as well as the presence of layers that limit access to other layers with shorter life expectancy.	
				Recyclability index	The index includes not only the devaluation of the virgin to recycled content market but also the relationship between the levels of carbon dioxide emitted during production and recovery.	
				Devaluation rate of products	The availability and effectiveness of reverse supply chains and recycling technologies can be gauged by the rate of devaluation of products.	
				Surface treatment index	Surface treatments are typically applied to building components in order to meet weather or fire protection requirements. Those coatings often adhere to the component using chemical agents that create an irreversible bond, thus affecting the material recovery potential of the component.	
				Biodegradability index	By definition, biodegradability is the potential for materials to be chemically consumed by bacteria or other biological agents. The ability of treatments to surface to biodegrade contributes to its recovery potential.	
				Binders index	The index consists of a biodegradability score and a primary CO_2 production.	
				Assembly level index	The montage assessment is inherently more qualitative as it focuses primarily on spatial design aspects.	
				Connection type index	Connections are typically measured by comparing two variables: reversibility and disassembly time.	
				Separation damage index	Damage scale with 5 values.	
				Disassembly time index	Estimating deconstruction time is not as effective as estimating product disassembly time. It is based on field observations, with more expected refinements as more information is collected during future phases of the project.	
				Tool type index	Used to concretely reflect the rather abstract notion of the level of effort. Since effort is essentially a subjective condition, users can find challenges in determining what constitutes a high, medium, or low level of effort.	
				Component integration index	The index links the degree of pre-assembly in a given assembly to its end-of-life material recovery potential. It should be noted that the integration index does not focuses on part count as an influencing factor in material recovery potential, but rather on the relationship between on-site and off-site assembly.	
				End-of-life recovery potential	-	
				End-of-life index	-	

Identifier	Authors	Title	Year	Indicador	Description	Case study
10	Linda Braakman, Silu Bhochhibhoya, Robin de Graaf	Exploring the relationship between the level of circularity and the lifecycle costs of a one-family house	2021	Level of Circularity (LoC)	-	Single-family house in the Netherlands.
				Material Circularity Indicator (MCI)	Described above.	
				Dissassembly Determining Factors (DFF)	They identify possibilities for material-independent disassembly in product design, focusing on the integration of functions and connection types.	
				Product Circularity Indicator (PCI)	Described above.	
				System Circularity Indicator (SCI)	Described above.	
				Building Circularity Indicator (BCI)	Described above.	
11	Shiyamini Ratnasabapathy, Ali Alashwal and Srinath Perera	Investigation of waste diversion rates in the construction and demolition sector in Australia	2020	Waste Diversion Rate (WDR)	The index evaluates the life cycle waste output under consideration for waste management benchmarking. Residual deviation rate (WDR) is the percentage of residuals diverted from the landfill through different interventions such as reuse, recycling, repair, treatment and energy recovery.	12 residential projects in the New South Wales and Victoria states (Australia).
				Waste generation rate (WGR)	Understanding the volume, type and composition of C&DW helps waste management professionals make informed decisions about sustainability development through waste minimization, which has been widely used as a KPI in benchmarking performance management waste.	
				Recycling Rate	-	
				Zero Waste Index (ZWI)	They are used to assess the effectiveness of waste management performance and help make informed decisions about developing strategies to improve waste management practices.	

Identifier	Authors	Title	Year	Indicador	Description	Case study
12	L. Bragança, R. Mateus	Obstacles and barriers for measuring building's circularity	2019	Material Circularity Indicator (MCI)	Described above.	-
13	Chengkang Gaoa, Chengbo Gao, Kaihui Song, Kejing Fang	Pathways towards regional circular economy evaluated using material flow analysis and system dynamics	2020	Direct Material Input (DMI)	-	Guangdong Province.
				Total Material Input (TMI)	-	
				Hidden Flow (HF)	-	
				Direct Material Output (DMO)	-	
				Total Material Output (TMO)	-	
14	Ernesto Antonini, Andrea Boeri, Massimo Lauria and Francesca Giglio	Reversibility and Durability as Potential Indicators for CircularBuilding Technologies	2020	Reversibility	Reversibility is the property of a process, system or device to return it to its original state through the transformation or disassembly of a building or parts of it, preserving the maximum integrity of removed elements and ensuring minimal damage to those kept in place. Reversibility is related to time and implies transience.	London Design Festival 2016 (United Kingdom).
				Durability	It is the ownership of a process, system or device to maintain its ability to provide the resources that it is designed for overtime. Closely related to the time, durability indicates permanence.	

Identifier	Authors	Title	Year	Indicador	Description	Case study
15	Pedro Núñez-Cacho Utrilla, Jarosław Górecki, Juan Manuel Maqueir.	Simulation-Based Management of Construction Companies under the Circular Economy Concept – Case Study	2020	Circular Economy Key Performance Indicators (KPIs)	They allow managers to identify and control whether a construction company is applying Circular Economy practices in the different phases of the works and with what intensity.	General Contractor (GC) Construction.
				The final CE index CE Index (CEI)	The index measures a degree of propensity of the construction company to implement the CE (called Scale CE). Shows the most likely values (score) for each indicator, group of indicators and the index so that these values can be used as cut off values in the graphical representation in Panels (Scale CE).	

TABLE 3. Circularity indicators and metrics for buildings, extracted from the systematic literature review (SLR).