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MATERIAL PASSPORTS FOR CIRCULARITY INDICATORS: A COMPATIBILITY METRIC

Usman Aftab, Rosa Agliata
Department of Engineering, University of Campania “L. Vanvitelli”, Via Roma 9, 81031, Aversa, CE, Italy

Abstract

Material Passports (MPs) can play a crucial role in advancing Circular Economy (CE) principles, thanks to their features of documenting and tracking material properties throughout lifecycle. This study explores the potential of MPs as a valuable source of information for circularity assessments. A systematic review identifies key quantitative circularity indicators and their data requirements, which are compared with MP data availability. The resulting compatibility metric highlights MPs’ capability to provide essential material parameters for CE assessments. The findings prove the potential of MPs to support and simplify circularity assessments for enhanced effectiveness and greater accessibility.

Introduction

The construction industry consumes 40% of global natural resources and produces 25% of global solid waste and 37% of gas emissions annually (Ossio et al., 2023; Yu et al., 2022). Recently, the implementation of Circular Economy (CE) principles and related digital tools is being encouraged in the AEC sector by promoting the reuse and recycling of building materials to mitigate waste and emissions. By giving multiple lives to construction materials and products, CE promotes sustainable decisions and waste reduction. While material reuse is an important aspect of CE, a building’s lifespan of 30 to 100 years, along with varying users and stakeholders, makes it difficult to conserve, update and disseminate the required material circularity data along the value chain. As a result, the authenticity and completeness of material data are compromised, impeding the reintegration of demolished material into the circular loop. Digitally storing information about materials and products, while regulating updates across all lifecycle stages and stakeholders, may help preserve and facilitate access to this data. This introduces the concept of Material Passports (MPs), that are digital records of detailed data regarding materials used in a construction facility. Encapsulating a material’s origin, characteristics, and lifelong changes, MPs ensure traceability of materials and products during the reuse phase (Wilson et al., 2023).

To evaluate the potential reuse of materials and products, it is essential to be aware of aspects such as masses, disassembly capacities, cost-benefits, energy consumption of construction waste management processes, etc. (Khadim et al., 2022). Based on these parameters, several circularity indicators (C-indicators) are being developed to measure CE implementation. However, data scarcity and lack of digital means pose significant challenges, possibly hindering the adoption of CE principles. These issues highlight the need for innovative and comprehensive data storage sources from which circularity parameters can be retrieved, such as MPs. The capability of integrating digital technologies, lifecycle information, and stakeholder collaboration, positions MPs as a viable tool for supporting circularity assessments (Honic et al., 2021).

This piece of research wants to explore the possibility of integrating MPs with C-indicators. The paper reviews current C-indicators and identifies their basic parameters for assessing circularity at material and product level. Then, the availability of the required data in MPs is studied, and the potential of integrating MPs with C-indicators is investigated.

Methodology

Covering both qualitative and quantitative analyses, a mixed-method research approach is adopted in this study to investigate whether MPs can foster circularity assessments by providing meaningful information for C-indicators. To this aim, separate keyword analyses are done to extract articles relevant to C-indicators and MPs. Scopus database is utilized using keywords analysis and filtered for specific parameters as described below and illustrated in Figure 1.

First, a review of research articles and review papers is done to find the taxonomy of C-indicators using keywords: (“circularity” OR “circular economy”) AND (“indicator” OR “measure” OR “index”) AND “building*”). A total of 23 articles are extracted with 53 indicators. Given the scope of MPs, content analysis is conducted to filter only the C-indicators based on quantitative parameters and applicable at micro-scale (materials and products). A list of C-indicators is then finalized to analyze their data requirements. Subjective and qualitative parameters are not considered as they fall beyond the scope of this analysis.

Secondly, MP data provision capabilities are analyzed by extracting articles that specifically explore MP compilation and generation for various purposes. Keywords include (“material passport*”) AND (“circular economy”). Various MP data domains are recognized using content analysis. Finally, two lists, respectively containing C-indicators data-requirements and MPs data-availability, are comprehensively compared to tabulate a compatibility metric that defines the synergies between MPs and C-indicators.

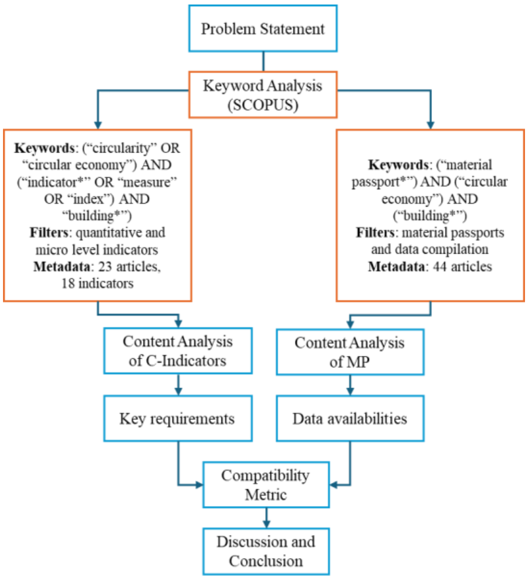

Figure 1: Methodology framework

Results and Discussion

Following the described methodology, a list of eighteen (18) selected C-indicators, along with their acronym and source, is presented in Table 1. The details of the C-indicators, their parameters and MP-data provision abilities are discussed in the subsequent subsections.

Table 1: List of selected C-indicators and their sources

C-indicator	Acronym	Reference
Material Circularity Indicator	MCI	(Ellen MacArthur Foundation, 2015; Goddin et al., 2019)
Product Circularity Indicator	PCI	(Ellen MacArthur Foundation, 2015)
System Circularity Indicator	SCI	(Ellen MacArthur Foundation, 2015)
Building Circularity Indicator	BCI	(Verberne, 2016)
Alba Building Circularity Index	BCIX	(van Schaik, 2019)
MADASTER	MAD-CI	(Madaster, 2018)
Element Circularity Index	ECI	(Gulck et al., 2021)
Predictive Building Circularity Indicator	PBCI	(Cottafava & Ritzen, 2021)
BIM-Based Building Circularity Assessment	BBCA	(Zhai, 2020)
Framework For Circular Buildings	FCB	(Ben Kubbinga et al., 2018)
Whole-Building Circularity Indicator	WBCI	(Khadim et al., 2023, 2024)
Circularity Indicator for Pedestrian Bridges	CIPB	(Anastasiades et al., 2020)
Building Circularity Indicator (Disassembly Reconsidered)	BCIDR	(van Vliet, 2018)
Circular Economy Index	CEI	(Di Maio & Rem, 2015)
Circular Business Model Based Circularity Indicator	CBMCI	(Di Biccari et al., 2019)
Circular Construction Evaluation Framework	CCEF	(Dams et al., 2021)
Circular Economy Toolkit	CET	(Evans & Bocken, 2013)
Product-Level Circularity Metric	PCM	(Linder et al., 2017)

C-Indicators classification and parameters

The identified indicators can be categorized in *base*, *derived* and *independent* frameworks. The *base* frameworks include MCI, PCI, SCI, and BCI. Although BCI is originally derived from MCI, it has frequently been adopted as an individual indicator in various studies, and categorized as a base indicator by Khadim et al. (2022); therefore, it is classified as a *base* framework in this study. The base indicators evaluate the circularity of products based on their virgin, and residual masses or volumes. In a disassembled or demolished waste, MCI requires the total mass of materials, fractions of virgin and non-virgin (reused) materials, and fractions of materials that are recoverable. Thus, its calculations are based on the bill of materials (BOM) and functional lifetimes of materials or products. Variables like linear flow index can be calculated using these fractions, whereas parameters like the utility factor or level of importance are described as fuzzy values. Adding upon this concept, PCI, SCI, and BCI include disassembly possibilities based on disassembly scenarios quantified in fuzzy values again.

The frameworks *derived* from the *base* frameworks include BCIX, MAD-CI, ECI, PBCI, BBCA, FCB, WBCI, CIPB and BCIDR. These C-indicators improve upon previous limitations by including further parameters. Disassembly factors along with type or accessibility of connections are included in BCIX, ECI, FCB, and BCIDR. Inclusion of Lifecycle Assessment (LCA) outputs in CE assessment could be found in PBCI and the latest version of WBCI that integrates Cradle-to-Cradle (C2C) and LCA parameters. Similarly, fractions of biodegradable material are required during the calculations of BBCA and WBCI. However, BBCA also requires Building Information Models (BIM) and Environmental Product Declaration (EPD) reports for material and product details. It is worth mentioning that in addition to MCI parameters, FCB considers the environmental and sustainable performance of a building influenced by BREEAM certification. It also requires the availability of MP as a data source. These distinguished considerations of the *derived* indicators give them more precision towards circularity assessments based on environmental and sustainable parameters. Additionally, the *derived* frameworks may also contain various subjective parameters like level of importance, building flexibility scores or building aesthetics, which are not considered in the current study.

Lastly, *independent* C-indicators are not based on MCI or BCI parameters; instead, they focus on cost, LCA or BIM based circularity evaluations. For instance, in PCM, authors underscore that the economic value of materials forms the foundation of CE, thus their evaluation should be based on cost analyses. Similarly, LCA is considered a key impact factor in CBMCI and CCEF.

Material Passports data sources

The literature analysis resulted in 44 articles addressing MP compilation and generation. They show that MPs can integrate numerous material data in digital form, along with their lifecycle, and supply chain information. However, due to lack of standardization and customized MP templates, different MPs encompass different data types and categories of information, mainly depending upon the MP data sources. The current study distinguishes these sources into three main data types: *lifecycle stakeholders, global or local databases* and *integrated software or digital tools. Stakeholders* are classified into various groups based on the material and product lifecycle. The identified stakeholders include architects, consultants, engineers, suppliers, maintenance managers, demolition contractors, recycling or reuse companies, and end-users or tenants (Çetin et al., 2023). The roles and responsibilities of these stakeholders depend upon the requirements of circular methods and assessments. For instance, in a study by Hradil et al. (2023), to compile a MP for storing and updating material trail, authors suggest data inputs from manufacturers into the Radio Frequency Identification (RFID) tags.

Additional to stakeholders' inputs, circularity principles also include environmental assessments or LCA results from *global or local material databases*. Examples of such sources are the *Austrian Institute for Building and Ecology* (IBO, 2024), and the *Baubook* (Eco2soft, 2018). These databases provide sustainability or ecological performance and compositions of building materials and products for various circular and sustainable processes, becoming a valuable source of information for MPs.

Furthermore, *digital integration of innovative tools and technologies* makes the greatest impact on the utilization of MPs. Technologies like blockchain, BIM, RFID, artificial intelligence (AI) and digital twins have revolutionized the traceability, security, comprehensiveness and authenticity of MP data across various domains of circular and sustainability strategies. For instance, material provenance embedded in RFID-based MPs for steel and concrete has enhanced the traceability and recoverability of these materials during recycling processes (Hradil et al., 2023; Vahidi et al., 2024). Similarly, BIM is known to be the best platform to generate MPs for building material sustainability assessments (Atta et al., 2021), evaluating recycling or reusability potentials (Honic et al., 2021) and coordinating CE information across material lifecycle (Lu et al., 2023). MPs integrated with blockchain are explored for its secure and reliable method of ownership and information transactions to safely trade recycled material across borders (Wu et al., 2023).

The identified data sources vary in nature and offer distinct types of information. For instance, the *global or local databases* are sources of static data, whereas sources like *lifecycle stakeholders* and *software or digital tools* provide real-time updates and assessments-based dynamic information (Honic et al., 2019). Similarly, only quantitative data is expected from *integrated software or digital tools*, meanwhile *qualitative data* can be obtained from *stakeholders* and *global or local databases.* Furthermore, various data models can be utilized as data sources. For example, hierarchical data models like Bills of Materials used in MCI, BCI and WBCI, relational data models like Ecoinvent for life cycle inventory information (Khadim et al., 2024), or semantic data models like BuildingSMART Data Dictionary (bSDD) (Tomczak et al., 2024).

C-indicators and MP compatibility

The metric in Table 2 illustrates the identified objective and the quantitative material/product-related required parameters of the 18 selected C-indicators. The content analysis reveals 5 different categories of parameters, which can be titled: *quantities, disassembly, cost-related, lifecycle information* and *data availability.* Light-blue boxes represent the quantitative parameters corresponding to the respective indicators, while grey-colored boxes denote parameters with fuzzy values. Green check marks (✓) indicate the possibility of acquiring these parameters directly from MPs, while red check marks (✓) denote the possibility of integrating these parameters into MPs using other databases or digital tools, as indicated in the studies. The black cross (**x**) stands for the unavailability of the parameters in MPs. For instance, BOM or LCA outputs can be collected by other software or online tools, and can be incorporated in MPs, as identified by Honic et al. (2019). Similarly, the authors of various indicators developed fuzzy values based on different scenarios, that can also be integrated in MPs. For instance, different type or accessibility of material/product connections are translated into numeric fuzzy values by Verberne (2016) in BCI.

Table 2: Compatibility metric for MPs and C-indicators

Required Parameters		C-indicators																	
		MCI	PCI	SCI	BCI	BCIX	MAD-CI	ECI	PBCI	BBCA	FCB	WBCI	CIPB	BCIDR	CEI	CBMCI	CCEF	CET	PCM
Quantities (fractions are in kg, m^3, %)	fraction of virgin material	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓		🟦 ✓	🟦 ✓	🟦 ✓					
	fraction of non-virgin material	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓			🟦 ✓	▨ ✔	
	fraction of recoverable waste	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	▨ ✔	🟦 ✓	🟦 ✓	🟦 ✓		▨ ✔	🟦 ✓	▨ ✔	
	fraction of unrecoverable waste	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓		🟦 ✓	🟦 ✓	🟦 ✓					
	fraction of biodegradable material									🟦 ✓		🟦 ✓						▨ ✔	
	fraction of additional material required for O&M											🟦 X							
	toxicity of material										▨ ✔						▨ ✔	▨ ✔	
Disassembly	disassembly factor/possibilities		▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔	▨ ✔				
	type of connection					▨ ✔		▨ ✔			▨ ✔			▨ ✔			▨ ✔		
	accessibility of connection					▨ ✔		▨ ✔			▨ ✔			▨ ✔					
Cost Related	cost of virgin materials															🟦 ✔			🟦 ✔
	cost of recycled material/cost of material after disassembly														🟦 ✓				🟦 ✔
	cost of reproduction from recovered material														🟦 X			▨ ✔	
Lifecycle information	functional or technical lifetime of material/product	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓	🟦 ✓		▨ ✔	🟦 ✓	🟦 ✓			🟦 ✓	▨ ✔	
	transportation distances											🟦 ✔							
	LCA outputs								▨ ✔			🟦 ✔				▨ ✔	▨ ✔		
	EPD																▨ ✔		
Data availability	BIM data									🟦 ✓						🟦 ✓			
	bill of materials (BOM)	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔	🟦 ✔					
	MP availability										🟦 ✓								

🟦 quantitative values ▨ fuzzy/fixed values ✓ embedded in MP ✔ collected into MP via databases/digital tools **X** not available in MP

As illustrated in the metric (Table 2), MPs cover almost all categories of C-indicators parameters. In the *quantities* category of required parameters, the C-indicators based on MCI framework require fractions of virgin material and non-virgin (reused/recycled) material used in a product or component of a building. Similarly, the amount of recoverable and unrecoverable material from the demolished building is also a required parameter, whereas the fractions of biodegradable materials are only required by BBCA and WBCI. All these fractions are readily available as basic data sets embedded in MPs during their compilation. As discussed by Çetin et al. (2023), virgin material weight, volume and quantities have high availability in MPs, whereas fractions of reused or recycled material input in a product have low availability. Similarly, information about possible recoverability, toxicity and the presence of biodegradable fractions in demolition waste are highly available in MPs.

From the literature analysis, it emerges that the only *quantitative* parameter that could not be incorporated using MPs is the amount of additional material required for construction, maintenance, and repairs, as described in WBCI. While this information does not directly relate to material circularity assessment, it is a necessary parameter in building level evaluation. Interestingly, in the *quantities* category of parameters, fuzzy values are also integrated within some C-indicators, such as the toxicity of materials required by FCB, CCEF, and CET. As an example of these values, FCB quantifies the avoidance or minimal use of hazardous materials in the form of scores (i.e. 0 or 1).

Disassembly requirements in C-indicators, mainly referred to as Disassembly Determining Factors (DDFs), Type of Connections (TOC) and Accessibility of Connections (AOC) in the literature, are suggested to be incorporated in the form of fuzzy variables (Verberne, 2016). These values correspond to the possibility of disassembly based on different types and accessibility options of connections among different building materials and components. For instance, dry connections are easily separable, thus having the highest fuzzy score for circularity, while hard chemical connections have the lowest score. An example taken from BCI is illustrated in Table 3.

Table 3: Example of fuzzy variables for "connection types" Source: Verberne (2016)

Connection Type	Fuzzy Score
Dry Connection	1.0
Connection with additional elements	0.8
Direct integral connection	0.6
Soft chemical connection	0.2
Hard chemical connection	0.1

Cost-related parameters fall under the *independent* category of C-indicators. The CEI indicator requires a simple ratio of the cost of recycled material to the cost of producing the same product(s). Similarly, both CBMCI and PCM necessitate the costs of virgin and recycled materials. This is because PCM calculates a ratio of the cost of recycled/reused product parts to the total cost of the parts, while CBMCI uses Lifecycle Cost (LCC)-based CE assessments. Availability of all these costs is high in MPs, except for the cost of reproduction from recovered material required by CEI. However, integrating this factor as Likert-scale values, as suggested by the authors of CET, is a compatible approach for MPs.

The parameters of *lifecycle information* required by various C-indicators are also found in MP literature. The functional or technical lifetime of a material or product is embedded in the MPs by default. However, LCA outputs and EPD reports could be either incorporated using local or global databases or by generating them with digital tools (e.g., the Global warming potential (GWP) and CO_2 emissions assessment with the virtue of BIM-based MP by Honic et al. (2021b)).

BOM is a unique cost-related parameter required in MCI-based indicators, enhancing the circularity assessment. Having the ability to integrate databases, MPs can provide this requirement for the assessments. Interestingly, incorporation of BIM and MPs is also required for various evaluations in C-indicators. For instance, BBCA and CBMCI require element-level details from BIM, whereas Dutch Green Building Council (DGBC) (2018) highlights the inclusion of MPs during circularity assessments in FCB.

Discussion

The literature analysis reveals that MPs inherently contain, or can integrate, through external sources, a diverse array of materials and products information, including composition, quantities, disassembly potential, and lifecycle environmental impacts. The compatibility assessment conducted between the information provided by MPs and the requirements of C-indicators demonstrates that MP aligns closely with most of the micro-level parameters used to evaluate the circularity of construction materials, particularly quantitative ones. Specifically, the *base* C-indicators, which mainly focus on quantity-based parameters (i.e., MCI, PCI, SCI, and BCI) can inherently retrieve the quantities and compositions of materials and products from MPs. Additionally, MPs also provide information regarding the indicators *derived* from *base* frameworks by integrating *disassembly* and *lifecycle* data. Parameters such as DDFs, TOC, and AOC could be incorporated into MPs using fuzzy values, while LCA and BIM could be linked to MPs using external databases or digital tools. For instance, the transportation distances in WBCI-LCA are taken from the NIBE database and LCA data is incorporated using Ecoinvent (Khadim et al., 2024). Furthermore, MPs also provide cost-related parameters that are included in the *individual* category of C-indicators such as CEI, CET, PCM, CBMCI, and CCEF. The only parameter absent from MP literature is the *fraction of additional material* *required in the Operation and Management phase,* which is used by a single C-indicator (WBCI). On the other hand, the cost of reproducing products from recovered material, which is considered in CEI and CET indicators, can only be accounted for using fuzzy values (this approach only works for the CET indicator).

The parameters of C-indicators address circularity across different scales or levels, i.e., materials, products, components, and buildings. The relationship observed between MPs and C-indicators in this study can be extended to higher-scale. For instance, while MPs primarily offer benefits during the end-of-life phases, product-level circular assessments of construction products can be integrated during the design, production, and use phases through digital product passports (Wan & Jiang, 2025).

Conclusions

To mitigate the fragmentation of material and product lifecycle information in building circularity assessments, this study investigates the potential of MPs to provide key parameters for CE assessments at the material and product levels. By comparing the requirements of C-indicators with the information embedded in MPs, a compatibility metric is introduced, identifying the key construction C-indicators that MPs can address. To explore a wide range of parameters, the study includes diverse sets of indicators, such as quantity-based, cost-related, lifecycle information, etc. It is found that both mass-based and cost-based indicators are commonly used in building circularity assessments. By including data on the weight of virgin and reused materials in original products, as well as the fractions of recoverable and non-recoverable materials in waste, MPs prove to be a reliable source for such indicators. Additionally, C-indicators encompass lifecycle parameters such as functional lifetime, LCA results, and environmental certifications. MPs either include this data or can integrate with LCA databases, EPDs, or other digital technologies that assess these parameters. While cost-related indicators can also be evaluated through MP integration, some comprehensive indicators require additional quantitative and lifecycle cost data from BOM and BIM. Moreover, the ability to ascertain various parameters of C-indicators using fuzzy variables strengthens the efficacy of MPs, particularly when assisted by a linked database of these values.

This study contributes to advancing knowledge on the possibility of the integration of CE with digital MPs, to make circularity assessments easier and more accessible. However, certain limitations should be acknowledged. First, the analysis focuses on the quantitative requirements of C-indicators. This limitation stems from the inability to readily translate qualitative data embedded in MPs. For instance, lack of standardized format for describing aesthetical state of a recycled material, and subjective or descriptive material conditions included in MPs cannot be easily comprehended into circularity assessments. Furthermore, by evaluating C-indicators at the micro level, the study is limited to materials and products, whereas a comprehensive circularity assessment should consider CE potential across multiple scales. Future research should explore the integration of component-, system-, and building-level data into MPs to enhance their applicability in holistic circularity evaluations. Another possible forthcoming development could be the exploration of MPs' potential in assessing parameters related to energy consumption.

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