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A Definition of Essential Characteristics for a Method to Measure Circularity Potential in Architectural Design

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Abstract

Circularity potential in the construction sector, a quality that quantifies the contribution to carbon and resource neutrality, is to be standardised in Europe yet. In order to do so, a harmonised definition and method of calculation that offers transparency is crucial. Simplicity in construction methods, a low-tech approach, and a limited variety and pure use of materials support the development of innovation towards a Circular Economy (CE). The state-of-the-art in architecture features both simple and complex constructions, which need to be quantified with respect to their circular performance in light of the European norm. A clear European standardised method and accompanying tool(s) to assess the circularity potential of a building or element will encourage designers to use secondary material, to limit waste production, and to enable multiple life cycles of buildings and elements to preserve primary natural resources.

In order to meet the target of a successful CE, firstly, a method to quantify success and inform the architectural design process have to be developed and adopted across Europe. Subsequently, the development of practical assessment tools to measure the circularity potential of building components is an essential step towards the implementation of CE. As a matter of fact, several methods are ready or under development, but none has reached the level to be implemented as a European standard. This study aims to provide answers on what characteristics a harmonised method and practical design tool should contain.

Two assessment metrics for circularity, one from Germany and one from the Netherlands, are reviewed to compare their applicability in the design process and point out opportunities for a harmonised European method. Five case studies, comprising prefabricated concrete façade elements, are assessed using both metrics. The results will be used to analyse the metrics' transparencies and abilities to holistically measure the amount of reused and recycled material in a building's substance and quantify the recyclability of building products in light of their intended recycling path in the future. The third aspect that is integrally analysed is, therefore, applicability in a design process.

Keywords

Circular Economy, circularity potential, architectural design, circularity assessment method, prefabricated concrete

1 INTRODUCTION

The evident contribution of the building sector to climate change fills the architectural discussion with ways to improve the architectural practice. Until now, the energy consumed during the use phase of buildings has been the focus of sustainable development ever since policymakers implemented energy efficiency restrictions in the 70'ies of the last century (Hildebrand et al., 2009), resulting in energy efficiency for the use phase of a building. On the other hand, little progress was made in the physical production and deconstruction of a building.

Still, the building industry consumes 40 - 50 % of the global resources, produces 60 % of the global waste and 33% of the global CO_2 emissions (UNEP, 2012). Consequently, it is the moral obligation of this industry to preserve resources and balance the industries impact on the environment. Although authorities set regulations to save natural resources and increase recycling rates, the linear economy is still dominant (Zabek et al., 2017). The European Commission introduced the EU Waste Directive in 2018 that requires all new construction to have a recycling rate of 70% by mass by 2020 (Commission, 2013). The gap between political directions and practice puts architects and planners in charge to bring principles of the Circular Economy (CE) into practice.

The ones who are willing to integrate the strategies of a CE on material level are facing different challenges: uncertainties within the closed-loop systems of products, an increased amount of information during design, lack of experienced stakeholders and different political regulations (Mackenbach et al., 2020). There are several ways to achieve circularity like a Low-Tech approach of construction method, detachable components, the use of reused and recycled material (EMF, 2017; TransitieteamCirculaireEconomy, 2018). But the key to practice is the ability to compare the environmental impact of design alternatives. Several characteristics of a method to measure circularity have been introduced on the market, such as the Circularity Indicators from the McArthur Foundation (Foundation; et al., 2015), which assesses, rates and reports on how well a product or company performs in the context of CE. Based on this method, the company Madaster uses the circularity indicators (Madaster, 2020) to assign a circularity score of buildings with the data being registered on their platform. Besides, several more methods are under development (Ebert et al., 2020) or available (Rosen, 2019) but none has reached a level to be implemented as a European standard tool yet (Rahla et al., 2019; wbcsd, 2018). This calls for a harmonised definition of the essential characteristics for methods to assess circularity during design. Hence, this paper reviews two circularity potential metrics for construction, one from Germany and one from the Netherlands by assessing five case studies to evaluate the metrics ability for standardisation with regard to their applicability in design, transparency and holistic perspective. The first metric has been selected due to its user-friendliness proved during student courses, and the second due to its integrity into a mandatory Dutch environmental impact assessment tool and focused approach to measure demountability as an indicator for circularity. The results are used to point out what characteristics a European harmonised method to measure circularity potential and practical tools should contain.

2 METHODOLOGY

Two metrics are introduced, and their parameters and calculation method are described based on publications. Both metrics are used to assess the circularity potential of five case study of a prefabricated façade element using the same input data, namely a bill of materials (BoM). Metric A assesses circularity including the reuse and recycling content in addition to the suitability for further use. Metric B focuses on the disassembly potential of building components and their composition. The metrics are compared in three categories, with a focus on the use in an architectural design process, in order to improve the design in regard to future reusability and generate a circular design.

Doing so, the reliability of the metrics was assumed to be a fact, and this fundamental requirement was excluded from the assessment. The categories include:

1 Applicability to Design: a method that is applicable in design should be supportive of the design process. It generates information that can be used to improve the design in an ongoing process (Saidani et al., 2017; wbcsd, 2018).
2 Transparency: a transparent method enables the user to learn from the design consequences and third parties to understand and reconstruct the design and calculation process (Linder et al., 2017).
3 Holistic perspective: a holistic view integrates all aspects of circular design, including closed life cycles through product longevity (high value/performance), life extension (material input) and disassembly (material output) (Ness et al., 2017). The weighting of results by mass and GWP (CO_2 equivalent). A holistic method, including the quantification of resource guarantees that a complete representation of the design task is part of the calculation (wbcsd, 2018).

The method leads to the following research step: the specific and shared characteristics of metrics A and B contribute to the categories identified and summarised as essential characteristics for a harmonised method.

2.1 METRIC A: ADVISORY METRIC OF MATERIAL IN- AND OUTPUT

This metric has been developed at the Chair of Reuse in Architecture at the RWTH Aachen University in 2017 and was first published in 2018. According to the authors (Hildebrand et al., 2018), the main goal is to provide information on the environmental benefit related to the design task and to distinguish the benefit that is potentially accessible after the buildings use phase. In relation to that (Hildebrand et al., 2019) the metric consists of two parts; 1) "input" which shows the use of (I) reused, (II) recycled and (III) renewable material and its future recycling path as 2) "potential output" with fractions that show different potential for further application. Both criteria are expressed in percentage of the Global Warming Potential GWP (CO_2 equivalent) or mass (kg).

2.1.1 Input

The materials that are planned to be part of the building substances are divided into four indicators:

- re: reused material
- rc: recycled material
- rw: renewable material
- pw: primary non-renewable material.

In the first step of the analysis, the items on the BoM are identified using data in "Ökobaudat", the Germany Sustainable Construction Information Portal (Kerz, 2012). Then, each layer is classified into four indicators listed above (re,rc,rw,rp). The calculation of the amount of material (input) used in one object for one indicator is:

Reused materials (re):

$$V_{re}=\frac{\sum_i M_i * M_{re}}{\sum_i M_i}$$

Recycled materials (rc):

$$V_{rc}=\frac{\sum_i M_i * M_{rc}}{\sum_i M_i}$$

Renewable materials (rw):

$$V_{rw}=\frac{\sum_i M_i * M_{rw}}{\sum_i M_i}$$

Primary materials (pw):

$$V_{pw}=\frac{\sum_i M_i * M_{pw}}{\sum_i M_i}$$

- Mi = Mass or GWP of an object or sub-object (i),
- Mrx = Percentage by mass or GWP of reused (re) / recycled (rc) / renewable (rw) / primary (pw) material input in a component,
- Vrx = Reused (re) / recycled (rc) / renewable (rw) / primary (pw) materials input as a percentage of a total component.

2.1.2 Potential Output

The future recycling path of a building component is mostly based on the component's connectivity, material family and potential hazardous substances. In order to display the building substance's reuse or recycling potential, the output is assessed based on the future material flow categorised into four different fractions (a,b,c,d):

A deconstructable, without damage, pure material with high potential for reuse
B deconstructable, with damage, pure material with high potential for recycling
C dismountable, with damage, mixed material with low potential for high-value recycling
D critical material with hazardous substances used for landfill.

The calculation of the potential output in one object of one indicator is:

Fraction a: $V_a = \sum_i M_i * M_a / \sum_i M_i$

Fraction b: $V_b = \sum_i M_i * M_b / \sum_i M_i$

Fraction c: $V_c = \sum_i M_i * M_c / \sum_i M_i$

Fraction d: $V_d = \sum_i M_i * M_d / \sum_i M_i$

- Mi = Mass or GWP of an object or sub-object (i),
- Mx = Percentage by mass or GWP of fraction (a) / (b) / (c) / (d) materials output in a component,
- Vx = Fraction (a)/(b)/(c)/(d) materials output as a percentage of a total component.

2.2 METRIC B: ASSESSMENT OF DISASSEMBLY POTENTIAL

The Dutch government aims for a CE in 2050 and pro-actively stimulates innovation towards that direction (TransitieteamCirculaireEconomy, 2018). In the slipstream of this ambition, several initiatives have been launched to speed up the transition. One of which is the development of a metric proposal for disassembly potential in constructions (Vliet, 2019), which is called Metric B in this publication. The degree of disassembly of buildings determines the probability of successful reuse of their parts. The scenarios in the 10-R model (Cramer, 2015) are used to express the degree of value retention through disassembly. A nationally adopted coding system, NL/SfB (BNA, 2005), is used to define the scale on which the assessment takes place. As such, the metric can be integrated in the mandatory Dutch environmental impact assessment system MilieuPrestatie van Gebouwen (MPG) in the near future. The MPG is an indicator of sustainable building based on LCA using data from a national database for environmental impact for construction (RVO, 2020)

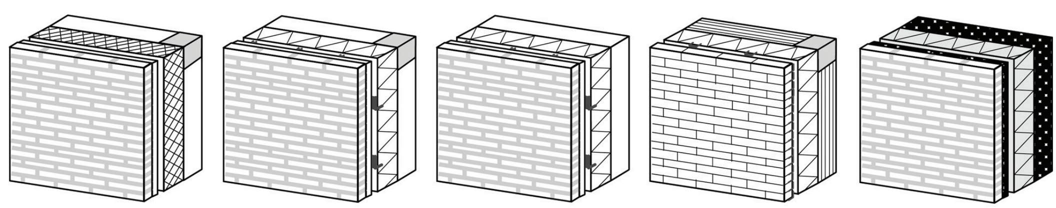
The potential to detach an element from the building depends both on the connection of the element to another and the composition of it. Metric B is used to calculate the disassembly potential. The disassembly potential of an element (LIn) is therefore equally composed of the disassembly potential of the object itself (LIcn) and the disassembly potential with other objects (LIsn). Four factors are used to rate this, detailed definitions are found in the method (Vliet, 2019). The result is subsequently normalised using a ratio of the object's and building's MPG.

- TVn = Object n connection type
- ToVn = Accessibility of object n connection
- DKn = Degree of integration of object n with other objects
- VIn = Shape of integration of element n

$$LI_n = \frac{LIc_n+LIs_n}{2}, \qquad LIc_n = \frac{TV_n+ToV_n}{2}, \qquad LIs_n = \frac{DK_n+VI_n}{2}$$

3 CASE STUDIES

The five case studies are variations on one functional unit, namely a 20 m^2 load-bearing prefabricated façade element (Figure 1 Case study context). The variation is created in material selection, deconstruction principle and end-of-life (Table 1 Case study design variants). The designs were developed for a residential highrise building of approximately 70m and a footprint of 47 x 16 meters. They have a similar load-bearing capacity for comparability. Other building components than the façade elements are excluded from the calculations. Furthermore, the alternative designs represent the state-of-the-art in prefabricated concrete construction.



1	2	3	4	5
Dfx Reuse	Dfx Dissassembly	Dfx Upgradability	Dfx Biological cycle	Dfx Life extension
Construction material Concrete – PIR – Brick and mortar	Construction material Concrete – Mineral wool – Brick and mortar	Construction material Concrete – Mineral wool – Brick and mortar	Construction material Cross-laminated timber – Mineral wool – Brick and backing system	Construction material Recycled concrete – Mineral wool – Brick and recycled mortar

TABLE 1 Case study design variants.

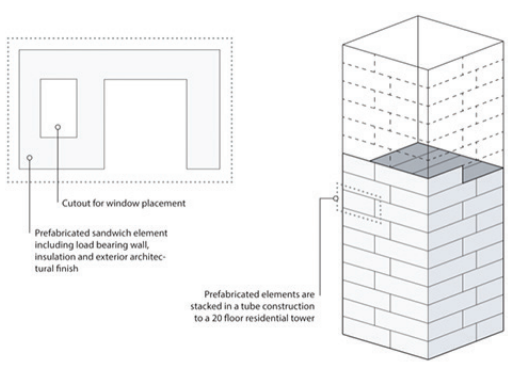


FIG. 1 Case study context

In order to achieve various life cycles of a product with high quality, the maintenance in its original format and the material purity play an important role. Mechanical connections improve the detachability of a component, and therefore its material can be rated with a higher reuse potential. Connections with high connectivity that can only be detached with heavy machinery, like plaster, must be rated with a low reuse potential. In this regard, element 4 has the highest performance achieved using both metrics (Fraction a=86%, Lin=0.55), although its design intention was a high amount of renewable material (Mrw=59.57%, Tab.1) presented in Table 2. Element 1 and 5 has the highest potential to end up as landfill (Fraction d=0.4, Tab.2) or be recycled with a low quality (Fraction b=89%, Tab.2) and therefore has the most inferior performance. Similar results are achieved with metric B (LIn= 0,1). Element 2 performs slightly better than Element 3 using both methods.

	METRIC A (proportions explained in Chapter 2.1.2)				METRIC B (proportions explained in Chapter 2.2)
	FRACTION A	FRACTION B	FRACTION C	FRACTION D	DISASSEMBLY POTENTIAL (LIn)
ELEMENT 1	0.46	10.1	89.02	0.42	0.18
ELEMENT 2	15.1	84.9	0.59	0	0.46
ELEMENT 3	0.45	82.9	16.64	0	0.33
ELEMENT 4	86.72	12.94	0	0	0.55
ELEMENT 5	0.46	9.43	89.68	0.43	0.15

TABLE 2 Case Study Circularity Potential derived from calculation in chapter 2.

Per element, one single score is generated from the calculation in metric B. A score between 0.4 and 0.6 is considered low, between 0.6 and 0.8 average, above 0.8 high. Scores below 0.4 are not labelled, although they can occur in theory and do in the calculation made in this research. Three elements are considered below par, and two elements score low, a meagre overall score which could indicate, based on the state-of-the-art techniques used in the case study, that this method wields a strict rating.

In comparison to metric A, metric B does not consider the input material as an indicator for circularity. Therefore, the results are not presented, although it is part of the calculation of metric A.

4 RESULTS

In order to achieve CE in the building industry, products must be designed with a high potential to be reused as well as containing a reduced amount of primary resources and kept at their highest level of utility and value at all times (EMF, 2017). A harmonised assessment method can inform circular design across Europe. This method should be 1) applicable to a design process from an early design stage, 2) transparent, and 3) apply a holistic perspective. These three categories are used to analyse the results presented in paragraph 3, created with the two presented metrics in paragraph 2, and essential characteristics have been developed in Tab.3.

CATEGORY	ESSENTIAL CHARACTERISTIC	METRIC A	METRIC B	NOTES
APPLICABLE TO DESIGN	Benchmark comparison	0	+	A: is missing a benchmark
	Readability of results	+	++	A: result consists of 8 categories B: result consists of a single score
	Offers insight to improve the design	++	+	A: separate categories allow the planner to improve the design within a specific category B: one score result shows little insight into derivation
	Level of additional knowledge needed to use the method and to improve the design	+	0	A: requires knowledge of material substances and connections B: requires detailed technical knowledge on the execution of the project
	Compatibility with sustainability assessment tools	+	++	A: LCA B: LCA, MPG, NL/SfB
TRANSPARENCY	Open-access data and pre-defined data sources	+	+	A: data from (www.oekobaudat.de, 06.06.2020) B: calculation is based on an MPG calculation, derived from an open-access or purchased tool
	Rating and concept definition	+	++	A: criteria are shortly explained in publications. B: criteria are clearly explained in the method's guideline
	Pre-defined assessment options	+	++	A: Connectivity level/future recycling path and materials substance is divided into 8 general categories B: 30 prescribed options for connectivity level
HOLISTIC PERSPECTIVE	Encourage designers to design according to CE objectives	++	0	A: includes a more holistic view due to the assessment of material in- and output B: only assesses the output material connectivity
	Complete life cycle data	++	++	A: is assessed based on GWP B: is assessed based on GWP
	Applicable to the entire design process (concept to detail) in order to influence circularity at an early design phase	+	+	A: applicable with detailed information about materials substance and connectivity B: applicable with detailed information about materials connectivity
	Relevant environmental indicators	++	++	A: Volume and GWP is used as indicators B is based on GWP and other indicators
	Assessment of materials flow and potential hazardous substance	++	+	A: assesses potential hazardous substances and future recycling path B: includes integration of various materials

TABLE 3 Characteristics of metrics A & B - (++) very good performance, (+) good performance, (0) poor performance

5 DISCUSSION

In the transition towards a CE in the built environment, there are several aspects that need to be faced, such as the lack of harmonised assessment methods for circularity. Authorities cannot implement restrictions on the usage of resources if a reliable method to measure circularity in construction is not available. In this research, two metrics for circularity potential have been evaluated in regard to applicability in the design process, transparency and their holistic perspective. Based on the observations, the following essential characteristics of a method have been identified:

Applicability to Design:

- Insight in improving the design for circularity during use of the method

- Definition of a realistic benchmark creates insight in the improvement of circularity potential and design quality
- Clear relation and compatibility with regulations and existing methods and tools
- Correlation with the average sustainability and circularity knowledge level of architects and engineers

Transparency:

- Detailed pre-defined options for assessment
- A readable, though nuanced score that indicates the circularity potential
- Based on open-access data and tools
- Applicability during concept design to detailed and execution design in order to improve the design according to CE principles
- Clear definitions of concepts and rating
- Clear and openly available guideline for use

Holistic perspective:

- A weighted contribution of materials to the final score, for instance, based on mass and CO2 emissions
- A holistic system perspective including input and potential output material
- Include the effort of reprocessing and recycling, contamination risk and hazardous materials rate

6 CONCLUSION

Measuring and rating the circularity of buildings results to be an intricate objective due the complex notion of a building as a conglomerate of different products and materials and uncertain lifespans (Rahla et al., 2019). In the past, several metrics had been developed, and two of them have been evaluated in this review. The path towards CE is dynamic and can be shaped with an integral and harmonised assessment method that should be implemented on a European level. The list of essential characteristics in this publication should be used as a starting point for the development of a systematic method and provides interpretation for other metrics in order to move towards an environmentally and technically high-performance building industry based on CE principles.

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