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Circular Construction Indicator: Assessing Circularity in the Design, Construction, and End-of-Life Phase

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Abstract: The construction industry is responsible for half of the currently excavated amount of raw materials. In addition, a quarter of all waste in the European Union is construction waste. This construction waste comprises numerous materials that can still be reused or recycled. Thus, a shift to a circular construction sector is necessary. To make this shift, it is vital to enable the measurement of and the progress toward circularity. Therefore, this paper investigates the currently available circularity indicators with regard to the 4 Rs—Reduce, Reuse, Recycle, Recover. Subsequently, a comprehensive Circular Construction Indicator framework is introduced that evaluates a construction project according to the three typical construction phases: design, construction, and end-of-life. In this, new partial indicators to assess material scarcity, structural efficiency, and service life prediction should help designers consider these aspects already in the conceptual design stage. Lastly, suggestions for further research are defined to develop further said new partial indicators.

Keywords: circular economy; circularity indicator; construction phases; 4 Rs

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1. Introduction

Our material demand has increased significantly over the last decades. Based on the current consumption rates, some of the earth's resources will already be depleted by 2025 [1], which is one of the reasons why our current linear economy has to reform to a Circular Economy (CE).

The construction sector plays an important role as it consumes about 50% of the amount of raw materials that are currently excavated [2]. In addition, approximately 25–30% of all waste generated in the European Union is Construction and Demolition Waste (CDW) [3]. This CDW comprises numerous materials that can still be reused or recycled [3]. Thus, circular principles can help to lower the environmental impact of buildings drastically [4].

To make a shift toward a CE, it is vital to enable the measurement of circularity and, thus, the progress toward a CE that is made [5]. A tool that is frequently discussed in the literature is Life Cycle Assessment (LCA). An LCA evaluates the environmental impact that a certain product causes during its complete life cycle. However, even though a CE aims to reduce the environmental impact, for example, by prioritising the reuse of components over recycling [6–10] or by eliminating waste in general [3], an LCA is not an assessment of the concerning product's circular potential. The latter requires a Circularity Indicator (CI). Saidani et al. (2019) describe an indicator as "a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention or to help assess the performance of a development actor" [11]. There is a plethora of CIs targeting various industries and products. By now, there is also a multitude of review papers on CIs (e.g., [12–16]) from which several conclusions can be drawn. First, this diverse range and scope of indicators may highlight the need for a uniform assessment method [14]. On the other hand, a sector- or product-specific indicator will yield more accurate results for the concerned sector or product than a generic indicator [17]. Subsequently, many available CIs focus mostly on the micro-level, with Ellen MacArthur's Material Circularity Indicator (MCI) [18] as a basis. Lastly, none of the currently available indicators cover all CE-related aspects. Focussing on the construction sector, Khadim et al. (2022) performed a review of several CIs for the built environment. Different aspects concerning Reuse and Recycle by incorporating Design for Disassembly (DfD) principles, as well as energy Recovery, were identified in the indicators, but, again, rarely all aspects were covered in one indicator [17].

In this paper, a comprehensive Circular Construction Indicator (CCI) is introduced. Therefore, first, an investigation of the state-of-the-art is performed to find partial indicators that can contribute to the CCI. In addition, existing partial indicators are amended, and new ways to measure certain aspects are introduced.

2. State-of-the-Art

For this state-of-the-art, several CIs were selected based on their applicability to the building sector or interesting approach of circularity to develop the CCI. Some CIs were not selected because they focus too narrowly on a single material or aspect or because they take environmental impact assessment as the basis. The selected CIs were investigated on which aspects of the 4 Rs they measure. The result of this investigation is shown in Table 1.

Table 1. Elaboration on what the different CIs actually measure.

Indicator	Functional Unit	Reduce	Reuse	Recycle	Recover
MCI [19]	mass	-input of sustainably produced renewable resources -waste generated through the recycling input and output processes -service life extension	-input of reused components -output of reusable components	-input of recycled material -output of recyclable material	-output of material for energy recovery -output of material for composting
CI Madaster [20]	mass	-input of rapidly renewable resources -waste generated through the recycling input and output processes -service life extension	-input of reused components -output of reusable components	-input of recycled material -output of recyclable material	
MCI Jiang [21]	Economic value/mass	-input of sustainably produced renewable resources -waste generated through the recycling input and output processes -service life extension	-input of reused components -output of reusable components -DfD allowing reuse -residual value indicator determining the deterioration rate of the material	-input of recycled material -output of recyclable material through functional-technical assessment	-output of material for energy recovery -output of material for composting
BCCI [22]	mass	-input of sustainably produced renewable resources -scarcity indicator based on Surplus Ore Potential -robustness indicator awards functional overdesign -adaptability indicator	-input of reused components -output of reusable components through their transportability and uniqueness	-input of recycled material -output of recyclable material	
BCI Verberne [23]	mass	-input of sustainably produced renewable resources -waste generated through the recycling input and output processes -service life extension	-input of reused components -output of reusable components -DfD allowing reuse	-input of recycled material -output of recyclable material	

Table 1. *Cont.*

Indicator	Functional Unit	Reduce	Reuse	Recycle	Recover
BCI van Vliet [24]	mass	-input of sustainably produced renewable resources -waste generated through the recycling input and output processes -service life extension	-input of reused components -output of reusable components -DfD allowing reuse	-input of recycled material -output of recyclable material	
BCI Alba Concepts [25]	mass	-waste generated through the recycling input and output processes -service life extension	-input of reused components -waste generated through the reuse output processes - DfD allowing reuse	-input of recycled material	
CBI [26]	mass	-input of sustainably produced renewable resources -waste generated through the recycling input and output processes -service life extension	-input of reused components -output of reusable components -DfD allowing reuse	-input of recycled material -output of recyclable material	
RPI [27]	mass			-potential recyclability of output material	
WLPE [28]	volume		-reuse potential of buildings through functional-technical assessment	-output of recyclable material through functional-technical assessment	
CPI [29]	mass			-potential recyclability of output material -environmental impact of recycling	-potential of output material for energy recovery -environmental impact of energy recovery
GRI [30]	mass	-scarcity indicator based on Abiotic Depletion Potential -geopolitical availability indicator		-recycling and dispersion to other processes	
CB'23 [31]	mass	-output waste -primary non-renewable material input -input of sustainably produced renewable resources -input of non-sustainably produced renewable resources -physical scarcity indicator -geopolitical scarcity indicator -environmental impact assessment	-input of reused components -output of reusable components through functional-technical and economic value assessment	-input of recycled material -output of recyclable material through functional-technical and economic value assessment	-output of material for energy recovery
3DR [32]	mass		-DfD allowing reuse -output of reusable components through functional-technical assessment		

There are a few recurring measured aspects in the different indicators. To measure Reduce, most indicators compare the input of virgin materials to the input of reused components, recycled materials, and sustainably produced renewable resources. In addition, some indicators also focus on the physical scarcity of materials and their geopolitical availability. This is, of course, very relevant because apart from the fact that virgin materials should be avoided in general, materials that are scarce in the earth's crust, or materials that are mined in geopolitically unstable regions, should be avoided at all costs.

Measuring Reuse is often done using DfD principles to assess the reusability of components. Sometimes, the transportability and the uniqueness of the components are also considered for determining their reusability, as well as their residual functional-technical value at the end of the lifecycle. The latter is particularly interesting because it acknowledges that the deterioration of products and materials over time influences the output of reusable components. Hence, it acknowledges that this is, in fact, a time function. The residual functional-technical value is sometimes also considered for the output of recyclable material at the end of the life cycle. In addition, for measuring Recycle, the efficiency of the recycling process is also taken into account, i.e., the materials waste that is produced in this process.

The output of material for energy recovery is considered to measure Recover.

Some indicators also incorporate environmental impact assessment. However, performing an LCA is a much more appropriate tool for this. Therefore, an LCA is often proposed as a complementary indicator to a CI.

Interestingly, all selected CIs use mass as a functional unit except for one that uses volume. However, no explanation is given why the volume was chosen over mass. In addition, volume and mass are interrelated through material density. As mass is the most commonly used function unit, this will be retained in what follows.

An important remark is that these indicators are all difficult to use because many factors still have to be determined and established. Apart from that, they require that the user has access to a lot of information that is often manufacturer dependent. It is self-evident that often this type of data is not available.

Another important remark is that the available CIs rarely consider the different phases separately in the life cycle of a building or product in general. There is always a design phase, a construction/production phase, and an End-of-Life (EoL) phase. In each phase, different aspects matter or require a different approach. Making this separation also allows us to evaluate the impact of different choices in the design and construction phase on the outcome in the EoL phase.

Lastly, several indicators consider service life extension as a measure for Reduce. Considering the different construction phases, this is only correct in the EoL phase, which should indeed be postponed as long as possible. However, none of the indicators actually measure Reduce in the design phase in the sense of a reduction in material requirement. Of course, it is important to reuse components and recycled materials as much as possible to minimise the demand for virgin materials and eliminate waste. However, also the amount of reusable components and recycled materials is limited. Hence, these resources also need to be applied with care. This is especially important for large construction projects with complex structural systems to achieve large spans or large heights. Measuring the structural efficiency will, therefore, be key.

3. Circular Construction Indicator

In this section, the CCI framework is introduced. It is schematically presented as a matrix in Figure 1. The rows represent the different phases of a construction project. The columns are arranged according to the 4 Rs of the CE. All aspects that should be measured and evaluated in each phase are shown in the different boxes and are organised according to the 4 Rs. The grey boxes represent indicators that can be (partially) adopted from the literature. The white boxes represent indicators that still need to be developed. The functional unit throughout the framework is mass.

For the proposed indicator, the different levels—element, component, system, and building—introduced by Durmisevic and Brouwer (2002) will be adopted. In this philosophy, a component is an assembly of elements; a system is an assembly of components, and the building, or more generally, the construction, is an assembly of systems [33].

3.1. Design

First, the design phase will be elaborated. The indicator on the element level is largely based on the MCI [19]. The major difference is that the MCI was developed to evaluate a complete product, whereas here, it is used to evaluate each element consisting of a single material separately. This will be more elaborately explained further. The flow of the different material fractions is shown in Figure 2. The symbols of the different fractions will be explained along with the equations in what follows.

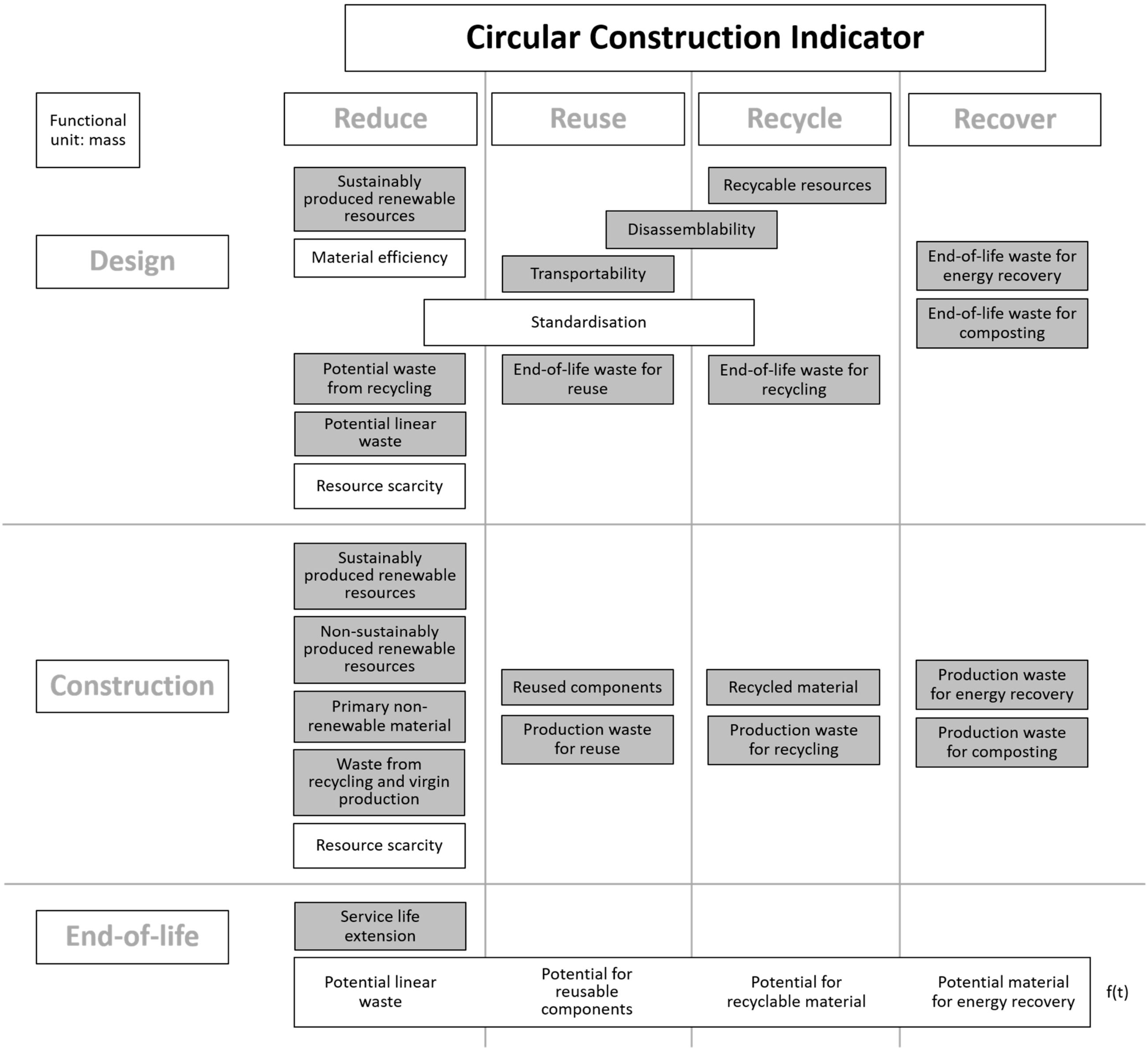

Figure 1. Overview of the CCI framework; the grey boxes indicate indicators that can be (partially) adopted from the literature.

In the first level, the element, a designer chooses certain materials, either directly or indirectly, through choosing a product. To design out waste, the elements as building stones for a product should always be either recyclable when it is a non-renewable resource or a sustainably produced renewable resource. The aim is to minimise, or completely eliminate, the linear flow that consists of the virgin materials V_d and waste $W_{el,d}$. The required virgin material V_d [19] for an element is given in Equation (1).

$$V_d = M_d \cdot (1 - F_{R,d} - F_{U,d} - F_{S,d}) = M_d \cdot (F_{V,d} + F_{NS,d}) \quad (1)$$

With:

- V_d: the mass of virgin materials in the element
- M_d: the total mass of material in the element
- $F_{R,d}$: the fraction of feedstock from recycled sources

- $F_{U,d}$: the fraction of feedstock from reused sources
- $F_{S,d}$: the fraction of sustainably produced renewable resources
- $F_{V,d}$: the fraction of virgin, non-renewable feedstock
- $F_{NS,d}$: the fraction of non-sustainably produced renewable resources

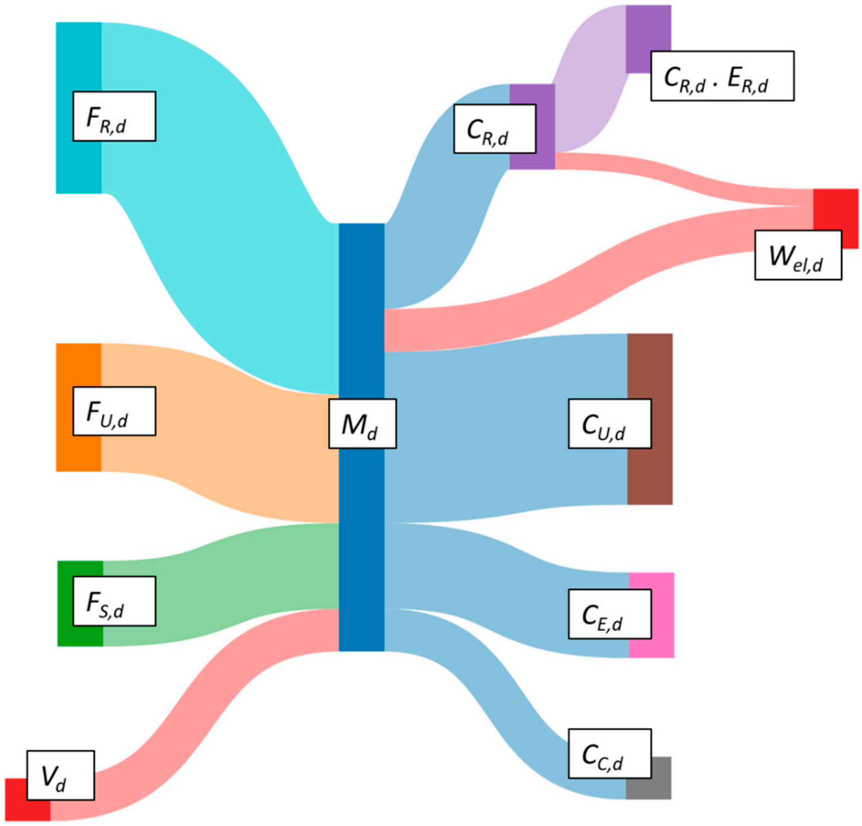

Figure 2. The flow of the different material fractions to be measured on the element level in the design phase.

In the ideal case, V_d equals zero, meaning the element is a reused element or comprises only recycled material or sustainably produced renewable material. In addition, only the element's material is considered. If it consists of several constituents, they should not be treated separately. In this, it is assumed that the element can be entirely reused, or its finished material can be recycled without separating the constituents. After all, separating the constituents is rarely possible. Hence, the fractions of the constituents are equal in both the linear and circular flows. As a clarifying example, a composite material like concrete, which is composed of cement, sand, and gravel, is considered as one material in the element level. However, the reinforcement bars in a concrete beam are a different element and are combined with the concrete at the product level, as explained further.

Subsequently, the amount of unrecoverable waste is calculated. Different waste streams should be considered, of which the direct waste W_d [19] in the EoL phase is calculated using Equation (2).

$$W_d = M_d \cdot (1 - C_{R,d} - C_{U,d} - C_{C,d} - C_{E,d}) \tag{2}$$

With:

- W_d: the direct waste in the EoL phase
- $C_{R,d}$: the fraction of material that is collected for Recycling
- $C_{U,d}$: the fraction of components that is Reused
- $C_{C,d}$: the fraction of uncontaminated biomaterials that is collected for composting
- $C_{E,d}$: the fraction of biomaterials that is used for energy Recovery

Note that by-products from composting and energy recovery must be made available as soil nutrients [19]. Reuse and Recycling are always the preferred subsequent cycles over composting and energy recovery. In addition, energy recovery from non-biological materials is not comprised in $C_{E,d}$, but is considered as waste in W_d. After all, the by-product from this process cannot be used as soil nutrients.

It is assumed that the different constituents in the finished material of the element cannot be separated anymore. Hence, if the element is assigned to $C_{R,d}$ in the EoL phase, it is assumed that the finished material is recyclable without separating the constituents.

$C_{U,d}$ depends on the design service life of the product, which the element is a part of, compared to the construction's design service life. If the product's design service life is higher, then reuse may be an option. In addition, the reuse potential of the product greatly influences the reuse in the EoL phase of the construction. This will be further elaborated at the product level.

Due to the efficiency $E_{R,d}$ of the recycling process (dependent on the type of material), an additional amount of waste $W_{R,d}$ [19] should be considered through Equation (3).

$$W_{R,d} = M_d \cdot (1 - E_{R,d}) \cdot C_{R,d} \tag{3}$$

The total unrecoverable waste $W_{el,d}$ in the EoL phase that should be considered is given in Equation (4).

$$W_{el,d} = W_d + W_{R,d} \tag{4}$$

The Linear Flow Index in the design phase LFI_d [19] can be obtained through Equation (5).

$$LFI_d = \frac{V_d + W_{el,d}}{2 \cdot M_d} \leq 1 \tag{5}$$

It should be discouraged to use materials that are defined as critical natural capital [34,35], especially when they induce a linear flow. Hence, a criticality indicator S is defined, which can be determined using the finished material's Surplus Ore Potential (SOP) [36,37]. In the design phase, S is implemented on the element level as S_d and can be calculated using Equation (6).

$$S_d = \sum_{q=1}^{s} f_{d,q} \cdot min\left\{1; \frac{1}{SOP_q}\right\} \leq 1 \tag{6}$$

With:

- $f_{d,q}$: the fraction of constituent q in the element's finished material
- SOP_q: the Surplus Ore Potential of constituent q
- s: the total number of constituents in the finished material

Eventually, the Element Circularity Index ECI_d can be calculated using Equation (7).

$$ECI_d = \left(1 - LFI_d{}^{S_d}\right) \leq 1 \tag{7}$$

Note that S_d is incorporated as the power of LFI_d. Hence, if the material consists of rare constituents, S_d will be small (closer to zero), which will result in a larger LFI_d (closer to one), reducing the ECI_d. The higher the ECI_d, the more circular the element is.

As elements are the building stones of a product, the way they are connected to each other determines whether they can be easily separated in the end-of-life phase to separate material streams. Hence, similar to the methodology proposed in the CBI [26], a new intermediate factor $ECI_{d,relation}$ is proposed, Equations (8) and (9), to express whether two connected elements can be easily disassembled. A visual representation of the methodology is shown in Figure 3.

$$ECI_{d,relation} = \frac{1}{M_r} \cdot \left(\sum_{i=1}^{2} ECI_{d,i} \cdot M_{d,i} \right) \cdot \frac{1}{7} \cdot \sum_{j=1}^{7} D_j \leq 1 \tag{8}$$

$$M_r = \sum_{i=1}^{2} M_{d,\mathrm{i}} \tag{9}$$

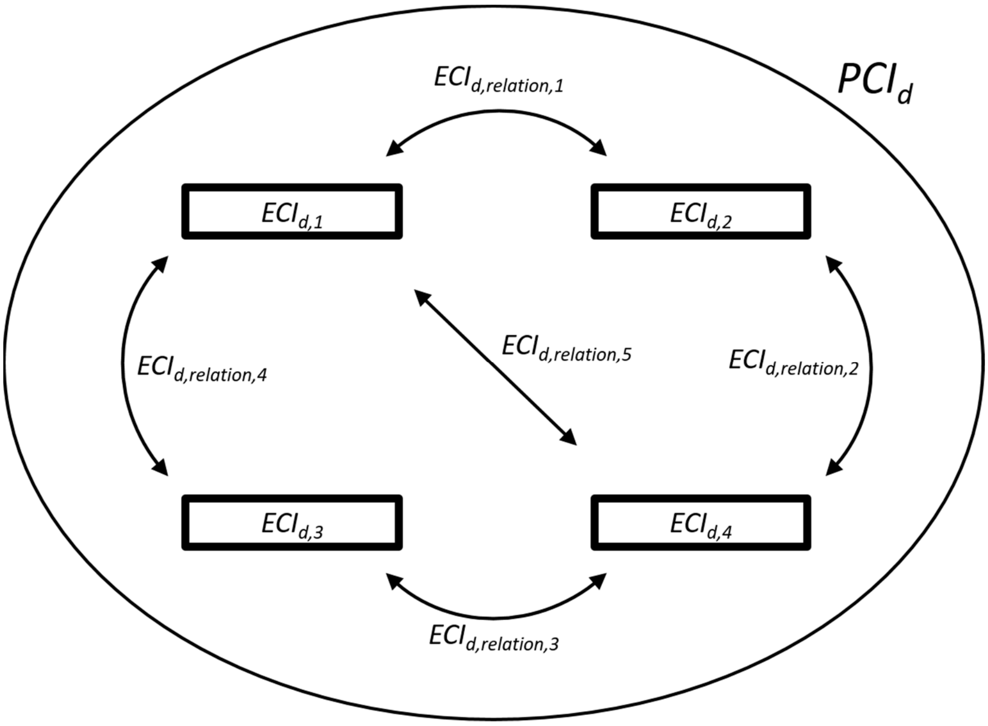

Figure 3. Visualisation of the relation between the element level and the product level. In this example, there are four elements ECI_d that are connected to each other, defined in $ECI_{d,relation}$, and together they form the product PCI_d.

With:

- $ECI_{d,i}$: the ECI_d of element i
- $M_{d,i}$: the design mass of finished element i
- M_r: the combined design mass of the two concerning elements
- D_j: a Disassembly Determining Factor (DDF) for category j

The DDF was defined by Durmisevic et al. (2003) [38]. An overview is given in the CBI [26].

Subsequently, the Product Circularity Index PCI_d [26] can be calculated by combining the total of u $ECI_{d,relation}$ as shown in Equations (10) and (11).

$$PCI_d = \frac{1}{M_p} \cdot \sum_{k=1}^{u} ECI_{d,relation,k} \cdot M_{r,k} \leq 1 \tag{10}$$

$$M_p = \sum_{k=1}^{u} M_{r,k} \tag{11}$$

Note that when a product consists of only one element, the ECI and PCI are the same. A common example is a steel beam. On the other hand, as mentioned before, a typical reinforced concrete beam is a combination of different elements: concrete (with constituents of cement, sand, gravel, and water) and steel (reinforcement bars). Both elements have their own ECI_d that should be combined into the PCI_d of the complete reinforced concrete beam.

As explained earlier, the reuse fraction $C_{U,d}$ in the EoL phase depends greatly on the product's design service life, as well as on its reuse potential. In this, it is assumed that a separate element is never reused if the product is not reusable. Therefore, two reusability checks are proposed as follows:

$$L_{construction,d} \leq \alpha \cdot L_{prod,d} \tag{12}$$

$$P_{U,d} = \beta \cdot \frac{1}{n} \cdot \sum_{j=1}^{n} D_j + \gamma \cdot N + \delta \cdot T \geq x \tag{13}$$

With:

- $L_{construction,d}$: the construction's design service life
- $L_{prod,d}$: the product's design service life
- $P_{U,d}$: the reuse potential indicator
- α: a constant between 0 and 1
- β, γ and δ: weighting factors
- N: the standardisation of the product
- T: the transportability of the product
- x: a minimum value for $P_{U,d}$

The BCCI [22] proposes a methodology to determine T, which can be adopted. For a standardised component, N can be assumed equal to one. Otherwise, it should be assumed to be zero. If the product is connected to several other products, the worst set of DDF should be retained. If both checks are true, the EoL treatment of all the elements that make up the product can be assigned to $C_{U,d}$, which then results in no waste. Otherwise, another appropriate treatment needs to be chosen depending on the type of material. If this is not possible for certain elements, they should be categorised as waste in the EoL phase.

Shifting to the system level is done using Equations (14)–(17) to calculate the System Circularity Index SCI [26]. The procedure is equivalent to the shift from *ECI* to *PCI*.

$$PCI_{d,relation} = \frac{1}{M_x} \cdot \left(\sum_{g=1}^{2} PCI_{d,g} \cdot M_{m,g} \right) \cdot \frac{1}{7} \cdot \sum_{j=1}^{7} D_j \leq 1 \tag{14}$$

$$M_x = \sum_{g=1}^{2} M_{m,g} \tag{15}$$

$$SCI_d = \frac{1}{M_s} \cdot \sum_{t=1}^{v} PCI_{d,relation,t} \cdot M_{x,t} \leq 1 \tag{16}$$

$$M_s = \sum_{t=1}^{v} M_{x,t} \tag{17}$$

With:

- $M_{m,g}$: the mass of product g with $PCI_{d,g}$

In the design phase, an additional Material Efficiency indicator E is introduced for systems that are part of the primary structure. E can be calculated using Equation (18).

$$E = \begin{cases} \frac{M_{lim}}{M_{PS}}, & M_{lim} \leq M_{PS} \\ 1, & M_{lim} > M_{PS} \end{cases} \tag{18}$$

With:

- M_{PS}: the weight of the designed primary structure
- M_{lim}: the reference weight of an optimally designed structural system adhering to the same conditions (i.e., material, span, maximum height)

Circular principles like DfD and standardised components are incorporated in M_{lim}, so it is a realistic material volume. The *SCI* for the primary structure should then be combined with *E* using Equation (19).

$$SCI_{PS,d} = SCI_d.E \leq 1 \quad (19)$$

The transition to the Circular Construction Design Index CCI_d is done using Equations (20)–(23), following the procedure proposed in the CBI [26]. The CCI_d is the final circularity indication for the design phase. It takes into consideration both the DDF and the Brand's shearing layers of longevity through the factor *LK* [38]. This factor considers that some systems (e.g., cladding, windows, and balustrades) will be changed/renewed more frequently than others. Hence, these systems' circularity weighs more on the construction's CCI_d than systems like the primary structure that are ideally used as long as possible. An overview of the factors *LK* is given in the CBI [26].

$$SCI_{d,relation} = \frac{1}{LK_l} \cdot \left(\sum_{h=1}^{2} SCI_{d,h} \cdot LK_h \right) \cdot \frac{1}{7} \cdot \sum_{j=1}^{7} D_j \leq 1 \quad (20)$$

$$LK_l = \sum_{h=1}^{2} LK_h \quad (21)$$

$$CCI_d = \frac{1}{LK_b} \cdot \sum_{f=1}^{w} SCI_{d,relation,f} \cdot LK_{l,f} \leq 1 \quad (22)$$

$$LK_b = \sum_{f=1}^{w} LK_{l,f} \quad (23)$$

With:

- LK_h: the factor expressing Brand's shearing layer to which system *h* with $SCI_{d,h}$ belongs

3.2. Construction

The circularity calculations in the construction phase are similar to the design phase. The major difference is that in this phase, the calculations are strictly limited to the production of the components and construction on site. The EoL phase of the construction is not considered. The methodology is shown in Figure 4. The symbols of the different fractions will again be explained along with the equations in what follows.

A composite material is again considered as one material at the element level. However, the linear flow of each constituent is calculated separately as the influx of virgin material and the waste created during the production phase may differ for each constituent.

First, the mass of virgin materials $V_{c,q}$ to manufacture the element is determined with Equation (24).

$$V_{c,q} = M_c \cdot f_{c,q} \cdot (1 - F_{R,c,q} - F_{U,c,q} - F_{S,c,q}) = M_c \cdot f_{c,q} \cdot (F_{V,c,q} + F_{NS,c,q}) \quad (24)$$

With:

- $V_{c,q}$: the mass of virgin materials of constituent*q*needed to manufacture the element
- M_c: the total mass of material needed to manufacture the element
- $f_{c,q}$: the fraction of constituent*q*to manufacture the element
- $F_{R,c,q}$: the fraction of feedstock from recycled sources
- $F_{U,c,q}$: the fraction of feedstock from reused sources
- $F_{S,c,q}$: the fraction of sustainably produced renewable resources
- $F_{V,c,q}$: the fraction of virgin, non-renewable feedstock
- $F_{NS,c,q}$: the fraction of non-sustainably produced renewable resources

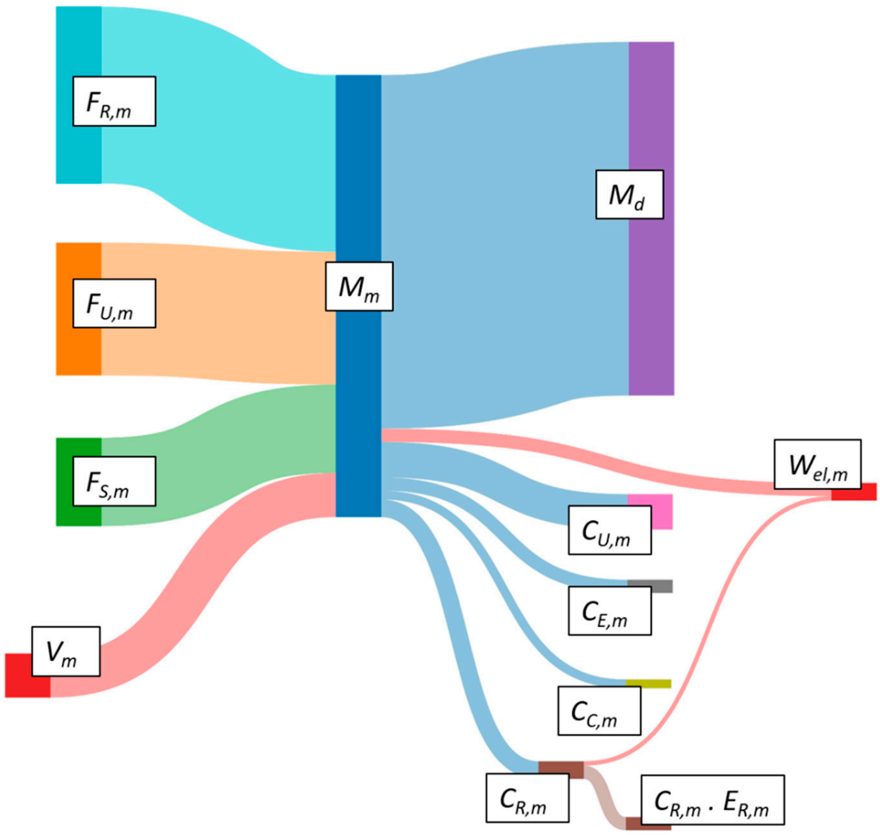

Figure 4. Flow of the different material fractions to be measured on the element level in the construction phase.

Note that $f_{c,q}$ equals one when the element's material consists of just one constituent. Another difference with V_d is that now M_c is used, the total mass of material needed to manufacture the element.

Subsequently, the amount of unrecoverable waste is calculated. Different waste streams should be considered, of which the direct waste $W_{c,q}$ in the manufacturing phase is calculated using Equation (25).

$$W_{c,q} = (M_c - M_d) \cdot f_{c,q} \cdot (1 - C_{R,c,q} - C_{U,c,q} - C_{C,c,q} - C_{E,c,q}) \tag{25}$$

With:

- $W_{c,q}$: the direct waste of constituent$q$in the manufacturing phase
- M_d: the design mass of the finished element
- $C_{R,c,q}$: the fraction of material that is collected for Recycling
- $C_{U,c,q}$: the fraction of components that is Reused
- $C_{C,c,q}$: the fraction of uncontaminated biomaterials that is collected for composting
- $C_{E,c,q}$: the fraction of biomaterials that is used for energy Recovery

Due to the efficiency $E_{R,c,q}$ of the recycling process (dependent on the type of material), an additional amount of waste $W_{R,c,q}$ should be considered through Equation (26).

$$W_{R,c,q} = (M_c - M_d) \cdot f_{c,q} \cdot (1 - E_{R,c,q}) \cdot C_{R,c,q} \tag{26}$$

Note that the recyclability of constituent$q$may depend on the recyclability of the element's materials in which it is comprised. Hence, $E_{R,c,q}$ may be equal for all constituents in the element's material.

The total amount of waste produced in the construction phase $W_{el,c,q}$ can be found with Equation (27).

$$W_{el,c,q} = W_{c,q} + W_{R,c,q} \tag{27}$$

Due to the proposed changes, the new Linear Flow Index of constituent$q$in the construction phase $LFI_{c,q}$ can be obtained through Equation (28).

$$LFI_{c,q} = \frac{V_{c,q} + W_{el,c,q}}{(2 \cdot M_c - M_d) \cdot f_{c,q}} \leq 1 \tag{28}$$

In addition, the use of scarce materials also impacts the construction phase. However, in the construction phase, every constituent is evaluated separately with S_q, using Equation (29).

$$S_q = min\left\{1; \frac{1}{SOP_q}\right\} \tag{29}$$

Note that the criticality of the element's material, comprising all its constituents, can be calculated using Equation (6).

Eventually, the Element Circularity Index ECI_c can be calculated by combining all y constituents needed to manufacture the element's material using Equation (30).

$$ECI_c = \sum_{q=1}^{y} f_{c,q} \cdot \left(1 - {LFI_{c,q}}^{S_q}\right) \leq 1 \tag{30}$$

Note that, also in the construction phase, each element should consist of just one material. Hence, considering again the example of reinforced concrete, the concrete (comprising of all its constituents), and the reinforcement bars are separate elements that are combined at the product level.

The transition to the product level (ECI_c to PCI_c) is equivalent to the design phase (see Equations (8)–(11)).

Shifting to the system level (PCI_c to SCI_c) is again equivalent to the design phase (see Equations (14)–(17)). However, in the construction phase, the material efficiency E of the primary structure is not considered. After all, in the construction phase, everything that was decided in the design phase is merely executed.

Finally, the transition to the Circular Construction, Construction Index CCI_c is again equivalent to the CCI_d (see Equations (20)–(23)).

3.3. End-of-Life

In the EoL phase, the indicator can be approached somewhat similarly. A major difference is that in the EoL phase, the input of virgin materials is not considered anymore. After all, this input is most important in the design and construction phase because such input can still be reduced. In the EoL phase, it is most important that the different material and waste streams can be separated to optimise component reuse and material recycling. The flow of the different material fractions corresponds to the right side of Figure 2. Hence, the total EoL waste on the element level $W_{el,e}$ can be calculated using Equations (31)–(33).

$$W_e = M_e \cdot (1 - C_{R,e} - C_{U,e} - C_{C,e} - C_{E,e}) \tag{31}$$

$$W_{R,e} = M_e \cdot (1 - E_{R,e}) \cdot C_{R,e} \tag{32}$$

$$W_{el,e} = W_e + W_{R,e} \tag{33}$$

Note that the EoL mass of the element M_e in these equations can be assumed equal to the design mass M_d if no further changes have been made to the structure. In addition, it is assumed again that the finished material is recyclable without separating the constituents if the element is assigned to $C_{R,d}$ in the EoL phase.

The Linear Flow Index in the EoL phase LFI_e can be obtained through Equation (34).

$$LFI_e = \frac{W_{el,e}}{M_e} \leq 1 \quad (34)$$

In the EoL phase, the criticality of the material is not considered. After all, the material is chosen in the design phase and cannot be changed anymore in the EoL phase. In the EoL phase, it is more important that the value of the different material streams is kept as high as possible. In addition, also service life extension becomes important in the EoL phase. The MCI approached this through the utility function *F(X)*, given in Equations (35) and (36), which compares how long a product was used to its industry average, t_{av} [19].

$$F(X) = \frac{0.9}{X} \quad (35)$$

$$X = \frac{t}{t_{av}} \quad (36)$$

Combining this with the reuse potential assessment in Equations (12) and (13) allows one again to determine further the fractions that are collected for reuse, recycling, composting, and energy recovery in the EoL phase.

The Element Circularity Index ECI_e can then be calculated [19] using Equation (37).

$$ECI_e = 1 - LFI_e \cdot F(X) \leq 1 \quad (37)$$

The transition from *ECIe* to *PCIe* is equivalent to the construction and design phase (see Equations (8)–(11)). Note that the reuse potential evaluation, see Equations (12) and (13), is used again to determine whether a product can be reused in the construction's EoL phase or whether it should be assigned to another material flow. As the EoL phase is time-dependent, it can be assumed that the number of reusable components will decrease the longer they have been in use.

Shifting to the system level (PCI_e to SCI_e) is equivalent to the construction phase (see Equations (8)–(11)). Moreover, in the EoL phase, the material efficiency of the primary structure is not important anymore.

The transition to the Circular Construction End-of-life Index CCI_e is similar to the CCI_d. However, in the EoL phase, only the disassemblability is important. The factors *LK* expressing Brand's shearing layers of longevity are not relevant anymore in the EoL phase. Therefore, the CCI_e is calculated as shown in Equations (38)–(41).

$$SCI_{e,relation} = \frac{1}{M_l} \cdot \left(\sum_{h=1}^{2} SCI_{e,h} \cdot M_{n,h} \right) \cdot \frac{1}{7} \cdot \sum_{j=1}^{7} D_j \leq 1 \quad (38)$$

$$M_l = \sum_{h=1}^{2} M_{n,h} \quad (39)$$

$$CCI_e = \frac{1}{M_b} \cdot \sum_{f=1}^{w} SCI_{e,relation,f} \cdot M_{l,f} \leq 1 \quad (40)$$

$$M_b = \sum_{f=1}^{w} M_{l,f} \quad (41)$$

With:

- $M_{n,h}$: the mass of system *h* with $SCI_{e,h}$

4. Discussion

The developed CCI framework considers the need for a uniform circularity assessment method [14] by taking the generally acknowledged MCI [19] as a basis. Nevertheless, the construction sector is very specific and, therefore, to yield more accurate results [17], several new partial indicators are introduced, and the results are split up according to the different phases of a construction project. The result of the CCI framework is a set of two fixed values CCI_d and CCI_c, combined with a time-dependent function CCI_e. Any partial indicator of interest can be shown as well, for example, the reuse potential indicator, the scarcity of the used materials, or the material efficiency indicator for the primary structure. This allows us to clearly show the impact of certain choices in the design and construction phases in the EoL phase or on any partial aspect of circularity. Hence, apart from using it as an evaluation tool, it can, more importantly, be used as a design tool. This allows the designer to optimise the construction for circularity in the design phase when changes can still be made. Note that the three indicators—CCI_d, CCI_c, CCI_e—can also be used independently from each other for specific design or evaluation purposes.

An additional advantage of this CCI framework is that many partial indicators in the framework can easily be altered or replaced in the future by a new partial indicator with a better approach.

All three indicators are designed around the different levels of the element, product, system, and construction. This allows one to implement partial indicators that may only be relevant at a certain level. Additionally, it allows us to show the impact of implementing DfD principles.

In the following, the newly introduced partial indicators in the different phases will be discussed.

4.1. Design

In the design phase, the procedure starts with determining the linear material flow, which is then translated into the ECI_d, largely following the methodology of the MCI [19]. Contrary to the MCI, the waste generated due to the recycling efficiency after the previous lifecycle of the material is not considered. The recycling efficiency is largely dependent on the separability of the material streams and, thus, on the design of the product it was part of in the previous life cycle. This information is rarely known, and moreover, an additional penalisation in the present lifecycle due to the poor design of the previous lifecycle is not appropriate.

On a critical note, recycling requires more energy than reuse. Until now, this is neither considered for the material influx nor for the outflow.

New is that the scarcity of the used materials is introduced. The scarcity is based on the SOP, which is an established method to assess resource scarcity that is also used in the ReCiPe LCA method [39,40]. It was calculated for 75 mineral resources [36]. A small SOP means that the mineral is abundantly available. However, the opposite is needed for S, where a small value should refer to a scarce mineral. In addition, S varies ideally between 0 and 1. There are several ways to transform the SOP into a usable value. The inverse of the SOP can be considered, or the SOP can be weighed using the SOP of gypsum, the most available mineral in the list, or iron, which is frequently used as reference material. Hence, a sensitivity analysis was executed to evaluate their performance. For the sensitivity analysis, the materials aluminium 6063, stainless steel S316, Corten steel grade A, and titanium grade II were chosen because they comprise several more and less rare constituents. The considered materials and their constituents are shown in Table 2. The obtained results for the different transformations of the SOP to obtain S are shown in Table 3. In Figure 5, different values of LFI ranging from 0.1 to 1.0 are plotted against LFI^S for the different analysed materials. Based on these results, the inverse of the SOP is chosen to determine S. The results show that a weighting using one mineral as a reference does not yield the desired results. Taking gypsum as a reference makes all materials scarce, and taking iron as a reference changes the order of scarcity of the materials.

Table 2. The selected materials with their constituents were used for the sensitivity analysis.

Material	Constituent	Fraction [%]
Aluminium 6063 [41]	aluminium (Al)	97.650
	magnesium (Mg)	0.900
	silicon (Si)	0.600
	iron (Fe)	0.350
	chrome (Cr)	0.100
	copper (Cu)	0.100
	manganese (Mn)	0.100
	titanium (Ti)	0.100
	zinc (Zn)	0.100
stainless steel S316 [41]	iron (Fe)	61.845
	nickel (Ni)	14.000
	chrome (Cr)	18.000
	molybdenum (Mo)	3.000
	silicon (Si)	1.000
	manganese (Mn)	0.100
	carbon (C)	0.080
	phosphorous (P)	0.045
	sulfur (S)	0.030
Corten steel grade A [42]	iron (Fe)	95.940
	nickel (Ni)	0.650
	chrome (Cr)	1.250
	copper (Cu)	0.550
	silicon (Si)	0.750
	manganese (Mn)	0.500
	aluminium (Al)	0.060
	carbon (C)	0.120
	phosphorous (P)	0.150
	sulfur (S)	0.030
titanium grade II [43]	titanium (Ti)	99.305
	iron (Fe)	0.300
	nitrogen (N)	0.030
	carbon (C)C	0.100
	oxygen (O)	0.250
	hydrogen (H)	0.015

Table 3. The different ways to calculate *S* from the SOP for the selected materials.

Material	S = SOPgypsum/SOP	S = 1/SOP	S = SOPFe/SOP
Al 6063	0.01	0.91	0.38
stainless steel S316	0.03	0.83	0.77
construction steel S235	0.04	1.00	1.00
Corten steel grade A	0.04	0.98	0.98
Ti grade II	0.01	0.14	0.06

Interestingly, the material with an SOP that approximates 1 is aluminium. This means that pure aluminium's *S* also approximates 1. Other frequently used construction materials like iron, clay, and gypsum have an *S* larger than 1, which is undesirable and, therefore, reduced to 1. Scarce construction materials like zinc, lead, titanium, and copper have an *S* smaller than 1. Note that the SOP and, thus, the scarcity indicator *S* can only be used for mineral resources. It can, thus, not be used for renewable materials, and a value $S = 1$ should then be used. However, a distinction is made between sustainably and non-sustainably produced renewable materials in the influx of virgin materials and waste streams.

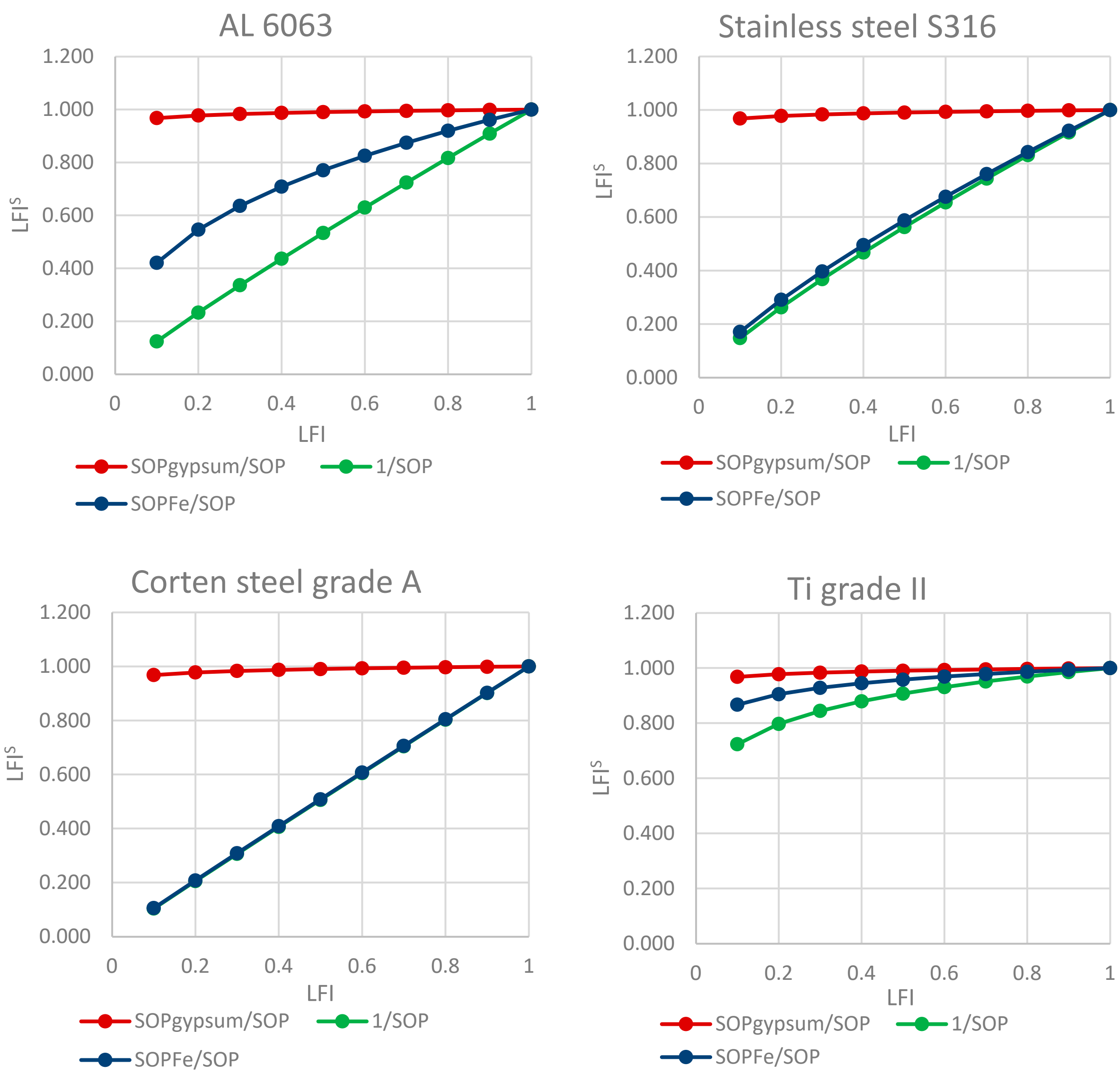

Figure 5. Visualisation of the impact of the different ways to calculate *S* from the SOP for the selected materials.

After calculating the ECI_d, the circularity index on the element level, the methodology of the CBI [26] is followed to proceed to the product, system, and construction level. At the product level, a new methodology is introduced to determine the reuse potential of a product in the construction's EoL phase, see Equations (12) and (13). The methodology compares the construction's design service life with the product's design service life. Subsequently, the way the product is connected to other products is established through the DDF. In addition, the standardisation *N* and transportability *T* of the product are determined. After all, for products to be reused, there must be an economic demand for them [44]. A proposal is formulated for *N*, but further research could introduce a more nuanced factor between 0 and 1. On a critical note, morphological standardisation in construction has largely remained limited to standardised cross-sections for steel and wooden beams [45]. Other dimensions and connections have not (yet) been considered for standardisation. Nevertheless, this is a key issue for enabling component reuse [5,45]. Returning to Equations (12) and (13), the weighting factors to combine the different reusability indicators still need to be determined. Often such weighting factors are established through expert interviews.

On the system level, a new factor *E* is introduced to evaluate the material efficiency of the primary structure, following the first R of the CE: Reduce. Brütting et al. (2020)

performed several simulations to find an optimum between the reuse of components and the environmental impact of the complete bridge structure. They confirmed that it is better to reuse as many components as possible, yet without deviating too far from the structural analysis results [46]. This confirms that material efficiency, thus, the reduction of the initial material requirement, is always key. Hence, the overdesign of the primary structure should be avoided [26,47,48]. The methodology compares the weight of the primary structure M_{PS} to the reference weight M_{lim} of an optimally designed structural system adhering to the same conditions (i.e., material, span, maximum height). This requires a methodology to predict M_{lim} before the structure is designed. In the ideal case, this methodology is more than merely an evaluation tool. It should become a design tool, providing the designer with clear information about the morphology of the most efficient structural system to create the desired span. Therefore, the theory of Morphological Indicators (MIs) can be used. MIs are dimensionless numbers expressing a geometrical or physical property of a structure [49]. They formalise the choice for the most efficient structural typology, which leads to material savings [50]. Anastasiades et al. (2022) state that the MIs can be used for the said material efficiency evaluation because they predict the most suited structural typology. The most important MI is the volume indicator W. However, the material volume predicted with W is not realistic [47]. Therefore, Anastasiades et al. (2022) developed a methodology for Warren trusses to correct the predicted material volume into a realistic one. They compared the results obtained from the MIs for different span trusses to results obtained from equivalent Finite Element Models (FEMs) [48]. The result is a set of correction curves that allows for correcting the volume obtained from W into a realistic volume, ultimately M_{lim}. In addition, as the methodology is based on the MIs, it provides the designer with the needed input on the required structural morphology. Yet, the methodology needs to be fine-tuned and extended to structural typologies other than trusses.

4.2. Construction

The circularity evaluation in the construction phase is parallel to the design phase. The major difference is that in this phase, the EoL of the construction is not considered. The linear material flow is determined for the production of the products and the actual construction. Therefore, at the element level, each constituent of the material is evaluated separately. Hence, also scarcity is considered for each separate constituent. The summation is done in the final step to calculate the ECI_c.

Note that in this phase, a lot of manufacturer-dependent information is required. However, by evaluating all phases separately, this possible lack of information can be limited to this phase.

Subsequently, the methodology proceeds to the product, system, and construction level. The difference with the design phase is that the reuse potential evaluation and the material efficiency of the primary structure are not relevant here. After all, these are all design dependent.

4.3. End-of-Life

In the EoL phase, the virgin material influx is not considered anymore because this can only be changed in the design and construction phases. Another major difference is that the EoL circularity is time-dependent through the utility function *F(X)*, adopted from the MCI [19]. Note that a structure is typically designed for a service life of 50 years [51]. Hence, if a construction is demolished sooner, *F(X)* will impose an additional penalisation in the EoL circularity evaluation. On the other hand, if the construction is maintained well and is used for a longer time, the EoL circularity score will increase.

The fractions of the EoL construction that are going to be collected for reuse, recycling, composting, and energy recovery, or that become linear waste, depend on the remaining quality of the products, elements, and materials. The reuse potential evaluation in Equations (12) and (13) is the first approach for determining the different material streams. However, these different material streams can additionally be described as interdependent through a time-quality function that is product- and material-specific. For instance, a wooden beam that is used in outdoor conditions will decay over time. Yet, this decay depends on several factors like the type of wood, preservation treatment, climate, sheltering, etc. These factors can be combined in a decay model to predict the remaining useful section of the beam which can be reused. The decayed volume that needs to be removed can be collected for energy recovery. Existing models for wood assessment, like ClickDesign [52] and Timberlife [53], could serve as the basis for further development to apply them to circularity metrics. Similar time-quality functions can be developed for other materials as well. Equivalent to the recoverability function proposed in the WLPE, this time-quality function can be more generally denoted as the reusability function U. It depends on several design specifications $Q(Q_1, Q_2, Q_3, \ldots)$ and a material-dependent deterioration function $D(t)$ [28], but also environmental specifications $E(E_1, E_2, E_3, \ldots)$ are determinant. Hence, U can be formally described with Equation (42). Combined with the reuse potential indicator $P_{U,d}$, given in Equation (13), this could complete the reusability check to determine the fractions $C_{U,e}$, $C_{R,e}$, $C_{C,e}$, and $C_{E,e}$.

$$U = f < Q(Q_1, Q_2, Q_3, \ldots), E(E_1, E_2, E_3, \ldots), D(t) > \tag{42}$$

If no dedicated methodology to assess the material degradation over time has been developed yet, then the more general methodology based on Weibull's bathtub curve proposed in the WLPE [28] can be adopted.

The shift to the product, system, and construction level is again equivalent to the CBI [26]. Only in the shift from system to construction level, Brand's shearing layers of longevity are not considered anymore. In the EoL phase, it is only important that components can be disassembled easily and that material streams can be separated.

5. Conclusions

To make a shift towards a CE, and more specifically, a circular construction industry, it is vital to enable the measurement of circularity [5]. Evaluating the latter requires a CI that measures the 4 Rs of the CE—Reduce, Reuse, Recycle, and Recover. An investigation of state of the art on CIs showed that Reduce is mostly measured through service life extension and by comparing the input of virgin materials to the input of reused components, recycled materials, and sustainably produced renewable resources. Sometimes material scarcity is considered. However, none of them actually measures reduce in terms of the absolute reduction of material use. Nevertheless, the material efficiency of complex structures, e.g., for large spans, is key to reducing the initial material requirement. Measuring Reuse is often done by assessing the reusability of components through DfD principles. Sometimes also, their transportability and uniqueness are considered, as well as their residual functional-technical value at the end of the lifecycle. For measuring Recycle, the efficiency of the recycling process is considered as this can also generate waste. Lastly, the output of material for energy recovery is considered to measure Recover. However, most of these CIs are difficult to use due to a lack of information. Additionally, they do not distinguish a circularity score for the design, construction, and EoL phases separately.

In this study, a new CCI framework is introduced. Contrary to previously developed CIs, it allows one to evaluate the circularity of a complete construction project by making a diversification between the design, construction, and EoL phases. For each phase, the aspects of circularity that are relevant in the concerning phase are considered. The contribution of this CCI framework over previously proposed CIs is that it presents methodologies to objectively evaluate the reusability of components in the EoL phase, both in the case where the construction has reached its design service life, as in the case where the construction would be disassembled at a different point in time. Future research will need to focus on establishing weighting factors to combine the different reusability indicators. Moreover, time-dependent technical-functional quality functions should be developed further, as they require a dedicated approach for each material separately.

To incorporate the physical scarcity of material into circularity assessments, a scarcity indicator based on the SOP of material is introduced. In the past, similar indicators have been proposed. The contribution of the currently introduced scarcity indicator is that it is readily and easily applicable.

Lastly, the framework presents a methodology to evaluate the R of Reduce for the primary structure through a material efficiency indicator. It is proposed that the theory of the MIs can serve as a basis to evaluate the structural efficiency and the consequent material requirement objectively. However, further research is required to fine-tune further and extend the methodology.

The advantage of the proposed framework is that it allows us to clearly show the impact of certain choices in the design and construction phases on the EoL phase or on any partial aspect of circularity. An additional advantage of this CCI framework is that many partial indicators in the framework can easily be altered or replaced by a new partial indicator with a better approach.

Apart from using it as an evaluation tool, the methodology can, more importantly, be used as a design tool. This allows the designer to optimise the construction for circularity in the conceptual design phase, when changes can still be made, hence improving the circular performance in the construction and EoL phases.

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Abbreviations

General	
4 R's	Reduce, Reuse, Recycle, Recover
CCI	Circular Construction Indicator
CDW	Construction and Demolition Waste
CE	Circular Economy
CI	Circularity Indicator
DDF	Disassembly Determining Factor
DfD	Design for Disassembly
EoL	End-of-Life
f(t)	Function of time
LCA	Life Cycle Assessment
State-of-the art circularity indicators	
3DR	Design for Disassembly, Deconstruction, and Resilience
BCCI	Bridge Circularity Composite Indicator
BCI Verberne	Building Circularity Indicator by Verberne
BCI van Vliet	Building Circularity Indicator by van Vliet
BCI Alba Concepts	Building Circularity Index by Alba Concepts
CB'23	Circular Construction 2023
CBI	Circular Bridge Indicator
CI Madaster	Madaster Circularity Indicator
CPI	Circular economy Performance Indicator
GRI	Global Resource Indicator
MCI	Ellen MacArthur's Material Circularity Indicator
MCI Jiang	Material Circularity Indicator by Jiang
RPI	Reuse Potential Indicator

WLPE	Whole-Life Performance Estimator
Design	
$C_{R,d}$	the fraction of material that is collected for Recycling
$C_{U,d}$	the fraction of components that is Reused
$C_{C,d}$	the fraction of uncontaminated biomaterials that is collected for composting
$C_{E,d}$	the fraction of biomaterials that is used for energy Recovery
CCI_d	Circular Construction Design Index
D_j	a Disassembly Determining Factor for category j
E	material efficiency indicator
$E_{R,d}$	the efficiency of the recycling process
ECI_d	Element Circularity Index in the design phase
$ECI_{d,i}$	the ECI_d of finished element i
$ECI_{d,relation}$	Intermediate factor defining whether two connected elements can be easily disassembled
$f_{d,q}$	the fraction of constituent$q$in the element's finished material
$F_{NS,d}$	the fraction of non-sustainably produced renewable resources
$F_{R,d}$	the fraction of feedstock from recycled sources
$F_{S,d}$	the fraction of sustainably produced renewable resources
$F_{U,d}$	the fraction of feedstock from reused sources
$F_{V,d}$	the fraction of virgin, non-renewable feedstock
$L_{construction,d}$	the construction's design service life
$L_{prod,d}$	the product's design service life
LFI_d	Linear Flow Index in the design phase
LK_b	the sum of all $LK_{l,f}$ belonging to all $SCI_{d,relation,f}$ that should be considered in CCI_d
LK_h	The factor that considers the Brand's shearing layers of longevity
LK_l	the sum of the LK_h that belong to the two considered systems in $SCI_{d,relation}$
M_d	the total mass of material in the element
$M_{d,i}$	the design mass of finished element i
M_{lim}	the reference weight of an optimally designed structural system adhering to the same conditions (i.e., material, span, maximum height)
$M_{m,g}$	the mass of product g with $PCI_{d,g}$
M_p	the sum of all $M_{r,k}$ belonging to all $ECI_{d,relation,k}$ that should be considered in PCI_d
M_{PS}	the weight of the designed primary structure
M_s	the sum of all $M_{x,t}$ belonging to all $PCI_{d,relation,t}$ that should be considered in SCI_d
M_r	the combined design mass of the two concerning elements in $ECI_{d,relation}$
$M_{r,k}$	the combined design mass of the two concerning elements in $ECI_{d,relation,k}$
M_x	the combined mass of the two concerning products in $PCI_{d,relation}$
N	the standardisation of the product
$P_{U,d}$	the reuse potential indicator
PCI_d	Product Circularity Index in the design phase
$PCI_{d,relation}$	Intermediate factor defining whether two connected products can be easily disassembled
s	the total number of constituents in the finished material
S_d	criticality indicator in the design phase
SCI_d	System Circularity Index in the design phase
$SCI_{d,relation}$	intermediate factor defining whether two connected systems can be easily disassembled, taking into account the shearing layers of longevity they are part of.
SOP_q	the Surplus Ore Potential of constituent q
T	the transportability of the product
V_d	the mass of virgin materials in the element
W_d	the direct waste in the EoL phase

$W_{el,d}$	the total unrecoverable waste on the element level
$W_{R,d}$	waste created during recycling
Construction	
$C_{C,c,q}$	the fraction of uncontaminated biomaterials that is collected for composting
$C_{E,c,q}$	the fraction of biomaterials that is used for energy Recovery
$C_{R,c,q}$	the fraction of material that is collected for Recycling
$C_{U,c,q}$	the fraction of components that is Reused
CCI_c	Circular Construction, Construction Index
$E_{R,c,q}$	the efficiency of the recycling process of constituent q
ECI_c	Element Circularity Index in the construction phase
$f_{c,q}$	the fraction of constituent q to manufacture the element
$F_{NS,c,q}$	the fraction of non-sustainably produced renewable resources
$F_{R,c,q}$	the fraction of feedstock from recycled sources
$F_{S,c,q}$	the fraction of sustainably produced renewable resources
$F_{U,c,q}$	the fraction of feedstock from reused sources
$F_{V,c,q}$	the fraction of virgin, non-renewable feedstock
$LFI_{c,q}$	Linear Flow Index of constituent q in the construction phase
M_c	the total mass of material needed to manufacture the element
PCI_c	Product Circularity Index in the construction phase
S_q	criticality indicator for constituent q
SCI_c	System Circularity Index in the construction phase
$V_{c,q}$	the mass of virgin materials of constituent q needed to manufacture the element
$W_{c,q}$	the direct waste of constituent q in the manufacturing phase
$W_{el,c,q}$	the total amount of waste of constituent q produced in the construction phase on the element level
$W_{R,c,q}$	waste created when recycling constituent q
End-of-Life	
$C_{R,e}$	the fraction of material that is collected for Recycling
$C_{U,e}$	the fraction of components that is Reused
$C_{C,e}$	the fraction of uncontaminated biomaterials that is collected for composting
$C_{E,e}$	the fraction of biomaterials that is used for energy Recovery
CCI_e	Circular Construction End-of-Life Index
$E_{R,e}$	the efficiency of the recycling process
ECI_e	Element Circularity Index in the end-of-life phase
$F(X)$	utility function
LFI_e	Linear Flow Index in the end-of-life phase
M_b	the sum of all $M_{l,f}$ belonging to all $SCI_{e,relation,f}$ that should be considered in CCI_e
M_e	the end-of-life mass of the element
M_l	the combined mass of the two concerning systems in $SCI_{e,relation}$
$M_{l,f}$	the combined mass of the two concerning systems in $SCI_{e,relation,f}$
$M_{n,h}$	the mass of system h with $SCI_{e,h}$
PCI_e	Product Circularity Index in the end-of-life phase
SCI_e	System Circularity Index in the end-of-life phase
$SCI_{e,relation}$	intermediate factor defining whether two connected systems can be easily disassembled
t	actual service life of the element
t_{av}	industry average of the element's service life
W_e	the direct waste in the EoL phase
$W_{el,e}$	the total unrecoverable waste on the element level
$W_{R,e}$	waste created during recycling
X	service life extension factor

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