Resources, Conservation & Recycling 186 (2022) 106541

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Measuring product-level circularity performance: An economic value-based metric with the indicator of residual value

Li Jiang [a], Silu Bhochhibhoya [b,*], Noud Slot [c], Robin de Graaf [a]

[a] *Department of Construction Management and Engineering from the Faculty of Engineering & Technology, University of Twente, Drienerlolaan 5, 7522NB, Enschede, The Netherlands*
[b] *Zuyd University of Applied Science, Smart Urban ReDesign, Academy Built Environment, Heerlen, 6400 AN, The Netherlands*
[c] *Plegt-Vos, Construction Company, Sherwood Rangers 1, 7551 KW, Hengelo, The Netherlands*

ARTICLE INFO

Keywords:
Circular economy
Material circularity indicator
Circularity metric
Economic value
Residual value

ABSTRACT

The construction industry is becoming circular, where resources are used in a closed loop. However, no standard method is available for measuring the circularity performance of building components. The Material Circularity Indicator (MCI) is one of the most ambitious methods. However, the MCI is criticized for its reliance on mass flow and the over-optimistic assumption regarding residual value. The research thus aims to adapt the MCI by addressing these limitations by using the economic value (E) as the measurement unit and introducing a new indicator of residual value (R). A residual value calculator is also developed to quantify R. A case study approach is adopted to evaluate the effect of E and R individually. The results show that using E can award materials' contributions regarding circularity based on their relative value. Furthermore, using R can capture value change and provides different significance to materials input and output considering value difference.

1. Introduction

The world is facing severe challenges: resources are being exhausted, excessive use of fossil fuels results in climate change, and the environment is being polluted (Circular Construction Economy, 2018). Those problems are due to the unsustainable linear production process, where virgin materials are taken from the environment, then used to make products, and eventually become worthless after the End of Life (EoL) (EMF, 2015). In response to the global challenges, the novel concept of Circular Economy (CE) has emerged, where resources in a system can be used continuously and long-lasting through circular strategies (Holland Circular Hotspot and Circle Economy, 2019). Recognizing the benefits that the CE can make towards creating a resilient and sustainable future, the Netherlands has set targets for the country: 50% less primary raw material consumption in 2030 and a fully circular economy by 2050. In concrete terms, this means that virgin resources should be minimized, and simultaneously, building components should be designed in a way to facilitate reuse possibilities with maximized retained value (Government of the Netherlands, 2021). As a resource-intensive sector, the construction industry is responsible for an estimated 50% of resource consumption and 40% of total waste in the Netherlands (Rijkswaterstaat, 2015). Many scholars have started their research concerning circularity transition in the construction sector, and the popularity of this topic has been rapidly increasing in recent years. One of the growing methodological debates and interests concerns how to measure and identify opportunities in circular strategies and how to award the benefits (Walker et al., 2018). This is because CE initiatives can only be guaranteed when there is an appropriate evaluation framework for monitoring progress toward a CE (Saidani et al., 2019).

Many different methods are available for measuring the circularity value of products (so-called product-level circularity assessment). EMF (2015) points out that “there is no recognized way of measuring how effective a product is in making the transition from linear to circular”, and has developed the Material Circularity Indicator (MCI) for assessing product-level circularity. The MCI has developed following the principle of lifecycle thinking, by considering the input, utility and output. Being user-friendly, the MCI can be used even by non-experts of CE (Saidani et al., 2017). Besides, the MCI can provide a first overview of product circularity performance with limited input data. Hence, it could be used to understand the effect of different material combinations on product performance, to help companies to make optimal decisions (Saidani et al., 2017). Sharing these advantages, the MCI is regarded as one of the most promising frameworks for measuring circularity performance (WBCSD, 2018) and provides a useful starting point (Linder et al., 2017).

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* Corresponding author.
E-mail address: silu.bhochhibhoya@zuyd.nl (S. Bhochhibhoya).

https://doi.org/10.1016/j.resconrec.2022.106541
Received 8 April 2022; Received in revised form 25 June 2022; Accepted 9 July 2022

Many other methods have been devised from the MCI and tailored to the construction sector (Zhang et al., 2021). For example, Verberne (2016) has built a Building Circularity Indicator for measuring how well a building performs in the context of circularity based on MCI, and further modified by van Vliet (2018) and Zhai (2020). Moreover, Zhang et al. (2021) and Coenen et al. (2021) have studied how to assess the material efficiency of buildings and infrastructure projects respectively, using the MCI as the basis. Similarly, the MCI has been customized by non-academic bodies like consultancy organizations and policy institutes to develop methods like the Building Circularity Index (Alba, 2015) and Madaster Circularity indicator (Madaster, 2018) in the construction industry. With the high popularity, an improved version of MCI was also published in 2019 (see EMF (2019)).

However, there is still a lack of a scientifically substantiated method for measuring circularity performance. As mentioned by Platform CB'23 (2019)[1], the existing methods need further improvements and there is an increasing desire to increase knowledge on the degree of circularity in the construction sector. Developing a tool for monitoring, evaluating and quantifying the circularity performance is vital (Walker et al., 2018), while it is challenging to develop a totally new method. WBCSD (2018) states a circular measurement framework should "build upon existing frameworks and standards". This is because building on top of popular approaches is more likely to uptake rather than create something new (WBCSD, 2018). As discussed before, the MCI is one of the widely used methods and may be applicable to measure product-level circularity. However, two limitations are evident in the MCI and also inherited by those MCI-based circularity methods. Firstly, the MCI is too dependent on the measurement unit – mass, which implies a product with a higher mass has a higher value in a CE. The main drawback of mass flow is that it does not consider the relative value scarcity of different materials. As the example proposed by Coenen et al. (2021), considering the relationship between demand and supply, a metric ton of gold is much more valuable compared with the same amount of gravel; hence, using materials' weight to differentiate their contribution to circularity performance is only one side of the story. Secondly, the MCI assumes that the quality/quantity of a product does not change over time and that no part of the product is degraded or lost during its use phase. In particular, this means the quality of the salvaged product can be seen as the same as the new one, and the residual value is equal to its original value before usage. In other words, the MCI is over-optimistic about the embedded value of assets in a closed-loop (reuse/recycling). Furthermore, it is widely agreed that value retention can be achieved in a closed loop with a CE. This is because products always maintain at least some value after EoL, and circular strategies provide opportunities for those materials to enter restoration cycles. However, there are no approaches that consider the residual value as an independent indicator for assessing the circularity performance in the construction sector. However, quantification of the residual value is a prerequisite to support a circularity assessment, for example; how much value is maintained after one exploitation period. Presently, it is still unclear in a CE, and as proposed by Platform CB'23 (2019), the knowledge and experience are insufficient to gain an insight into the degree to which value is created, used and lost.

In sum, MCI has the potential to contribute to a standard circularity metric and has also been adapted or referred to by many other methods in academia and the construction industry. However, these two limitations of the MCI regarding the dependency on mass flow and the over-optimistic assumption concerning residual value may provide unjustified circularity insights. Hence, this study aims to develop a new circularity metric by addressing these two limitations. The specific research questions are:

1) How can the issue of the mass flow be adjusted to represent the value scarcity of different materials in the MCI?
2) How can the residual value of building components be quantified more realistically and how it can support the circularity assessment in the MCI?

The research was conducted in different phases, starting with reviewing state-of-art to address the aforementioned limitations (phase 1). The mathematical models for estimating the circularity performance based on the MCI were developed in phase 2, including a tool for quantifying the residual value of a building component. To visualize and test the functioning of the mathematical models, a case study was conducted in phase 3 using a real project with a prefab façade. The study ends with a discussion and conclusion, emphasizing the advantages of the adjusted method and recommendations for future work.

2. Phase 1 - state of the art

This chapter presents the literature review, in which the possible measurement units of circularity methods and factors that affect the residual value of building components are discussed.

2.1. Possible measurement units

The measurement units used to assess circularity performance are fundamental for a metric. Linder et al. (2017) state that there are various units including mass, volume, energy, and usage time; however, each of them could not distinguish the different types of materials and their scarcity. Di Maio et al. (2017) mention that the shortcomings of these units can be alleviated by complementing the value of materials, instead of focusing only on physical units. To integrate different materials into a single circularity value, the chosen units should allow for the comparison of the relative value (Linder et al., 2017). In this way, the circularity metric can send clear information; for example, 1 kilogram of gravel is counted as less important than the same weight of gold. Satisfying those requirements, the "economic value of materials" is proposed as a reasonable unit, as introduced by Di Maio et al. (2017): "a key advantage of using economic value is that while mass represents only quantity, economic value embodies both quantity and quality". The idea of using economic value as the measurement unit is not new and has repeatedly been applied in the existing circularity metrics (See Di Maio et al. (2017).

However, in the current market, there is no specific information about the economic value of each material or product (Linder et al., 2017). Therefore, in essence, the problem is: how to obtain information of economic value embedded in materials, or what information can be used to represent the economic value? On the one hand, the price can be served as an excellent source of information for economic value, which is "the price that will be paid for the highest and best use of real estate" (Roulac et al., 2006). Di Maio et al. (2017) also argue that the prices of materials or the market value are excellent information to reflect the scarcity of resources in a market-based economy. On the other hand, Linder et al. (2017) criticize that the materials' prices are not equal to their economic value, since prices could only express available information in a market, and may convey distorted information where market failures occur. However, the approximations of economic value have to be used to make the economic value-based metric applicable in practice, and the price is often the best available representation of the materials' relative scarcity, although it could not represent the accurate information of the economic value.

2.2. Possible solution for the residual value calculator

In this study, the residual value is defined as the value of a building component when undergoing demolishment or deconstruction. It is presented as a percentage compared with a new product (represented by

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[1] The platform CB'23 has committed to draft agreements for the entire construction sector, to contribute circularity transition in the Netherlands.

100%), to estimate the amount of value maintained when the component is approaching its EoL. Although it is essential for the circularity assessment, the literature on the residual value is still in its early stage. Note that there is much uncertainty regarding the remaining value after several years of usage. Despite all the uncertainties, this study (or the residual value calculator) assumes that the residual performance of recovered building products can be predicted during the design phase and also affected by the deterioration factor, based on the study of Akanbi et al. (2018). These two groups of factors will be discussed in the remainder of this subchapter.

2.2.1. *Design strategies*

It is assumed that if a great deal of effort is devoted to the design by keeping further profits in mind, the material and added value can be maintained at the highest level (Akanbi et al., 2018), although it is difficult to conduct life cycle analysis for the salvaged products because the information is still unavailable during the design phase (Akinade et al., 2015). Similarly, Amory (2019) introduces that value retention and value recovery can be achieved by means of a clear and anticipating design called Design for Circularity (DfC), and the circular performance of a building is improved by various aspects of circularity, represented as Design for X (DfX). According to Amory (2019), there is no standard set of DfX identified among scholars, and these strategies are complementary or partly overlap with each other rather than mutually exclusive. Design for Disassembly (DfD) can be represented as the most important design strategy (Webster, 2007) since, on the one hand, its application guarantees the realization of other strategies to a certain degree. For example, Design for Maintenance (DfM) is a circular strategy proposed among scholars (Abdullah et al., 2017), aiming to ensure easily repairability and replacement at reasonable costs during the operational phase (Amory, 2019; EMF, 2014). A building that applied DfD strategies is more likely to have good inspectability and modularity, and hence, assures the maintenance possibility without too many difficulties. Furthermore, EMF (2014) introduces that the reuse potentials of materials are largely dependent on easy disassembly; as a result, DfD is necessary for the achievement of the strategy – Design for Reuse. Besides, EMF (2014) introduces DfD can also increase product utility (Design for Product Life Extension) and allows for remanufacturing after usage (Design for Remanufacturing). On the other hand, Webster (2007) argues that except from environmental benefits (e.g. reducing energy consumption), applying DfD yields economic benefits for construction companies. With growing interest in green buildings, there is a robust market for reused/recycled materials (e.g. brick and timber), and the prices of those salvaged materials are more likely to increase in the future, pushed by the cost of raw materials (Webster, 2007). Therefore, extracting salvageable materials from a building designed with DfD strategies would be easier and cost-effective, increasing the financial profits for the companies. In sum, DfD is the core circular strategy with far-reaching consequences. There are extensive studies conducted on principles, factors and guides for DfD to realize building disassembly rather than demolishment after EoL (van Vliet, 2018). Being one of the most complementary methods, the Disassembly Determining Factors (DDF) assess the disassembly potential from functional, technical and physical aspects (Durmisevic, 2006). Afterward, van Vliet (2018) has determined the most important DDF, which are categorized into two groups: product disassembly factors and connection disassembly factors, to assess the disassembly potential of a product and all related connections.

Another design strategy – Design for Recovery (DfR) is considered as a complementary circular strategy with DfD in academia. That is because those principles belonging to DfD could not guarantee material recovery (reusability/recyclability) (Akinade et al., 2015). Akinade et al. (2015) further introduced that using materials without toxicity and secondary finishes can foster material to be reused or recycled after EoL, and hence improves the residual performance of products, while these strategies are not useful for building disassembly. However, estimating the residual performance of a product is complex, and may be affected by various design strategies, and some of them may be difficult to quantify. For example, Design for Durability is one strategy highlighted by various scholars for maintaining the material value and could not be guaranteed by DfD or DfR. Although there are a few studies conducted for analysing the product durability (e.g. NEN-EN 350[2]), the durability or the quality assessment for most materials is still unavailable, which means it is difficult to quantify this strategy currently. For alleviating this limitation, the residual value calculator will be designed as an open function, and it is recommended to incorporate more factors (which can be assessed objectively) in further research.

2.2.2. *Deterioration factor*

An asset depreciates over time, which is caused by three different reasons, namely, physical deterioration, functional obsolescence, and external obsolescence (Manganelli, 2013; Wilhelmsson, 2008). Among these, physical deterioration is the effect of the passage of time on the building (Akanbi et al., 2018), expressed as the decrease in the length of the life cycle and therefore the equivalent loss of value, measurable during buildings' useful life (Manganelli, 2013). In this study, physical deterioration is considered, representing the decline in value with respect to increasing age, decay or natural wear and tear of an asset. To model a situation for the needs of the physical deterioration analysis, the Weibull distribution function or the 'bathtub' model is most commonly applied to describe the reliability behavior of products through their lifecycle (Akanbi et al., 2018), as shown in Fig. 1.

The failure rate is high in the initial phase due to design and manufacturing errors and decreases to a constant level during the useful life of the product (Akanbi et al., 2018). Afterwards, the product enters the wear-out phase with an increasing failure rate when approaching its expected lifetime (Akanbi et al., 2018). The cumulative distribution function of the bathtub model $F(t)$, can be represented by the standard two-parameters shown as (Nowogońska, 2016):

$$F(t) = 1 - R(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{1}$$

Where $R(t)$ is the reliability function, and the cumulative failure rate of the bathtub curve is represented as $h(t)$ is determined by the scale parameter α and the shape parameter β. A detailed explanation of the parameters is provided in Xie and Lai (1996).

$$h(t) = \left(\frac{t}{\alpha}\right)^{\beta} \tag{2}$$

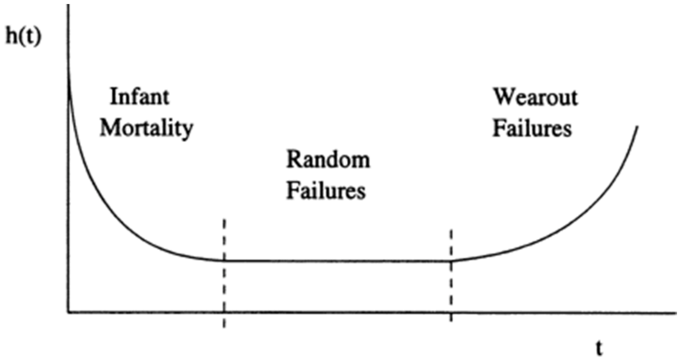

Fig. 1. The Bathtub curve - the failure rate against time (Akanbi et al., 2018; Klutke et al., 2003).

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[2] NEN-EN 350 is a set of standards for classifying the durability of biological agents and wood/wood-based materials.

Maintenance strategies can protect material value from depreciation, and hence; contribute to a higher residual value. Furthermore, EMF (2012) mentioned a circular principle of "power of inner circle", where maintenance is the most encouraged circular strategy. This is because the larger saving (e.g. material and energy) can be achieved with the help of appropriate maintenance planning rather than reuse or recycling. Wilhelmsson (2008) argues that although the value loss is expected over time, the depreciation rate can be slowed down with good maintenance. Similarly, Farahani et al. (2019) argue that maintenance can increase the component's performance or its condition state. Therefore, the effect of maintenance activities should be considered when designing a deterioration function for a building component. In academia, the maintenance effect on the building value is often represented as a percentage. For example, Junnila et al. (2006) conclude that maintenance activities can contribute about 4–15% of the overall life cycle impact of a building and in Farahani's study (2019), the maintenance effects of 20% and 16% were given to wooden windows and cementous façades, respectively.

When maintenance actions are incorporated, it should be considered how these measures affect the deterioration curve. The slope of the hazard function $h(t)$ should increase after each maintenance action due to both externally and internally induced conditions (Monga and Zuo, 2001; Nakagawa, 1988). Therefore, the failure rate of a component during ith interval is (Monga and Zuo, 2001):

$$h_i(t) = \theta_i * h(t) \; for \; i = 1, 2, 3. \tag{3}$$

Where $h(t)$ is the failure rate function before going through any maintenance actions, and θ_i is the deterioration factor, following the condition of $\theta_1 = 1$ and $\theta_{(i+1)} \geq \theta_i$ (Monga and Zuo, 2001). Users can define the value of θ_i based on the practical situation, and Nakagawa (1988) also provides a mathematical expression:

$$\theta_i = \sum_{k=0}^{i-1} \left(1 + \frac{k}{k+1}\right) \tag{4}$$

3. Phase 2 - model development

In the chapter above, possible solutions for addressing the limitations of the MCI are discussed. Specifically, it is proposed to replace mass flow with the measurement unit of economic value and introduce a new indicator to capture the value change of building products. Moreover, several groups of factors influencing the residual value are also discussed, to make the new indicator applicable with a residual value calculator. A detailed description of the adapted circularity metric is covered first in this chapter, followed by the development of the residual value calculator.

3.1. *The circularity metric development*

With the new measurement unit of economic value (represented by E) and the indicator of residual value (represented by R), the circularity metric so-called MCI' can be adapted, as shown in Table 1. Same with the MCI, the MCI' is developed by first calculating the virgin feedstock and the unrecoverable waste, and then constructing the utility factor. Fig. 2 is the diagrammatic representation of the assessment process of the MCI', which will be introduced in the rest of this section.

3.1.1. *Calculating virgin feedstock*

Consider a product in which Fu', Fr' and Fb' represent the fraction derived from reused, recycled and bio-based sources respectively. The economic value of the virgin materials can be calculated by:

$$V' = E(1 - Fu' - Fr' - Fb') \tag{5}$$

Where E is the economic value of the material input in total.

Compared with the MCI, the measurement unit – mass (M) is replaced by economic value (E) in Eq. (5). Fu', Fr' and Fb' can be calculated by Eq. (6) adapted from Linder et al. (2017):

Table 1
Comparison of formulas between MCI and MCI'.

Formulas MCI	Formulas MCI'
V = M * (1-Fu-Fr-Fb)	V' = E * (1-Fu'-Fr'-Fb')
Wo = M * (1-Cu-Cr)	Wo' = E * R * (1-Cu'-Cr')
W = Wo + Wc	W' = Wo' + Wc'
LFI = (V + W) / 2M	LFI' = (V'+W') / (E + E*R)
MCI = max [0, 1-LFI * F(X)]	MCI' = max [0, 1-LFI' * F(X)]
Where:	
V/V'	Virgin feedstock expressed by mass or economic value
W/W'	Unrecoverable waste expressed by mass or economic value
Fu/Fu'	Fraction of reused sources based on material mass or economic value
Fr/Fr'	Fraction of recycled sources based on material mass or economic value
Fb/Fb'	Fraction of bio-based sources based on material mass or economic value
Cr/Cr'	Fraction of materials collected for recycling based on material mass or economic value
Cu/Cu'	Fraction of materials collected for reuse based on material mass or economic value
Wc/Wc'	Waste generated in the recycling process expressed by mass or economic value
Wo/Wo'	Materials going to landfill/incineration expressed by mass or economic value
LFI/LFI	Linear flow index based on mass or economic value
M	Material mass
E	Economic value
R	Residual value
F(X)	A function of the product utility

$$Fu' \Big/ Fr' \Big/ Fb' = \frac{economic\ value\ of\ reused/recycled/biobased\ mateirals}{economic\ value\ of\ all\ materials} \tag{6}$$

3.1.2. *Calculating unrecoverable waste*

Supposing Cu' represents the fraction of the economic value of the materials in the product being collected for reuse after EoL and Cr' is the fraction of the economic value going into the recycling process. The value loss due to landfill/incineration is Wo' and can be calculated by:

$$Wo' = E'(1 - Cu' - Cr') \tag{7}$$

Where E' is the economic value of the recovered materials in the product after EoL.

As discussed in sub-chapter 2.2, the indicator of residual value (represented as R) is assumed to express the ratio of the value after EoL compared with the new one or the input; for example, 0.5 means that the materials retain half of the value after usage. Therefore, E' can be represented as the percentage of the economic value of the material input (E):

$$E' = E * R \tag{8}$$

Hence, Wo' can be revised as:

$$Wo' = E * R * (1 - Cu' - Cr') \tag{9}$$

Considering Ec' is used to express the efficiency of the recycling process (the percentage of retained material value in a new product); therefore, the loss of economic value generated in the recycling process is given by:

$$Wc' = E * R * Cr' * (1 - Ec') \tag{10}$$

Hence, the economic value loss of all unrecoverable waste is given by:

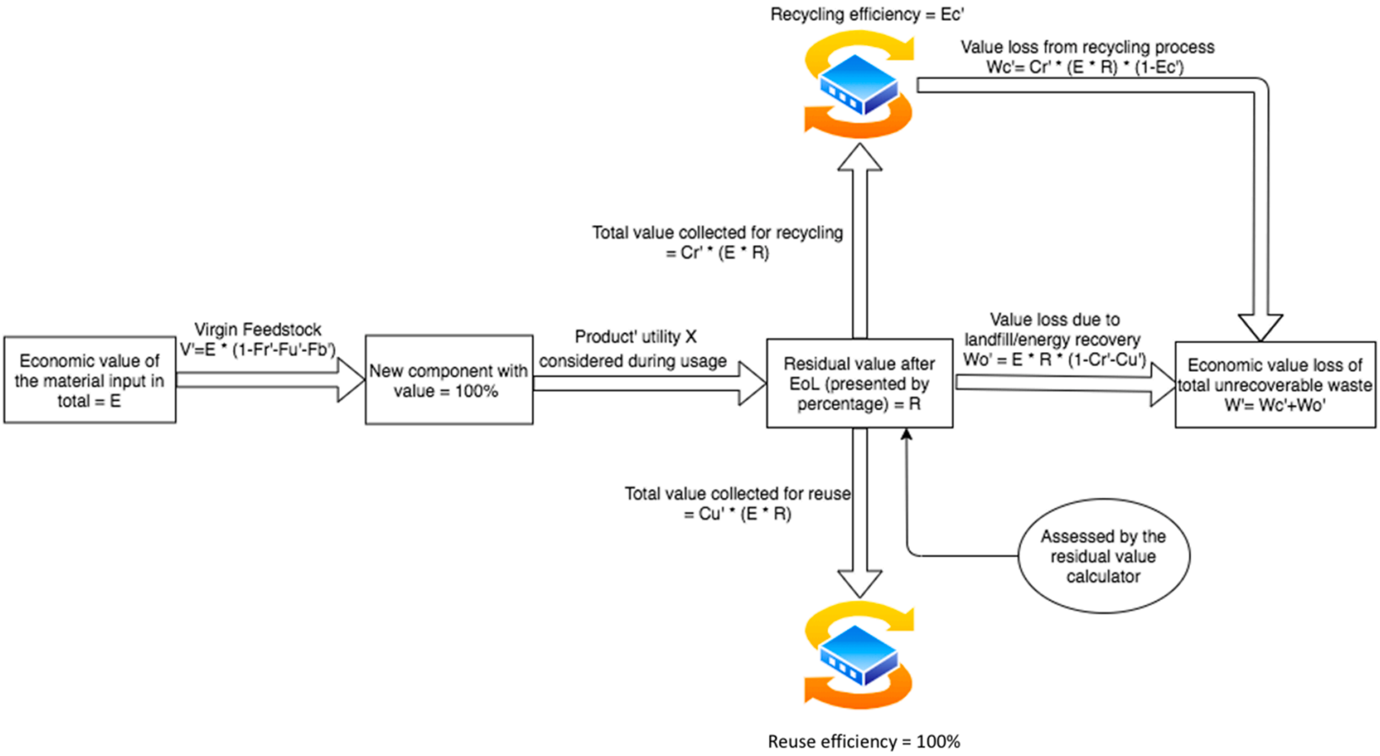

Fig. 2. Diagrammatic representation of the assessment process (adapted from EMF (2019)).

$$W' = Wo' + Wc' \tag{11}$$

3.1.3. *Calculating the linear flow index and utility factor*

Adapted from the MCI, the linear flow index (LFI') measures the economic value of the materials flowing in a linear procedure, as presented in Eq. (12). The numerator is the amount of economic value flowing in a linear fashion, which can be represented as the value of the virgin feedstock and the unrecoverable waste ($V' + W'$). The denominator is the sum of the amounts of economic value flowing in the system ($E + E'$). The index can range from 0 to 1, where 1 is a purely linear flow, and 0 is a completely circular flow.

$$LFI' = \frac{V' + W'}{E + E'} = \frac{V' + W'}{E + E * R} = \frac{V' + W'}{E * (1 + R)} \tag{12}$$

Furthermore, same with the MCI, the MCI' assumes that increased serviceable life or higher use intensity can lead to material saving, represented by the utility factor X, which can be calculated by dividing a product's technical lifespan by its functional lifespan.

3.1.4. *Calculating the adapted material circularity indicator*

Considering the input, utility and output, the MCI' is determined as:

$$MCI' = 1 - LFI' * F(X) \tag{13}$$

Where $F(X)$ is a function of the utility X, determining the effect of the product's utility on its MCI score. Same with the MCI, to avoid a negative value for the circularity score, the bottom-line (0) is taken into consideration, and the final determination of MCI' is:

$$MCI' = Max[0,\ 1 - LFI' * F(X)] \tag{14}$$

3.2. *The residual value calculator development*

As shown in Fig. 2, the MCI' introduces the residual value (R) as an independent indicator, which is assessed by a residual value calculator. Specifically, the calculator is expressed as a function of circular design strategies S and deterioration factor $D(t)$, which both influence the residual performance of building products. This is represented in Eq. (15), referred from Akanbi et al. (2018).

$$R = S * D(t) \tag{15}$$

3.2.1. *Design strategies*

Two design strategies are highlighted in this study including Design for Disassembly (Sd) and Design for Recovery (Sr). As the most important design strategy, the application of Design for Disassembly can realize value retention by assuring the maintenance possibility, increasing product utility and guaranteeing reuse potentials, and possible yield economic benefits as discussed in sub-chapter 2.2.1. Furthermore, the strategy of Design for Recovery aims to foster material reusability/recyclability through circular design strategies, which has a positive impact on the residual performance of products. Assuming these two factors affect the residual value equally (with a weighting factor of 1/2), an expression of residual value (S) is presented in Eq. (16). The assumption of the same level of significance for different design strategies may not practicable, however; no research has looked into this. Note that the residual calculator can be seen as an open function, allowing for the incorporation of different design strategies with different factors.

$$S = \frac{1}{2} * Sd + \frac{1}{2} * Sr \tag{16}$$

The level of DfD or the disassembly potential of a product (Sd) can be measured using Eq. (17). This method is referred from van Vliet (2018), to assess the disassembly possibilities from seven aspects at the product and connection level. Here, the weights for these disassembly factors (represented by PD_j or CD_j) are equal with 1/7.

$$Sd = \frac{1}{7} * \left(\sum_{j=1}^{n} PD_j + \sum_{j=1}^{n} CD_j \right) \tag{17}$$

Where,

PD_j = product disassembly potential of factor j including assembly shape, independency, method of fabrication and type of relational pattern

CD_j = connection disassembly potential of factor j including assessability of connection, type of connection and assembly sequences

The Design for Recovery can be embodied from two aspects: avoidance of materials with secondary finishes and using materials with no toxic or hazardous content, based on the study of Akanbi et al. (2018). Consider Sr represents the level of DfR or the recovery potential of a building component and can be expressed as (Akanbi et al., 2018):

$$Sr = \frac{1}{2} * \frac{vf}{vm} + \frac{1}{2} * \frac{vh}{vm} \tag{18}$$

Where,

vf = volume of materials without secondary finishes

vh = volume of materials without hazardous content

vm = total volume of material in a building component

Therefore, bringing Eq. (17), and 18 into Eq. (16), the overall effect of design strategies becomes:

$$S = \frac{1}{2} * \frac{1}{7} * \left(\sum_{j=1}^{n} PDj + \sum_{j=1}^{n} CDj \right) + \frac{1}{2} * \frac{1}{2} * \left(\frac{vf}{vm} + \frac{vh}{vm} \right) \tag{19}$$

3.2.2. *Deterioration factor*

Deterioration is normally inevitable, which is an important indicator of the valuation process of an asset (Dziadosz and Meszek, 2015). In this study, physical deterioration is focused on, and it is assumed that maintenance measures can offset the negative effect of aging on the building value. To allow the incorporation of the maintenance strategies, the deterioration behavior of building components is described in two phases as a reliability function based on the Weibull distribution and Farahani's study (2019), as shown in Eq. (20). Phase one describes the initial irreversible degradation process, and phase two outlines the process where the value of a building is improved after applying maintenance strategies. Assuming the deterioration value at time "0" or the $D(0)$ is 100%, the deterioration model is used to predict the future deterioration value *"D(t)"* of a component at time *"t"*.

$$D(t) = \begin{cases} \exp\left[-\left(\frac{t}{\alpha_1}\right)^{\beta 1} \right] Phase\ 1 (t \le t_i) \\ D(t_i) * \exp\left[-\left(\frac{t - t_i}{\alpha_i}\right)^{\beta i} \right] Phase\ 2\ (t \ge t_i) \end{cases} \tag{20}$$

Where,

t_i = the time when phase 1 ends and phase 2 begins (years)

$D(t_i)$ = deterioration value in percentage at "t_i"

For clarity, an example of considering the value of α and β is provided. The value of β can be estimated considering the shape of the failure rate: 1) increase with $\beta > 1$; 2) constant with $\beta = 1$; 3) decrease with $\beta < 1$ based on the definition of Weibull distribution. Nowogońska (2016) argues that time-related wear is the main cause of building deterioration. Therefore, for example, the component can be assumed to degrade with a linearly increasing hazard rate in each phase with $\beta_1 = \beta_i = 2$. The next step is to choose a threshold deterioration value (e.g. 0.2 from Farahani's study (2019), which represents the minimum acceptable quality of the component. Given an expected lifespan (e.g. 75 years), the value of α_1 can be easily calculated (e.g. $\alpha_1 = 60$). Besides, for modeling the situation where the slope of hazard rate increases after maintenance actions, the factor θ_i is considered, and the mathematical function (Eq. (4)) can be applied to calculate the value of θ_i. Afterward, from Eq. (2) and 3, the value of α_i can be obtained. However, in practice, the input variables α, β, $D(t_i)$ can be defined or estimated by users, and the accuracy can be improved using time-performance data (obtained from inspection). Finally, with design strategies S and deterioration factor $D(t)$, the residual value of a building component can be estimated using Eq. (15).

4. Phase 3 – validation

A mathematical model for estimating the circularity performance is formulated above by addressing two limitations in the MCI (mass flow and residual value). To visualize the effect of these two adjustments, a prefab façade was chosen to compare the effectiveness of the MCI and the MCI' proposed in this study. Specifically, the façade is cladded by lightweight brick slips with glue connections and is composed of various natural materials (e.g. wood and glass wool).

In phase 3, the validation followed two steps. In step 1, the circularity performance of the façade was calculated based on mass and economic value respectively. The first step aims to gain an understanding of how these two different measurement units affect the circularity value, to answer the first research question about the issue of mass flow in the MCI. Step 2 was designed for the second research question to examine the effect of the new indicator of residual value. It firstly calculated the residual value (step 2. a) and then compared the circularity performance with and without integrating the indicator (step 2. b). Furthermore, four different scenarios were designed as follows:

1) base scenario: the brick slips were produced with purely virgin materials and expected to become totally unrecoverable after usage;
2) scenario 2: the brick slips are assumed to be produced with totally virgin materials and fully recycled after usage;
3) scenario 3: the brick slips are assumed to be produced with totally virgin materials and fully reused after usage;
4) scenario 4: the brick slips are assumed to be produced by 100% reused materials and become worthless after usage.

The base scenario represents the current project situation, where materials flow in a linear manner. Other scenarios simulate common circular strategies in practice. Among them, scenario 2 and scenario 3 pay closer attention to collecting materials for the reuse or recycling process after EoL, while scenario 4 considers the input stream by replacing virgin materials with recovered ones. The usage of these scenarios can examine how effective the circularity method (either MCI or MCI') can guide decision-makers to move from a linear scenario toward a circular scenario. Furthermore, how users can make decisions when several circular possibilities are available (e.g., scenario 3 and scenario 4) with the circularity method(s). Note that except for the brick slips in different scenarios, the rest of the materials involved in the façade maintain the same as in the base scenario. The reason for focusing on the cladding is because the brick slips are lightweight while costly in the project; hence, the comparison differences would be more significant for explanations.

As the backbone of a circularity metric, the information of the measurement units should be obtained firstly. In this study, the materials' weight and the purchase prices (representing the economic value) of the façade used in the MCI and the MCI' were obtained. Based on the above Equations, the required information for calculating materials' origins and waste scenarios includes the fraction of recycled/reused/bio-based feedstock and the percentage of materials collected for reuse and recycling after the expected lifespan. Furthermore, for assessing the residual value of the façade, the disassembly and recovery potential were assessed based on the design plans provided by the relevant construction company.

4.1. *The effect of the economic value (Step 1)*

To analyze the effect of different measurement units in a metric, the circularity performance of the façade is calculated based on the mass flow and economic value respectively in step 1. As shown in Table 2, the performance score of the façade is 0.66 based on the MCI. Following the

Table 2
Results of different scenarios (with $R = 0.58$ from step 2. a).

I Scenarios	II MCI (mass “M”)	III Adjusted metric (economic value “E”)	IV Adjusted metric (economic value “E” + residual value “R”)
Base scenario	0.66	0.280	0.282
Scenario 2 – recycle brick slips after usage	0.68 (3.0%)	0.44 (57.1%)	0.40 (41.8%)
Scenario 3 – reuse brick slips after usage	0.69 (4.5%)	0.55 (96.4%)	0.48 (70.2%)
Scenario 4 – reused input for producing brick slips	0.69 (4.5%)	0.55 (96.4%)	0.63(123.4%)

assessment process of the MCI’ (from Eq. (5) to 14), another circularity score of 0.28 can be calculated based on the unit of the economic value. Here, the condition of “$R = 1$″ is involved, which means the materials’ value is still under the optimistic assumption where the value loss is neglected. This is because step 1 is designed to compare the measurement units – mass and economic value, without considering the effect of R.

Assuming the brick slips can be recycled after usage in scenario 2 (with an efficiency of 60%), as compared with the base scenario, the circularity performance is improved by only 3% using the mass unit; while more than 50% assessed based on the economic value, as shown in Table 2. The differences are more significant in scenario 3 where the brick slips are assumed to be reused with an efficiency of 100%. The circularity performance is improved by nearly double using the economic value, while there is only a small increase (4.5%) based on the materials’ weight. These results show that using different measurement units affects the circularity assessment significantly. The difference is mainly determined by the critical material – brick slips, which are lightweight with a density of 5 kg/m^3, accounting for 6.8% of the product’s weight. However, the brick slips contribute more than 60% of the cost. The dependence on using mass flow may send wrong information to users, who are discouraged to adopt circular strategies with only small improvements in a situation when many lightweight materials are used. In contrast, the value scarcity can be captured based on economic value, which may provide more precise information for decision-makers.

4.2. *The effect of the indicator R (Step 2)*

4.2.1. *Calculating the value of R (Step 2.a)*

Two groups of factors, including the design strategies and the deterioration factor, are considered when calculating the residual value. The façade has a high recovery potential without toxic and secondary finishes. However, with the traditional connections (e.g. glue, staples and taps), the scores of "accessibility to connection" and "type of connection" are low, with 0.4 and 0.2 respectively, based on the assessment criteria provided by Durmisevic (2006) (see details in van Vliet (2018)). Using Eq. (19), the effect of design strategies S on the residual performance is assessed as 0.9. Based on Eq. (20), the deterioration curve of the façade is illustrated, where value improvement represents a maintenance effect (or a combination of activities taken together) at a given time. The input variables (α; β) are calculated using the example provided in subchapter 3.2.2. Furthermore, due to unavailable information, it is assumed that the maintenance measures would be carried out within the time interval of 30 years (at the 30th year and 60th year), compromising 15% building value. As shown in Fig. 3, the orange line follows the same deterioration pattern as the blue line before 30 years. When incorporating the maintenance effect, the deterioration value $D(t)$ at the 75th year (the expected lifespan) increases from 0.21 to 0.64 as illustrated in Fig. 3.

Integrating the effect of S and $D(t)$, the residual value after the expected lifecycle of 75 years can be estimated as 0.58 using Eq. (15). It is the input of the indicator R to support the overall circularity assessment, as shown in Fig. 2 and will be introduced in the next step (step 2. b).

4.2.2. *Examining the effect of R (Step 2. b)*

The processes of assessing circularity performance with or without considering the indicator of residual value (R) are almost the same, following Eqs. (5) to 14. A specific value should be given to R (0.58 calculated in step 2. a) when taking value change into account;

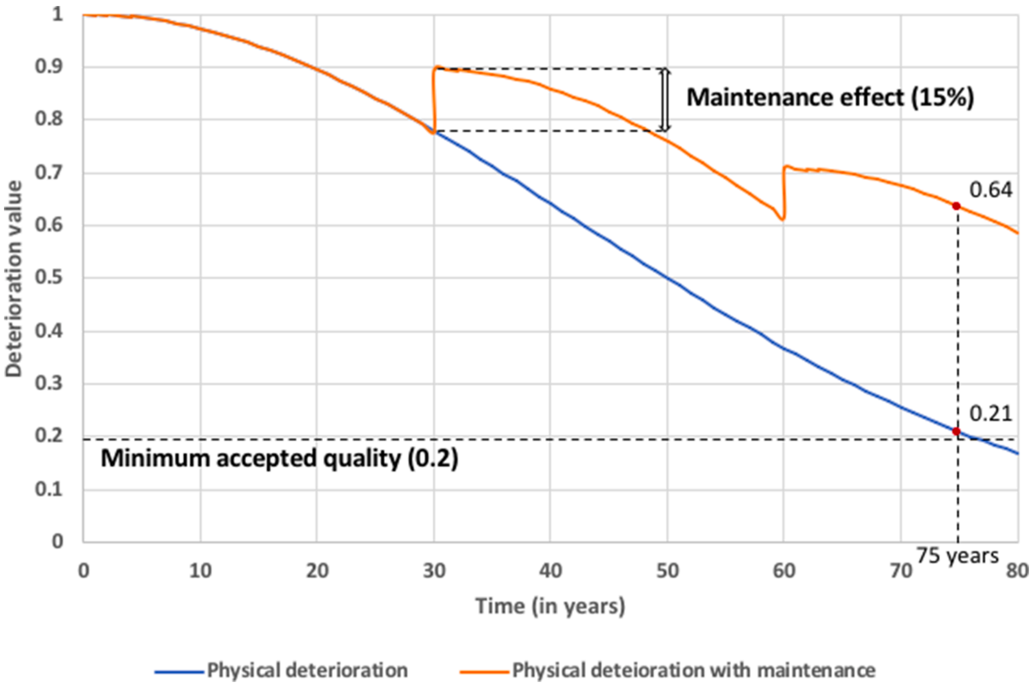

Fig. 3. Physical deterioration with/without maintenance.

otherwise, R=1. For further comparison, scenario 4 is created, where the brick slips are assumed to be produced using reused materials. As presented in Table 1 (column III), the results of scenario 3 and 4 are the same when only considering the economic value and ignoring the value change ($R = 1$). However, as shown in column III and column IV of Table 2, integrating R ($R = 0.58$) provides a negative effect; for example, the increase rate becomes smaller from 57% to 42% in scenario 2, and from 96% to 70% in scenario 3. In contrast, R has a positive effect on circularity performance, increasing the score from 0.55 to 0.63 in scenario 4.

The circularity performance is largely determined by the value of the Linear Flow Index (LFI') as presented in Eq. (12). Therefore, the LFI' is used to discuss how R affects the overall results. When the same factor of the numerator and denominator (E) is removed, LFI' can be represented as:

$$LFI' = \frac{V' + W'}{E*(1+R)} = \frac{E*V'_f + E*R*W'_f}{E*(1+R)} = \frac{V'_f + R*W'_f}{(1+R)} \tag{21}$$

Where V'_f and W'_f can be interpreted as the economic value fraction of the virgin input and the unrecoverable waste.

As shown in Eq. (21), the indicator R can be seen as the coefficient of W'_f. When the residual value is not considered (or R =1), V'_f and W'_f have the same significance on the circularity performance, which means efforts made for feedstock and waste are regarded as the same. That is why the same circularity value (0.55) is given to scenario 3 and 4 (column III in Table 2), taking the effect of using reused materials and reusing materials as the same. If $R < 1$, the significance of W' is lower than V', which means when the materials' value declines over time, it is more important to use fewer virgin materials rather than increasing the recovery rate (reuse or recycle) under consistent conditions, and vice versa. Therefore, R provides a negative effect in scenario 2 and scenario 3, while showing positively in scenario 4.

The positive/negative effect becomes more evident when a smaller value is given to R, as presented in Table 3. When the residual value decreases from 0.58 to 0.3, reducing recoverable waste in scenario 3 has a relatively smaller contribution to the overall circularity performance (from 0.48 to 0.41). However, the positive effect of R becomes more significant (from 0.63 to 0.70) when decreasing the amount of virgin feedstock in scenario 4. By contrast, when the residual value is expected to be larger than its original one ($R > 1$), facilitating recycling or reuse after EoL is more meaningful for improving the overall circularity performance from an economic perspective. As seen in Table 3, when R equals 1.3, reusing the brick slips can bring more circularity benefits (0.59) than using reused/recycled materials (0.52). Similarly, the conclusion is more evident when a bigger value ($R = 1.8$) is predicted.

However, the conclusions drawn above are not tenable under the condition of "$W'_f = V'_f$", which means R has no effect (positive or negative) on the circularity performance when the economic value fraction of the virgin feedstock and the unrecoverable waste are the same. This could explain the base scenario, where the circularity performance is almost equal with and without integrating R, since the value fraction of the unrecoverable waste is only slightly higher than the virgin feedstock.

Table 3
Results of different scenarios (with a different value for R).

	$R =$ 0.3	$R =$ 0.58	$R =$ 1.3	$R =$ 1.8
Base scenario	0.283	0.282	0.280	0.280
Scenario 3 - reuse brick slips after usage	0.41	0.48	0.59	0.63
Scenario 4 - reused input for producing the brick slips	0.70	0.63	0.52	0.47

5. Discussion

5.1. Scientific contribution

In the section above, a circularity metric (MCI') based on the MCI is outlined, and it is expected to contribute to the standard agreements of the circularity measurement. Keeping the advantages of the MCI, the MCI' is developed with lifecycle thinking by capturing the development phase, usage phase and EoL phase. Simultaneously, the MCI' is improved by covering two weaknesses in the MCI: too much dependent on mass and over-optimistic about the residual value.

Concerning contributions, the MCI' pays closer attention to the measurement units, representing the value embedded in the materials. The unit of economic value is proposed by complementing the value of materials, instead of focusing only on physical units. In this study, the effect of using the mass flow and the economic value of materials are compared. Table 2 (column II and column III) shows that these two units affect the circularity value significantly. These results reveal that only a small increase (less than 5%) was observed in circular scenarios compared to the linear scenario (base scenario) when depending on mass flow. The dependence on mass flow underestimates the effort made for those critical materials that are lightweight, but valuable. In contrast, when using economic value as the measurement unit, the efforts made for critical materials are awarded correspondingly based on their relative value. By doing this, the users are encouraged to consider a wider variety of materials, instead of focussing only on heavy materials. This can be reflected by a big score increase when transmitting from linear to circular scenarios in Table 2.

Another contribution of the study is the residual value calculator to examine how much value is maintained after EoL. In the calculator, design strategies are involved, which allow the companies to understand how those circular strategies affect value retention, thus, facilitating the CE implementation at the early stage. Furthermore, a two-phase deterioration function is developed with the incorporation of condition-improving maintenance actions. Because of this, companies are encouraged to maintain the material's value during the usage phase with maintenance, obeying the circular principle of "power of inner circle" to acquire a larger saving. Moreover, this study examines the effect of using residual value as a new indicator in the MCI'. Table 2 (column III and column IV) shows that the indicator (R) affects the circularity performance differently in different scenarios; for example, has a negative and positive effect in scenario 3 and scenario 4 respectively. This is because integrating R gives different significance to materials input and output based on value change. When the materials' value is expected to decline over time with $R < 1$, more value is embedded in material input rather than output. Hence, under this condition, the indicator R in the MCI' encourages decision-makers to pay closer attention to materials input instead of output based on their value difference, for example; reducing the amount of virgin feedstock (in scenario 4) rather than decreasing waste quantities (in scenario 3). In contrast, when $R > 1$, the value of materials increases, hence; circular attempts of collecting those materials for reuse and recycling (to reduce waste quantities) are more attractive. In sum, integrating R can help users to make appropriate circularity-related decisions from a value perspective when different circularity possibilities are available.

5.2. Limitations in the circularity assessment and future research

Although some work has been done on circularity assessment of building products, this study is limited to direct materials contained in a product and does not provide information on other dimensions like energy, water and emission. The focus of the MCI' may mislead decision-makers. For example, the high possibility of recycling can improve the circularity performance based on the MCI', while on the other hand, it may result in a negative effect on energy efficiency. Similarly, although the metric proposes to use the unit of economic value in order to share a link between economic benefits and circularity performance, it does not contain information regarding issues that are linked to the lifecycle cost. For example, the MCI' only contains the positive effect of maintenance on the residual value based on an estimated plan, neglecting the cost for inspection, maintenance or renovation. Hence, it is recommended that other indicators are used to gauge the cost bearing in the whole lifecycle (e.g. Life Cycle Costing LCC). Furthermore, the MCI' was only applied to a single case study and is limited to light-weighted materials inside the case of the façade. The feasibility of the methods should be further validated with different building components with different materials.

Moreover, the residual value calculator only considers two groups of factors that influence the remaining value of building components after EoL. Because of this, a certain degree of uncertainty may be involved in the calculator given its narrow focus. Specifically, regarding the design strategies, other strategies that protect value loss like Design for Durability or Design for Adaptability could be integrated into the calculator. Besides, it is impracticable that the same level of significance is used for the identified design strategies (DfD and DfR), but there is no available research that makes a distinction between different strategies. In terms of the deterioration factor, physical deterioration is mainly focused on, ignoring the functional and external depreciation. Besides, except for the maintenance effect, other factors (like a price appreciation of materials) may also offset the negative effect of aging on the components. Except for the limitations pointed out before, there are no clear guidelines to support users to identify input variables in the residual value calculator, which may hinder the implementation of the tool in practice. Last but not least, as mentioned in the sub-chapter of 4.2.2, the indicator R losses its ability to capture value change in the MCI', when the fraction of the virgin materials is equal to the fraction of the waste. Hence, the mathematical model may need to be modified to accommodate this possible situation.

6. Conclusion

There is an urgent need for a well-established approach to quantify product-level circularity, aiming to estimate the progress of circularity transition. Being one of the most popular approaches, the MCI is served as a good starting point for developing a standard circularity metric. In this study, a new circularity metric (MCI') was developed by addressing two limitations in the MCI including its dependency on using mass flow and over-optimistic assumptions about the residual value. Firstly, the MCI is criticized that it is too dependent on mass flow, which could not effectively represent the value scarcity of, for example, lightweight but valuable materials. The study proposes using the unit of economic value (E) to provide information regarding materials' relative value. Secondly, the MCI fails to capture changes in materials' value and the residual value (after EoL), which is assumed to be the same as its new one. For addressing this limitation, an independent indicator – the residual value (R) is proposed. This covers the over-optimistic assumptions about the embedded value of materials in the MCI. Furthermore, this study considers how to quantify R, by developing a residual value calculator that considers design strategies and a deterioration factor.

A case study (façade) with four scenarios was used to examine the effect of R and E individually. The façade was built with a critical material (brick slips), accounting for only 6.8% of the product's weight while contributing 60% of the cost. Regarding the effect of E, the MCI (based on mass) scored much higher than the MCI' (based on E) in a linear scenario as shown in Table 2 (column II and III). Moreover, when circular attempts were made for this critical material in other scenarios, the MCI scores barely change in different scenarios compared with the results' changes assessed by the MCI'. It is concluded that the MCI underestimates the circularity influence of those light materials and the usage of economic value as the measurement unit instead, can provide more precise circularity-related information in a situation where many lightweight materials are used. Furthermore, the effect of the new indicator (R) was also examined and it was shown that R is capable of capturing value change and hence, differentiating the significance of materials input and output. When the materials' value declines over time ($R<1$) based on the residual value calculator, the involvement of R encourages circular efforts made for reducing virgin feedstock rather than decreasing unrecoverable waste. This is because the value involved in the material input is higher than the output in a component system. With the new indicator of residual value (R), decision-makers can make better decisions to improve the circularity performance from a value perspective.

In sum, this study develops an adjusted MCI' which could provide more reliable information compared to the MCI, by considering the value difference of materials (with E as the measurement unit) and the value change over the whole lifespan (with R as a new indicator). However, certain limitations are involved in the current study. Specifically, future work is required to consider the other aspects of a circular model such as energy and water consumption, to evaluate the circularity performance comprehensively. Furthermore, there are few studies concerned with the way of calculating the residual value in a CE, and the proposed residual value calculator is still in its early stage and should be improved further, for example; by involving other important factors.

CRediT authorship contribution statement

Li Jiang: Conceptualization, Methodology, Writing – review & editing, Data curation, Formal analysis, Validation, Visualization, Writing – original draft. **Silu Bhochhibhoya:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Noud Slot:** Conceptualization, Data curation, Supervision. **Robin de Graaf:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

We would like to thank the construction company - Plegt-Vos in the Netherlands to provide us with an appropriate case. Thank you, Ir. Berri de Jonge for your time and support during the research.

References

Abdullah, M.A.A., Ariff, N.R.M., Muhamad, N., Ismail, N., Kaliwon, J., 2017. Façade maintainability for mosques: a review for maintenance consideration. In. J. Real Estate Stud. 11 (2), 21–24.

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator. Resour. Conserv. Recycl. 129, 175–186.

Akinade, O.O., Oyedele, L.O., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A., Bello, S. A., 2015. Waste minimisation through deconstruction: a BIM based Deconstructability Assessment Score (BIM-DAS). Resour. Conserv. Recycl. 105, 167–176. https://doi.org/10.1016/j.resconrec.2015.10.018.

Alba. (2015). *Building Circularity Index* Retrieved 1/14 from https://albaconcepts.nl/building-circularity-index/#slide-1-wat-is-bci.

Amory, J., 2019. A Guidance Tool For Circular Building Design. Delft University of Technology, Architecture and the Built Environment: Delft, The Netherlands.

Circular Construction Economy. (2018). *Transition agenda Circular Economy*. https://hollandcircularhotspot.nl/wp-content/uploads/2019/09/Circular-Construction-Economy.pdf.

Coenen, T.B.J., Santos, J., Fennis, S.A.A.M., Halman, J.I.M., 2021. Development of a bridge circularity assessment framework to promote resource efficiency in infrastructure projects. J. Ind. Ecol. 25 (2), 288–304.

Di Maio, F., Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: a market value approach. Resour. Conserv. Recycl. 122, 163–171. https://doi.org/10.1016/j.resconrec.2017.02.009.

Durmisevic, E., 2006. *Design For Disassembly As a Way to Introduce Sustainable Engenieering to Building Design & Construction* Delft University of Technology]. Delft. http://resolver.tudelft.nl/uuid:9d2406e5-0cce-4788-8ee0-c19cbf38ea9a.

Dziadosz, A., Meszek, W., 2015. Selected aspects of determining of building facility deterioration for real estate valuation. Procedia Eng. 122, 266–273. https://doi.org/10.1016/j.proeng.2015.10.035.

EMF. (2012). *Towards the circular economy*. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.

EMF. (2014). *Designing for a circular economy*. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.

EMF. (2015). *Circularity indicators - an approach to measuring circularity*. https://www.ellenmacarthurfoundation.org/assets/downloads/Circularity-Indicators-Methodology.pdf.

EMF. (2019). *Circularity Indicators - An Approach to Measuring Circularity*https://ellenmacarthurfoundation.org/material-circularity-indicator.

Farahani, A., Wallbaum, H., Dalenbäck, J.-O., 2019. Optimized maintenance and renovation scheduling in multifamily buildings–a systematic approach based on condition state and life cycle cost of building components. Construc. Manage. Econ. 37 (3), 139–155. https://doi.org/10.1080/01446193.2018.1512750.

Government of the Netherlands. (2021). *Inland Shipping: inland shipping as a response to the growth in container flow*. https://www.government.nl/topics/freight-transportation/inland-shipping.

Holland Circular Hotspot, & Circle Economy. (2019). *Circular cities: accelerating the transition towards circular cities*. https://hollandcircularhotspot.nl/wp-content/uploads/2019/04/HCH-Brochure-20190410-web_DEF.pdf.

Junnila, S., Horvath, A., Guggemos, A.A., 2006. Life-cycle assessment of office buildings in Europe and the United States. J. Infrastruct. Syst. 12 (1), 10–17.

Klutke, G.-A., Kiessler, P.C., Wortman, M.A., 2003. A critical look at the bathtub curve. IEEE Trans. Reliab. 52 (1), 125–129. https://doi.org/10.1109/TR.2002.804492.

Linder, M., Sarasini, S., van Loon, P., 2017. A metric for quantifying product-level circularity. J. Ind. Ecol. 21 (3), 545–558. https://doi.org/10.1111/jiec.12552.

Madaster. (2018). *Madaster – the digital library of materials*. Retrieved 1/14 from https://madaster.com/.

Manganelli, B., 2013. Maintenance, building depreciation and land rent. Appl. Mech. Mater. Trans. Tech. Publ. 357, 2207–2214, 10.4028/. www.scientific.net/AMM.357-360.2207.

Monga, A., Zuo, M.J., 2001. Optimal design of series-parallel systems considering maintenance and salvage value. Comput. Ind. Eng. 40 (4), 323–337. https://doi.org/10.1016/S0360-8352(01)00032-8.

Nakagawa, T., 1988. Sequential imperfect preventive maintenance policies. IEEE Trans. Reliab. 37 (3), 295–298. https://doi.org/10.1109/24.3758.

Nowogońska, B., 2016. The life cycle of a building as a technical object. Periodica Polytechnica Civil Eng. 60 (3), 331–336. https://doi.org/10.3311/PPci.7932.

Platform CB'23. (2019). *Circular construction framework version 1.0.*Delft. https://platformcb23.nl/downloads.

Rijkswaterstaat. (2015). *Circular economy in the Dutch construction sector: a perspective for the market and government.* rivm.nl/bibliotheek/rapporten/2016-0024.pd.

Roulac, S., Adair, A., McGreal, S., Berry, J., Allen, S., 2006. Real estate value: creation and destruction. J. Property Invest. Finance. https://doi.org/10.1108/14635780610708293.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling 2 (1), 6. https://doi.org/10.3390/recycling2010006.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559.

van Vliet, M.M., 2018. *Disassembling the Steps Towards Building Circularity Redeveloping the Building Disassembly Assessment Method in the Building Circularity Indicator* Eindhoven University of Technology]. Eindhoven.

Verberne, J., 2016. Building Circularity indicators: an Approach For Measuring Circularity of a Building. Eindhoven Univ. Technol.

Walker, S., Coleman, N., Hodgson, P., Collins, N., Brimacombe, L., 2018. Evaluating the environmental dimension of material efficiency strategies relating to the circular economy. Sustainability 10 (3), 666.

WBCSD. (2018). *Circular Metrics Landscape Analysis*. http://docs.wbcsd.org/2018/06/Circular_Metrics-Landscape_analysis.pdf.

Webster, M.D. (2007). Structural design for adaptability and deconstruction: a strategy for closing the materials loop and increasing building value. In *New horizons and better practices* (pp. 1–6). https://doi.org/10.1061/40946(248)27.

Wilhelmsson, M., 2008. House price depreciation rates and level of maintenance. J. Hous. Econ. 17 (1), 88–101. https://doi.org/10.1016/j.jhe.2007.09.001.

Xie, M., Lai, C.D., 1996. Reliability analysis using an additive Weibull model with bathtub-shaped failure rate function. Reliab. Eng. Syst. Saf. 52 (1), 87–93. https://doi.org/10.1016/0951-8320(95)00149-2.

Zhai, J. (2020). *BIM-based building circularity assessment from the early design stages* Eindhoven University of Technology (TU/e)].

Zhang, N., Han, Q., de Vries, B., 2021. Building circularity assessment in the architecture, engineering, and construction industry: a new framework. Sustainability 13 (22). https://doi.org/10.3390/su132212466.