MASTER THESIS

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

Author
L. Jiang
University of Twente
Construction Management and Engineering (CME)

University supervisors
Dr. Ir. R. S. de Graaf
Dr. S. Bhochhibhoya

Company supervisors
Ir. Berri de Jonge
Ir. Noud Slot

02-06-2020

UNIVERSITY OF TWENTE.

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

Li Jiang

Department of Construction Management and Engineering from the Faculty of Engineering & Technology, University of Twente, Drienerlolaan 5, 7522NB, Enschede, The Netherlands

Abstract:

Circularity metrics are essential for assessing the progress of circular transition, which creating a resilient and sustainable further. It is widely agreed that the Material Circularity Indicator (MCI) is the most ambitious circularity framework and can be served as a good starting point. Hence, the research objective is: To develop a circularity metric by recovering the limitations inherent in the MCI at product-level in the construction sector. Two limitations are focused in this study. Firstly, the MCI is too dependent on the measurement unit – mass, which could not effectively represent the value embedded in the materials/products, and fails to distinguish the relative value scarcity of different materials. The shortcomings of the mass flow are revised by introducing the economic value of materials (E), instead of focusing only on physical units. Secondly, in the MCI, the quantity/quality of a product maintains the same over time, which assumes over-optimistically about the residual value of the product after the end of life. An independent indicator - Residual Value (R) is designed for the circularity metric to measure value change after usage. Furthermore, a residual value calculator, involving the design strategies and deterioration factors, is developed to quantify R and hence support the circularity assessment. A case study approach is adopted to evaluate the effect of each and combined adjustment (E and R). The results show using E as the measurement unit can provide more accurate information on the circularity performance of a product from an economic perspective. Furthermore, involving R gives different significance to virgin feedstock and unrecoverable waste based on value change, which can balance the circularity performance and economic benefits. With these advantages, it is expected that the circularity metric contributes the standard agreements of the circularity measurement, and thus, help construction companies estimate how advanced on their way from linear to circular.

Keywords: Circular Economy; Material Circularity Indicator; circularity metric; economic value; residual value

1. Introduction

1.1 Background

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 procedure, where virgin materials are taken from the environment, then be used to make products and eventually become worthless after End of Life (EoL) (Ellen Macarthur Foundation & Granta Design, 2015). In response to the global challenges, the novel concept "Circular Economy (CE)" has emerged. In a CE, resources in a system can be used continuously and long-lasting through circular strategies such as reuse, repair, remanufacture and recycle (Holland Circular Hotspot & Circle Economy, 2019). Recognizing the benefits that the CE can make towards creating a resilient and sustainable further, the Netherlands sets targets for the country: 50% less primary raw material consumption in 2030 and a fully circular by 2050. In concrete terms, this means that raw materials should be used and reused in an efficient way (Government of the Netherlands, 2016). Furthermore, materials and products will be designed wisely, to ensure the reuse possibilities after EoL, with maximized retained value and without any harmful emissions into the environment (Government of the Netherlands, 2016).

The built environment is responsible for an estimated 50% resource consumption and 40% of the total energy consumption (Government of the Netherlands, 2016), being considered as the highest priority in a CE. 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. Large quantities of questions provided by scholars concern the circularity measurement (Saidani et al., 2019). For example, Potting et al. (2017) raise a question about how to assess the progress of the transition towards a CE. In addition, the European Academies Science Advisory Council (2016) asks how we should measure the circularity performance (e.g. reduce, reuse, recycle) to distinguish those in the traditional linear economy (Saidani et al., 2019). According to a report published by European Environment Agency in 2016, there is no recognized way for assessing the progress of the European Union, a country or even a company. Saidani et al. (2017) pointed out there is only a limited number of published studies focusing on circularity metrics; therefore calling for further research. Similarly, the platform CB'23[1] (2019) has recognized that there is increasing desires concerning the information about the degree of circularity in the construction sector, while the existing methods are insufficient.

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

1.2 Research Objective and Questions

Developing a tool for monitoring, evaluating and quantifying the circularity progress is vital (Walker et al. 2018). However, it is challenging to develop a totally new method for assessing the circularity level in the construction sector. WBCSD (2018) introduces 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 creating something new (WBCSD, 2018). Several metrics are available and may be applicable to measure product-level circularity (see, e.g. Linder et al., 2017; Di Maio and Rem, 2015). Ellen MacArthur Foundation & Granta Design (2015) introduces that “there is no recognized way of measuring how effective a product is in making the transition from linear to circular”, and develop 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 for even non-experts of CE (Saidani et al., 2017). The MCI can provide a first overview of product circularity performance with limited input data. Hence, it could effectively 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 the circularity performance outside of the private sector (WBCSD, 2018). Similarly, Linder et al. (2017) argue that the MCI provides a useful starting point.

However, the drawbacks and limitations of the MCI are also evident. The MCI is too dependent on the measurement unit – mass, which could not effectively represent the materials’ value, and fails to distinguish the relative value scarcity of different materials. Furthermore, the value change could not be captured in the MCI, and the residual value of materials is assumed as the same as the new one, which is unreliable in particular. Therefore, given the clear need for a standard and effective circularity metric, it is urgent to find solutions to recover the limitations. Hence, the research objective is: To develop a circularity metric by recovering the limitations inherent in the MCI at product-level in the construction sector.

In order to achieve the study’s objective, the main questions concerning two limitations are:
Research question 1: *How to recover the issue of the mass flow to represent value scarcity in the MCI?*
Research question 2: *How to measure the residual value of materials to support the circularity assessment in the MCI?*

These two limitations and corresponding research questions will be discussed more in chapter 2.2. After answering the research questions, the metric proposed in this study is expected to contribute the standard agreements of circularity measurement, and hence, help construction companies estimate how advanced on their way from linear to circular.

1.3 Research Scope

The building can be decomposed into different layers, including site, structure, skin, services, space plan, and stuff (Brand, 1995). Similarly, Circle Economy (2019) introduces the building in a CE is not as a whole system, but a collection of layers with different lifespans. Developing qualitative methods for assessing the circularity level and the residual value of a whole building system is not feasible and extensive. As argued by Akanbi et al. (2018), a building is a complex system, where each layer/component is identically affected by various factors. Furthermore, Paoloni et al. (2018) introduce that the “layer” corresponding to the exterior surface has the largest impact on a building especially for technical durability; thus, the performance of the envelope is closely associated when deciding whether to renovate or remove an old structure. Therefore, the scope of this research is narrowed to the material analysis of the facades (exterior walls) in a building at product-level.

2. MCI overview

2.1 Explanation of the MCI

The MCI has been developed by Ellen MacArthur Foundation together with Granta Design in 2015 and is mainly used to assess how well a product or company performs in the context of a CE.

<u>Input information</u>

V=	Virgin Feedback
W=	Unrecoverable waste
Fr, Fu =	Fraction of non-virgin (recycled and reused) sources
Cr, Cu =	Recoverable waste after end of use by recycling and reuse
M=	Material mass
Wo=	Unrecoverable waste going to landfill or incineration
Wf, Wc	Unrecoverable waste generated from recycling the product/ producing a recycled product
X=	Utility of a product (technical/functional lifespan)

<u>Formulas of MCI</u>

V=	M*(1-Fr-Fu)
Wo=	M*(1-Cr-Cu)
W=	Wo+(Wf+Wc)/2
LFI=	(V+W)/2M
F(X)=	0.9/X
MCI=	**1-LFI*F(X)**

Figure 1 Input information and relevant formulas of the MCI (adapted from Ellen MacArthur Foundation & Granta Design, 2015)

The MCI considers the material’s original, waste scenario and product’s utility (Braakman, 2019). The final result of the MCI is quantitative with a range 0 to 1. The MCI 0 represents an entirely linear product, using totally virgin feedstock and generating purely unrecoverable waste after EoL. On the other hand, a fully circular product implies no virgin material input and can be realized with 100% reuse or recycle (Ellen MacArthur Foundation & Granta Design, 2015). The required input information and relevant formulas for calculating the MCI are provided in Figure 1.

2.2 Limitations of the MCI

Two limitations inherent in the MCI are focused in this study, as introduced below.

2.2.1 Fail to distinguish the value scarcity using mass flow

The materials' value is represented by units in a circularity metric among scholars, and the mass flow of materials is the backbone of conducting the MCI as shown in Figure 1. This implies a product with larger quantities has higher value in a CE based on the MCI. However, Verberne (2016) points out that the current MCI assessment is too dependent on the material mass. Braakman (2019) also argues the inaccuracy of using mass units in most cases, such as low mass materials with high volume (e.g. insulation and roof elements). This limitation is also acknowledged by Ellen MacArthur Foundation & Granta Design (2015), as "a further way of improving the efficiency of a product's portion of linear material flow is to reduce its weight whilst retaining all other product characteristics".

The weakness of using mass as the measurement unit can be elaborated using the example of steel and aluminium materials. As introduced by Muzathik et al. (2012), aluminium is a relatively more expensive material compared with steel, although its weight is only one-third of the steel. Furthermore, Di Maio and Rem (2015) argue that producing aluminium emits more greenhouse gases than the same amount of steel. Hence, recycling/reuse aluminium can provide not only economic value, but also environmental benefits rather than steel. However, the recyclers are more willing to separate the steel instead of aluminium considering the available technologies (Di Maio and Rem, 2015), and will be further encouraged if the mass unit used as the measurement unit. Therefore, the main drawback of mass flow is its incapability to make a distinction between relative value scarcity of different materials. Therefore, one of the study concerns is (research question 1): *How to recover the issue of the mass flow to represent value scarcity in the MCI?*

2.2.2 Over-optimistic assumptions for the embedded value

The MCI assumes that the quality/quantity of a product does not change over time, and 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. Hence, the MCI examines over-optimistically about the embedded value of assets in a closed-loop (reuse/recycling). This limitation is also closely associated with the mass flow used in the MCI, which could not capture value change throughout the lifecycle. After using a more reasonable unit which can embody materials' value, the next concern is how to represent the residual value of materials after EoL, to recover the over-optimistic assumptions as discussed before.

Furthermore, there is no doubt that a high circularity level normally leads to increased residual value and vice versa. However, there is no approach (e.g. MCI) which considers the residual value as an independent indicator for assessing the circularity performance at the construction sector. In contrast, the most dominating option for the assets at the end of their life is to undergo demolishment in a linear economy, resulting in a very low or even no residual value (TNO, 2019). It is widely agreed that value retention can be achieved in a closed loop with a CE. This is because products always maintain value after EoL, and circular strategies provide opportunities for those materials to enter restoration cycles (e.g. reuse, recycle). Overall, it is essential to consider the residual value as an indicator in a circularity metric to make a distinction between a linear and circular economy, and more importantly, recover the over-optimistic assumptions about the embedded value of materials in the MCI.

In order to support the circularity metric in particular, how to quantify the indicator – residual value is fundamental. There are several urgent questions concerning the residual value; for example, how much value is maintained after one exploitation period, and are there any measures that can achieve a high retained value (Material Economics, 2018). However, these questions are still unclear in a CE, and only few scholars have developed relevant approaches for assessing the residual performance, let alone in the field of construction. As proposed by the platform CB'23 (2019), the knowledge and experience are insufficient to gain an insight into the degree in which value is created, used and lost. Therefore, the question is (research question 2): *How to measure the residual value of materials to support the circularity assessment in the MCI?*

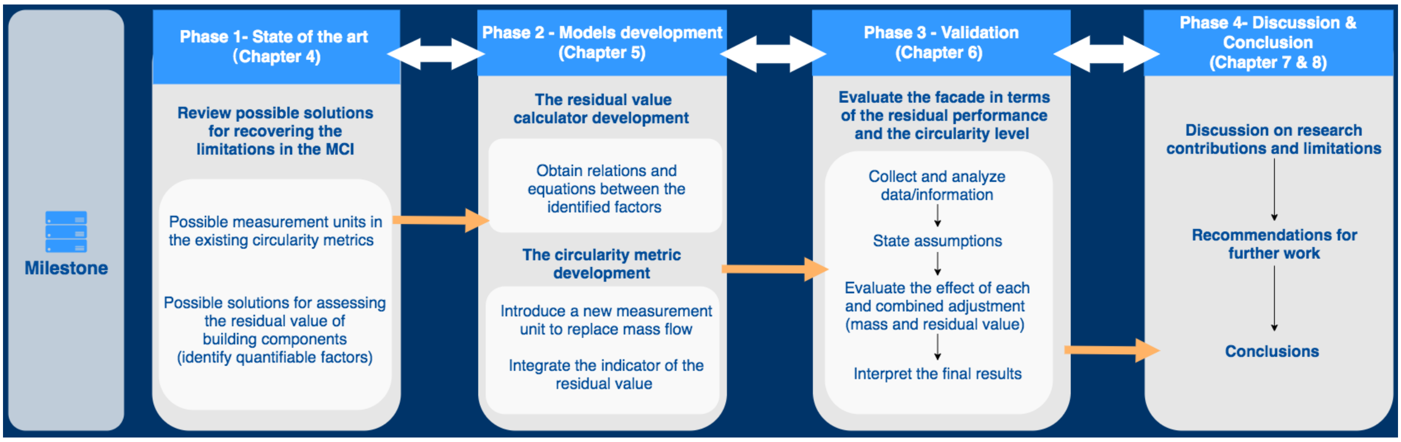

Figure 2 Research Structure

Table 1 Case study design

Step	Actions	Expected Outcomes
Step 1	• Evaluate the circularity level of the façade using the mass unit (MCI) • Evaluate the circularity level of the façade using the unit of economic value	Understand how the new measurement unit (economic value) affects the circularity level of building components compared with the mass unit used in the MCI.
Step 2.a	• Evaluate the residual value of the facade (R)	Understand how the new indicator "R" affects the circularity level of building components in the adjusted metric.
Step 2.b	• Evaluate the circularity level of the façade using the unit of economic value (can obtain the result directly from step 1) • Evaluate the circularity level of the façade using the unit of economic value and the indicator "R"	

3. Research Methodology

The research was conducted in different phases following in a linear process, finalizing with a case study which validates the mathematical models formulated in the previous phases, and hence, leads to the possibility of having conclusions out of this study. It is divided into four phases, as shown in Figure 2, and further explanation is presented next. It should be mentioned that the milestones of the study will be presented in different chapters following the research structure.

- **Phase 1 - State of the art (Chapter 4)**

Given the clear objectives, the research started by carefully reviewing the available options for recovering the limitations inherent in the MCI. Following the research questions (corresponding with two limitations), the literature review was designed into two parts: 1) reviewing possible measurement units in the existing circularity metrics proposed among scholars; 2) searching for the possible solutions to calculate the residual value of building components. However, there is no academic research has determined a specific way of assessing the residual value of products/materials. Therefore, the main idea of phase 1 (the second part) is to identify quantifiable factors which affecting the residual value of building components.

- **Phase 2 - Models development (Chapter 5)**

After a review of the literature on the possible solutions of recovering the two limitations (mass flow and residual value), the mathematical model for estimating the circularity performance based on the MCI can be developed. As discussed before, to visualize the value change over time, a tool for calculating the residual value of a building component is required to support the circularity assessment. Hence, two mathematical models: the residual value calculator and the circularity metric were built in phase 2.

For the residual value calculator, it is essential to obtain relations and equations between those factors (identified in phase 1), under a set of assumptions. Furthermore, the MCI was revised from two aspects to develop a new circularity metric. Firstly, the new measurement unit (obtained from phase 1) was used to replace the mass flow in the MCI to solve the research question 1. Furthermore, an indicator "R" which represents the residual value was then built to recover the optimistic assumption about the embedded value of materials in the MCI. The value of R was estimated using the residual value calculator developed earlier in phase 2; therefore, the research question 2 can then be answered.

- **Phase 3 - Validation (Chapter 6)**

To visualize and test the functioning of the mathematical models built in phase 2 for estimating the residual value and circularity performance of building components, it is necessary to simulate these models with a practical data set. Furthermore, the circularity metric is developed based on the MCI, and the differences between these two approaches can be summarised as follows: 1) a new measurement unit; 2) a new indicator (residual value). It is essential to understand the effect of each and combined adjustment on the overall circularity performance; hence, a case study approach was adopted in phase 3 using a practical project with a prefab façade. The façade is cladded by light-weight brick slips with glue connection, and composed by various natural materials (e.g. wood; glass wool; fiber board), as shown in Figure 3, and will be further introduced in chapter 6.

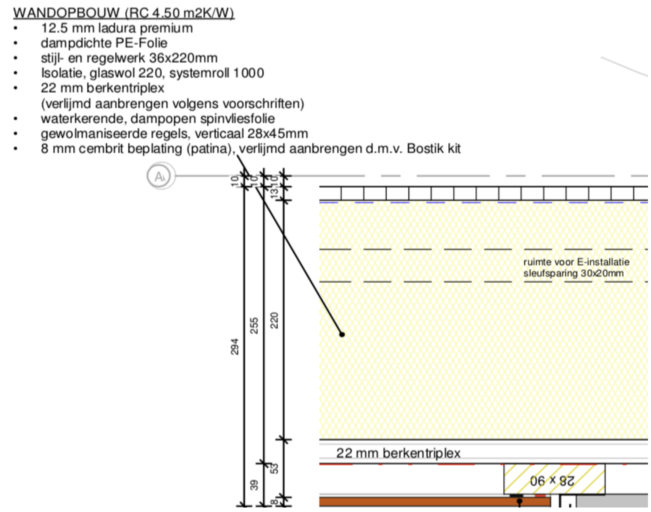

Figure 3 Material composition of the front façade (provided by Plegt-Vos)

As discussed in subsection 2.2.2, the over-optimistic assumption about the embedded value should be solved by firstly using a unit which can embody materials' value, and then consider an indicator to capture the residual value. This means the indicator R is only applicable after recovering the first limitation by using a new measurement unit ("economic value" in this study, which will be introduced later). Therefore, the case study follows two steps, as presented in

Table 1. Firstly, the circularity performance of the façade was calculated based on the mass flow and economic value respectively in step 1, aiming to drive an understanding on how these two different measurement units affect the final circularity value. Step 2 was developed to examine the effect of the indicator R, by comparing the circularity performance with and without integrating R. It should be mentioned that the value of R was calculated by the residual value calculator firstly in step 2.a, which was an input value in step 2.b.

However, a single scenario was unable to guarantee the expected outcomes of each step; therefore, for further comparison, four different scenarios were designed:

Base scenario: The current situation of the project, where the façade cladding – brick slips were produced with purely virgin materials and expected to become totally unrecoverable after usage.

Scenario 2: The brick slips are assumed to be produced with totally virgin materials while fully recycled after usage.

Scenario 3: The brick slips are assumed to be produced with totally virgin materials while fully reused after usage.

Scenario 4: This scenario considers the input streams, where the brick slips are assumed being produced by 100% reused or recycled materials, while becoming worthless after usage.

Except for the brick slips in different scenarios, the rest of the materials involved in the façade maintain the same as the base scenario. The reason for focusing on the cladding is because the brick slips are light-weight while costly in the project; hence, the comparison differences would be more significant for explanations, which will be introduced further in chapter 6.

- **Phase 4 - Discussion and Conclusion (Chapter 7&8)**

The last phase including chapter 7 and 8 discussed and concluded the research outcomes. Chapter 7 presents the discussion, where the differences between the circularity metric and the MCI are further discussed, emphasizing the advantages of the new method proposed in this study. Moreover, recommendations on further work are given in chapter 7, considering the limitations of the current residual value calculator and the circularity metric. The final conclusion of the study is provided in chapter 8, corresponding with recommendations for companies.

4. Phase 1 - State of the art

In this chapter, the possible solutions used for recovering the limitations are discussed, following the first phase of the research structure (Figure 2). Chapter 4.1 introduces a reasonable measurement unit which can distinguish value scarcity of different materials to answer question 1. The possible solution for developing a calculator to measure residual value (question 2) is elaborated in chapter 4.2.

4.1 Possible measurement unit – Economic Value

The measurement units used to assess circularity performance is fundamental for a metric. Linder et al. (2017) introduce that there are various suggested 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) introduce that the shortcomings of these units (e.g. mass) 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). Therefore, the circularity metric can send clear information; for example, 1 kilogram of steel is counted as less important as the same weight of aluminium, as discussed in section 2.2.1. 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 applied in the existing circularity metrics. For example, Linder et al. (2017) have developed a circularity metric using the economic value as the basic unit, by considering the fraction of a product that comes from recirculated parts. Similarly, the Circularity Economy Index (CEI) developed by Di Maio & Rem (2015) introduces the economic value to express recycling efficiency.

In the current market, there is no specific information about economic value for 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?. Using an expert committee to compile a material weight would be a good solution, while it is too extensive and will go beyond the scope of this research. It is widely agreed that the price can be served as an excellent source of information for economic value. For example, according to Roulac et al. (2006) argue economic value is: “the price that will be paid for the highest and best use of real estate which, in an unfettered market, is determined by the forces of demand and supply”. 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. However, 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.

4.2 Possible solution for the residual value calculator

The most common way for estimating the residual value is the market approach, where the value of EoL can be determined by comparing similar products in the second-hand market (Bokkinga, 2018). However, such markets may not always exist for salvaged materials or products (Linder et al., 2017). One of the most advanced organizations in calculating the residual value is TNO[2], which has started developing its own tool to assess the residual performance of inner walls in offices, by considering the craftsmanship, technology and machine utilization of the initial product manufacturing (Braakman, 2019). However, the calculator is not published now.

In this study, corresponding to the same measurement unit in the circularity metric, the residual value is defined as the economic value of a building component when undergoing demolishment or deconstruction. It is presented as a percentage compared with a new one, to estimate the amount of value maintained when the component is approaching its usage time. Although it is essential for the circularity assessment, the residual value is still in its early stage, and the evaluation of the residual value is the most complex task in this study. As discussed in chapter 3, the main idea of developing the residual value calculator is to identify and quantify the relevant factors which have a significant impact on the residual performance of building components. In this section, an extensive literature study is conducted to provide theoretical backgrounds for the calculator.

4.2.1 Factors influencing the residual value

Amory (2019) introduces the product, or building value can be divided into two groups, namely, material value and added value. On the one hand, the material value considers the value of the raw materials. Circular materials usage aims to prevent or slow material degradation, enhance possibilities for materials regeneration to protect and maintain the material value (Amory, 2019). For example, following the principle of "Power of circling longer" proposed by Ellen MacArthur Foundation (2012), proactive maintenance strategies can offset the aging effect; hence, slow down the degradation process and keep products/materials in use longer to achieve value retention. Similarly, the selection of materials is crucial in overcoming degradation or functional obsolescence following the principle of "Design for Durability". On the other hand, an added value is created by designing the composition of the materials in a product following circular strategies (Amory, 2019). By doing this, products/materials are more likely to enter multiple circles after EoL; hence, the highest amount of added value is retained (Amory, 2019). Furthermore, Amory (2019) introduces that value retention and value recovery can be achieved by means of clear and anticipating design, or called Design for Circularity (DfC). The circular performance of a building is improved from various aspect of circularity, represented as Design for X (DfX).

Therefore, although it is difficult to conduct life cycle analysis for the salvaged products after EoL because the information is still unavailable during the design phase (Akinade et al., 2015), 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). Furthermore, the deterioration process should be focused on, to examine whether the materials are used in a circular way and maintain the highest amount of material value. Hence, the residual value calculator assumes that the residual performance of building components can be predicted during the design phase and also affected by the deterioration factor. These two groups of factors are discussed next: what sub-factors are involved in the calculator and why they are important to be considered.

4.2.1.1 Design strategies

According to Amory (2019), there is no standard set of DfX identified among scholars, and these strategies are complement or partly overlap with each other rather than mutually exclusive. Design for Disassembly (DfD) can be represented as the most important design strategy (Webster et al., 2007) since its application guarantees the realization of other strategies at a certain degree. For example, Design for Maintenance (DfM) is a circular strategy proposed among scholars (e.g. Kanniyapan et al., 2015; Abdullah et al., 2017), aiming to ensure easily reparability and replacement at reasonable cots during operational phase (Amory, 2019; Ellen MacArthur Foundation, 2014). A building applied DfD strategies is more likely to have a good inspectability and modularity, and hence, assures the maintenance possibility without too many difficulties. Furthermore, Ellen MacArthur Foundation (2014) introduces that 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. Similarly, Ellen MacArthur Foundation (2014) introduces DfD can increase product utility (Design for Product Life Extension) and allow for the remanufacturing after usage (Design for Remanufacturing).

Webster et al. (2007) argue that except for environmental benefits (e.g. reduce 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 further, pushed by the cost of raw materials (Webster, 2007). Therefore, extracting salvageable materials from a building being applied DfD strategies would be easier and cost-effective, increasing the financial profits for the companies. Therefore, it is proposed that DfD is the core circular strategy with far-reaching consequences, and it should be involved in the residual value calculator.

There are extensive studies conducted to principles, factors and guides for DfD in order to realize building disassembly rather than demolishment after EoL (van Vliet, 2018). Akanbi et al. (2018) take factors such as the connection type into consideration, by calculating the fraction of the total number of connections in a building that are demountable. However, the method could not examine the disassembly possibility of

[2] TNO is an independent organization for Applied Scientific Research in the Netherlands

a component appropriately (e.g. chemical connection could not be assessed). 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, using the grading system developed by Durmisevic (2006) in Appendix A.

Except for DfD, another design strategy – Design for Recovery (DfR) should also be considered, as a complementary circular strategy with DfD. As highlighted by Akinade et al. (2015), those principles belong to DfD could not guarantee material recovery; therefore, other aspects contribute to reusability/recyclability should be considered in the residual value calculator. Akinade et al. (2015) and Akanbi et al.(2018) introduce 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, as discussed before, 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 conducting for analyzing the product durability (e.g. NEN-EN 350[3]), the durability or the quality assessment for the most materials are 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. Therefore, in this study, only two design strategies: DfD and DfR are involved when developing the residual value calculator.

4.2.1.2 Deterioration factor

An asset depreciates over time, which caused by three different reasons, namely, physical deterioration, functional and external obsolescence (Wilhelmsson, 2008; Manganelli, 2013). The functional obsolescence is due to, for example, the technological changes and layout designs. Usual causes originating external obsolescence is the changes in the neighbourhood, such as the increase in traffic volume (Wilhelmsson, 2008). Both of the obsolescence are difficult to measure. On the other hand, 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 (Mangenelli, 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.

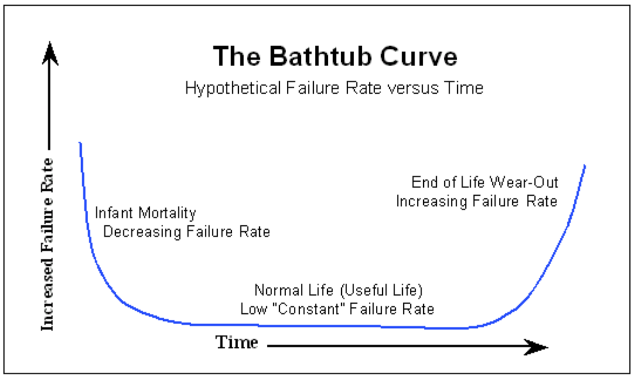

Figure 4 The bathtub curve against time (Wilkins, 2002)

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 behaviour of products through their lifecycle, as shown in Figure 4.

The failure rate is high at 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). Afterward, the product enters the "wear-out phase" with an increasing failure rate when approaching its expected lifetime (Wilkins, 2002; 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 represented as $h(t)$ is determined by the scale parameter "α" and the shape parameter "β":

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

As discussed before, maintenance strategies can protect material value from depreciation. Furthermore, Ellen MacArthur Foundation (2012) introduces 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

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

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. 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. According to Nakagawa (1988) and Monga & Zuo (2001), the slope of the hazard function should increase after each maintenance action due to both externally and internally induced conditions. Therefore, the failure rate of a component during ith interval is (Monga, 2001) :

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

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

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

Where k is the number of maintenance actions

5. Phase 2 - Models development

With the theocratical backgrounds provided in phase 1, two models: the residual value calculator and the circularity metric can then be built in phase 2 and will be introduced in this chapter respectively. The notations used in the models are presented in Figure 5.

	Residual value calculator
R	Residual value
S	Set of design strategies
Sd	Design for Disassembly
Sr	Design for Recovery
PD_j	Product disassembly of factor j
CD_j	Connection disassembly of factor j
vm	Total volume of materials in a building component
vf	Volume of materials without secondary finishes
vh	Volume of materials without hazardous content
$D(t)$	Deterioration function of the building component, which is a function of time
t	Age of component in year(s)
t_i	The time when phase 1 ends and phase 2 begins (years); or the time of taking maintenance actions
$D(t_i)$	Deterioration value in percentage at t_i
$\alpha; \beta$	The scale parameter and the shape parameter in Weibull distribution, used to determine the failure rate
	Circularity metric
E	Economic value
V'	Economic value of virgin materials
Fu'	Fraction of materials from recycled sources
Fr'	Fraction of materials from reused sources
Fb'	Fraction of materials from bio-based sources
Wo'	Value loss due to the unrecoverable waste going to landfill/energy recovery directly
Cu'	Fraction of waste being collected for reuse
Cr'	Fraction of waste being collected for recycling
E'	Economic value of the salvaged materials, can be calculated by E*R
Ec'	Recycling efficiency, represented by the fraction of material's value used to produce a new product
Wc'	Value loss generated in the recycling process
W'	Value loss of all unrecoverable waste
LFI'	Linear flow index; to measure the economic value of materials flowing in a linear procedure
X	Utility factor
F(X)	A function of the utility X
MCI'	The circularity metric/the adjusted MCI

Figure 5 Notations of the residual calculator and the circularity metric

5.1 The residual value calculator development

The residual value denoted by R is expressed as a function of circular design strategies S and deterioration factor $D(t)$, adapted from Akanbi et al. (2018):

$$R = S * D(t) \tag{5}$$

5.1.1 Design strategies

Two identified design strategies are: 1) Design for Disassembly (Sd); 2) Design for Recovery (Sr) for this study. An expression for S is presented in equation 6.

$$S = \frac{1}{2} * Sd + \frac{1}{2} * Sr \tag{6}$$

In this study, an assumption is made that residual value is affected by these two factors equally with 1/2. Furthermore, the residual calculator can be seen as an open function, allowing for the incorporation of different design strategies, as discussed in subsection 4.2.1.1.

The level of DfD or the disassembly potential of a product (Sd) can be measured using equation 7 adapted from van Vliet (2018), by considering the disassembly possibility at product and connection level.

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

Where
PD_j = product disassembly potential of factor *j*
CD_j =connection disassembly potential of factor *j*

The grading system of these two groups of disassembly factors is presented in Appendix A.

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):

$$Sr = \frac{1}{2} * \frac{vf}{vm} + \frac{1}{2} * \frac{vh}{vm} \tag{8}$$

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, considering equation 6, 7 and 8, the overall effect of design strategies becomes:

$$S = \frac{1}{2} * \frac{1}{7} * (\sum_{j=1}^{n} PDj + \sum_{j=1}^{n} CDj) + \frac{1}{2} * \frac{1}{2} * \left(\frac{vf}{vm} + \frac{vh}{vm}\right) \tag{9}$$

5.1.2 Deterioration factor

Deterioration is normally inevitable, which is an important indicator of the valuation process of an asset (Dziadosz & Meszek, 2015). In this study, physical deterioration is focused. Furthermore, as discussed in subsection 4.2.1.2, maintenance measures can offset the negative effect of aging on the building value. It should be mentioned that there is no distinction between proactive and reactive actions in the current study, although the deterioration rates may be affected by different types of maintenance (Flikweert, 2009). To allow the incorporation of the maintenance strategies, the deterioration behaviour of building components is described in two phases as a reliability function (failure rate), based on the Weibull distribution and Farahani's study (2019), as shown in equation 10. 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 further deterioration value "$D(t)$" of a component at time "t".

$$D(t) = \begin{cases} exp\left[-\left(\frac{t}{\alpha_1}\right)^{\beta 1}\right] & Phase\ 1\ (t \le t_i) \\ D(t_i) * exp\left[-\left(\frac{t-t_i}{\alpha_i}\right)^{\beta i}\right] & Phase\ 2\ \ (t \ge t_i) \end{cases} \tag{10}$$

Where
t_i = the time when phase 1 ends and phase 2 begins (years)
$D(t_i)$ = deterioration value in percentage at "t_i"

The proposed deterioration function satisfies the following three conditions:

1). The deterioration function is a monotonically decreasing function in each phase, and the slope of hazard rate increases after each maintenance action based on Nakagawa (1998) and Monga & Zuo (2001) such that:

$$\left(\frac{t}{\alpha_1}\right)^{\beta_1} \le \left(\frac{t - t_i}{\alpha_i}\right)^{\beta_i} \le \left(\frac{t - t_{i+1}}{\alpha_{i+1}}\right)^{\beta_{i+1}} \tag{11}$$

2). At the end of each phase, the deterioration value of the building components increases to a new state as:

$$exp\left[-\left(\frac{t_i}{\alpha_1}\right)^{\beta 1}\right] < D(t_i) \tag{12}$$

3). The value of salvaged materials is determined by the physical deterioration and condition-improving maintenances in this study. The price fluctuation and tax effects of material disposal are ignored.

For simplicity, an example of considering the value of α and β is provided. The value of β can be estimated considering the shape of failure rate: 1) increase with $\beta > 1$; 2) constant with $\beta = 1$; 3) decrease with $\beta < 1$ based on the definition of Weibull distribution (Wilkins, 2002). Nowogońska (2016) argues that time-related wear is the main cause of the 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

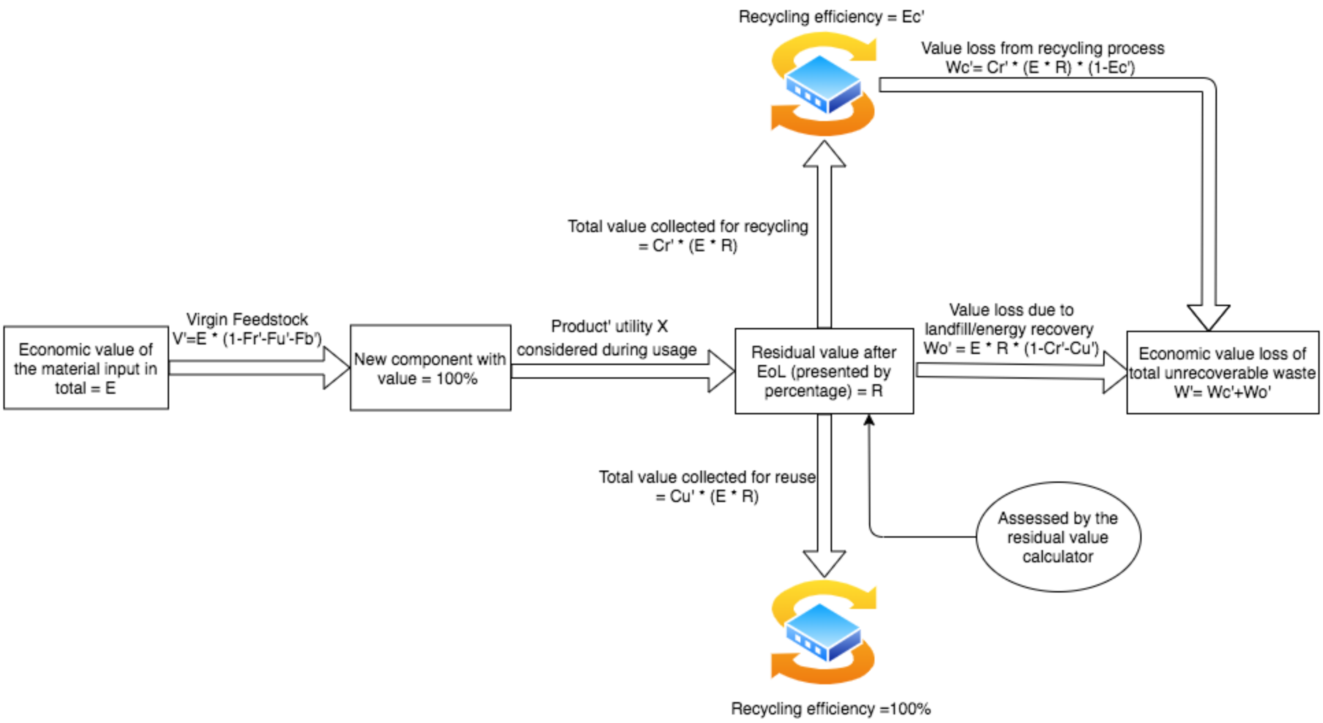

Figure 6 Diagrammatic representation of the assessment process (adapted from Ellen MacArthur Foundation & Granta Design, 2015)

minimum acceptable quality of the component. Giving an expected lifespan (e.g. 75 years), the value of α_1 can be easily calculated (e.g. $\alpha_1 = 60$). Besides, for modelling the situation where the slope of hazard rate increases after maintenance actions, the factor θ_i is considered, and the mathematical function (equation 4) can be applied to calculate the value of θ_i. Afterward, from equation 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 to satisfy the above conditions, and the accuracy can be improved using time-performance data (obtained from inspection).

With design strategies S and deterioration factor $D(t)$, the residual value of a building component can be estimated using equation 5.

5.2 The circularity metric development

The MCI only considers recirculated materials from reuse or recycling sources. Verberne (2016) argues that biological or natural materials such as wooden may have a positive impact on circularity performance since it can separately reduce the amount of virgin material input. Besides, the platform CB'23 (2019) also highlights the importance of renewable feedstock (e.g. natural materials). Hence, the circularity metric assumes both the recirculated and bio-based materials can provide significant benefits for a CE. Furthermore, following the assumptions in the MCI, the reuse process is assumed with an efficiency of 100%, since the more economic value can be obtained in an inner cycle (Ellen MacArthur Foundation, 2012). Furthermore, in the current market, accurate information regarding economic value does not exist, as introduced in subsection 4.1. Therefore, the approximates of economic value have to be used to make the economic value-based metric applicable in practice. Although the price could not represent the accurate information of the economic value, it is often the best available representation of the materials' relative scarcity. Hence, this study assumes the market prices of materials are served to represent their economic value.

There are two improvements in the circularity metric compared with the MCI, including the new measurement unit-economic value and the new indicator-residual value. These will be introduced following the assessment process of the circularity metric, which is adapted based on the report of "Circularity Indicator – An Approach to Measuring circularity" provided by Ellen MacArthur Foundation & Granta Design (2015).

5.2.1 Assessment process of the circularity metric

Same with the MCI, the adjusted circularity metric is developed by first calculating the virgin feedstock and the unrecoverable waste, and then constructing the utility factor. The diagrammatic representation of the assessment process is illustrated in Figure 6.

- **Calculating Virgin Feedstock**

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

$$V' = E(1 - Fu' - Fr' - Fb') \qquad (13)$$

Where E is the economic value of the material input in total. Compared with the MCI (as shown in Figure 1), the measurement unit – mass (M) is replaced by economic value

(E) in equation 13. Furthermore, Fu', Fr' and Fb' can be calculated by equation 14 adapted from Linder et al. (2017):

$$Fu'/Fr'/Fb' = \frac{economic\ value\ of\ reused/recycled/biobased\ mateirals}{economic\ value\ of\ all\ materials} \quad (14)$$

- **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/energy recovery is Wo' and can be calculated by:

$$Wo' = E'(1 - Cu' - Cr') \quad (15)$$

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

As discussed in subsection 4.2, the indicator - 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):

$$E' = E * R \quad (16)$$

Hence, Wo' can be revised as:

$$Wo' = E * R * (1 - Cu' - Cr') \quad (17)$$

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

$$Wc' = E * R * (1 - Ec') * Cr' \quad (18)$$

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

$$W' = Wo' + Wc' \quad (19)$$

- **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 equation 20. 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 between 0 to 1, where 1 is a purely linear flow, and 0 is a completely circular flow.

$$LFI' = \frac{V' + W'}{E + E'} = \frac{V' + W'}{E + E * R} = \frac{V' + W'}{E * (1 + R)} \quad (20)$$

Furthermore, same with the MCI, the circularity metric assumes that increased serviceable life or higher use intensity can lead to material saving, represented by the utility factor X as shown in Figure 1.

- **Calculating the adjusted Material Circularity Indicator**

Considering the input, utility and output, the circularity metric (MCI') is determined as:

$$MCI' = 1 - LFI' * F(X) \quad (21)$$

Where $F(X)$ is a function of the utility X, determining the effect of the product's utility on its MCI' score, as shown in Figure 1. 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:

$$MCI' = Max[0, 1 - LFI' * F(X)] \quad (22)$$

6. Phase 3 – Validation

A mathematical model for estimating the circularity performance is formulated above by recovering two limitations in the MCI (mass flow and residual value). To visualize the effect of these two adjustments, it is necessary to simulate the circularity metric and the MCI with a practical project. As discussed in chapter 3, a prefab façade provided by Plegt-Vos is chosen.

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 (represent the economic value) of the façade used in the MCI and the circularity metric were provided by Plegt-Vos, as shown in Table 2.

Table 2 Project (Façade) information

Basic Elements (from outside to inside)	Mass (kg)	Overall cost (€)
Flexible mineral brick slips	79.65	[redacted]
Glue for the brick slips	-	[redacted]
Primer for the stone strips	-	[redacted]
Reinforcement tape for the brick slips	-	[redacted]
Power panel H2O	199.13	[redacted]
Ventilation rows	39.62	[redacted]
Underlay membrane protection film	4.78	[redacted]
LPDE foil	2.25	[redacted]
Construction birch plywood B/BB	241.82	[redacted]
Glass wool & System rolls	19.87	[redacted]
Gypsum fibre board	200.72	[redacted]
Staples for fixation	-	[redacted]
FSC Spruce	378.07	[redacted]
	1165.90	[redacted]

Table 8 (Appendix C) presents the required information/data for calculating materials' origins and waste scenarios, considering the fraction of recycled/reused/bio-based feedstock and the percentage of materials collected for

Table 3 Results of different scenarios (with R=0.58)

Scenarios	**MCI (mass "M")**	**Adjusted metric (economic value "E")**	**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 – recycled/reused input for producing brick slips	0.69 (4.5%)	0.55 (96.4%)	0.63 (123.4%)

reuse and recycling after the expected lifespan (75 years). This information/data was estimated based on the assumptions in Table 7 (Appendix B). Furthermore, for assessing the residual value of the façade, the disassembly and recovery potential were assessed based on the design plans provided by Plegt-Vos, which will be further introduced in section 6.2. The detailed assessment results of the MCI and the circularity metric (MCI') in different scenarios are provided in Appendix D and E, using the information/data introduced above. Furthermore, it should be mentioned that for a fair comparison, both bio-based materials and the recirculated materials (reused/recycled) were considered as feedstock in the MCI.

In this chapter, the analysis is presented following the steps presented in Table 1.

6.1 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 was calculated based on the mass flow and economic value respectively in step 1. As shown in Table 3, the performance score of the façade is 0.66 based on the formulas of the MCI (Figure 1). Following the assessment process of the circularity metric (from equation 13 to 22), another circularity value with 0.28 can be calculated based on the unit of the economic value. In here, the condition of "R=1" was involved, which means the materials' value was still under the optimistic assumption where the value loss was neglected. This is because step 1 was designed to compare the measurement units – mass and economic value, without considering the effect of R. These results show that using different measurement units affect the circularity assessment significantly. The difference is mainly determined by the key material – brick slips, which are light-weight with a density of $5kg/m^3$, accounting for 6.8% of the product's weight. However, the brick slips contribute more than 60% of the cost.

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 only 3% using the mass unit; while more than 50% assessed based on the economic value, as shown in Table 3. 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 nearly double using the economic value, while there is only a small increase (4.5%) based on the materials' weight. Overall, the performance score of the façade increases when using the brick slips in a circular way based on the economic value, as compared the base scenario and scenario 2 (or 3) in Table 3. However, the effort made for the brick slips could not be reflected appropriately based on the mass flow. Hence, it is proposed that economic value is a more reasonable measurement unit in a situation where light-weight (while valuable) materials are used.

6.2 The effect of the indicator R (Step 2)

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

Two groups of factors, including design strategies and deterioration factor, were 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), as shown in Table 6 (Appendix A). Using equation 9, the effect of design strategies S on the residual performance was assessed as 0.9, as shown in Table 9 (Appendix D).

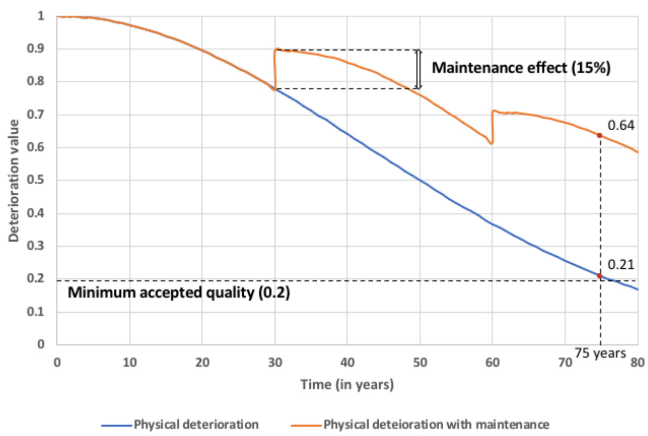

Figure 7 Physical deterioration with/without maintenance

Based on equation 10, the deterioration curve of the façade was illustrated, where value improvement represents a maintenance effect (or a combination of activities taken together) at a given time. The input variables (α; β) were calculated using the example provided in subsection 5.1.2. Furthermore, due to unavailable information, it was assumed that the maintenance measures would be carried out with the time interval of 30 years (at the 30th year and 60th year), compromising 15% building value. As shown in Figure 7, 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 Figure 7.

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 equation 5. It is the input of the indicator R to support the overall circularity assessment, as shown in Figure 6 and will be introduced in the next step (step 2.b).

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

The processes of assessing circularity performance with or without considering the indicator R are almost the same, following equation 13 to 22. However, a specific value should be given to R (0.58 calculated in step 2.a) when taking value change into account; otherwise, R=1. As shown in Table 3, the results are different when the residual value is considered or not. The circularity performance is largely determined by the value of Linear Flow Index (LFI') as presented in equation 21. Therefore, the LFI' function 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 (In here, V' and W'can be interpreted as the economic value fraction of the virgin input and the unrecoverable waste):

$$LFI' = \frac{V' + R * W'}{(1 + R)} \tag{23}$$

Considering the results are equal with/without R:

$$\frac{V' + R * W'}{(1 + R)} = \frac{V' + W'}{2} \tag{24}$$

Therefore, when W' is equal to V', the circularity performance is assessed as the same when integrating R or not. In the base scenario, 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.

The brick slips are supposed to be recycled (or reused) in scenario 2 (or 3), which implies that the economic loss resulting from the unrecoverable waste is reduced while the value inherent in virgin materials maintains the same, compared with the base scenario. As pretended in Table 3, there is a significant improvement in terms of circularity performance when the unit of economic value is based on. However, integrating R 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. For further comparison, scenario 4 is created, where the brick slips are assumed to be produced using recycled or reused materials; hence, the quantities of virgin input V' is reduced and the amount of unrecoverable waste W' maintains the same (compared with the base scenario). As presented in Table 3, the results of scenario 3 and 4 are the same when only considering the economic value. However, R has a positive effect on circularity performance, increasing the score from 0.55 to 0.63 in scenario 4.

To answer how the effect of R shows differently in different scenarios (positive or negative), the analysis is conducted. As shown in equation 22, the indicator R can be seen as the coefficient of W'. When the residual value is not considered (R =1), V' and W' have the same significance on the circularity performance and the efforts made for feedstock and waste are regarded as the same. If R < 1, the significance of W' is lower than V', which means when the materials' value decline within time, it is more important to use as less as virgin materials rather than increasing the recovery rate (reuse or recycle). Therefore, R provides a negative effect in scenario 2 and 3, while shows positively in scenario 4.

Table 4 Results of different scenarios (with a different value for R)

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

The positive/negative effect becomes more evident when a smaller value is given to R, as presented in Table 4. 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 4, when R equals to 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, as mentioned above (according to equation 24), the conclusions drawn above are not tenable under the condition of "$W' = V'$", 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 is the same.

7. Phase 4 - Discussion

It is widely agreed that there is no a standardized or well-established method for measuring circularity, which is essential for a CE. In the section above, a circularity metric at product-level is outlined, and it is expected to contribute to the standard agreements of the circularity measurement.

Keeping the advantages of the MCI, the circularity metric is developed with lifecycle thinking. The different lifecycle phases are abstracted using different indicators: the virgin feedstock (development phase), the utility factor (usage phase), and the unrecoverable waste (the EoL phase). Simultaneously, the metric is improved by recovering two weaknesses: incapacity of mass flow and over-optimistic about the residual value. The circularity metric is proved that it can provide more precise information from an economic perspective, compared with the MCI. In this chapter, the outcome of the study and its contributions will be discussed first, following the limitations and corresponding further work with literature study.

7.1 Contributions to the circularity measurement

Firstly, the metric pays closer attention to the measurement units, which represents the value embedded in the materials. In the MCI, materials in a product with larger quantities have a significant effect on the overall circularity performance. However, it is inaccurate of using mass flow in most cases, which can be embodied in the exemplary case study, where light-weighted (while costly) materials are used. A more reasonable unit – economic value (E) is proposed by complementing the value of materials, instead of focusing only on physical units. By doing this, the company is recommended to recycle/reuse those materials with high value, in order to create more economic benefits and improve the circularity performance. Another advantage of using economic value can be reflected during the calculation process. Commonly, the information of material's weight could not be obtained directly and should be calculated based on its density and square/volume. Furthermore, it is also impossible for part of materials to calculate their mass (e.g. glue and primer shown in Table 2); hence, these materials could not be considered in the MCI. Therefore, using the mass measurement may cause calculation difficulties and inaccurate results; while these limitations can be alleviated with the help of the economic value.

Another contribution of the study is the residual value calculator to examine how much value is maintained after EoL. Although the calculator is designed to support the circularity metric, it can be used independently. In the calculator, design strategies are involved, which allow the companies to understand how those circular strategies affect the value retention, and thus, facilitating the CE implementation at the early stage. Furthermore, a two-phase deterioration function is developed, which allows the incorporation of condition-improving maintenance actions. By doing 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. Furthermore, the deterioration curve can also be modified thanks to the flexibility of the Weibull distribution considering the particular conditions.

As pointed by Saidani et al. (2017), the MCI only considers the degree of recirculated materials in a product, and several essential aspects of a circular model are not considered, including modularity, connectivity and easy disassembly. With the help of the residual value calculator (or the new indicator R), the metric can evaluate circularity performance of a product more comprehensively. Furthermore, as introduced in 2.2.2, one of the weaknesses in the MCI is to assume that no part of the product is consumed, degrade or lost during its usage phase. However, it is unreliable since the material value inherent in the input and output should be different. The residual value calculator can recover this limitation by examining the value change throughout time, and it can help companies make a better decision to balance products' circularity performance and their economic benefits.

7.2 Limitations and Further work

The differences of circularity performance based on the economic value and the mass flow mainly result from one of the materials (brick slips). This means the conclusion is only applicable in a case when using light-weight materials, and more examples of different kind of materials should be conducted for further comparison. Furthermore, the method proposed in this study aims to estimate the circularity performance of building components, while only the case of façade was used to test the functioning of the circularity metric. Hence, it is necessary to validate the method using different components such as inner wall and flooring in further work.

The circularity metric is currently limited to measure the circularity performance of direct materials (containing in a product); however, it could not provide information on other aspects of the product. In theory, a metric should contain different aspects, to assess products' circularity in a complete and comprehensive way (Linder et al., 2017). For example, according to the study of Nuñez-Cacho et al. (2018), except for material efficiency, the academic and professional world are seriously concern about energy and water consumption. Hence, the narrow focus of the metric is viewed as one-sidedness, which may mislead decision-makers. For example, the high possibility of recycling can improve the circularity performance based on the metric, while on the other hand, it may result in a negative effect on energy efficiency. However, there are few studies concerning energy efficiency and other resources in a CE. Angioletti et al. (2017) have developed the concept of "ECI (Energy Circularity Indicator)" to complement with the MCI, while did not provide clear guidelines for practical application. Therefore, how to assess other aspects of the circularity as additional support is still a challenge for further research.

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 metric 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). Similarly, in the circularity metric, the recycling efficiency is represented by the percentage of materials' value used to produce a new product and does not consider the incurred cost during the recycling process. Di

Maio & Rem (2015) have developed an indicator called the CEI to assess the recycling efficiency as:

$$CEI = \frac{Recyling\ frim\ revenus - non\ factor\ costs}{Material\ value\ for\ (re-producing)EoL\ product(s)} \quad (24)$$

The recycling firm revenues refer to the recycling profits obtained by the company like the revenues from selling the recycled materials, and the non-factor costs include any costs incurred during the recycling process such as the consumption of energy and input materials. The CEI is a better indicator which can be used to recover the limitation as discussed above. However, the current metric did not consider the CEI, in order to allow the combination with other indicators such as LCC. If the CEI is integrated into the metric, it may cause double-counting regarding the effect of recycling cost; while it is recommended to consider the CEI when the recycling process is focused on independently.

In order to capture the effect of product life extension on the realization of an improved CE, the utility factor in the MCI is maintained in the circularity metric. However, calculating the usage intensity is based on the estimated average life spans, which may invite ambiguous and optimistic circularity estimations (Linder et al., 2017). Furthermore, as pointed by Braakman (2019), materials with a high utility factor may consume more virgin materials and generate more waste; however, it could not be reflected in the circularity metric. A possible solution is to let the circularity metric only focus on the fraction of materials in a closed-loop and use complementary indicators. These may include, for example, indicators like LCA (Life Cycle Analysis) to quantify the environmental impacts (Linder et al., 2017). Furthermore, in terms of the indicator R in the circularity metric, it is inapplicable when the economic value fraction of the virgin feedstock is equal to the fraction of the unrecoverable waste.

Regarding the residual value calculator, the main idea is to identify relevant factors which have an impact on the economic value of building components after EoL. Estimating the residual performance of a product is complex, and affected by various factors and some of them may be difficult to quantify (Akanbi et al., 2018). Developing a holistic tool to contain different aspects is cumbersome and may not be practicable, and in this study, a limited number of factors are involved. The narrow focuses can be viewed as a weakness in practical. For example, it is assumed that the disassembly and recovery possibility are the most important design strategies for a building component. However, there are different strategies concerned among scholars such as Design for Durability and Design for Adaptability, which are not considered in 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. Furthermore, physical deterioration is mainly focused on, ignoring the functional and external depreciation, which are important factors affecting the economic value of a product. Besides, except for the maintenance effect, a price appreciation of materials may offset the negative effect of ageing on the components. As pointed by Webster (2007), the cost of virgin materials is more likely to increase in the further driving up the value of salvaged materials. However, it is difficult to estimate the price fluctuation of materials in such as a long period (e.g. 75 years in the case study); hence, a stable price is assumed in the calculator. In practical, it is suggested to assess the residual value at a certain time, to integrate the effect of price fluctuation in real-time.

Except for the limitations pointed out before, there is no clear guideline to support users to identify input variables in the residual value calculator. Although an example of designing the factor α and β is provided, it contains similar problems as the utility factor: requiring the information of the product's expected lifespan. Similarly, the maintenance effect or new deterioration value is under assumptions due to unavailable information in this study. To ensure effective assessment of the residual value, the status and quality of materials must be known. To achieve it, performance evaluation of materials during and after EoL is essential for an arcuate assessment (Akanbi et al., 2018). There is a huge potential of using digital technologies to support the circularity measurement. For example, one of the key benefits of using BIM[4] is its capability to collect lifecycle information about a building for the circularity assessment process (Akanbi et al., 2018). Furthermore, as mentioned in chapter 1.3, currently, the circularity metric is narrowed to the material analysis of a building component, and expanding the method to a larger scale (e.g. buildings) is necessary for further research. One possible difficulty is that the whole calculation process will become much complex, and it is no doubt that the application of digital technologies can make it effective. Therefore, further studies on the utilization of digital technologies for the circularity measurement are calling for.

8. Phase 4 - 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. However, the limitations in the MCI are obvious: incapacity of using mass flow and over-optimistic assumptions about the residual value. Hence, in this study, the research objective is: To develop a circularity metric by recovering the limitations inherent in the MCI at product-level in the construction sector. Two corresponding research questions are pointed out related to the two limitations. Firstly, the MCI is criticized that it is too dependent on the mass flow, which could not effectively represent the value scarcity. In order to recover

[4] Building Information Modelling is an integrated process that involves different stakeholders (e.g. designers and contractors) collaboratively to facilitate lifecycle management of buildings.

this limitation (research question 1), the first consideration is about how to select an appropriate measurement unit which can provide information regarding the material relative value, and hence weighing and aggregating different parts into a single value to express the overall circularity performance. It is suggested to use the unit – economic value which embodies the materials' characteristics, in both quantity and quality aspects.

Furthermore, the value change could not be captured in the MCI, and the residual value is under the over-optimistic assumption that maintains the same as the new one. In order to solve this limitation (the research question 2), it is proposed to consider the residual value as an independent indicator in a circularity metric. With the integration of R, the circularity metric can make a distinction effectively between a linear and circular economy, and more importantly, recover the over-optimistic assumptions about the embedded value of materials in the MCI. Furthermore, how to quantify R is fundamental, and a residual value calculator is designed by considering design strategies and deterioration factors. Specifically, products'/materials' disassembly and recovery possibilities are suggested to be examined. Besides, a two-phase deterioration function is designed to capture the effect of aging and maintenance measures on the residual performance.

The whole assessment process of the circularity metric is then presented, considering these two adjustments (economic value and residual value) compared with the MCI. A case study (façade) with four scenarios is used to examine the effect of each and combined improvement. In the base scenario, the adjusted metric gives a low score (0.28) on the circularity performance, compared with 0.66 assessed by the MCI. The big difference is mainly caused by the light-weight (while valuable) brick slips, which flow in a linear procedure (with 100% virgin feedstocks and 100% unrecoverable waste) in the base scenario. The performance of the façade is improved when using brick slips in a more circular way, with the comparison between the base scenario and scenario 2 (or 3), based on the economic value. However, the same effort made for the brick slips could not be reflected appropriately based on the mass flow, with only a limited improvement. Hence, it is proposed that the usage of economic value as the measurement unit can provide more precise information, in a situation where light-weight materials are used. Furthermore, involving R gives different significance to virgin feedstock and unrecoverable waste based on the value change. The residual value of the project is assessed as 0.58 (R<1), which means the materials' value decline within time. Under this condition, improvements on the feedstock are more encouraged rather than waste scenario, since economic value embedded in the input is relatively higher than its output, and vice versa. With the new indicator R, decisions makers can make a better decision to improve the circularity performance for an economic perspective.

Considering the differences between the circularity metric and the MCI as discussed above, suggestions are provided for the company about how to choose these two approaches:

- It is suggested to use economic value as the measurement unit when light-weight materials are used. Furthermore, the MCI is still a good choice for traditional projects, where mass can roughly represent materials' relative value.
- The circularity metric considers residual value as an independent indicator, which means the assessment process may be more complex compared with the MCI. Hence, it is suggested that the company can assume the materials' value maintains the same in a short period (R=1), where the value change can be neglected. Furthermore, R is inapplicable when the economic value fraction of the virgin feedstock is equal to the fraction of the unrecoverable waste, which means it is unnecessary to calculate the value of R under this condition.

Furthermore, recommendations are considered based on the circularity metric proposed in this study as follows:

- Facilitating the circular design strategies at the early stage (design phase) is important for value retention. Furthermore, companies are encouraged to take appropriate maintenance actions during the usage phase to protect the residual value of the materials.
- Companies are recommended to recycle/reuse those materials with high value, in order to increase the circularity level, and simultaneously, acquire more economic benefits.
- It is recommended to pay closer attention to material input rather than waste scenario in a situation where the economic value of a product is predicted to be declining throughout the lifecycle. By the contrary, when the residual value is estimated to be higher than its original one, increasing recovery rate (reuse or recycling) is relatively more important.
- The circularity metric is narrowed to focus on material flows in a closed-loop, and other indicators (e.g. LCC and LCA) are suggested to complement to support companies to make optimal decisions.

Considering the limitations in this study, further work is calling for to consider the other aspects in a circular model such as energy and water consumption, to evaluate the circularity performance comprehensively. Furthermore, currently, the circularity metric is narrowed to material analysis at product-level instead of the whole building system, and it is necessary to expand the metric to a larger scale. There are few studies concerns the way of calculating the residual value in a CE, and the proposed residual value calculator is still in the early stage and should be improved further by involving other important factors. Last but not least, it is suggested to explore the huge potential of using digital technologies (e.g. BIM) to support the lifecycle circularity measurement.

9. Acknowledgements

The research was conducted with the help of different supervisors. They are Dr. S. Bhochhibhoya and Dr.Ir. R.S. de Graaf from the University of Twente. Furthermore, the case study was provided by Plegt-Vos in the Netherlands and under the guidance of Ir. Noud Slot and Ir. Berri de Jonge. Sincere gratitude to you all!

10. 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. *International Journal of Real Estate Studies, 11*(2), 21-24.

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Delgado, M. D., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, conservation and recycling, 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 minimization through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources, conservation and recycling, 105*, 167-176.

Amory, J. (2019). The Marinepassage: A case study project for circular design & material usage strategies in architecture.

Angioletti, C. M., Despeisse, M., & Rocca, R. (2017). *Product Circularity Assessment Methodology.* Paper presented at the IFIP International Conference on Advances in *Production Management Systems.*

Bokkinga, D. (2018). *The influence of a material passport on the value of real estate within the circular built environment*. (Master). Eindhoven University of Technology.

Braakman, L. (2019). *Assessing life cycle costs over increasing building circularity levels.* University of Twente,

Brand, S. (1995). *How buildings learn: What happens after they're built*: Penguin.

Circle Economy. (2019). Building Value - A pathway to circular construction finance Retrieved from https://www.circle-economy.com/news/new-financing-needed-to-accelerate-circular-built-environment

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

Di Maio, F., & Rem, P. C. (2015). A robust indicator for promoting circular economy through recycling. *Journal of Environmental Protection, 6*(10), 1095-1104.

Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources, conservation and recycling, 122*, 163-171.

Durmisevic, E. Design for disassembly as a way to introduce sustainable engenieering to building design & construction.

Dziadosz, A., & Meszek, W. (2015). Selected aspects of determining of building facility deterioration for real estate valuation. *Procedia Engineering, 122*, 266-273.

EASAC. (2016). *Indicators for a Circular Economy*. Retrieved from Halle,Germany.: https://www.easac.eu/fileadmin/PDF_s/reports_statements/Circular_Economy/EASAC_Indicators_web_complete.pdf

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

Ellen Macarthur Foundation. (2014). DESIGNING FOR A CIRCULAR ECONOMY. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/Floras-CEIP-report-Designing-for-a-Circular-Economy.pdf

Ellen Macarthur Foundation, & Granta Design. (2015). Circularity Indicators An Approch to Measuring Circulairty Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Project-Overview_May2015.pdf

European Environment Agency. 2016. Circular economy in Europe - Developing the knowledge base. EEA Report No 2/2016, 37 pp.

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. *Construction management and economics, 37*(3), 139-155.

Flikweert, J. (2009). Guidance on determining asset deterioration and the use of condition grade deterioration curves.

Government of the Netherlands. (2016). A Circular Economy in the Netherlands in 2050. Retrieved from https://www.government.nl/documents/leaflets/2016/09/22/a-circular-economy-in-the-netherlands-by-2050

Holland Circular Hotspot., & Circle Economy. (2019). Circular Cities Retrieved from https://hollandcircularhotspot.nl/wp-content/uploads/2019/04/HCH-Brochure-20190410-web_DEF.pdf

Junnila, S., Horvath, A., & Guggemos, A. A. (2006). Lifecycle assessment of office buildings in Europe and the United States. *Journal of Infrastructure systems, 12*(1), 10-17.

Kanniyapan, G., Mohammad, I. S., Nesan, L. J., Mohammed, A. H., & Ganisen, S. (2015). Façade material selection criteria for optimizing building maintainability. *Jurnal Teknologi, 75*(10).

Linder, M., Sarasini, S., & van Loon, P. (2017). A metric for quantifying product-level circularity. *Journal of Industrial Ecology, 21*(3), 545-558.

Nakagawa, T. (1988). Sequential imperfect preventive maintenance policies. *IEEE Transactions on Reliability, 37*(3), 295-298.

Nowogońska, B. (2016). The Life Cycle of a Building as a Technical Object. *Periodica Polytechnica Civil Engineering, 60*(3), 331-336.

Nuñez-Cacho, P., Górecki, J., Molina-Moreno, V., & Corpas-Iglesias, F. A. (2018). What gets measured, gets done:Development of a circular economy measurement scale for building industry. *Sustainability, 10*(7), 2340.

Material Economics. (2018). Retaining Value In The Swedish Material System.

Manganelli, B. (2013). *Maintenance, building depreciation and land rent.* Paper presented at the Applied Mechanics and Materials.

Monga, A., & Zuo, M. J. (2001). Optimal design of series-parallel systems considering maintenance and salvage value. *Computers & industrial engineering, 40*(4), 323-337.

Muzathik, A., Ferry, M., Chan, M., Samo, K., & Noor, C. (2012). Comparison of aluminium alloy and steel materials as deckhouses for offshore support vessels. Paper presented at the International Conference on Marine

Technology.
Platform CB'23. (2019). Kernmethode voor het meten van circulariteit in de bouw.
Paoloni, F., Ferrante, T., & Villani, T. (2018). MAINTENANCE SYSTEMS AND COSTS FOR WOODEN FAÇADES.
Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*: PBL Publishers.
Roulac, S., Adair, A., McGreal, S., Berry, J., & Allen, S. (2006). Real estate value: creation and destruction. Journal of Property Investment & Finance, 24(6), 474-489.
Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production, 207*, 542-559.
Schut, E., Crielaard, M., & Mesman, M. (2016). Circular economy in the Dutch construction sector: A perspective for the market and government.
TNO. (2019). Calculation model shows the residaul value of building products Retrieved from https://www.tno.nl/en/focus-areas/circular-economy-environment/roadmaps/circular-economy/circular-building/residual-value-calculation/
Verberne, J. J. (2016). Building circularity indicators: an approach for measuring circularity of a building.
van Vliet, M. M. (2018). *Disassembling the steps towards building circularity: redeveloping the building disassembly assessment method in the building circularity indicator.* (Master).
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*. Retrieved from https://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).
Wilhelmsson, M. (2008). House price depreciation rates and level of maintenance. *Journal of Housing Economics, 17*(1), 88-101.
Wilkins, D. J. (2002). The Bathtub Curve and Product Failure Behavior (Part One) Retrieved from https://www.weibull.com/hotwire/issue21/hottopics21.htm

Appendix A – Disassembly factors

Table 5 Overview of disassembly factors (van Vliet, 2018)

Product disassembly factors	Connection disassembly factors
Assembly shape	Accessibility to connection
Independency	Type of connection
Method of fabrication	Assembly sequences
Type of relational pattern	

Table 6 Grading system of Disassembly Determining Factors (Durmisevic,2006)

Disassembly factor	Factor weight	Attribute	Score
Accessibility to connection	1.0	Accessible	1.0
		Accessible with additional operation which causes no damage	0.8
		Accessible with additional operation which is reparable damage	0.6
		Accessible with additional operation which cases damage	0.4
		not accessible - total damage of elements	0.1
Type of connection	1.0	Accessory external connection or connection system	1.0
		Direct connection with additional fixing devices	0.8
		Direct integral connection with inserts (pin)	0.6
		Filled soft chemical connection	0.2
		Filled hard chemical connection	0.1
		Direct chemical connection	0.1
Assembly shape	1.0	Open linear	1.0
		Symmetrical overlapping	0.8
		Overlapping on one side	0.7
		Unsymmetrical overlapping	0.4
		Insert on one side	0.2
		Insert on two sides	0.1
Independency	1.0	Modular zoning	1.0
		Planned interpenetrating for different solutions (overcapacity)	0.8
		Planed for one solution	0.4
		Unplanned interpenetrating	0.2
		total dependence	0.1
Method of fabrication	1.0	Pre-made geometry	1.0
		Half standardised geometry	0.5
		Geometry made on the construction site	0.1
Assembly Sequence	1.0	Same level / Same level	1.0
		High level / Low level	0.5
		Low level / High level	0.1
Type of relational pattern	1.0	One or two connections	1.0
		Three connections	0.6
		Four connections	0.4
		Five or more connections	0.1

Appendix B– Assumptions for the case study (base scenario)

Table 7 Assumptions for the case study

Origin of materials	The origins of materials have been obtained from the information (e.g. product reports, websites) provided by suppliers. For example, the mineral brick slips were made by raw materials, while recycled glass (up to 80%) and recycled paper (100%) were collected for producing glass wool and fibre board respectively. If there was no specific information introducing the material composition (reuse, recycled), it is assumed that the component was produced using purely virgin materials.
Waste scenario of materials	The waste scenarios of materials after the expected lifespan have also been obtained from suppliers. If the supplier mentions the component is recyclable, the percentage of recycling is assumed as 100% instead of incinerated. Furthermore, the company estimations (based on the current situation) have been taken if there was no available information for the waste scenarios.
Utility factor	The functional lifespan is assumed as 75 years, as same as its technical lifespan (predicted by Plegt-Vos); therefore, the utility factor is stated as 1 in the case study.
Efficiency of recycling process	According to Schut et al. (2015), there are only 3-4% of secondary materials used in the buildings, although more than 95% of construction waste has been recycled in the Netherlands. Therefore, the recycling process mainly happens in an open market rather than a closed-loop. There are two factors Ef and Ec used in the MCI. Ec/Ec' is the efficiency of recycling the product after EoL, and then can be sourced in an open market, which is estimated at 60% in this study. Ef, as the efficiency of producing recycled feedstock, is not considered in the circularity metric (and the MCI, for a fair comparison), since there is only a small part of materials as discussed before can be recycled in a closed-loop currently.

Appendix C - Data input for the case study (base scenario)

Table 8 Input for the circularity metric and the MCI

Basic Elements (from outside to inside)	Recycled Feedback/%	Reused Feedback/%	Bio-based Feedback/%	Recycled materials/%	Reused materials/%
Flexible mineral brick slips	0	0	0	0	0
Glue for the brick slips	0	0	0	0	0
Primer for the stone strips	0	0	0	0	0
Reinforcement tape for the brick slips	0	0	0	0	0
Power panel H2O	0	0	0	1	0
Ventilation rows	0	0	0	0	0
Underlay membrane protection film	0	0	0	0	0
LPDE foil	0	0	0	0	0
Construction birch plywood B/BB	0	0	1	1	0
Glass wool & System rolls	0.8	0	0	1	0
Gypsum fibre board	1	0	0	1	0
FSC Spruce	0	0	1	1	0
	Fr/Fr'	**Fu/Fu'**	**Fb'**	**Cr/Cr'**	**Cu/Cu'**
Based on mass	0.19	0.00	0.53	0.89	0.00
Based on economic value	0.05	0.00	0.18	0.32	0.00

Table 9 Input for the residual value calculator

Design Strategies		Sub-criteria	Score
Design for Recovery		Avoidance usage of toxic materials	1
		Avoidance usage of secondary finishes	1
Design for Disassembly	Connection disassembly factors	Accessibility to connection	0.4
		Type of connection	0.2
		Assembly sequence	1
	Product disassembly factors	Independency	1
		Method of fabrication	1
		Assembly shape	1
		Type of relational pattern	1
Overall Score		**0.9**	

Appendix D– Results of case study 1

Table 3 summaries the results of different scenarios under the condition of R=0.58, while Table 10 to 13 present the more detailed assessment results of each scenario.

Table 10 Results of base scenario with R=0.58

	Fr	Fu	Fb	Cr	Cu	V	Wo	Wc	W	LFI	MCI
Based on the mass flow	0.19	0	0.53	0.89	0	329.34	126.3	415.84	542.14	0.37	0.66
	Fr’	**Fu’**	**Fb’**	**Cr’**	**Cu’**	**V’**	**Wo’**	**Wc’**	**W’**	**LFI’**	**MCI’**
Based on the economic value	0.05	0	0.16	0.32	0	2491.25	2119.14	407.60	2526.74	0.80	0.28
Based on the economic value and residual value	0.05	0	0.16	0.32	0	2491.25	1229.10	236.41	1465.51	0.80	0.28

Table 11 Results of scenario 2 with R=0.58

	Fr	Fu	Fb	Cr	Cu	V	Wo	Wc	W	LFI	MCI
Based on the mass flow	0.19	0	0.53	0.96	0	329.40	46.65	415.84	462.49	0.34	0.69
	Fr’	**Fu’**	**Fb’**	**Cr’**	**Cu’**	**V’**	**Wo’**	**Wc’**	**W’**	**LFI’**	**MCI’**
Based on the economic value	0.05	0	0.16	0.93	0	2491.25	207.54	1172.24	1379.78	0.66	0.44
Based on the economic value and residual value	0.05	0	0.16	0.93	0	2491.25	120.37	679.90	800.27	0.62	0.40

Table 12 Results of scenario 3 with R=0.58

	Fr	Fu	Fb	Cr	Cu	V	Wo	Wc	W	LFI	MCI
Based on the mass flow	0.19	0	0.53	0.89	0.07	329.40	46.65	447.70	494.35	0.35	0.68
	Fr’	**Fu’**	**Fb’**	**Cr’**	**Cu’**	**V’**	**Wo’**	**Wc’**	**W’**	**LFI’**	**MCI’**
Based on the economic value	0.05	0	0.16	0.32	0	2491.25	207.54	407.60	615.14	0.49	0.55
Based on the economic value and residual value	0.05	0	0.16	0.32	0	2491.25	120.37	236.41	356.78	0.57	0.48

Table 13 Results of scenario 4 with R=0.58

	Fr	Fu	Fb	Cr	Cu	V	Wo	Wc	W	LFI	MCI
Based on the mass flow	0.25	0	0.53	0.89	0	249.75	126.30	415.84	542.14	0.34	0.69
	Fr’	**Fu’**	**Fb’**	**Cr’**	**Cu’**	**V’**	**Wo’**	**Wc’**	**W’**	**LFI’**	**MCI’**
Based on the economic value	0.66	0	0.16	0.32	0	579.65	2119.14	407.60	2526.74	0.49	0.55
Based on the economic value and residual value	0.66	0	0.16	0.32	0	579.65	1229.10	236.41	1465.51	0.41	0.63

Appendix E– Results of case study 2

Table 4 summaries the results of different scenarios with different value of R, while Table 14 to 16 present the more detailed assessment results of each scenario.

Table 14 Results of base scenario with different R

	Fr’	Fu’	Fb’	Cr’	Cu’	V’	Wo’	Wc’	W’	LFI’	MCI’
R=0.58	0.05	0	0.16	0.32	0	2491.25	2119.14	407.60	2526.74	0.80	0.28
R=0.3	0.05	0	0.16	0.32	0	2491.25	2119.14	407.60	2526.74	0.80	0.28
R=1.3	0.05	0	0.16	0.32	0	2491.25	2119.14	407.60	2526.74	0.80	0.28
R=1.8	0.05	0	0.16	0.32	0	2491.25	2119.14	407.60	2526.74	0.80	0.28

Table 15 Results of scenario 3 with different R

	Fr’	Fu’	Fb’	Cr’	Cu’	V’	Wo’	Wc’	W’	LFI’	MCI’
R=0.58	0.05	0	0.16	0.32	0.61	2491.25	120.37	236.41	356.78	0.57	0.48
R=0.3	0.05	0	0.16	0.32	0	2491.25	62.26	122.28	184.54	0.66	0.41
R=1.3	**0.05**	0.00	0.16	0.32	0.61	2491.25	269.80	529.88	799.69	0.46	0.59
R=1.8	**0.05**	0.00	0.16	0.32	0.61	2491.25	373.57	733.68	1107.26	0.41	0.63

Table 16 Results of scenario 4 with different R

	Fr’	Fu’	Fb’	Cr’	Cu’	V’	Wo’	Wc’	W’	LFI’	MCI’
R=0.58	0.66	0.00	0.16	0.32	0.00	579.65	1229.10	236.41	1465.51	0.41	0.63
R=0.3	0.66	0.00	0.16	0.32	0.00	579.65	635.74	122.28	758.02	0.33	0.70
R=1.3	0.66	0.00	0.16	0.32	0.00	579.65	2754.88	529.88	3284.77	0.54	0.52
R=1.8	0.66	0.00	0.16	0.32	0.00	579.65	3814.45	733.68	4548.14	0.58	0.47