FINANCIAL ANALYSIS OF A RENOVATION IN THE CIRCULAR ECONOMY

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FINANCIAL ANALYSIS OF A RENOVATION IN THE CIRCULAR ECONOMY

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Learning has been beautiful. Learning has let me always see the world where I live from various perspectives. Learning has let me understand the reasons why people, and myself, make certain decisions. Learning has let me see the resulting implications in the world from our decision makings. Learning has let me empathise joyfulness, pain, and other states of mind of people affected by the decisions, and of course, myself as well. The given emotions have led me to seek another learning point.

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ABSTRACT

Purpose – To address its immense raw material consumption, the built environment is called for achieving a Circular Economy (CE), potentially saving 350 billion Euros in the process. Renovation of existing buildings, as a possible solution, is to be prioritised rather than constructing new buildings. To achieve a CE, strategies have been developed that can be applied to renovation projects. Yet, as an emerging field of science and lack of financial analysis-based literature, it remains challenging to understand these CE strategies from a financial perspective. Hence, this study aimed to develop a financial analysis method to show the financial attractiveness of CE strategies applied to renovation projects.

Methods - This study designed six renovation options where the reuse, repair and recycle CE strategies are applied to parts of a renovated building. This study employed three different methods to estimate the values of reused, repaired and newly produced building elements, respectively. This study used the following three financial performance measures to rank six renovation options from a financial perspective: the total cost, the net cost, and the return of investment. This study tested the developed financial analysis methods to a case study.

Results - The following two renovation options were mostly preferred from a financial perspective: the in-place reuse and repair of the existing building elements. Yet, the three financial performance measures ranked renovation options differently per each part of the building. Throughout the sensitivity analysis, it was observed that the subjective judgements that a user of the financial analysis makes considerably influence the renovation options' rankings.

Discussion and conclusion – The two main findings are as follows. Firstly, it is a natural consequence that value is subjectively judged. Nonetheless, providing the elaborated criteria to show how the subjective factors are formulated can be helpful to reduce the intervention of intuition, emotions and prejudice. Secondly, a lack of information on both the existing building elements and secondary building elements limits the accuracy by which the value of reused building elements can be estimated. That limitation may lower the credibility of a result, even though the financial analysis shows that using secondary building elements is preferred, Thus, it was recommended to maintain the current material passport system and establish a platform where the information is share.

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1 INTRODUCTION

This chapter outlines the background and reasons why this study investigates the financial analysis method for a renovation in a circular economy. Section 1.1 explains the background information on the financial analysis of a renovation project in a circular economy. Section 1.2 defines the problems that this study intends to solve. Section 1.3 describes the aim and research questions of this study.

1.1 Background

1.1.1 The built environment as a waste generator and renovation as a solution

The built environment is the largest consumer of raw materials all around the world (World Economic Forum, 2016). Manufacturing building construction materials consumes 6% of global energy, which is responsible for 11% of global emission (International Energy Agency & UN Environment Programme, 2019). Looking into Europe, half of the total raw material consumption occurs in housing alone. More than 60% of total aggregate materials, like sand, and around 20% of total metals are consumed for building projects (Ecorys, 2014). This results in construction and demolition waste (CDW) to become the excessive waste stream in the EU, which is a third of all waste (European Commission, 2019).

Renovation poses a possible solution. Around 80% of all buildings currently existing in the Northern Hemisphere will still be in use by 2050 (International Energy Agency, 2014). Considering the raw material consumptions for new building constructions and the resulting waste generation, utilising the existing buildings must be a priority (ARUP, 2016). Renovation only replaces or adds parts of a building, such as outer walls or internal installations (Ástmarsson, Jensen, & Maslesa, 2013). Renovation can also increase the efficiency of resource use, followed by minimizing waste generation in the built environment (Bullen, 2007; Conejos, Langston, & Smith, 2015; James, 2014). Additionally, renovation can save more time and cost than rebuilding after demolition (ARUP, 2016; Bullen, 2007; Langston, 2008).

1.1.2 Circular renovation – renovation according to circular economy principles

By definition, renovation does not necessarily reduce the raw material consumptions, as the term ‘renovation’ embodies a multitude of concepts (Lopes, 2014). It is, therefore, necessary to redefine renovation according to principles of the circular economy (CE). A CE is referred to as an alternative growth strategy that decouples the raw material consumption from economic development, consequently mitigating environmental degradation (Reike, Vermeulen, & Witjes, 2018). It is expected that achieving a CE in the European built environment would save 350 billion euro (Ellen MacArthur Foundation, 2015). For these reasons, the built environment is called for achieving a circular economy (CE).

This study will use the terminology 'circular renovation' to describe a conceptual renovation aimed to achieve a CE. A circular renovation project applies the strategies designed to achieve a CE, such as reduce and repair, to parts of a building as follows. Firstly, existing parts of a building are reused or repaired and discarded as of little as possible, but if so, recycled within a closed-loop (Adams, et al, 2017). Secondly, newly installed parts have been used elsewhere or are designed to decrease the amount of raw materials used in their manufacture processes.

Yet, it is a challenge to decide a CE strategy applied to a circular renovation project.

1.2 Problem Definition

Circular economy (CE) principles have gained much interest from a social as well as scientific perspective. Much of this, however, has had a focus on the impact of resource consumption and consumer waste reduction on the environment (Singh & Ordoñez, 2016), and mainly in the food and fashion industries. While this has seemed to have a great impact on consumers' awareness, ethical decision making and behaviours (European Commission, 2018), CE for the built environment is still a relatively nascent field of science (Lieder & Rashid, 2016). Particularly CE attractiveness from a financial perspective is still not well understood. The financial attractiveness of applied CE strategies, however, is shown to be the most critical factor to a building owner[a] who decides on applying a CE strategy (Adams, Osmani, Thorpe, & Thornback, 2017; Pardo-Bosch, Cervera, & Ysa, 2019).

Understanding a preferred CE strategy from a financial perspective is challenging. To understand the financial attractiveness, a building owner utilizes financial analysis[b]. The financial analysis firstly estimates the financial implications of applying a CE strategy, such as cost and value. Using the estimated financial implications, financial performance measures,

[a] Decision makers who decide applied CE strategies may be individuals and government agencies who own renovated buildings, or construction businesses in charge of a renovation project. For convenience, this study will use this term 'building owner'.

such as the return of investment, show the most preferred CE strategy. Understanding the cost and value of applying CE strategies is complicated (Beers, 2019). The literature mentioned recycled contents and the detachability of a building element as factors influencing the financial implications (Adams, et al, 2017; Geldermans, 2016; Sanchez & Haas, 2018). Yet, it is uncertain in what way to involve these factors. Also, a few of relevant studies calculated the costs, however, their different cost calculation methods cause ambiguity (Hart, Adams, Giesekam, Tingley, & Pomponi, 2019).

1.3 Aim and Research Question

Addressing this gap in literature and practice, this research aims to formulate methods to determine a preferred CE strategy from a financial perspective. The formulated methods are aimed to be ready-to-use for practitioners in the built environment. Hence, this research can help practitioners who would apply CE strategies in real renovation projects to use this new field of knowledge. To achieve this research objective, the following understanding is necessary: i) financial analysis methods used for a renovation project, ii) aspects to be considered in the financial analysis for a circular renovation project.

The main research question of this study is:

"How can we assess CE strategies applied to a renovation project from a financial perspective?"

To answer the main research question, the following sub-questions (SQ) will be answered:

SQ1. What financial analysis methods have previously been used for a renovation project?

There is a limited amount of studies related to financial analysis for a circular renovation project. Thus, it is needed to review the financial analysis methods that the current literature use. The answer to this question will allow for a better understanding of key factors of financial analysis to be considered in a renovation project.

SQ2. What aspects must be considered for the financial analysis of a circular renovation project?

The financial analyses previously used for conventional renovation projects could not be directly used for circular renovation projects. This question will allow an understanding of how each CE strategy can be applied to a circular renovation project. This question will allow understanding of which aspects in respect to CE strategy application have to be considered for the financial analysis.

SQ3. How can the financial analysis methods for a circular renovation be formulated?

Based on the findings for the first and second sub-questions, this research will formulate the financial analysis methods for a circular renovation project. The formulated financial analysis methods will be tested by a case study. The way to formulate the financial analysis methods for a circular renovation project will be explained in the methodology chapter.

2 THEORETICAL FRAMEWORK

2.1 Financial analysis procedure in a circular renovation

Table 1 illustrates the key phases of a circular renovation project. In the first phase, the goal and budget of a renovation project are set up to define the scope of the renovation project (Lopes, 2014). Subsequently, the type of renovation project is determined as a circular renovation project.

Table 2-1 The procedure of a circular renovation project, adapted from (Lopes, 2014) & (Langdon, 2007).

Step 1: Project setup
Phase 1: Scope of the renovation project
Phase 2: Determining the type of project *"Circular renovation: application of CE strategies to both existing building elements in place and newly installed building elements"*
Step 2: Renovation options setup
Phase 1: Analysis of the main objectives
Phase 2: Financial analysis 2-1) Identify the renovation options to be analysed (section 2.2) 2-2) Assembly of financial implications data to be used in the analysis (section 2.3) 2-3) Carry out the financial analysis
Phase 3: Selection of renovation options
Step 3: Implementation
Phase 1: Implementation of the project Phase 2: Testing and commissioning
Step 4: Verification
Phase 1: Verifying the achievement of objectives Phase 2: Maintenance of building services systems

In the second phase, firstly, the main objective of financial analysis is defined. This study considers that main objective as informing a building owner about the preferred circular renovation options from a financial perspective. Next, circular renovation options are designed in line with the concept of circular renovation, which is applying CE strategies to both existing in place building elements as well as newly installed building elements (Section 1.1). To decide an executed circular renovation option, the financial analysis is carried out. For the financial analysis, the following two factors are selected: i) financial implications that the financial analysis will assess and ii) financial performance measures, such as the total cost, that show the most preferred circular renovation option from a financial perspective. Considering the results that the financial performance measures provide, an executed circular renovation is finally selected.

The following section explains i) three CE strategies that are employed in circular renovation option design, and ii) the six circular renovation options this study designed.

2.2 The circular renovation options

2.2.1 The CE strategies applied to building elements

The concept of circular renovation is a renovation project that applies CE strategies to both existing building elements in a to-be-renovated building and newly installed building elements that will be externally sourced, to limit waste and raw material consumption, and consequently, mitigate environmental degradation. Thus, to identify circular renovation options, this study looks into the CE strategies that could be applied. Potting, Hekkert, Worrell, & Hanemaaijer (2017) developed the R-list, which comprises of 10 CE strategies that are designed to achieve the CE principle. The ten strategies from ‘refuse (R0)’ to ‘recover (R9)’ are ranked in order of circularity; the refuse being most circular and the recover being least circular. This circularity means the ‘extent to which a production chain of material(s) is locked so that additional natural resources are not demanded to produce materials, and discarded products do not become waste’. This implies a CE strategy that is closer to R0 consumes fewer natural resources and puts less environmental pressure.

Table 2-2 The hierarchy amongst 10 CE strategies (Potting et al., 2017)

CE strategy		**Explanation**
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)

	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend the lifespan of a product and its parts	**R3 Reuse**	**Reuse by another consumer of discarded product which is still in good condition and fulfils its original function**
	R4 Repair	**Repair and maintenance of defective product so it can be used with its original function**
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of a discarded product in a new product with the same function
	R7 Repurpose	Use a discarded product or its parts in a new product with a different function
Useful application of materials	**R8 Recycle**	**Process materials to obtain the same (high grade) or lower (low grade) quality**
	R9 Recover	Incineration of materials with energy recovery

Of all the 10 strategies, this study only employs the three CE strategies ‘reuse (R3)’, ‘repair (R4)’ and ‘recycle (R8)’. The reason for this is as follows. The three highest CE strategies from ‘refuse’ to ‘reduce’ that deny the initial manufacture, cannot be applied as existing building elements of a building have already been manufactured. Existing building elements can be directly reused again unless they need maintenances. ‘Repair (R4)’, in the context of the built environment, can represent both the ‘refurbishment (R5)’ and ‘remanufacturing (R6)’ strategies, which is because all of these three strategies aim at restoring the existing building elements to take back their original functions (Potting et al., 2017). Yet, ‘repurpose (R7)’ aims to get different or upgraded functions from the original status (ibid; Reike et al., 2018). Predicting how a specific building element will be upgraded is complicated, thus, refurbishment is out of scope in this research. Since not all parts of a building can be reused and repaired, some of them are unavoidably discarded (Beers, 2019). In such case ‘recycle (R8)’, which is a down-cycling option, is employed (Reike et al., 2018). This study does not consider ‘recover (R9)’. This is because it is uncertain whether a building owner can independently decide to recover the energy from discarded building elements, due to regional regulations and technological limitations. Instead, this research considers the recover as a way of CDW treatment strategy.

2.2.2 The six circular renovation options

With those three CE strategies 'reuse', 'repair' and 'recycle', this study designed six circular renovation options, as presented in Table 2-3. There are two considerations with regards to the reuse strategy. According to the definition Potting et al. (2017, p. 15) offered, reuse is referred to as re-using discarded products from elsewhere. This definition does not consider the case a building owner decides to use existing building elements in place again as reuse. To cover this, and to clearly distinguish from repair, this study adopts the following definition based the definition of 'reuse' in the dictionary (Cambridge University Press, n.d.) and Ripanti (2016): 'to use something again, without any modification'.

This study used the following two terminologies to describe each circular renovation option: i) building element and ii) building material. Building materials, such as wood, are a subset of a building element, like a door. Accordingly, a building element comprises one or more building materials (TU Delft, n.d.; Circle Economy, 2019).

A building element that will be ultimately used in the renovation project is either an existing in-place building element or externally sourced. A building owner can directly reuse an existing building element in place (Op. 1) or repair it before reuse (Op. 2). Alternatively, a building owner removes an existing building element and externally sources a replacing building element. In turn, a replacement building element is either a secondary building element that has been used elsewhere or is newly produced. Firstly, if a secondary building element is sourced, a building owner can either directly reuse it (Op. 3) or repair the sourced element before reusing it (Op. 4). Next, a building owner can also purchase a newly produced building element from recycled building materials (Op. 5) or virgin building materials (Op. 6).

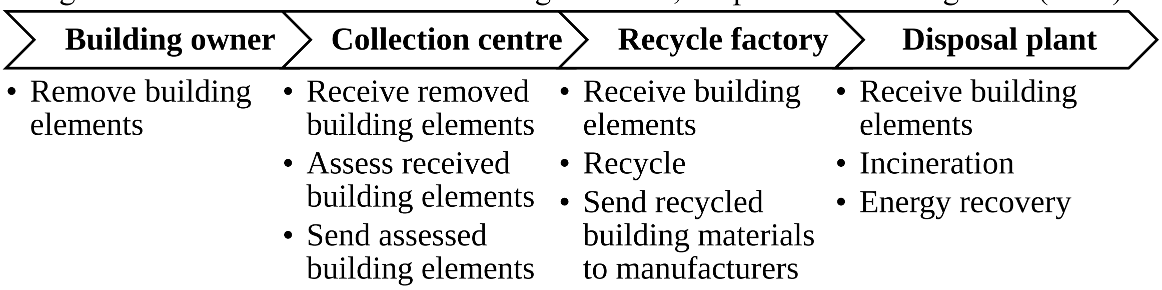
Table 2-3 Circular renovation options considered in this study.

Category	**Option**	**Applied CE strategy**	**Description**
Using the existing building elements in place	Op. 1	Reuse	Direct reuse an existing building element in place
	Op. 2	Repair	Repair an existing building element in place, and reuse
Using externally sourced building elements	Op. 3	Reuse	Directly reuse a secondary building element that has been used elsewhere
	Op. 4	Repair	Repair a secondary building element that has been used elsewhere, and reuse

	Op. 5	Recycle	Purchase a recycled building element
	Op. 6	Virgin	Purchase a virgin building element

This study considers that CE strategies are applied only to a building element that will ultimately be used as a result of the circular renovation. This is because removed building elements are sent to a construction and demolition waste (CDW) collection centre as of now, and the CDW collection centre decides the applied CE strategies independently (Figure 2-1). A building owner cannot control the CDW treatment process, due to technical limitations and regional regulations. Nonetheless, there are ongoing studies about establishing platforms where used building elements are traded, yet their revenue structures are still uncertain (ING Bank N.V., 2017). Moreover, even if a building owner would sell removed building elements, the decision about what happens after the sells, whether directly reusing or repairing them, is in the hands of the buyer and beyond the control of the building owner.

Figure 2-1 Channel of removed building elements, adapted from Potting et al. (2017)



This study acknowledges that the most financially attractive circular renovation option might differ depending on the type of building element. This is because each building element may have a unique lifespan and physical characteristics (Brand, 1994). For those same reasons, building elements may also have different repair and replacement periodicities (Galle, De Temmerman, & De Meyer, 2017). Therefore, it is not financially preferable nor necessary to apply the same renovation option to all building elements. Instead, a building owner should be in the position to select an option of the six circular renovation options per building element. To appropriately select one of six circular renovation options, the financial analysis assesses the financial implications of executing the various options on the building elements. The next section describes the financial implications of executing circular renovation options.

2.3 Financial implications of a circular renovation project

This section explains the following two financial implications, cost and value, and performance measures, TC, NC and ROI, that the study considers. Section 2.3.1 shows the costs that a building owner pays for executing circular renovation options. Section 2.3.2 describes the value that a building owner acquires from executing circular renovation options. Lastly, in Section 2.3.3 the financial performance measures are described.

2.3.1 The costs executing circular renovation options

The cost is the fixed amount of money that a building owner has to pay. That fixed amount of money is the estimation submitted by business involved throughout the execution procedure of a circular renovation option. The cost is considered as the main criterion when it comes to a financial decision (European Commission, 2017). The cost will be estimated as the sum of labour, materials, transportation and equipment costs throughout the execution procedure, which are key resources and activities enabling the execution (Osterwalder & Pigneur, 2010).

This study considers the cost of executing each circular renovation option is the sum of disassembly cost, CDW collection cost, installation cost, and repair cost. This study regards that a removed building element is to be disassembled into its constitutive building materials, not just discarded (Cambridge, n.d). According to (Das, Yedlarajiah, & Narendra, 2000), disassembly has the following two advantages about CE: i) it enables valuable materials can be separated, not disposed and ii) reusable parts can be used in remanufacture procedures. Yet, the cost of disassembly is complicated to estimate (ibid). This is because the standardised cost inventory of a renovation project is harder to find than that of a new building construction project (Ashuri & Lu, 2010; Bonakdar, 2018; Bullen, 2007).

2.3.2 The values acquired from executing circular renovation options

A building owner considers value that he or she will get through executing a circular renovation option. As a result of a circular renovation, a building owner will get to use a building element where the CE strategy is applied. This research, therefore, focuses on the value of a consequently used building element. Undoubtedly, the term “value” is defined differently according to the context in which it is used (Reinecke, 2010). This research uses an adaptation of the dictionary definition of value: the amount of money a building element might be sold for (Cambridge University Press, n.d.).

The six circular renovation options involve the following three categories of building elements: directly reused, repaired and newly produced building elements. Both directly reused and repaired building elements have experienced physical depreciation because of wear. The physical depreciation adds up to economic depreciation (OECD, 2009). This leads the value of a previously used building element to be estimated lower than that of a newly produced building element (ibid). Yet, if a previously used building element is repaired, its physical performances can be improved. This implies the value of a repaired building element would be estimated higher than that of a directly reused building element. Therefore, the values of reused, repaired and newly produced building elements are to be differently estimated.

Value estimation for directly reused building elements

The value of directly reused building element could be estimated based on the straight-line depreciation method. Depreciation method estimates the present depreciated value of a tangible asset at any given time, throughout its service life (OECD, 2009). The straight-line depreciation method depreciates the value equally every year. Other depreciation methods, like accelerated depreciation, assume that the value is exponentially depreciated during early days, otherwise, ageing of an asset increases the depreciation rate (Jackson, Rodgers, & Tuttle, 2010). However, once building elements are installed, they service steadily throughout their service lives, and the amounts of their services are consistent (Storchmann, 2004), making the straight-line depreciation method most appropriate. Consequently, the annual depreciation is described as follows (Liapis & Kantianis, 2015):

$$Annual\ depreciation = \frac{Cost\ of\ building\ element\ -\ Its\ residual\ value}{Service\ life\ of\ building\ element} \tag{2.1}$$

As seen in Equation 2.1, the following two concepts are to be clarified to employ the depreciation method: i) residual value and ii) service life. Firstly, this study considers the residual value as the expected selling price of a building element in the market at the end of the service life (Fan, AbouRizk, Kim, & Zaiane, 2008; Gobbi, 2011). TNO (2019) has discussed the following influencing factors: the possibility for disassembly, standardisation, quantity and quality, adaptability, processing costs, and logistic issues, and others. Secondly, the service life is referred to as the period during which a building element meets its performance requirement (ISO 15686-5:2017, International Organization for Standardization, 2020). There are the following five types of service life: physical life, economic life, functional life, technological life, and social/legal life (Langdon, 2007). This study considers the physical life as the service life because the physical life is estimated as the longest period based on the assumption that a building element is used until disassembled. The physical life is estimated by the factor method, Equation 2.2 (Straub, 2015; Straub, 2011). The following two factors are considered in the factor method: i) the reference service life and ii) 7 types of factors that are subjectively judged by practitioners. The subjective factors assess the physical environment around a building element.

$$ESLC = RSLC \times F(A) \times F(B) \times F(C) \times F(D) \times F(E) \times F(F) \times F(G) \quad (2.2)$$

$ESLC$= the estimated service life of a building element;

$RSLC$= the reference service life of a building element;

$F(A)$ = the quality of building element (from 0.9 to 1.1);

$F(B)$ = the design level (from 0.9 to 1.1);

$F(C)$ = the work execution level (from 0.9 to 1.1);

$F(D)$ = the indoor environment (from 0.9 to 1.1);

$F(E)$ = the outdoor environment (from 0.9 to 1.1);

$F(F)$ = the in-use conditions (from 0.9 to 1.1);

$F(G)$ = the maintenance level (from 0.9 to 1.1).

Value estimation for repaired building elements

Since repaired building elements will get back to their original states, their values are expected to get higher than reused building elements. Yet, they have been in use anyway, their values might not be higher than just newly produced building elements. According to Vorasayan and Ryan (2006), the value of a repaired building element[c] is proportional to its perceived quality by building users, and the value of a newly produced building element. A

[c] Vorasayan and Ryan (2006) used the term 'refurbished product' not 'repaired product'. They defined refurbished products as "those that have been verified by the manufacturer to be as functional as new products". This definition is, however, in line with that of repaired product which Potting et al., (2017) have developed. According to Potting et al., (2017), a defective product can be used with its original function by repair, while refurbishing a product is "to restore an old product and bring it up to date". This research employs the CE strategies of Potting et al., (2017), hence, this research employed the equation of Vorasayan and Ryan (2006).

building owner perceives the quality of repaired building element based on a variety of factors, like the technical specification, warranty period and physical appearance.

2.3.3 Financial performance measures

Financial analyses have been done using a diverse set of financial metrics, such as Net-Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), Payback Period (PBP), and others.

Currently, the total cost (TC) is still considered as the main criterion when it comes to making a financial decision on operating a construction project (European Commission, 2017). However, this metric focuses solely on the total costs, while omitting the potential value of a project. Then, customers might need differently expressed indicators depending on their investment behaviours. To communicate with the owners, quantified the net costs are necessary (ARUP, 2016), which already incorporate the value. Similarly, ROI, widely used by decision-makers to compare efficiencies of investments, also incorporates the value, but in a simpler form, proportional to the investments or costs (Alkaraan & Northcott, 2006; Sinclair, 2010). It might be complicated to use the payback period for a circular renovation, since a circular renovation does not generate periodic values, such as monthly energy saving.

Hence, this study considers using the following three financial performance measures: i) the TC, ii) the NC and iii) the ROI. The reason why multiple measures are used is that building owners have different investment behaviours, therefore, using one measure might not be sufficient.

In the following chapter, this study explains the methodology to formulate and assess the cost and value estimations that were reviewed in this chapter, for a circular renovation project.

3 METHODOLOGY

This chapter explains how the financial analysis of a circular renovation project is carried out. To assess the financial implications of circular renovation a Decision Support System (DSS) was built. The DSS aims to inform a building owner, the intended user of the DSS, of the preferred circular renovation options from a financial perspective (Section 2.1). This study developed the DSS and applied the DSS to a case study. Section 3.1 reviews how the DSS was formulated, after which Section 3.2 illustrates the case study.

3.1 Decision Support System (DSS) development

This section explains the design and development of DSS. This study used Microsoft Excel to make data-driven DSS. The process to use the DSS is presented in Table 3-1, and the presentation of the DSS is illustrated in Appendix 1. The DSS comprises the six circular renovation options that this study suggested in Section 2.2.2. Moreover, the DSS assesses two financial implications of executing the circular renovation options, cost and value explained in Section 2.2.3, on the building elements. Based on the assessed financial implications, three financial performance measures are employed in the DSS by which the six circular renovation options are ranked.

Table 3-1 The manual to use the DSS

Step 1: Input the information on a building element
Step 1-1: Input the size of a building element Step 1-2: Input the material composition of a building element
Step 2: Fill up the building material inventory
Step 2-1: Input the price data of scrap building materials
Step 3: Input the cost and value estimation data
Step 3-1: Input the costs for executing six circular renovation options Step 3-2: Input the data and factors for the value estimation
Step 4: Check the results that the employed financial performance measures offer

There are the following two considerations that a building owner must take into account when using the DSS. Firstly, it would be impossible that all building elements are freely renovated in different ways, due to architectural features like interdependences of building elements. Yet, the architectural complexity is out of the scope of this study, therefore, the DSS does not take this into account. Secondly, the circular renovation options which will ultimately be executed should not solely be decided based on the financial implications provided by the DSS. This is because, in reality, all the six circular renovation options may not be executable, for example, because of a lack of supply or technical obstacles to installing them in other places. These market situations and construction method-related issues are not considered by the DSS.

3.1.1 The input of building element information

The first step to use the DSS is to input the information on a building element. Table 3-2 presents the information of a building element to be inputted in the first and second steps in the DSS (Section 1.1). The DSS requires two types of data as follows. Firstly, it is required to input the size of a building element on which a circular renovation option is executed. This is because the size of the building element is proportional to the cost of executing a circular renovation. For instance, the generally bigger size of building element would demand more labour hours for repair and require more natural and human resources within its manufacture, delivery, and installation procedures. The size is inputted in length (m), width (m) and height (m). Secondly, the material composition is required as input. The material composition refers to the following data of the building materials that constitute a building element: i) the name, ii) density in kg/m^3 and iii) proportion of volume in % relative to the building element of which it is part. The reasons that these data are needed are as follow. Prices of building materials differ, and this influences both the costs of purchasing building elements as well as the revenue obtained from reselling them.

The second step is to fill out the building materials inventory. The data in this inventory includes each constitutive building material and is described in the material composition as follows: i) the current price of scrap building material, ii) the escalation rate for the price of scrap building material, and iii) the discount rate for that price. These three data are used for estimating the residual value (Section 2.3.2).

Table 3-2 Information on building element to be inputted in the DSS.

Suspended ceilings	**Size**		
	Length [m]	Width [m]	Height [m]
	1.5	0.6	0.02
	Material composition		

Name	Density [kg/m3]	Proportion [%]	Volume [m3]	Mass [kg]
Rockwool	22	100%	0.018	0.369

3.1.2 Cost and value estimation

Based on the provided input information of the building element in the first and second steps, the following two financial implications for executing the six circular renovation options are estimated: i) the cost for executing a circular renovation option, and ii) the generated value from applying of a CE strategy to a building element that will be used consequently. These costs and values are estimated in Euros.

Cost

The cost is the amount of money that a building owner has to pay to execute a circular renovation option on a particular element. The cost for each circular renovation options is the sum of costs generated throughout the execution procedure, as explained in Section 2.3.1. These processes and their respective costs are broken down in the cost estimation equation:

$$C = D + W + P + R + A \qquad (2.3.3.1)$$

where:

D = disassembly cost (in €);

W = CD&W collection cost (in €);

P = purchasing cost = $M + I$ (in €);

R = repair cost (in €);

A = contingency allowance = $10\% \times (D + W + P + R)$ (in €);

M = material cost (in €);

I = installation cost (in €).

Value

The DSS employs different value estimation methods for the following three categories of building elements: reused, repaired and newly produced building elements (Section 2.3.2). First of all, the equation for calculating the value of a newly produced building element (V_{new}), which is made either of virgin or recycled materials, became:

$$\boldsymbol{V_{new} = M} \tag{2.3.3.2}$$

where:

M = material cost (in €)

Secondly, the value of the reused building element is the yearly depreciated value of V_{new} as discussed in Section 2.3.2. The DSS considers a reused building element will be disassembled at the end of the service life into constitutive building materials (Section 2.3.2). Moreover, the DSS considers that a directly reused building element was made of virgin materials, and not recycled building materials. This is because recycling technologies would not be common practice when the building element was produced. Consequently, the equation for calculating the value of a reused building element (V_{reu}) is:

$$V_{reu} = V_{new\ (vir)} - \{(V_{new\ (vir)} - R)/s\} \times (y_{cur} - y_{acq}) \tag{2.3.3.3}$$

where:

$V_{new\ (vir)}$ = the value of a newly produced building element with virgin building materials (in €);

R = the residual value of a reused building element (in €);

s = the service life of a reused building element (in €);

y_{cur} = the current year when a circular renovation is executed;

y_{acq} = the year when a reused building element was acquired.

Residual rate R in Equation 3.3, in turn, consists of the revenue from selling building materials and the cost for disassembling a building element (2.3.2). Consequently, the equation for determining R is:

$$R = \sum rev_j (1 - r_j)^{-(y_{ser} - y_{cur})} - C_{dis}(1 + d_{dis})^{-(y_{ser} - y_{cur})} \tag{2.3.3.4}$$

where:

rev_j = the revenue of selling disassembled building material *j* making of a building element at the end of service life = $s_j \times (1 + e_j)^{y_{ser} - y_{cur}}$;

r_j = the discount rate applicable to rev_{jt};

y_{ser} = the year of the end of service life;

y_{cur}	= the current year when a circular renovation is executed;
C_{dis}	= the cost of disassembling a building element at the end of service life = $D \times (1 + e_d)^{y_{ser} - y_{cur}}$ (in €);
d_{dis}	= the discount rate applicable to C_{dis};
y_{acq}	= the year when a directly reused building element was acquired;
s_j	= the cost of scrap building material j; (in €)
e_j	= the escalation rate applied to s_j:
D	= the disassembly cost in e.q. 3.1;
e_d	= the escalation rate applied to D.

Thirdly, the value of a repaired building element is proportional to the perceived quality of a repaired building element concerning the value of the same element newly produced (Section 2.3.2). Subsequently, the equation for calculating the value of a repaired building element (V_{rep}) is as follows:

$$V_{rep} = \delta V_{new\ (vir)} \qquad (2.3.3.5)$$

where:

$V_{new(vir)}$	= the value of a newly produced building element with virgin building materials (in €);
δ	= the building users' perceived quality factor of a repaired building element (0 < α <1).

3.1.3 Financial performance measures

The DSS employs the following three widely used financial performance measures in the built environment to rank the six renovation options from a financial perspective: i) the total cost (TC, Equation 3.5), ii) the net cost (NC, Equation 3.6) and iii) the return of investment (ROI, Equation 3.7.). Circular renovation options whose TC and NC are lower, and ROI is lower are ranked higher based on the premise that a building owner makes a decision bringing the maximized profit (Gluch & Baumann, 2004). The reason why the DSS employs multiple financial performance measures is that all users would have different financial decision behaviours.

$$TC = C \tag{2.3.3.6}$$

$$NC = V - C \tag{2.3.3.7}$$

$$ROI = \frac{V}{C} \tag{2.3.3.8}$$

This study applied the developed DSS to a case study, and the following section explains the procedure of the case study.

3.2 DSS application: a case study

To test the developed DSS, this study conducted a case study. A case study was applied to a circular renovation project of the Van Unnik building located in Utrecht, the Netherlands. The Van Unnik building was built between 1967 and 1969, roughly 50 years before the time of writing, and contains a significant amount of asbestos that poses threats public health (Swuste, Burdorf, & Ruers, 2004; Utrecht University, 2019a). The building administrators decided to renovate the Van Unnik building, only preserving its foundation and concrete frame (University Utrecht, 2019b). Since the building administrators have to decide whether they will reuse the remaining building elements or replace them, this research aimed to help this decision-making by applying the DSS in practice.

3.2.1 General information and material composition input

This study tested the DSS to the following five building elements installed in the Van Unnik building (Table 3-3): suspended ceilings, indoor staircases, outdoor staircases, doors, windows and frames of windows. The first phase of using the DSS was to input the following information on the existing building elements in place: i) size, ii) the number, and iii) the material composition. To access this information, this study used the material passport[d] of the Van Unnik building that BOOT organiserend ingenieursburo B.V. published in 2019 and other literature.

[d] To be able to reuse a building product or material many years after initial use, it is essential that sufficient information is available about its composition. The idea of the materials passport is to allow this information to travel with the product itself through time (Rijkswaterstaat, 2016, p. 22).

Table 3-3 The information on the tested building in the Van Unnik building

Building element	Size			Material composition		
	Length [m]	Width [m]	Height [m]	Name	Density [kg/m3]	Proportion [%]
The suspended ceilings (H), 12	1.5	0.6	0.02	Rockwool	22	100
The indoor staircases (H), 36	3.4	1.4	0.25	Concrete	2400	80
The outdoor staircases (H), 7	2.8	0.6	0.3	Aluminium	2710	2
The doors (L), 1476	0.01	0.8	2.0	B-Wood	616	20
The windows (L), 692	0.1	1.1	1.5	Aluminium	2710	2
				Glass	2500	6

In the first phase, there were the following considerations. First of all, multiple building elements were of the same type with the same material composition but varied in size depending on their locations. In this case, the, because of their unique sizes, DSS would recognize each of those building elements as different building elements. As a result, it would take a long time to test the DSS multiple times for each yet the same type of building element. Therefore, this study grouped them in one building element and averaged their sizes using a weighted mean, as shown in Table 3-4.

Table 3-4 Grouping similar building elements.

Before grouping

Nr.	Description	Location	L (mm)	W (mm)	H (mm)	The number	Material composition	
							Building material	Proportion
1	Door	H	100	1115	2365	4	B-wood	100%
28	Door	H	114	1700	2130	42	B-wood	100%

48	Door	H	100	1115	2950	294	B-wood	100%
50	Door	H	100	1115	2650	379	B-wood	100%
				…				
105	Door	H	90	910	2180	5	B-wood	100%

After grouping

Building element	**Location**	**L (mm)**	**W (mm)**	**H (mm)**	**The number**	**Material composition**	
						Building material	**Proportion**
Door	H	100	1151	2689	1049	B-wood	100%

Secondly, the Van Unnik building comprises both higher and lower buildings. The suspended ceilings, the indoor staircases and the outdoor staircases are installed in the lower building. The rest of the doors, the windows, and the frame of windows are installed in the higher building. The material passport of the higher building, however, is still a work in progress. Thus, this study assumed that building elements with a similar outward appearance in both higher and lower buildings have the same material compositions.

Thirdly, the material composition offered by the material passport only covered the building material that constitutes the largest volume of a building element under the applied methodology. Nevertheless, this research used the original material composition data without additional investigations. This is because it is complicated to determine the remaining building materials unless special devices or fragmenting would have been used.

3.2.2 The cost and value estimation

The second phase was to input the data for cost estimation. Beforehand, this study considered the following two assumptions: i) a removed building element is collected and treated by local CD&W collection business, ii) a replacing building element is sourced within the Netherlands[e], iii) a replacing building element has the same material composition as that of the existing building element in place, and iv) a secondary building element is picked up for free. The reason for considering the third assumption is as follow. The purpose of this study is seeing the financial implications derived from executing different CE strategies on a building element, not from different production processes. Regarding the fourth assumption, it was

[e] The distance from a supplier of a replacing building element, whether that is a secondary or a newly produced building element, was consequently fixed at 200 km. Unnik is located in the middle of the Netherlands. The furthermost cities from Unnik are Groningen and Maastricht, and these cities are approximately 200 km far from Unnik. The transportation cost of the purchasing price was calculated by using (Gao & Lin, 2017) (Appendix 2).

complicated to access the data that shows the secondary building elements that could be picked up, but also, its price was not available in public (section 2.2.2).

The cost data input

This study collected the cost data from the following sources: i) websites of construction-related businesses in the Netherlands[f], ii) academic/non-academic literature, iii) Eurostat, iv) Centre of Statistics Netherlands (CBS), v) London Metal Exchange, and vi) online supplement. There were the following three challenges: i) difficulty of collecting the disassembly and repair costs, ii) non-publicly available CDW collection cost data per each building material, and iii) distinction between recycled and virgin building element.

First of all, it was challenging to collect the disassembly cost (D, Equation 1) and the repair cost (R, Equation 1) as mentioned in Section 2.3.1. Regarding the disassembly cost, unlike the cost of demolishing a whole building or a space that is estimated per m^2, the cost for disassembling is not publicly available. It was complicated to find the general cost of repair, compared to that of installation. This is because repairing a building element demands different work processes depending on factors such as its current state of wear and tear and the types of constitutive building materials. For the repair cost estimation, interviewing practitioners who work for the construction sector has been considered, however, it was complicated due to the health emergency issues (COVID-19) occurring at the time of performing the research. Thus, this study used the labour cost for the installation as the disassembly cost, since this research considered that disassembly is the reversed process of installation. Moreover, this study used half of the labour cost for the installation as the repair cost. This was based on the assumption that the amount of repair work is corresponding to that of installation, but the repair process may be less labour intensive than installation work.

Second of all, in practice, CDW collection cost differed depending on the type of building material. For example, unlike metals and A/B-woods, additional costs were imposed on insulation materials and glass (Renewi, 2017). This specific cost data was not publicly available since publicizing that information might compromise the competitiveness of the CDW collection businesses. Thus, this study only considered the CDW collection cost per volume.

[f] Manufacturers of building materials such as (e.g. Mebin), CD&W collection business (e.g. Renewi), and intermediary companies (e.g. Offerteadviseur).

Lastly, the material costs of recycled outdoor staircases, doors, window and frames of windows (M_{rec}) were not available since they may not be commercialised. Due to that reason, this study developed a formula to estimate their M_{rec} (e.q 3.8). To develop e.q 3.8, this study considered the following two findings of current literature: i) the constitutive building materials of the outdoor staircases, the doors, the windows and the frames of windows are produced with both scrap and virgin materials (Mulders, 2013), ii) the ratio of the material cost of manufacturing construction materials is around 20% (PBL Netherlands Environmental Assessment Agency, 2014). Consequently, the equation is:

$$M_r = M_v \times (1 - \alpha) + M_v \times \frac{\alpha}{\beta \times s + (1 - \beta) \times v} \times s \qquad (3.9)$$

$M_{new\,(rec)}$	= the material cost of newly produced building element with recycled building materials;
M_v	= the material cost of newly produced building element with virgin building e;
α	= the share of the material cost of the total price of construction materials
β	= the share of recycling a building material;
s	= the cost of a scrap building material;
v	= the cost of a virgin building material.

3.2.3 The value estimation

The next phase to the cost estimation, this study estimated the values of reused, repaired and newly produced building elements. This study assumed that the secondary building element was made in the same year when an existing building element was made. This is due to the lack of information on the secondary building element. The considerations for the subjectivity variables are as follows. This study inputted the reference service life of a building element (s, Equation 3.3 in Section 3.2.2 and theory in Section 2.3.3) offered by Standard Business Reporting in the Netherlands (Straub, van Nunen, Janssen, & Liebregts, 2011). This study arbitrarily regarded the perceived quality factor (δ, Equation 3.5, Section 3.2.2) as 0.5. This study collected the data for the value estimation from i) academic/non-academic literature, ii) Eurostat, iii) Centre of Statistics Netherlands (CBS), iv) London Metal Exchange and v) and online supplement resources.

The estimated costs and values are described in Appendix 4. As discussed in this section, there were variables that this study arbitrarily inputted because those data are limited in practice as of now or acquire subjective judgements of building owners. To check what extent to which these variables influence the rankings, this study employed the sensitivity analysis. The following section explains the process of sensitivity analysis.

3.2.4 Sensitivity analysis

This study applied the sensitivity analysis to the following five cost and value variables as presented in Table 3-5: i) repair cost (R, Equation 3.1), ii) material cost of purchased recycled building element (M_{rec}, Equation 3.1), iii) service life (s, Equation 3.3), iv) discount rate applied to the revenue obtained from selling disassembled building materials (r, Equation 3.4), and v) user's perceived quality factor (δ, Equation 3.5). The variation processes are explained in Table 3-5.

Table 3-5 The variations in the sensitivity analysis variables

Variable		**Variation**
Cost	R	Increase by 1.5, 2 and 2.5 times
	M_{rec}	Input 90% and 100% of virgin building element's material cost (M_{vir})
Value	s	Maximise using the factor method explained in section 2.
	r	Apply 2.5%, excluding the risk premium
	δ	Decrease to 0.3, increase to 0.7 and 0.9

As for the variables for the cost estimation, firstly, this study increased R from 1.5 to 2.5 times since this study arbitrarily considered the repair cost as the halved labour cost of installation cost (Section 3.2.2). Next, M_{rec} was considered as both 90% and 100% of M_{vir}. This was because this study used the developed formula by itself to calculate M_{rec}. Regarding the variables for the value estimations, this study maximised s using the factor method introduced in section 2.3.2. The reason for that was to see what extent to which positive judgement of building owners about the factors involved in the lifespan of building element influence the results of financial analysis. Secondly, this study considered r as the sum of the risk premium (3%) and the discount rate (2.5) (Appendix 3). Yet, this study examined whether the risk premium which is assigned by a building owner's subjective judgement impact the results offered by the DSS. Lastly, this study inputted the lower and higher δ to see the extent to which the attitude of building owners influences the rankings.

The next chapter describes the rankings of six circular renovation options that the DSS offered based on the cost and value estimations.

4 RESULTS

The input information, all six circular renovation options, the financial implications and the financial performance measures were combined in the DSS. Subsequently, the DSS provided the rankings of the six circular renovation options for the building elements based on the three financial performance measures (TC, NC, and ROI). Section 4.1.1 explains the most attractive circular renovation option per building element. Section 4.1.2 presents the result of the sensitivity analysis.

4.1 The financially preferred circular renovation options

The suspended ceilings

Table 4-1 shows the rankings of the six circular renovation options based on a financial perspective for the suspended ceilings in the Van Unnik building per TC, NC and ROI financial performance measure.

Table 4-1 The rankings of the six circular renovation options based on a financial perspective for the suspended ceilings.

Values rounded to integer

Option	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6
Step 1. Financial implication estimation						
Cost	€ 0	€ 178	€ 1,128	€ 1,306	€ 1,406	€ 1,415
Value	-€ 117	€ 120	-€ 117	€ 120	€ 232	€ 239
Step 2. Financial performance measure application illustrated in ranking [TC/NC/ROI]						
TC	1 [€ 0]	2 [€ 178]	3 [€ 1,128]	4 [€ 1,306]	5 [€ 1,406]	6 [€ 1,415]
NC	2 [€ 117]	1 [€ 59]	6 [€ 1,224]	5 [€ 1,186]	3 [€ 1,174]	4 [€ 1,175]
ROI	6 [-∞%]	1 [67%]	5 [-11%]	4 [9%]	3 [17%]	2 [17%]

* Op. 1: Direct reuse an existing building element in the Van Unnik building
Op. 2: Repair an existing building element in the Van Unnik building, and reuse
Op. 3: Directly reuse a secondary building element that has used elsewhere
Op. 4: Repair a secondary building element that has been used elsewhere, and reuse
Op. 5: Purchase a recycled building element
Op. 6: Purchase a virgin building element

The TC measure ranked the direct reuse of the existing suspended ceilings in the Van Unnik building as the most attractive circular renovation option, followed by the in-place repair. The third best option was the reuse of secondary suspended ceilings. The two reasons why both reuse options were preferred are i) the direct in-place reuse does not generate any cost according to its definition (section 2.2.2), ii) secondary suspended ceilings are picked up for free based on the assumption of this study (section 3.2.2).

The NC measure, on the other hand, resulted in repairing the existing suspended ceilings as the number one option. According to the NC measure, the direct in-place reuse was the second most attractive option. This was due to the significantly lower value of the reused suspended ceilings (-€ 117) compared to the value of the repaired suspended ceilings (€ 120). For that reason, despite its cost (€ 178), the in-place repair could be a more attractive option, from the NC perspective. Purchasing recycled and virgin suspended ceilings were ranked higher than installing secondary suspended ceilings by the NC perspective. This was because purchasing newly produced suspended ceilings was considered more attractive than spending costs for installing and repairing secondary building elements whose values were low.

The ROI measure also preferred repairing the existing suspended ceilings in the Van Unnik building. The ROI, however, ranked the direct reuse of the suspended ceilings as the least attractive option. This was because of both the negative value of the directly reused suspended ceilings, as well as the zero cost of direct in-place reuse. This resulted in the negative infinity of the ROI for the direct in-place reuse. Furthermore, the second-best option that the ROI measure preferred was purchasing virgin suspended ceilings. Moreover, the third-best option was purchasing recycled suspended ceilings. This is due to the methodological characteristics of the ROI. The ROI method is more sensitive to the amount of value than the NC method. This is explained by the purpose of employing the ROI method. Decision-makers use the ROI method simply to look into how much return they could get compared to the amounts of their investments (Alkaraan & Northcott, 2006; Sinclair, 2010). For that reason, the ROI is presented in percentages and decision-makers can easily pick an investment option with higher value, relative to its cost.

The doors

Table 4-2 shows the rankings of the six circular renovation options based on a financial perspective for the doors in the Van Unnik building per TC, NC and ROI financial performance measure.

Table 4-2 The rankings of the six circular renovation options based on a financial perspective for the doors.

Values in Thousands

Option	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6

Cost	€ 0	€ 49	€ 219	€ 268	€ 370	€ 378
Value	-€ 7	€ 66	-€ 7	€ 66	€ 126	€ 133
TC	1 [€ 0]	2 [€ 49]	3 [€ 219]	4 [€ 268]	5 [€ 370]	6 [€ 378]
NC	2 [€ 7]	1 [-€ 18]	4 [€ 226]	3 [€ 201]	5 [€ 244]	6 [€ 246]
ROI	6 [-∞%]	1 [136%]	5 [-3%]	4 [25%]	3 [34%]	2 [35%]

* Op. 1: Direct reuse an existing building element in the Van Unnik building
Op. 2: Repair an existing building element in the Van Unnik building, and reuse
Op. 3: Directly reuse a secondary building element that has used elsewhere
Op. 4: Repair a secondary building element that has been used elsewhere, and reuse
Op. 5: Purchase a recycled building element
Op. 6: Purchase a virgin building element

The TC measure preferred the direct reuse of the existing doors in the Van Unnik building most, followed by the in-place repair, and the reused of secondary doors. The NC measure ranked the in-place repair as the best option, and the in-place reuse was regarded as the second-best option. The NC measure considered repairing secondary doors was the third-best option, and reusing secondary doors was ranked as the fourth-best option. This is because the DSS considered purchasing newly produced doors still expensive options. The ROI measure preferred the in-door repair most and purchasing virgin and recycled doors were ranked as the second and third best options by the same reason as the suspended ceilings.

The next two building elements, the windows (Table 4-4) and the frame of windows (Table 4-5), had the same rankings as the doors with the same reasons.

The windows

Table 4-3 shows the rankings of six circular renovation options applied to both the frames of windows and the glasses of windows in the Van Unnik building.

Table 4-3 The rankings of the six circular renovation options based on a financial perspective for the windows.

Values in Thousands

Option	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6
Cost	€ 0	€ 129	€ 544	€ 673	€ 912	€ 983
Value	-€ 21	€ 183	-€ 21	€ 183	€ 307	€ 366
TC	1 [€ 0]	2 [€ 129]	3 [€ 544]	4 [€ 673]	5 [€ 912]	6 [€ 983]
NC	2 [€ 21]	1 [-€ 54]	4 [€ 565]	3 [€ 490]	5 [€ 604]	6 [€ 617]
ROI	6 [-∞%]	1 [142%]	5 [-4%]	4 [27%]	3 [34%]	2 [37%]

* Op. 1: Direct reuse an existing building element in the Van Unnik building
Op. 2: Repair an existing building element in the Van Unnik building, and reuse
Op. 3: Directly reuse a secondary building element that has used elsewhere
Op. 4: Repair a secondary building element that has been used elsewhere, and reuse
Op. 5: Purchase a recycled building element
Op. 6: Purchase a virgin building element

The frames of windows

Table 4-4 shows the rankings of the six circular renovation options applied to only the frames of windows in the Van Unnik building. The rankings were the same as that of the windows.

Table 4-4 The rankings of the six circular renovation options based on a financial perspective for the window frames.

Values in Thousands

Option	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6
Cost	€ 0	€ 97	€ 409	€ 506	€ 753	€ 796
Value	-€ 2	€ 161	-€ 2	€ 161	€ 287	€ 322
TC	1 [€ 0]	2 [€ 97]	3 [€ 409]	4 [€ 506]	5 [€ 753]	6 [€ 796]
NC	2 [€ 1]	1 [-€ 64]	4 [€ 411]	3 [€ 344]	5 [€ 466]	6 [€ 473]
ROI	6 [-∞%]	1 [167%]	5 [0%]	4 [32%]	3 [38%]	2 [41%]

* Op. 1: Direct reuse an existing building element in the Van Unnik building
Op. 2: Repair an existing building element in the Van Unnik building, and reuse
Op. 3: Directly reuse a secondary building element that has used elsewhere
Op. 4: Repair a secondary building element that has been used elsewhere, and reuse
Op. 5: Purchase a recycled building element
Op. 6: Purchase a virgin building element

Outdoor staircase

Table 4-5 shows the rankings of the six circular renovation options applied to the outdoor staircases in the Van Unnik building.

Table 4-5 The rankings of the six circular renovation options based on a financial perspective for the outdoor staircases.

Values were rounded to integer

Option	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6
Cost	€ 0	€ 385	€ 2,117	€ 2,502	€ 9,069	€ 9,677
Value	-€ 620	€ 3,150	-€ 620	€ 3,150	€ 5,793	€ 6,300
M1. TC	1 [€ 0]	2 [€ 385]	3 [€ 2,117]	4 [€ 2,502]	5 [€ 9,069]	6 [€ 9,677]
M2. NC	3 [€ 620]	1 [-€ 2,765]	4 [€ 2,737]	2 [-€ 648]	5 [€ 3,276]	6 [€ 3,377]
M3. ROI	6 [-∞%]	1 [818%]	5 [-29%]	2 [126%]	4 [64%]	3 [65%]

* Op. 1: Direct reuse an existing building element in the Van Unnik building
Op. 2: Repair an existing building element in the Van Unnik building, and reuse
Op. 3: Directly reuse a secondary building element that has used elsewhere
Op. 4: Repair a secondary building element that has been used elsewhere, and reuse
Op. 5: Purchase a recycled building element
Op. 6: Purchase a virgin building element

The TC measure preferred the reuse of the existing outdoor staircases in the Van Unnik building most, followed by the in-place repair, and the reused of secondary doors. The NC measure ranked the in-place repair as the best option. Interestingly, the NC measure ranked the repair of secondary outdoor staircases as the second-best option. The in-place reuse and the reuse of secondary outdoor staircases regarded as the third and fourth-best options respectively. The reason for these results was mainly that the values of reused indoor staircases were considerably low, due to that their service lives have already exceeded (Appendix X).

The ROI measure also preferred the in-door repair most. The ROI measure ranked the repair of secondary outdoor staircases as the second-best option. The reason why the ROI more preferred repairing both the existing secondary outdoor staircases and secondary ones than directly reusing them was the considerably high value of repaired outdoor staircases.

Indoor staircase

Table 4-6 shows the rankings of the six circular renovation option based on a financial perspective for the indoor staircases in the Van Unnik building per the TC, the NC and the ROI measure.

Table 4-6 The rankings of the six circular renovation options based on a financial perspective for the indoor staircases.

Values in Thousands

CR option	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6
Cost	€ 0	€ 2	€ 20	€ 22	€ 69	€ 68
Value	€ 117	€ 20	€ 117	€ 20	€ 40	€ 40
M1. TC	1 [€ 0]	2 [€ 2]	3 [€ 20]	4 [€ 22]	6 [€ 69]	5 [€ 68]
M2. NC	1 [-€ 118]	3 [-€ 18]	2 [-€ 98]	4 [€ 2]	6 [€ 28]	5 [€ 28]
M3. ROI	1 [∞%]	2 [818%]	3 [596%]	4 [91%]	5 [59%]	6 [59%]

* Op. 1: Direct reuse an existing building element in the Van Unnik building
Op. 2: Repair an existing building element in the Van Unnik building, and reuse
Op. 3: Directly reuse a secondary building element that has used elsewhere
Op. 4: Repair a secondary building element that has been used elsewhere, and reuse
Op. 5: Purchase a recycled building element
Op. 6: Purchase a virgin building element

All of the TC, NC and ROI measures ranked the direct reuse of the existing indoor staircases in the Van Unnik building as the most attractive circular renovation option. This is because the estimated value of the directly reused indoor staircases was positive, but also, much higher than the value of the newly manufactured indoor staircases. Because of this reason, the NC considered reusing secondary indoor staircases as the second-best option, followed by the in-place repair. The ROI regarded the in-place repair as the second-best option and ranked the reuse of secondary indoor staircases as the third-best option despite its higher value. This is because the repair did not generate much cost considering the cost of installation.

4.2 Sensitivity analysis

Through a sensitivity analysis, this study observed how variations in the cost and value variables affect the rankings provided by the DSS. The variations applied to each variable are presented in Table X. The full result of the sensitivity analysis is presented in Appendix X.

Cost

Firstly, the repair cost (*R*) increased up to 2.5 times, from 0.5 to 1.25, in the sensitivity analysis. This variation made only the NC measure rank the direct reuse of building element as the most attractive option rather than in-place repair, as shown for windows and doors in Figure 4-1. When *R* increases by 2 times, direct reuse became the number one option for the doors, the windows and the window frames. Despite the 2.5 times increase of *R*, in-place repair of the outdoor staircases remained the most attractive option. Next, the variation applied to the material cost of recycled building elements (M_{rec}) only reversed the rankings between purchasing newly manufactured recycled and virgin elements which were not the most attractive options.

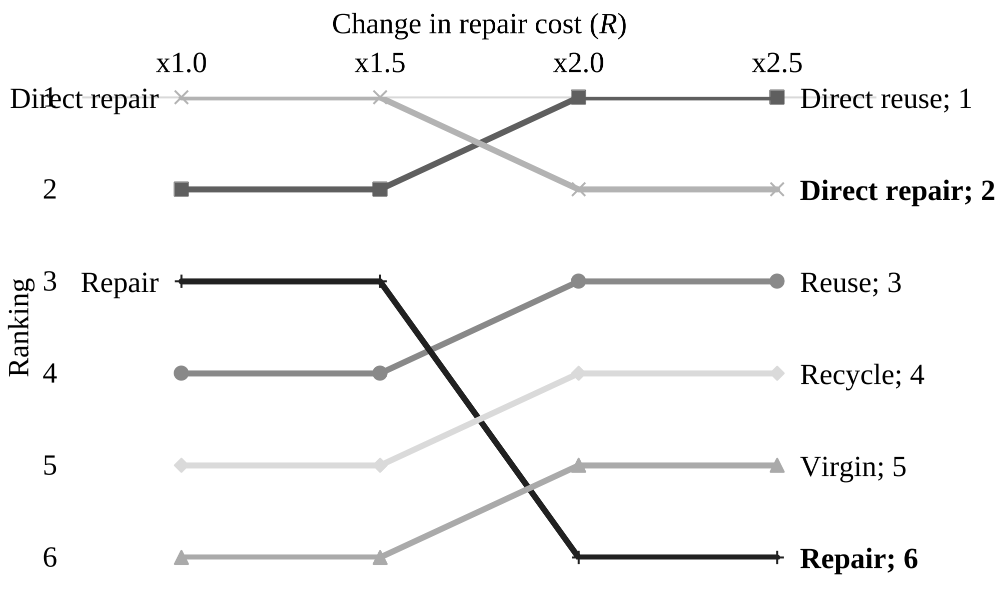


Figure 4-1: Change in ranking for NC of windows and doors, if repair costs are increased.

Value

Firstly, the discount rate (*r*) of 2.5%, which excluded the 3% of the risk premium, did not impact any ranking. Secondly, unsurprisingly, increasing the service life (*s*) let all measures for all building elements to favour the more circular renovation options. The maximum service life (*s*) led all of the measures to result in the direct reuse of the existing building elements in the Van Unnik building as the preferred option, except for the outdoor staircases. For the outdoor staircases, the NC measure remained in favour of repairing the existing elements in the Van Unnik building. Particularly from an ROI perspective for the windows and doors, direct reuse and reuse after external sourcing saw a significant increase in their ranking, from 6 to 1 and 5 to 2 respectively, as shown in Figure 4-2.

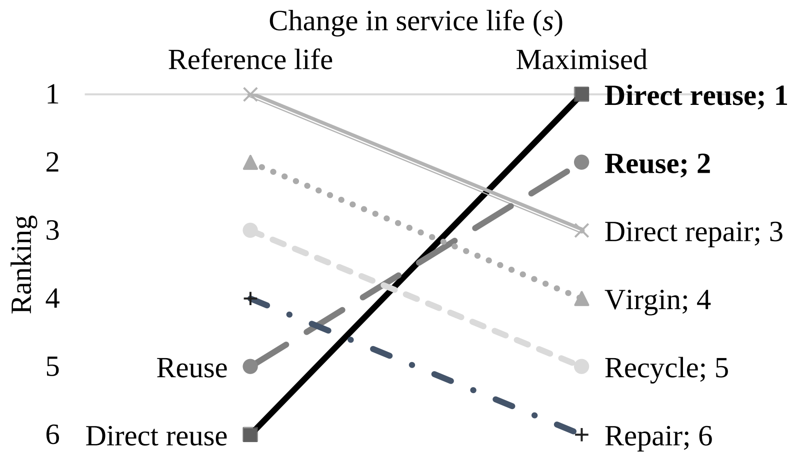


Figure 4-2: Change in the ranking of options for ROI of windows and doors, if service life is increased from reference service life to its maximum based on the factor method.

Thirdly, despite lowering perceived quality factor δ from default 0.5 to 0.3, in-place repair remained the preferred renovation option from an ROI measure, except for the indoor staircase. For the indoor staircase, when decreasing δ the repair options became less attractive from an ROI perspective, with direct repair going from 2 to 3 and repair after externally sourcing from 4 to 6 in rank. An increase in perceived quality resulted in the repair options to become more attractive for some elements. When the perceived quality factor is increased to 0.7 and 0.9, the ROI measure showed an increase in ranking for the repair of the externally sourced doors, windows and window frames, becoming second in rank after in-place repair. Figure 4-3 represents this change for the window and window frames. Hence, in a scenario of higher perceived quality, if direct repair appears infeasible, repairing those externally sourced types of elements becomes more attractive than sourcing virgin or recycled ones.

On the NC performance measure, when the perceived quality factor is lowered to 0.3, on for doors the results show direct reuse to become the preferred option over the in-place repair.

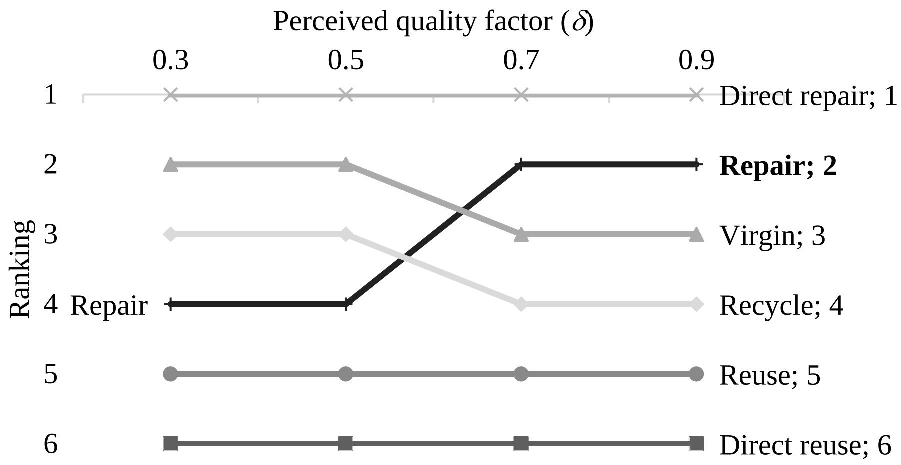


Figure 4-3: Change in the ranking of options for windows and window frames on the ROI measure, when the perceived quality factor is changed.

5 Discussion

Despite the call for applying CE strategies in the built environment, the financial analysis of its application is challenging. To solve this problem, this study developed a DSS that shows the performance of CE strategies based on their attractiveness from a financial perspective. Section 5.1 provides interpretations of the results. This section also gives the considerations that a building owner is to take into account regarding the DSS use. Section 5.2 introduces opinions about the DSS given by practitioners and the interpretations of this research about the opinions. Lastly, section 5.3 demonstrates the limitations of this research and suggestions for future research.

5.1 Interpretation of the results

This section illustrates the following three interpretations concerning the results: i) three characteristics of building elements that are preferred to be reused in place, ii) considerations regarding the competing decisions ‘reuse versus repair’ and ‘purchasing recycled versus virgin elements’, and iii) challenges due to the lack of information on secondary building elements.

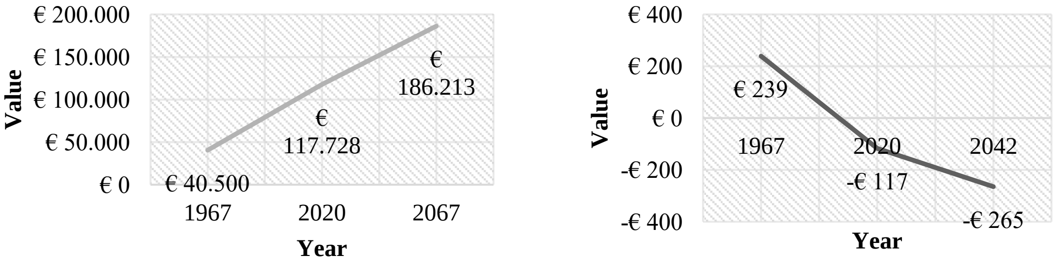
5.1.1 Characteristics of building elements preferred to be reused

This study designed the DSS to be used per each building element and applied the DSS only to six building elements. It might be challenging in practice because it would demand a significant amount of workload. Thus, this study investigated the reasons why all of the three financial performance measures preferred the in-place reuse of the indoor staircases, unlike the other building elements. Because the found reasons could be indications of other building elements that are also preferred to be reused in place.

Consequently, the reason why the direct in-place reuse of the indoor staircases was financially preferred was because of their high residual value. The residual value was considered as the revenue obtained from selling disassembled building materials at the end of their service lives (Section 2.3.2). The residual value of the indoor staircases was higher than the value of newly produced indoor staircases. This characteristic was only observed from the indoor staircases. It was observed that the values of the indoor staircases increase throughout its service life from its acquisition year, whereas the values of the other building elements decreased (Figure 5-1).

Figure 5-1 The opposite trends of values between the indoor staircases and the others

The indoor staircase | **The suspended ceiling (example)**



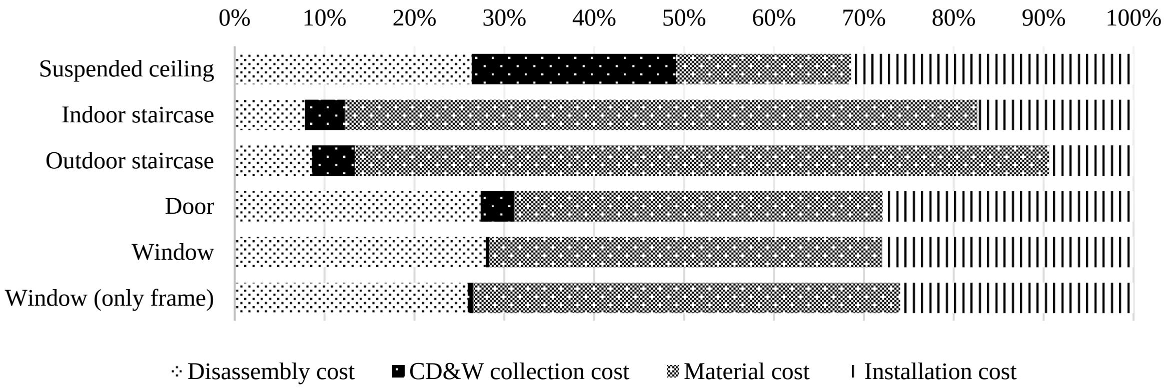
1967: the acquisition year
2020: the current year
2067: the end of service life (the indoor staircases)
2042: the end of service life (the suspended ceilings)

The reason why the residual value of the indoor staircases was high was threefold. Firstly, a substantial amount of concrete can be obtained from disassembling the indoor staircases[g], due to that concrete constitutes 80% of the volume of an indoor staircase. The second reason was the low cost of disassembly compared to the revenue from selling the disassembled building materials. As presented in Figure 5-2, the disassembly cost is approximately a ninth of the material cost of newly produced indoor staircases[h]. The last reason is the long service life, 100 years (Section 4.1.1). It is, therefore, preferable to reuse building elements that have also those three characteristics, from a financial perspective.

[g] Because of the high constitutive percentage, 1,920kg of concrete will be obtained per m3 of the indoor staircase, while only 54.2kg of aluminium will be obtained per m3 of the outdoor staircase.

[h] The same goes for the outdoor staircases as seen in Figure 5-2. Nonetheless, the proportion of aluminium which is the constitutive building material of the outdoor staircases is 2%, but also its exceeded service life particularly influenced the lower value of reused outdoor staircases.

Figure 5-2 The cost breakdown structure of purchasing and installing newly produced virgin building elements



5.1.2 Competing decisions

The results showed the following two types of competing decisions: i) reuse versus repair, and ii) purchasing virgin building elements or recycled building elements. Two considerations may help those decisions.

Firstly, regarding the suspended ceilings, the doors, the windows and the window frames, the TC measure preferred the direct in-place reuse of these building elements. The NC and ROI measures, on the other hand, preferred in-place repair. However, through the sensitivity analysis, this study observed that the maximum service life led the NC and ROI to prefer direct in-place reuse. Yet, the maximum service life can only be realised when the maintenance is performed properly, and in-use conditions are kept (Section 2.3.2). From a financial perspective, there is no absolute answer for choosing in-place direct reuse over in-place repair, or vice versa. Instead, the decision would be a matter of a building owner's personal preference; restoring a building element to its original function with instant payment or reusing it in its present condition.

Secondly, building owners are recommended to consider whether the value of the recycled building element should differ to the value of virgin building element. The definition of value in this research was the material cost of a building element (Section 3.1.2). Except for the indoor staircases, the material costs of virgin building elements were higher than that of recycled elements. This made the value of recycled elements lower than virgin elements. Accordingly, the ROI, which weights cost investment and return value evenly preferred purchasing virgin building elements. Also, in practice, not all recycled building materials have an equivalent amount of materialistic value to virgin building elements, amongst others because of being degraded from recycling (Mulders, 2013). Nonetheless, it is uncertain that being degraded impacts the functionality as a building element. Therefore, before using the DSS, a building owner has to be aware of this point.

5.1.3 The lack of information

The existing building elements in the Van Unnik building could not be reused or repaired, despite their financial attractiveness. Consequently, a building owner has to consider the next best options concerning installing secondary building elements. Yet, due to two issues related to the lack of information on secondary building elements, building owners may be hesitant to accept the decisions the DSS offers. First of all, it would be hard to get to know whether a secondary building element has impairment until a building owner gets to use. This lack of information on the secondary building element leads to perceived risk for building owners (Pappas, 2016). Due to this perceived risk, a building owner might be hesitant to accept the results of the DSS and make decisions accordingly (Kumar, 2019).

Moreover, the DSS is mainly based on the material composition of building elements, and their respective costs and values. Even if both a used building element and a newly manufactured building element have the same material composition, the design or manufacturing processes may be different. Overall other factors that may be related to quality and durability, like design and manufacturing methods, are not considered in the DSS while these do impact cost and value. Both the limited amount of information the DSS deals with and secondary building elements made a building owner find it difficult to accept the given results.

5.2 The role of a financial analysis of a circular renovation project

At the beginning of the research phase, this study aimed to develop the DSS as a 'ready-of-use' for practitioners working in the built environment. To ask their opinions, this study discussed with two practitioners who currently work in financial analysis in the built environment in the Netherlands. The purpose of the discussion was to get impressions of the practitioners who may work with the DSS concerning its use in practice, beyond the academic perspective. Both practitioners showed different opinions about the value estimation method of the DSS. Section 5.2.1 shows their different points of view with supporting literature. Section 5.2.2 provides the interpretations of this study about different opinions.

5.2.1 DSS user's perspective on value estimation

As discussed in section 4.2, value estimation is a critical factor in ranking the options for the NC and ROI financial performance measures. Practitioner A mentioned that the value of a building element must be estimated based on the future revenue obtained from selling constitutive building materials. For that reason, practitioner A suggested making different investment and financial analysis strategies depending on each type of building element, by using different discount rates considering the type of building material and the service life of a building element. This point of view is consistent with that of Wang, Xia and Zhang (2014) who suggested a business model that aims to increase the circularity of building materials. According to them, the proper business model is to be set up depending on the building materials' characteristics such as lifecycle, risks involved in their supply chains, and value retention potentials.

On the other hand, practitioner B mentioned that more factors are to be involved in estimating the value of a building element than just the physical quality and material characteristics. For that reason, practitioner B suggested applying the user's perceived quality factor to all circular renovation options with the following two reasons. Firstly, practitioner B did not agree that the value of building element is depreciated based on its service life. For instance, a door that has been in use for a longer time than its service life can still exist as a door with its function. The second reason is that no matter how a renovation happens in line with the CE principles, the value estimation is based on a building owner's perception. This perception is influenced by subjective factors, such as aesthetic preference, antiqueness and refresh feeling given when a user is aware of that he or she uses a new product. This practitioner B's point of view is similar to that found by Mehrabian and Russel (1974) (Jang & Namkung, 2009). According to them, a building owner's response is dependent on intangible emotions given by environmental stimuli. These environmental stimuli can be perceived performances of building elements, such as colours, textures and cleanliness, which influence building users' satisfaction (Kim & de Dear, 2012).

5.2.2 The interpretations of the different opinions on the value estimation methods

Those different points of view about the value estimation method are a natural phenomenon. This is because the cost is the fixed amount of money that a building owner has to pay according to the estimation submitted by a construction company. By contrast, this study already reviewed that subjectivity factors are involved in value estimation in section 2.3.2.

Moreover, even though the definition of value is set up, the value is subjectively estimated by a building owner depending on social, personal, cultural and psychological factors (Kotler, Keller, Brady, Goodman, & Hansen, 2009). This study observed that longer service life, which is also subjectively judged, increases the value of building element. Nonetheless, that durability may not be a critical factor depending on a building owner's age (Hervé & Mullet, 2009).

Regarding those different opinions, this study provides three considerations for improving the DSS. First of all, a better approach would be to diversify the value estimation method in the DSS so that every building owner can choose an appropriate method in line with his or her concept of the value. Just forcing a building owner to use a certain method against his or her idea is likely to decrease the credibility of results which the DSS offers. Yet, it would not be the best way to let a building owner estimate the value freely. This is because it might be challenging to think of the way to input a certain number as the value of used building elements without any background information. Hence, DSS could describe the rationale behind why each value estimation method is used. This gives a building owner a learning opportunity when he or she tries to use different methods and realises to what extent the results change. This simulation provides a building owner with a better understanding of the value of an already used building element (Piramuthu & Shaw, 2009).

Furthermore, it might be the case that any method for the value estimation may involve other subjective factors. To reduce judgements which heavily rely on intuitions or emotions, the DSS could provide elaborate criteria to show how the subjectivity factors are formulated. This research observed that subjective factors, such as service life and perceived quality, considerably change the results in the sensitivity analysis (Section 4.2). If the DSS just mentions the names of variables without any information, a building owner might simply input the reference or arbitrary numbers. To resolve this for the service life, the DSS could elaborate on the factor method and criteria (Section 2.3.2). Then, a building owner could more objectively set the input values for the service life (Straub, 2011; Straub, 2015). For the perceived value, the DSS could provide Indoor Environmental Quality (IEQ) criteria, which estimate the indoor environment (Kim & de Dear, 2012).

The cost is the fixed number; therefore, a building owner does not even think of the reason behind the cost estimation. The DSS is to be improved to clearly show the cost breakdown structure, such that a building owner gets to be aware of all costs involved in a renovation project. That helps a building owner to decide how much money they pay to acquire a certain value of building element.

5.3 Limitations and future research

Section 5.3.1 demonstrates the following two types of limitation in this research: i) the lack of information on the renovation cost, and ii) the methodological issues found in the DSS.

5.3.1 Limitations of this research

The main challenge for this study was the lack of data for the cost estimation for the Van Unnik case study as discussed in Section 3.2.2. First of all, both the disassembly and repair costs were inputted based on the assumption described. Secondly, this research used the same CDW collection costs, independent of the type of building material. Thirdly, when estimating the material cost of a recycled building element, this study only considered the price of recycled building materials (Section 3.2.2, e.q 3.8), omitting other potential cost variables such as energy reduction. For that reason, the costs of virgin and recycled building elements that this study inputted in the DSS are not exact. However, the DSS gave a first impression of what the cost could be. Also, when a building owner, in reality, uses the DSS, construction-related businesses would submit the cost estimations that a building owner has to input in the DSS.

As the methodological issues, firstly, the ROI of direct in-place reuse is infinitely positive or negative. These infinities made it complicated to compare the results of TC, NC and ROI. Thus, the ROI may not be a useful measure to the case a circular renovation has the zero cost. Secondly, the DSS does not apply the same factors to the value estimate of reused, repaired and newly produced building elements, consistently. The values of these three building elements might be related to each other. Yet, because of the inconsistent methods, unexpected outcomes could be made. For example, when it comes to a building element that has been used very shortly, the value of the reused building element is very slightly depreciated. However, it a building owner assigns 0.5 as this study did, the value of repaired building element could be estimated lower than the reused building element. Thus, it is recommended to use carefully subjective factors.

The final limitation of this study is that the DSS offers only a financial perspective, therefore, the results the DSS offers may not be sufficient to decision making in practice.

5.3.2 Suggestions for future research

The disassembly and repair costs were hard to find, compared to the new construction and demolition costs. Thus, it is recommended to measure the productivity of each sub-work in kg/manhour or m^3/manhour like Zaballos Palop (2016) and others have done in construction work. Next, it is recommended to investigate the material cost of recycled building elements considering various factors involved in the manufacture and other operations processes. Thirdly, it is recommended to research the way to improve and standardise buildings' material passport. The material passport that this study used only showed the largest constitutive building material. Consequently, the residual value estimation was less elaborate. Standardising and expanding the material passport will make application of the DSS more accurate and reliable. Lastly, it is recommended to further research the information platform where a building owner can access, purchase or supply secondary building elements (ING Bank N.V., 2017).

Lastly, this study is limited to the bounded rationality of users. The DSS shows an option which has the lowest cost or the highest return as the most financially attractive option. This is because the DSS is based on the neoclassical economic theory that affirms a building owner is so rational that prefers to maximise his or her profit (Gluch & Baumann, 2004).

6 Conclusion

This study investigated the way to apply CE strategies to a renovation project and designed six circular renovation options that allow CE strategies to be applied to building elements. This study developed a DSS that assesses and ranks the six circular renovation options based on their financial performances. To apply the DSS, this study conducted a case study on the Van Unnik building, which is marked for renovation while preserving the foundation and concrete frame. Since CE for the built environment is a nascent field of studies, there is a limited amount of literature related to its financial analysis. This study aimed to formulate methods to determine a preferred CE strategy from a financial perspective. At the beginning of this research, this study formulated one main research question and three sub-research questions. To ultimately answer the question "*How can we assess CE strategies applied to a renovation project from a financial perspective?*", the sub-questions were to be answered as follows.

Firstly, to answer the question "*What aspects must be considered for the financial analysis of a circular renovation project?*",

Before going into the financial analysis, the following works must be done: i) the circular renovation options have to be designed, where the CE strategies can be applied. Then, ii) the financial implications of executing each circular renovation option have to be defined. The next step is to seek financial analysis methods that can estimate the defined financial implications.

Secondly, to answer the question "*What financial analysis methods that have previously been used for a circular renovation project?*".

This study considered the following two financial implications: the cost and value. This study had to evaluate the values of reused, repaired and newly produced building elements separately. This study, at first, considered the value of newly produced building element as its material cost. Based on the value of newly produced building element, this study employed the straight-line depreciation method for estimating the value of reused building element, the perceived quality factor for estimating the value of repaired building element. To rank circular renovation options from a financial perspective, this study employed the following three financial performance measures: the total cost, the net cost, and the return of investment.

Thirdly, to answer the question "*How can the financial analysis methods for a circular renovation be formulated?*", The value is subjectively judged, and this is a natural consequence. Thus, the following points have to be considered. Firstly, the DSS has to offer various value estimation methods so that building owners can choose their value estimation method. Yet, the DSS has to also provide the rationale behind each value estimation method. Secondly, the DSS has to elaborate on the criteria to show that the subjectivity factors involved in the value estimations are formulated based on each criterion.

Lastly, the answer to the main research question, ***"How can we assess CE strategies applied to a renovation project from a financial perspective?"*** is presented as follows.

To assess CE strategies, we can firstly design circular renovation options where CE strategies are applied. Then, we define which financial implications that the financial analysis considers. Consequently, we can employ the financial analysis methods that have been used previously, however, the following point must be considered: used building elements have their values, and the value estimation methods must be employed for them. Yet, the value estimation methods involve the factors that are subjectively judged by a building owner. The subjectivity factors significantly influence the results of the financial analysis. Thus, the financial analysis must provide the criteria to show that how the subjective factors are formulated.

Nonetheless, the following three aspects make it complicated that a building owner accepts the results of the financial analysis that this study developed: i) a building owner's dilemma regarding whether the recycled building elements have the same values as that of virgin building elements, ii) the lack of information on both existing building elements in place and secondary building elements and iii) the inherent complexity of financial decision making. Hence, it is recommended to investigate distinguished characteristics between recycled and virgin building elements, and how these characteristics influence building elements that building owners use. It is recommended to build a platform where a building owner can search the following information on secondary building elements: ii-1) the amount of secondary building elements that are potentially supplied per year and region, ii-2) the appearance, size, material composition, acquisition year, and wear and tear, ii-3) the costs, the delivery conditions, warranty, etc. Lastly, is recommended to carry out two types of future research concerning the complexity of decision making: iii-1) the way to combine other implications in the financial analysis, such as environmental implications, iii-2) the way to estimate the value by other ways.

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8 Appendix

8.1 User interface of the DSS

1) Input the general information on the building element

Decision Support System for Circular Renovation

General Information Input

Renovated building element	Suspended ceiling	
<< Click the (+) button to input the general information of building element (size, the number, the material composition)		
Size		
Length	[m per element]	1.500
Width	[m per element]	0.600
Height	[m per element]	0.020
The number of the builidng element	[-]	12

Building material inventory

Nr.	Name	Density [kg per m3]	Revenue from selling the building material [€ per kg]	Escalation rate for the building element	Discount rate for the builidng element
1	Rockwool	22	0.088	2.06%	5.50%
2	Concrete	2400	0.100	1.06%	5.50%
3	Aluminium	2710	0.450	2.36%	5.50%
4	Glass	2500	0.050	2.14%	5.50%
5	Iron	7874	0.220	2.36%	5.50%
6	B-wood	616.89	0.060	1.72%	5.50%

2) The residual value estimation (The cells in yellow need to be filled up, and the rests are automatically calculated)

Decision Support System for Circular Renovation

General Information Input

Renovated building element Suspended ceiling

<< Click the (+) button to input the general information of building element (size, the number, the material composition)

Size			
Length		[m per element]	1.500
Width		[m per element]	0.600
Height		[m per element]	0.020
The number of the builidng element		[-]	12
Material composition			
M1	**Rockwool**		
	Density	[kg/m3]	22
	Proportion	[% of L × W × H]	100%
	Volume	[m3]	0.216
	Mass	[kg]	4.752
	Current revenue from selling the building material M1	[€]	€ 0.42
	Escalation rate of M1's revenue	[%]	2.06%
	Discount rate applied to M1	[%]	5.50%
	Residual value estimation		
	It will be automatically calculated once the reference service life ((4) in Method 2, I133) is filled out		
	Future revenue from selling the building material M1	[€]	€ 0.65
	Present value of the future revenue	[€]	€ 2.27
M2			
	Density	[kg/m3]	0
	Proportion	[% of L × W × H]	0%

3) The cost estimation (The cells in yellow need to be filled up, and the rests are automatically calculated based on the assumptions in the methodology)

Decision Support System for Circular Renovation

General Information Input

Renovated building element Suspended ceiling

<< Click the (+) button to input the general information of building element (size, the number, the material composition)

Circular renovation options		Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
1st decision: retain or remove the existing building element		(1) Retain		(2) Remove			
2nd decision: select a CE strategy applied to a building element that will be used		(a) Reuse	(b) Repair	(a) Reuse	(b) Repair	(c) Recycle	-

Data input

Cost estimation							
Disassembly	[€]	€ 0	€ 0	€ 324	€ 324	€ 324	€ 324
CD&W collection cost	[€]	€ 0	€ 0	€ 280	€ 280	€ 280	€ 280
Purchasing cost	[€]	€ 0	€ 0	€ 370	€ 370	€ 602	€ 609
Material cost	[€]	€ 0	€ 0	€ 0	€ 0	€ 232	€ 239
Installation cost	[€]	€ 0	€ 0	€ 370	€ 370	€ 370	€ 370
Repair cost (if a building element is repaired)	[€]	€ 0	€ 162	€ 0	€ 162	€ 0	€ 0
Contingency allowance	[€]	€ 0	€ 16	€ 134	€ 151	€ 181	€ 182
Total cost	[€]	**€ 0**	**€ 178**	**€ 1,108**	**€ 1,287**	**€ 1,387**	**€ 1,395**

4) The value estimation (The cells in yellow need to be filled up, and the rests are automatically calculated based on the assumptions in the methodology)

Decision Support System for Circular Renovation

General Information Input

Renovated building element Suspended ceiling

<< Click the (+) button to input the general information of building element (size, the number, the material composition)

Circular renovation options		**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**
1st decision: retain or remove the existing building element		**(1) Retain**		**(2) Remove**			
2nd decision: select a CE strategy applied to a building element that will be used		**(a) Reuse**	**(b) Repair**	**(a) Reuse**	**(b) Repair**	**(c) Recycle**	**-**
Value estimation							
Method 1. Newly produced building element: The material cost included in purchasing cost						€ 232.44	€ 239.28
Method 2. Reused building element: Straight-line depreciation method							
1) Value of a newly produced building element	[€]	€ 239.28		€ 239.28			
2) Current year when a circular renovation is executed	[year]	2020		2020			
3) When the existing building element was acquired	[year]	1967		1967			
4) Reference service life of the existing building element	[-]	75		75			
5) Residual value estimation							
Year of the end of service life	[year]	2042		2042			
Present value of the revenue of selling the material	[€]	€ 2.27		€ 2.27			
Disassembly cost	[€]	€ 324.00		€ 324.00			
Escalation rate of disassembly cost	[%]	1.60%		1.60%			
Discount rate applied to the disassembly cost	[%]	2.50%		2.5%			
Future disassembly cost	[€]	€ 459.42		€ 459.42			
Present disassembly cost	[€]	€ 266.86		€ 266.86			
Residual value	[€]	-€ 264.59		-€ 264.59			
6) Estimated value	[€]	-€ 116.79		-€ 116.79			
Method 3. Repaired builidng element: Vorasayan and Ryan (2006)							
1) Value of a newly produced building element	[€]		€ 239.28		€ 239.28		
2) Users' perceived qualtiy factor of a repaired building element	[%]		0.5		0.5		
Estimated value		**-€ 116.79**	**€ 119.64**	**-€ 116.79**	**€ 119.64**	**€ 232.44**	**€ 239.28**

Decision-making

Decision criteria	**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**
1 Total cost	**€ 0.00**	**€ 178.20**	**€ 1,108.35**	**€ 1,286.55**	**€ 1,387.27**	**€ 1,395.48**
Ranking	**1**	**2**	**3**	**4**	**5**	**6**
2 Net cost	**€ 116.79**	**€ 58.56**	**€ 1,225.13**	**€ 1,166.91**	**€ 1,154.83**	**€ 1,156.20**
Ranking	**2**	**1**	**6**	**5**	**3**	**4**
3 ROI	**-11679%**	**67%**	**-11%**	**9%**	**16.8%**	**17.1%**
Ranking	**6**	**1**	**5**	**4**	**3**	**2**

2. Transportation cost estimation

The transportation cost was estimated by Equation 1 (Gao & Lin, 2017), and inputted variables are presented below. This study assumed that the fuel type of truck is diesel. The energy content of diesel was considered as 10 kWh/litre (European Commission, 2017) and the inputted fuel cost was 1.4 €/litre which was the average diesel cost in 2019 in the Netherlands (Shell Nederland, 2020).

$$W = m \times V \times \frac{dV}{dt} + 0.5 \times \rho \times C_d \times A_f \times V^3 + m \times g \times C_{rr} \times V + m \times g \times V \times \sin(\theta) \qquad (1)$$

Variable	Definition	Assumed value
m	Truck weight, including passengers and building elements	It assumed that payload of a truck is 1500 kg/truck, and two personnel whose weights are 80kg take a truck.
V	Velocity (m/s)	22.2 (European Commission, 2016)
$\frac{dV}{dt}$	Acceleration (m^2/s)	0
ρ	Air density (kg/m^3)	1.2
C_d	Aerodynamic drag coefficient (-)	0.608 (Bayindirli, Akansu, & Salman, 2016)
A_f	Frontal area (m^2/truck)	2
g	Gravity acceleration (m/s^2)	9.8
C_{rr}	Rolling resistance coefficient (-)	0.0125
θ	Road gradient (-)	0

3. Input variables

Building material information

This study considered the revenue obtained from selling disassembled building materials as the price of scrap building materials. The discount rate added 3% of risk premium to 2.5% discount rate. These revenues significantly fluctuate all the time. Hence, this research recommends checking the recent price and escalation rate data.

Building material	**Density [kg per m3]**	**Revenue from selling the building material [€ per kg]**	**Escalation rate**	**Discount rate**
Rockwool	22	0.088	2.06%	5.50%
Concrete	2,400	0.100	1.06%	5.50%
Aluminium	2,710	0.450	2.36%	5.50%
Glass	2,500	0.050	2.14%	5.50%
Iron	7,874	0.220	2.36%	5.50%
B-wood	616.89	0.060	1.72%	5.50%

ROCKWOOL (n.d); ROCKWOOL (2020); Sukontasukkul (2009); calculated by using Mebin (2020) and PBL (2014); Thyssenkrupp (n.d); Krommenhoek Metal (2020); Markovska (2018); Eurostat (2020); LME (2020); AmesWeb (n.d); CBS (2020)

4. The cost and value estimation results

The suspended ceilings

Cost estimation			**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Disassembly cost			€ 0	€ 0	€ 324	€ 324	€ 324	€ 324
CDW collection cost			€ 0	€ 0	€ 280	€ 280	€ 280	€ 280
Purchasing cost	Material cost		€ 0	€ 0	€ 0	€ 0	€ 232	€ 239
	Installation cost	Labour cost	€ 0	€ 0	€ 324	€ 324	€ 324	€ 324
		Transportation cost	€ 0	€ 0	€ 62	€ 62	€ 62	€ 62

Repair cost	€ 0	€ 162	€ 0	€ 162	€ 0	€ 0
Contingency allowance	€ 0	€ 16	€ 138	€ 154	€ 184	€ 185
Total cost	**€ 0**	**€ 178**	**€ 1,128**	**€ 1,306**	**€ 1,406**	**€ 1,415**

Value estimation	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Method 1. Newly produced building element					€ 232	€ 239
Method 2. Reused building element						
1) Value of a newly produced building element	€ 239		€ 239			
2) Current year when a circular renovation is executed	2020		2020			
3) When the existing building element was acquired	1967		1967			
4) Reference service life of the existing building element	75		75			
5) Residual value estimation						
5-1) Year of the end of service life	2042		2042			
5-2) Present value of the revenue of selling the material	€ 2		€ 2			
5-3) Disassembly cost	€ 324		€ 324			
5-4) Escalation rate of disassembly cost	1.60%		1.60%			
5-5) Discount rate applied to the disassembly cost	2.50%		2.5%			
5-6) Future disassembly cost	€ 459		€ 459			
5-7) Present disassembly cost	€ 267		€ 267			
5-8) Residual value	-€ 265		-€ 265			
6) Estimated value	-€ 117		-€ 117			
Method 3. Repaired building element: Vorasayan and Ryan (2006)						
1) Value of a newly produced building element		€ 239		€ 239		
2) Users' perceived quality factor of a repaired building element		0.5		0.5		
Estimated value	**-€ 117**	**€ 120**	**-€ 117**	**€ 120**	**€ 232**	**€ 239**

The indoor staircases

Cost estimation	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**

Disassembly cost			€ 0	€ 0	€ 4,500	€ 4,500	€ 4,500	€ 4,500
CDW collection cost			€ 0	€ 0	€ 2,550	€ 2,550	€ 2,550	€ 2,550
Purchasing cost	Material cost		€ 0	€ 0	€ 0	€ 0	€ 40,815	€ 40,500
	Installation cost	Labour cost	€ 0	€ 0	€ 4,500	€ 4,500	€ 4,500	€ 4,500
		Transportation cost	€ 0	€ 0	€ 5,493	€ 5,493	€ 5,493	€ 5,493
Repair cost			€ 0	€ 2,250	€ 0	€ 2,250	€ 0	€ 0
Contingency allowance			€ 0	€ 225	€ 2,704	€ 2,929	€ 10,867	€ 10,804
Total cost			**€ 0**	**€ 2,475**	**€ 19,746**	**€ 22,221**	**€ 68,725**	**€ 68,346**

Value estimation	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Method 1. Newly produced building element					€ 40,815	€ 40,500
Method 2. Reused building element						
1) Value of a newly produced building element	€ 40,500		€ 40,500			
2) Current year when a circular renovation is executed	2020		2020			
3) When the existing building element was acquired	1967		1967			
4) Reference service life of the existing building element	100		100			
5) Residual value estimation						
5-1) Year of the end of service life	2067		2067			
5-2) Present value of the revenue of selling the material	€ 189,186		€ 189,186			
5-3) Disassembly cost	€ 4,500		€ 4,500			
5-4) Escalation rate of disassembly cost	1.60%		1.60%			
5-5) Discount rate applied to the disassembly cost	2.50%		2.5%			
5-6) Future disassembly cost	€ 9,489		€ 9,489			
5-7) Present disassembly cost	€ 2,973		€ 2,973			
5-8) Residual value	€ 186,213		€ 186,213			
6) Estimated value	€ 117,728		€ 117,728			
Method 3. Repaired building element: Vorasayan and Ryan (2006)						
1) Value of a newly produced building element		€ 40,500		€ 40,500		
2) Users' perceived quality factor of a repaired building element		0.5		0.5		
Estimated value	**€ 117,728**	**€ 20,250**	**€ 117,728**	**€ 20,250**	**€ 40,815**	**€ 40,500**

The outdoor staircases

Cost estimation			Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6
Disassembly cost			€ 0	€ 0	€ 700	€ 700	€ 700	€ 700
CDW collection cost			€ 0	€ 0	€ 390	€ 390	€ 390	€ 390
Purchasing cost	Material cost		€ 0	€ 0	€ 0	€ 0	€ 5,793	€ 6,300
	Installation cost	Labour cost	€ 0	€ 0	€ 700	€ 700	€ 700	€ 700
		Transportation cost	€ 0	€ 0	€ 65	€ 65	€ 65	€ 65
Repair cost			€ 0	€ 350	€ 0	€ 350	€ 0	€ 0
Contingency allowance			€ 0	€ 35	€ 262	€ 297	€ 1,421	€ 1,522
Total cost			**€ 0**	**€ 385**	**€ 2,117**	**€ 2,502**	**€ 9,069**	**€ 9,677**

Value estimation	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6
Method 1. Newly produced building element					€ 5,793	€ 6,300
Method 2. Reused building element						
1) Value of a newly produced building element	€ 6,300		€ 6,300			
2) Current year when a circular renovation is executed	2020		2020			
3) When the existing building element was acquired	1967		1967			
4) Reference service life of the existing building element	53		53			
5) Residual value estimation						
5-1) Year of the end of service life	2020		2020			
5-2) Present value of the revenue of selling the material	€ 80		€ 80			
5-3) Disassembly cost	€ 700		€ 700			
5-4) Escalation rate of disassembly cost	1.60%		1.60%			
5-5) Discount rate applied to the disassembly cost	2.50%		2.5%			
5-6) Future disassembly cost	€ 700		€ 700			
5-7) Present disassembly cost	€ 700		€ 700			
5-8) Residual value	-€ 620		-€ 620			
6) Estimated value	-€ 620		-€ 620			

Method 3. Repaired building element: Vorasayan and Ryan (2006)						
1) Value of a newly produced building element		€ 6,300		€ 6,300		
2) Users' perceived quality factor of a repaired building element		0.5		0.5		
Estimated value	**-€ 620**	**€ 3,150**	**-€ 620**	**€ 3,150**	**€ 5,793**	**€ 6,300**

The doors

Cost estimation			**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Disassembly cost			€ 0	€ 0	€ 88,560	€ 88,560	€ 88,560	€ 88,560
CDW collection cost			€ 0	€ 0	€ 12,009	€ 12,009	€ 12,009	€ 12,009
Purchasing cost	Material cost		€ 0	€ 0	€ 89,894	€ 89,894	€ 216,098	€ 222,734
	Installation cost	Labour cost	€ 0	€ 0	€ 88,560	€ 88,560	€ 88,560	€ 88,560
		Transportation cost	€ 0	€ 0	€ 1,787	€ 1,787	€ 1,787	€ 1,787
Repair cost			€ 0	€ 44,280	€ 0	€ 44,280	€ 0	€ 0
Contingency allowance			€ 0	€ 4,428	€ 28,126	€ 32,554	€ 53,367	€ 54,695
Total cost			**€ 0**	**€ 48,708**	**€ 219,042**	**€ 267,750**	**€ 370,487**	**€ 378,450**

Value estimation	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Method 1. Newly produced building element					€ 126,204	€ 132,840
Method 2. Reused building element						
1) Value of a newly produced building element	€ 132,840		€ 132,840			
2) Current year when a circular renovation is executed	2020		2020			
3) When the existing building element was acquired	1967		1967			
4) Reference service life of the existing building element	75		75			
5) Residual value estimation						
5-1) Year of the end of service life	2042		2042			
5-2) Present value of the revenue of selling the material	€ 7,819		€ 7,819			
5-3) Disassembly cost	€ 88,560		€ 88,560			
5-4) Escalation rate of disassembly cost	1.60%		1.60%			

5-5) Discount rate applied to the disassembly cost	2.50%		2.5%			
5-6) Future disassembly cost	€ 125,574		€ 125,574			
5-7) Present disassembly cost	€ 72,941		€ 72,941			
5-8) Residual value	-€ 65,122		-€ 65,122			
6) Estimated value	-€ 7,053		-€ 7,053			
Method 3. Repaired building element: Vorasayan and Ryan (2006)						
1) Value of a newly produced building element		€ 132,840		€ 132,840		
2) Users' perceived quality factor of a repaired building element		0.5		0.5		
Estimated value	**-€ 7,053**	**€ 66,420**	**-€ 7,053**	**€ 66,420**	**€ 126,204**	**€ 132,840**

The windows (frames and glasses)

Cost estimation			**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Disassembly cost			€ 0	€ 0	€ 234,353	€ 234,353	€ 234,353	€ 234,353
CDW collection cost			€ 0	€ 0	€ 3,450	€ 3,450	€ 3,450	€ 3,450
Purchasing cost	Material cost		€ 0	€ 0	€ 0	€ 0	€ 306,653	€ 366,172
	Installation cost	Labour cost	€ 0	€ 0	€ 234,353	€ 234,353	€ 234,353	€ 234,353
		Transportation cost	€ 0	€ 0	€ 873	€ 873	€ 873	€ 873
Repair cost			€ 0	€ 117,176	€ 0	€ 117,176	€ 0	€ 0
Contingency allowance			€ 0	€ 11,718	€ 70,825	€ 82,543	€ 132,156	€ 144,060
Total cost			**€ 0**	**€ 128,894**	**€ 543,853**	**€ 672,747**	**€ 911,837**	**€ 983,260**

Value estimation	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Method 1. Newly produced building element					€ 306,653	€ 366,172
Method 2. Reused building element						
1) Value of a newly produced building element	€ 366,172		€ 366,172			
2) Current year when a circular renovation is executed	2020		2020			
3) When the existing building element was acquired	1967		1967			
4) Reference service life of the existing building element	75		75			
5) Residual value estimation						

5-1) Year of the end of service life	2042		2042			
5-2) Present value of the revenue of selling the material	€ 10,717		€ 10,717			
5-3) Disassembly cost	€ 234,353		€ 234,353			
5-4) Escalation rate of disassembly cost	1.60%		1.60%			
5-5) Discount rate applied to the disassembly cost	2.50%		2.5%			
5-6) Future disassembly cost	€ 332,301		€ 332,301			
5-7) Present disassembly cost	€ 193,022		€ 193,022			
5-8) Residual value	-€ 182,305		-€ 182,305			
6) Estimated value	-€ 21,418		-€ 21,418			
Method 3. Repaired building element: Vorasayan and Ryan (2006)						
1) Value of a newly produced building element		€ 366,172		€ 366,172		
2) Users' perceived quality factor of a repaired building element		0.5		0.5		
Estimated value	**-€ 21,418**	**€ 183,086**	**-€ 21,418**	**€ 183,086**	**€ 306,653**	**€ 366,172**

The windows (only frames)

Cost estimation			**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Disassembly cost			€ 0	€ 0	€ 175,768	€ 175,768	€ 175,768	€ 175,768
CDW collection cost			€ 0	€ 0	€ 3,900	€ 3,900	€ 3,900	€ 3,900
Purchasing cost	Material cost		€ 0	€ 0	€ 0	€ 0	€ 286,841	€ 322,230
	Installation cost	Labour cost	€ 0	€ 0	€ 175,768	€ 175,768	€ 175,768	€ 175,768
		Transportation cost	€ 0	€ 0	€ 253	€ 253	€ 253	€ 253
Repair cost			€ 0	€ 87,884	€ 0	€ 87,884	€ 0	€ 0
Contingency allowance			€ 0	€ 8,788	€ 53,171	€ 61,959	€ 110,539	€ 117,617
Total cost			**€ 0**	**€ 96,672**	**€ 408,859**	**€ 505,532**	**€ 753,069**	**€ 795,535**

Value estimation	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Op. 6**
Method 1. Newly produced building element					€ 286,841	€ 322,230
Method 2. Reused building element						

1) Value of a newly produced building element	€ 322,230		€ 322,230			
2) Current year when a circular renovation is executed	2020		2020			
3) When the existing building element was acquired	1967		1967			
4) Reference service life of the existing building element	75		75			
5) Residual value estimation						
5-1) Year of the end of service life	2042		2042			
5-2) Present value of the revenue of selling the material	€ 8,287		€ 8,287			
5-3) Disassembly cost	€ 175,768		€ 175,768			
5-4) Escalation rate of disassembly cost	1.60%		1.60%			
5-5) Discount rate applied to the disassembly cost	2.50%		2.5%			
5-6) Future disassembly cost	€ 249,231		€ 249,231			
5-7) Present disassembly cost	€ 144,769		€ 144,769			
5-8) Residual value	-€ 136,483		-€ 136,483			
6) Estimated value	-€ 1,927		-€ 1,927			
Method 3. Repaired building element: Vorasayan and Ryan (2006)						
1) Value of a newly produced building element		€ 322,230		€ 322,230		
2) Users' perceived quality factor of a repaired building element		0.5		0.5		
Estimated value	**-€ 1,927**	**€ 161,115**	**-€ 1,927**	**€ 161,115**	**€ 286,841**	**€ 322,230**