A decision support model for analysing the reuse potential of hollow-core slab floor components

-- By Dominique Bleuel --

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Preface

This master thesis research of *'A decision support model for analysing the reuse potential of hollow-core slab floor components'* is the final product of my graduation project at Delft University of Technology. The graduation thesis is part of the master Building Engineering within the specialization of Structural Design at the faculty of Civil Engineering and Geosciences.

Society and the building industry would like to know in which way the circular economy can be implemented. The circular economy is asking for a transition of the building industry towards reuse, refurbish or recycle the existing building components instead of throwing them away as waste. An interesting building component for the building industry is the hollow-core slab floor component; a component that can be used for non-residential and residential buildings. Moreover, these existing hollow-core slab floor components have a long lifespan but are often demolished earlier. The building industry has the ambition to reuse these components, but not much is known about how beneficial it is to reuse existing building components. It should be economically favourable, but also the reuse of existing building components must be better for the environment than manufactured components.

This research project focuses on realizing a decision support model for analysing the reuse potential of an existing hollow-core slab floor component. A comparison can be made between an existing and manufactured building component based on the calculated environmental and economic impact of these building components. Based on this comparison, the reuse potential is determined and a substantiated decision can be made about whether or not to reuse the building component.

For me, this research project is the ideal combination of my interest in the sustainable environment and my master Building Engineering at the TU Delft. I am always triggered to find solutions for current challenges from a sustainable point of view. During my study, especially while attending the courses related to sustainability, I discovered that the concept of the circular economy is still unclear and the construction industry needs more tools to eventually become circular.

This research will be conducted at the University of Technology in Delft.

Dominique Naomi Bleuel
November 2019

Samenvatting

Niet alleen ons klimaat verandert, maar ook het gebruik van hulpbronnen wordt beperkt. In Nederland is de bouwsector de meest vervuilende en hulpbronnen-intensieve sector. Deze sector verbruikt meer dan de helft van de totale wereldwijde hulpbronnen, produceert de meest volumineuze afvalstroom, en is verantwoordelijk voor meer dan een derde van het totale wereldwijde energieverbruik en uitstoot van emissies. 'Hergebruik' wordt daarom ook sterk aanbevolen, omdat hergebruik gezien wordt als een materiaal en koolstof besparend proces. De vraag is dus hoe een component of materiaal moet worden beoordeeld op zijn herbruikbaarheid. Het hergebruikspotentiaalfactor is dus essentieel om te weten.

Dit proefschrift *'A decision support model for analysing the reuse potential of hollow-core slab floor components'* beschrijft het onderzoek naar de ontwikkeling van een beslissingsondersteunend model om het hergebruikpotentieel van een bouwcomponent te kunnen onderzoeken. Voor dit onderzoek is de kanaalplaatvloer gekozen als het te hergebruiken bouwcomponent. De belangrijkste onderzoeksvraag die zal worden beantwoord, is: '*Hoe kunnen verschillende methoden en kennis worden geïntegreerd in een beslissingsondersteunend model om te beslissen over het hergebruikpotentieel van een kanaalplaatvloer om de materiaalcyclus te sluiten?'* Het proefschrift bestaat uit twee delen: het ene deel beschrijft de noodzaak om een beslissingsondersteunend model te ontwikkelen en het andere deel gaat dieper in op het ontwikkelde beslissingsondersteunende model en de resultaten van het model.

Deel I: Verkennend onderzoek naar het hergebruikspotentieel van kanaalplaatvloeren.

De ambitie van de Nederlandse overheid is om van een lineaire economie naar een circulaire economie te gaan, waarbij afval wordt uitgesloten en producten op een hoogwaardig niveau langer in het systeem blijven. De belemmering voor de implementatie van hoogwaardig hergebruik is echter het gebrek aan kennis om de kansen en de impact van hoogwaardig hergebruik te begrijpen.

Wat is de huidige stand van zaken met betrekking tot het hergebruik van kanaalplaatvloeren?
Het blijkt dat hergebruik van kanaalplaatvloeren nog niet gebruikelijk is vanwege de onzekerheid en de risico's die verbonden zijn aan het hergebruik van deze componenten. De kanaalplaatvloer heeft verschillende eigenschappen die voordelig zijn voor het hergebruik van de componenten, zoals het lichte gewicht van het component, de lange technische levensduur en de standaardisatie van het component. Daartegenover wordt de betonnen druklaag, de 'natte' verbindingen en de hoge prijzen voor het deconstrueren van de componenten gezien als barrières voor het hergebruik van de componenten. Wel is onderzocht dat het mogelijk is om de vloercomponenten langer te gebruiken dan ze momenteel worden gebruikt. Dit is alleen mogelijk als er volledig inzicht is in de omkeerbaarheid, de opties van hergebruik en hoe het hergebruikspotentieel van kanaalplaatvloeren kan worden vergroot.

Welke methoden, hulpmiddelen en kennisbronnen zijn momenteel beschikbaar om het hergebruikpotentieel van kanaalplaatvloeren te kunnen beoordelen?
Er zijn al enkele methoden, hulpmiddelen en kennisbronnen met betrekking tot het bepalen van het hergebruikpotentieel. De 'hergebruikspotentiaalfactor' is een factor tussen de 0 -'afval'- en 1.0 -'hergebruik'- en wordt gedefinieerd als het bepalen in hoeverre het component zijn functionaliteit kan behouden na het einde van zijn primaire levensduur en wat de economische en milieu impact is van het hergebruiken van deze componenten. De factoren gerelateerd aan de kwaliteit - kwalificatiefactoren - moeten daarom worden getest en de economische en ecologische impact factoren - kwantificatiefactoren - moeten worden bepaald. Twee bestaande modellen, ARP-model en RFID-technologie, bepalen het hergebruikspotentieel door de kwaliteit van gebouwen en componenten te bepalen. Echter verwaarlozen deze modellen de kwantitatieve prestaties van het gebouw. Life Cycle Assessment (LCA) en Life Cycle Costing (LCC) zijn bestaande hulpmiddelen om de milieu-impact en de economische impact van componenten gedurende hun gehele levenscyclus te analyseren. Er bestaat dus nog niet een beslissingsondersteunend model dat de kwaliteit van de componenten kan testen en de economische- en milieukosten kan berekenen gebaseerd op de kwaliteit en de aanpassingen die gedaan moeten worden aan het component.

Deel II: Beslissingsondersteunend model voor het beoordelen van het hergebruikspotentieel

Er is behoefte aan een model dat de prestaties van bouwcomponenten test om vervolgens het hergebruikspotentieel van het bouwcomponenten aan het einde van de levensduur te beoordelen. Het gaat er om dat er een keuze gemaakt moet kunnen worden tussen het gebruiken van een nieuw gefabriceerd vloercomponenten of een hergebruikt vloercomponent waarbij de impact op het milieu en de economie beperkt blijft.

Hoe is het mogelijk om de hergebruikspotentiaalfactor van een kanaalplaatvloer te bepalen?
De eerste stap om de hergebruikspotentiaalfactor van het vloercomponent te bepalen, is de hergebruiksanalyse waarbij de kwaliteit van het te hergebruiken component moet worden bepaald op basis van kwalificatiefactoren. De kwalificatiefactoren van het vloercomponent zijn de levensduurprestaties, de technische prestaties, de functionele prestaties, de esthetische prestaties en de bijkomende prestaties. De tweede stap is de evaluatie van het hergebruik waarbij de 'kosten' van het bestaande component worden berekend op basis van de kwantificatiefactoren. Dit zijn de milieu-impactkosten en den economische impactkosten op basis van de LCA- en LCC-tool.

Het beslissingsondersteunend model is onderverdeeld in vier verschillende fase: inventarisatiefase, testfase van de kwaliteitsprestaties, modificatie fase, en de testfase van de kwantiteitsprestaties. De methode voor het beslissingsondersteunende model is het analyseren van de relatie tussen de kwaliteits- en kwantiteitsfactoren van de kanaalplaatvloer en deze uitkomst te vergelijken met de factoren van de nieuwe gefabriceerde kanaalplaatvloer. De kwalificatiefactoren van het bestaande vloercomponent worden getest om te zien of ze voldoen aan de vereiste prestaties, anders moet het onderdeel eerst aangepast worden. Dit zal de 'kosten' en de hergebruikspotentiaalfactor beïnvloeden.

Leidt het beslissingsondersteunende model tot realistische resultaten?
Er is aangenomen dat de hergebruikspotentiaalfactor hoger zal zijn wanneer de kwalificatiefactoren hogere scoren en de kwantificatiefactoren lagere scoren dan een gefabriceerd vloercomponent. Het resultaat van het model kan worden beïnvloed door parameters van de kwalificatiefactoren te wijzigen om realistische resultaten te bereiken. Elke kwalificatiefactor heeft zijn eigen bijdrage aan de hergebruikspotentiaal en daarom is de 'gevoeligheid' van het model gebaseerd op deze kwalificatiefactoren.

Resultaten uit het model tonen aan dat het hergebruikspotentiaalfactor verschilt wanneer verschillende gebruiksfuncties worden toegepast. Om dit aan te tonen wordt een twee verdiepingen hoog kantoorgebouw gekozen als referentieproject en voor elk nieuwbouwproject zullen de gebouwfuncties anders zijn. De belangrijkste resultaten zijn:

- De potentiele hergebruiksfactor voor een gebouw met dezelfde gebouwfunctie als het bestande gebouw is 0,82. Dit komt doordat de economische kosten zijn relatief hoog vanwege het demontageproces.
- De potentiele hergebruiksfactor voor een gebouw met een andere gebouwfunctie, bijvoorbeeld een appartementencomplex, is 0,63. Een verklaring hiervoor is dat de eisen voor een andere functie verschillen met de prestaties geleverd door het bestaande vloercomponent en dit betekent dat er meer aanpassingen aan het vloercomponent moeten worden gedaan.
- De potentiele hergebruiksfactor in het geval dat het bestaande gebouw een demontabel gebouw is en het nieuwbouwproject een andere functie heeft, is 1.0. Dit betekent dat de vloercomponenten zeker kunnen worden hergebruikt. De demontagekosten zijn lager voor een demontabel gebouw en daarom is de hergebruikspotentiaalfactor hoger.

Een beperking van het beslissingsondersteunende model is dat het niet altijd op zichzelf kan werken. Soms zijn specialisten nodig om parameters in te voeren of is de database nog te beperkt. Ook worden alle factoren in het model op gelijk niveau geschaald, terwijl de invloed van de factoren wel verschilt. Het beslissingsondersteunende model kan een hulpmiddel zijn om de ambitie van de Nederlandse overheid - de transitie naar een circulaire economie - te realiseren.

Summary

Not only is our climate changing but resource consumption is also becoming limited. In the Netherlands, the building industry causes most of the pollution, negatively contributing to climate change, and is the most resource-intensive sector. This sector consumes more than half of the total global resources, it produces the most voluminous waste stream globally, and it is responsible for more than a third of the total global energy use and corresponding emissions. Therefore, 'reuse' is highly recommended as it is considered to be a material and carbon saving practice. The question is how a building component or material can be assessed for its reusability. Therefore, the reuse potential factor is essential to know.

This thesis *'A decision support model for analysing the reuse potential of hollow-core slab floor components'* describes the development of a decision support model to investigate the reuse potential of a structural building component. For this research, the hollow-core slab floor component is chosen as the structural building component to be reused. The main research question to be answered is: '*How can various methods and knowledge be integrated into a decision support model for deciding on the reuse potential of a hollow-core slab floor component to close the material cycle?'* The research consists of two parts; part I describes the need to develop a decision support model, and part II elaborates on the developed decision support model and the results of the model.

<u>*PART I: Explorative research about the reuse potential of HCS*</u>

The ambition of the Dutch Government is to transform from a linear economy to a circular economy, whereby waste is excluded and products will remain in the system for longer at a high-level value. However, the barrier preventing the implementation of high-value reuse is the lack of knowledge to understand the opportunities and the impact of high-value reuse.

What is the current state-of-art concerning the reuse of hollow-core slab floor components?
It appears that the reuse of hollow-core slab floor components is not yet common because of the uncertainty and risks involved in the reuse of these components. The component has various properties that are advantageous for the reuse of these components, such as the lightweight of the component, the long technical lifespan and the standard dimensions of the component to use it all over the world. By way of contrast, a concrete topping, bonded connections, and the high costs for the deconstruction of the components are seen as barriers to reuse the components. However, it has been investigated that it is possible to use these floor components for longer than they are currently being used. Still, this is only possible if there is a full understanding of the reversibility, the reuse options, and how to increase the reuse potential of these floor components.

Which methods, tools and knowledge are currently available to be able to assess the reuse potential of hollow-core slab floor components?
There are already methods, tools, and knowledge sources with regard to determining the potential of reusing components. The 'reuse potential factor' is a factor between 0 -"waste-like"- and 1.0 -"resource -like"- and it is defined as a factor measuring the ability of a construction component to retain its functionality after the end of its primary life related to the economic and environmental impact of reusing this component. Therefore, the factors related to the quality – qualification factors – should be tested and the factors related to the economic and environmental impact – quantification factors – should be determined. Two existing models, the ARP-model and RFID technology, measure the reuse potential of buildings and their building components by determining the quality of these buildings and components. However, these models neglect the quantitative performance of the building, such as the impact on the environment and economy. The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are existing tools to analyse the environmental impact – expressed in shadow costs, €/m^2 – and the economic impact – expressed in costs, € – of components during their entire life cycle. A decision support model that can test the quality of a component <u>and</u> can calculate economic and environmental costs related to the quality and the upgrade needed to reuse the component, does not yet exist.

<u>*PART II: Decision support model for assessing the reuse potential*</u>

There is a demand for a model that tests the performance of building components to assess the reuse potential of building components at the end-of-life stage. It is about making a decision about the consideration of the use of a new manufactured structural building component or a reused structural building component where the impact on the environment and economy remains limited.

How is it possible to measure the reuse potential factor of a hollow-core slab floor component?
The first step to measure the reuse potential factor of the floor component is the reuse analysis in which the quality of the reused component should be determined based on the qualification factors. The qualification factors to be tested are the lifespan performance, technical performance, functional performance, aesthetical performance, and additional performance. The second step is the reuse evaluation where the 'costs' of the reused component are calculated based on the quantification factors. The quantification factors are the environmental impact costs and the economic impact costs based on the LCA and LCC tool.

The decision support model is divided into four different phases: *inventory phase, quality performance test phase, modification phase,* and *quantity performance test phase*. The decision support model analyses the relationship between the qualification and quantification factors of the reused hollow-core slab floor component and to compare the outcomes with the factors of a new manufactured hollow-core slab floor component. The qualification factors of the existing floor component are tested to see if they meet the required performance of the new construction project, or if the component must be adjusted. This will influence the 'costs' and the reuse potential factor.

Does the decision support model lead to realistic results with regard to the reuse potential factor?
It is assumed that the reuse potential factor will be higher when the qualification factors have a higher score and the quantification factors have a lower score than the newly manufactured floor component. The result of the model can be influenced by changing the parameters of the qualification factors to achieve realistic results. Each qualification factor has its own contribution to the reuse potential factor and, therefore, the 'sensitivity' of the model is based on the qualification factors.

Results from the model show that the reuse potential factor of hollow-core slab floor components is different when different building functions are applied. For this purpose, a two-story-high office building is chosen as a reference project; building functions will be different for every other construction project. The most important results are as follows:

- The reuse potential factor for a building with the same building function as the existing building is 0.82. This is because the economic costs are relatively high due to the disassembly process.
- The reuse potential factor for a building with a different building function, for example, a low-rise apartment building, is 0.63. An explanation for this is that the requirements for a different function differ from the performance provided by the existing floor component and this means that more adjustments must be made to the floor component.
- In the case that the existing building is a demountable building and the new construction project has a different function, the reuse potential factor is 1.0. This means that the floor components can certainly be reused. The disassembly costs are lower for a demountable building and, therefore, the reuse potential factor is higher.

A limitation of the decision support model is that it cannot always work on its own. Sometimes specialists are required to enter parameters in the model or the database is limited. Furthermore, all performance factors are treated equally, although there are differences in how much impact these performances have on the reuse of the component. Nevertheless, the decision support model can be a tool that positively contributes to the ambition of the ambition of the Dutch Government about the transition to a circular economy.

List of Abbreviations

CO_2	=	Carbon dioxide
CE	=	Circular economy
$D_{n;T;A;k}$	=	Airborne noise level
EPD	=	Environmental Product Declaration
ES	=	Existing structure
EVR	=	Eco-cost value ratio
HCS	=	Hollow-core slab
$L_{n;T;A}$	=	Impact sound level
LCA	=	Life Cycle Analysis
LCI	=	Life Cycle Inventory
LCIA	=	Life Cycle Impact Assessement
LCC	=	Life Cycle Cost
LE	=	Linear economy
MKI	=	Milieu Kosten Indicator (Environmental Costs Indicator)
NMD	=	Nationale Milieu Database
NS	=	New structure
RP	=	Reuse Potential factor
SBK	=	Stichting Bouwkwaliteit
SLS	=	Serviceability limit state
ULS	=	Ultimate limit state

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1. Problem exploration

1.1 Introduction
The initial step of this research project is to explore a current problem. Each element of research contributes to improving or adding information to existing studies and to developing ever-better solutions. In this first chapter, the problem will be introduced. The thesis will include a description of the project, including an explanation of the current state of affairs. In addition to this, the impact of the problem on today's world will be identified and discussed. Therefore, this chapter will first describe the research context for a better understanding of the current state of the world's climate; the exhaustion of resources and the reuse of existing building components. Hereafter the problem is summarized into a statement that explains also the scope of this graduation project.

1.2 Research context
Nowadays, the world's population is growing rapidly and the use of our resources has increased due to economic growth. The global use of materials is expected to triple by 2050. This will lead to a shortage of resources in this century. The effect will have a major impact on our current situation because we cannot maintain the current living standards without raw-materials. Where energy can still be generated, the raw-materials will simply be depleted after consumption. The issue of resource scarcity will increase over time and the question now is how we can defuse it (Loppies, 2015); (Verberne, 2016).

1.2.1 The changing economy
Since the Industrial Revolution, the global economy has provided certain changes and strong economic growth due to a series of advances in technology. The technological advances have been created within a context of seemingly unlimited raw-materials. This has resulted in a linear model where raw materials are extracted and taken, products are made and disposed of after use: a linear model of resource consumption that follows the 'take-make-dispose' model of production (Hieminga, 2015). Materials, energy, and labour would be applied in order to produce a product. After the production, the product is then sold to the end consumers who then discard the product when it reaches the end of its lifetime. The linear life cycle model is related to unnecessary resource losses, like waste in the production chain, end-of-life waste, erosion of ecosystem services, and energy consumption. And therefore, the linear model depends on the global commodity stock (Verberne, 2016).

The linear model has been in cycle for centuries because until now resources were cheap and in replenishable supply. However, the prices for natural resources increased over time and this resulted in a turning point in the price trend since the year 2000, as shown in figure 1. The inflated prices are causing unrest for several market economies. It is a reaction to the increased demand against the exhaustion of building resources. This results in a depletion of our materials and causes us to find an alternative approach. With this in mind, we are required to develop a new economy, whereby the availability of resources remains in balance with the limit of growth. This new economy is based on the concept of a 'circular' model, in which more products are reused, refurbished, and redistributed, with materials or elements being remanufactured and recycled. This change to a circular model will lead to economic benefit and reduced pressure on the resource supplies (Ellen MacArthur Foundation, 2013); (Wientjes et al., 2016).

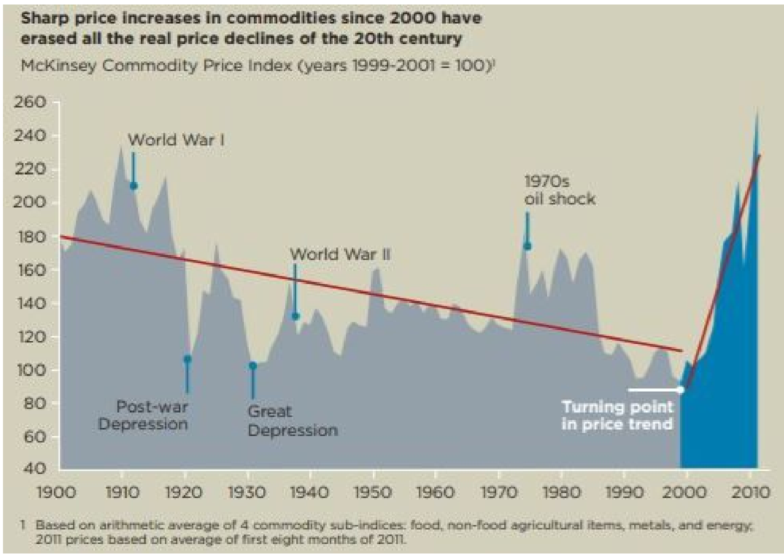


Figure 1. Increases in the prices for the resources (Ellen MacArthur Foundation, 2013).

The shift towards a circular model will change the balance between economy and ecology. This would result in creating an economy that regenerates raw materials by closing material cycles to reduce the impact on the ecological system: the Circular Economy (Loppies, 2015). According to the Ellen MacArthur Foundation (2015), the CE is a global economic model that aims to decouple the economic development and growth from the consumption of finite resources. It is important to keep products, components, and materials at their highest value and utility at all times. Therefore the model is restorative or regenerative by intention and design. The end-of-life concept of a system will be replaced with the concepts of *reuse*, *refurbish* or *recycle* to close the material cycles and to avoid waste generation (Ellen MacArthur Foundation & Granta Design, 2015). So, in a CE; materials and components are re-used and recycled, new materials are produced more efficiently and sustainably, and products are designed to be reusable (European Commission, 2018).

To close the loop of a circular economy, waste should be excluded and products will remain in the system for longer at a high-value level. As a result, the use of resources should be minimized. This will not only reduce the environmental impact associated with the use of raw materials but also the dependence on the international suppliers of raw materials and therefore the risk that scarce resources are no longer supplied. The concepts of *reuse*, *refurbish* and *recycle* can be ranked in relation to the value creation, whereby higher ranking concepts in principle save more resources and embedded energy and therefore avoid environmental pollution (Rood et al., 2019). With this in mind, the concept of *reuse* is the highest-ranked, because products and components - that are no longer used – are restored back to their original states in a way that consumes the least amount of resources to deliver the same or improved function. As a result, product value is preserved at the highest level and the risk associated with resource scarcity, price volatility, energy demand, and environmental impact is reduced (Circle Economy; MVO Nederland, 2015). Thus, the reuse of resources is central; maximizing value retention and minimizing value destruction (Ellen MacArthur Foundation, 2013).

1.2.2 Response from the building industry

The Dutch Government has formed a Government-wide program aimed to develop a circular economy in the Netherlands by 2050. The ambition of the Cabinet is to realize a reduction of 50% in the use of primary raw materials by 2030. The final goal, to be achieved by 2050, is to efficiently use and reuse raw materials without the release of harmful emissions into the environment (Government of Netherlands, 2016). The Dutch Government would like to focus also on greenhouse gas emissions, reducing their CO_2 emissions to 49% by 2030, and to achieve a reduction of 95% CO_2 emissions by 2050 (Rijksoverheid, n.d.).

The most resource-intensive sector in the Netherlands, and in the world, is the construction sector, in particular the building industry. This sector consumes more than half of the total global resources, it produces the most voluminous waste stream globally, and it is responsible for more than a third of the total global energy use and resulting emissions. ‘Reuse’ is highly recommended for the construction sector, because reuse is considered to be a material and carbon saving practice and therefore it can help to address both waste types, including solving the resource scarcity, and carbon emission targets. ‘Reuse’ in the construction sector is to conserve resources and offers the opportunity to create environmental, economic, social and technical value (Iacovidou & Purnell, 2016). The construction sector is known for its long technical lifetime of a building and its components/materials, and therefore it could be used more than once. However, still too often, the building and its embedded materials and components end up as waste when the construction reaches the end of its life-time (Blok et al., 2016).

For the transition to a circular economy, it is important to reuse products at a high-value level. For the building industry, it is required to reuse products that save the most resources and embedded energy. Eekhout (1997) has developed a hierarchy of different building levels. Every step higher on the hierarchy means an increase in the value of labour, energy, material, and use of equipment. The hierarchy is described by Eekhout (1997) as follows: building, building component, (sub) component, (sub) element, raw material. Durmisevic (2006) has also developed a top-down hierarchy based on the hierarchy of Eekhout (1997), see figure 2. So, the higher the building level, the less embodied energy gets lost and the less energy is needed to construct/deconstruct a building (Naber, 2012). Regarding reuse, the closer you are to the core of the existing structure, the more value is retained and the lower the environmental impact (Wenting, Van Haalen, Van Wolfwinkel, & Hofmans, 2018). Hence, the highest possible building level to be reused in case a building is taken down is the level of building components described by Eekhout (1997) (Naber, 2012).

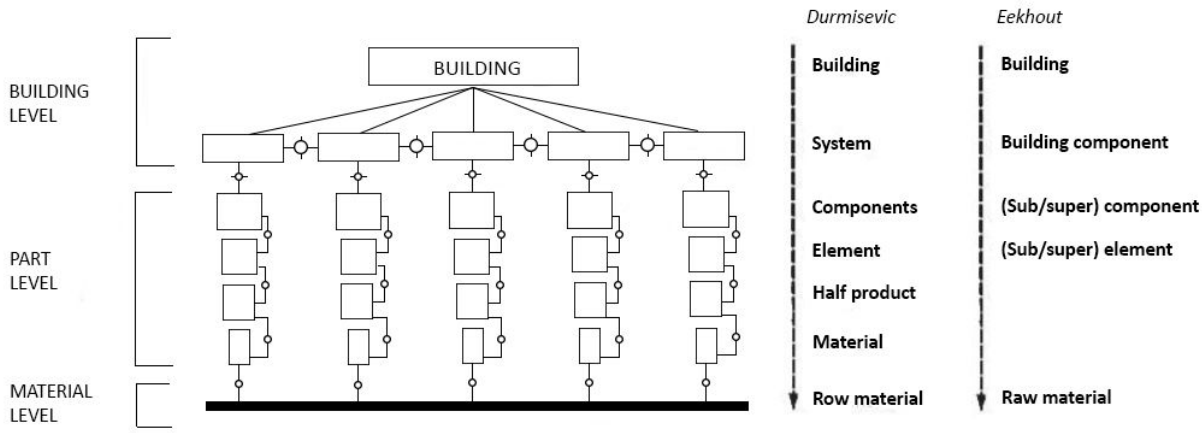


Figure 2. The hierarchy of the building levels according to Eekhout (1997) and Durmisevic (2006) (Naber, 2012).

In this case, the term of high reuse means to preserve value by reusing building components. The reuse of building components prevents an increase in the percentage of waste. In the Netherlands, the building industry produces 18 million tonnes of waste per year (VROM, 2001). The most common material of waste production was concrete in 2001, see figure 3. Although 85 % of concrete is recycled and used as road base, this is not high reuse. This recycling is called ‘down-cycling’ because the recycled aggregate cannot be reused and reach the same quality as the concrete. Therefore, high reuse of concrete building elements could prevent the high waste production and a lower environmental impact (de Vos, Keijzer, Mulder, Bonte, & Bastein, 2017);(Durmisevic, 2006).

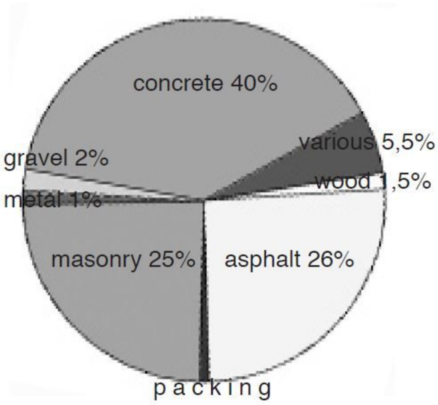


Figure 3. The construction and demolition waste in the Netherlands of 2001 (VROM, 2001).

A concrete structural building component for reuse can be a hollow-core slab floor component. In the Dutch building industry, there is a high demand for these components because they are used in both residential and non-residential constructions (de Lange, 2018). Nowadays, the HCS components are crushed to rubble and recycled for landfill and downgraded, which means the quality of the component goes down. However, the technical lifespan of an HCS component is many times longer than the service life of a building in which it is used and therefore it is not necessary to demolish the component (Naber, Keulen, & Haas, 2013);(VBI, n.d.-a).

1.2.3 The scientific gap

According to Bastein et al (2013), the barrier preventing the implementation of high-value reuse is the lack of knowledge to understand the opportunities of high-value reuse and the impact of reuse. This results in uncertainty to reuse HCS components. It is important to know how good, reliable, and useful these existing HCS components still are, if the reuse of these components has a positive effect on the environment, and if it is feasible from an economic point of view (Leest, 2018);(Naber et al., 2013). However, methods are known for measuring the environmental impact – the Life Cycle Assessment – and the economic impact – the Life Cycle Costing – but these methods are based on the linear approach instead of the circular approach regarding reuse. So, the challenge is to gain quantitative insight into the reuse potential for a circular approach (De Valk & Quik, 2017).

According to Iacovidou & Purnell (2016), "a typology system developed based on the properties and lifetime of construction components is required in order to provide transparency and guidance in the way construction components are used and reused, in order to make them readily available to designers and contractors". The system should be supported by efficient tracking and archiving to provide information relevant to the environmental and economic savings and to enable better decision-making for construction and deconstruction works (Iacovidou & Purnell, 2016). Currently, there is still no method with which the circularity – the reuse at a high-quality level – of a structural building component can be quantified (W/E adviseurs, 2017). There is a lack of evaluative tools and decision making protocols to support and ground the efforts towards reuse; "the reuse potential indicator" should be known for structural building components to stimulate decision-making and manage waste as a resource. 'Waste' is often reused, if the value of the reuse component is recognized and perceived by testing the performances of the component (Park & Chertow, 2014); (Durmisevic, Beurskens, Adrosevic, & Westerdijk, 2017). To conclude, there is a demand for a model that tests the structural building component performance to assess the reuse potential of the structural building component all along the lifecycle (Hobbs & Adams, 2017); (Saidani, Yannou, Leroy, & Cluzel, 2017).

1.3 Problem statement

The transition towards a circular economy requires a different way of working within the building industry. The structural building components, especially the HCS components, no longer have to end up as waste, but the components will be brought back into the material cycle by reusing them. Due to the long life of these structural building components, it is possible to reuse the HCS components for multiple life cycles. However, it is difficult to determine how these components will perform after a long life span and if it is possible to reuse them for another life cycle without harming the environment and economic position. *Therefore, there is a need for a model to test the component performances and to give proper advice towards the reuse of HCS components; the reuse potential should be measured to stimulate the right decision of reusing the structural building component or not.*

Until now, there has been no entrenched way to measure the reuse potential of HCS components by using a quantitative model. So, all the existing hollow-core slab floor components are currently being reused at a low-value level – recycled or disposed of – due to the lack of knowledge. However, the transition towards a circular economy is asking for a sustainable building process for the new building projects. This requires more use of existing building components that can still be used for another lifetime. Though, it should be first determined whether the existing building components can be reused. At the last stage - end-of-life stage - of the life cycle of a building, the building and its components can be demolished or reused. In order to make the right assessment, it is important that the existing building component is tested for whether it is possible to reuse it. So, during the last stage of building a quantitative model is useful to verify the reuse potential of the existing structural building components otherwise the structural building components should be demolished.

1.4 Project scope

This study will focus on the reuse of one particular structural building component: a *hollow-core slab floor component*. These components are common in both residential and non-residential construction and the components are suitable for reuse due to the long technical lifespan compared to the service life of a building. Other structural building components are generally beyond the scope of this thesis because these components have different properties that influence the reuse process. It is expected that the hollow-core slab floor components have several advantages for reuse; this will be clarified in chapter 3.

Within this project, the attention lies in the current supply of the hollow-core slab floor components present in the *existing building structures*. The focus will not be on designing for disassembly in future building projects, but it will be examined how the components from the existing building constructions can be reused in the best possible way and placed in a new building structure. Furthermore, the destination of the reused components will be a new building project and for this study, the focus will be not to reuse the components in a building to be renovated. It is believed that the requirements and wishes from the client are better known for new building projects than for renovated building projects.

In addition, the study will focus on the *Dutch building industry*, because the information is easily accessible for the author and there is an immediate need for change in this building market. The results found may be applicable to other countries, although requirements and desires may vary and therefore change the result.

Moreover, in this thesis, the *reuse potential* is studied. Reuse potential is related to quality and quantity. The quality of the component and the impact categories - environmental impact and economic impact – related to the upgrade of the quality are important for the decision to reuse the component.

At least, the focus will be on the *life cycle of the hollow-core slab floor component* to be able to analyse the reuse process. Many aspects of the entire life cycle are relevant to this investigation and we, therefore, must keep these in mind for the reuse of components. If something has been done within the 'construction phase' or damage has occurred during the 'use phase', this will have consequences for the 'reuse phase'.

2. Research approach

2.1 Introduction

This thesis has been structured with the aim to clearly convey its core aim. Varying stages of research and their sequence help to clearly establish the project and make it easier for the reader to study it. In this chapter, the structure and methodology of the research will be elaborated on. But first, the aim of the research will be described, taking into account the main research question, and its sub-questions. Hereafter, the research methodology will be discussed to structure the research thesis. Finally, the framework of the research can be elaborated on and illustrated in the figure of the thesis structure.

2.2 Aim

The building industry would like to know in what way the circular economy can be implemented, even if the building industry is changing. The Government makes arrangements for the coming years to encourage the return of products. However, the incentive required to catalyse this shift has not yet been realized (Arup, 2016). The circular economy is asking for a closed material cycle and the reuse of building components could close this cycle. Structural building components, such as hollow-core slab floor components, are common in the building industry and therefore these components are important to investigate in order to make major developments in the direction of the circular economy.

2.2.1 Research aim and main research question

As specified in the problem statement, the entrenched way of measuring the reuse potential of a hollow-core slab floor component is missing. <u>*Therefore, the aim of this study is to develop a decision support model for measuring the reuse potential based on the impact of the environment and economics and by qualifying the critical factors of the component with respect to the reuse of a component.*</u> The model can be used as an instrument for decision-making of the reuse of existing hollow-core slab floor component compared to the use of a manufactured hollow-core slab floor components.

Critical factors with respect to reuse hollow-core slab floor components are those related to the new requirements and wishes from the clients. Components may need to be upgraded to comply with these requirements and wishes and this will have an effect on the environmental and economic impact. The more upgrading is needed, the higher the environmental and economic impact is. Therefore, the question is; when does reuse still have a positive effect compared to the use of a manufactured component? The manufactured component will also have a certain impact on the environment and economic costs due to the production and construction process. The reuse potential can be estimated by comparing the existing and manufactured HCS components based on the impact categories.

The decision support model gives the designer of the new building project incentives to become more aware of the reuse potential of an existing building component compared to the use of a manufactured building component. Through a decision support model, designers are encouraged to design with existing structural building components when the environmental and economic performances have a positive outcome. Therefore, one central question emerges:

How can various methods and knowledge be integrated into a decision support model for deciding on the reuse potential of a hollow-core slab floor component to close the material cycle?

This is the main research question to be answered in this report. The following subsection will discuss this by also creating sub-questions.

2.2.2 Research sub-questions

In order to structurally answer this main research question, four different sub-questions have been developed:

1. *What is the current state-of-art concerning the reuse of hollow-core slab floor components?*
   It is important to know whether the hollow-core floor slab components are currently being reused and how this is being done. By making an inventory of this situation, it is possible to properly determine the level of demand that is necessary to assess the reuse potential of these building components.

2. *Which methods, tools and knowledge are currently available to be able to assess the reuse potential of hollow-core slab floor components?*
   Before the potential of reusing a component can be measured, a better understanding of the methods and knowledge currently available is necessary. The factors on which the existing and manufactured hollow-core slab floor components should be assessed in order to determine whether these components meet the requested requirements for the new building project.

3. *How is it possible to measure the reuse potential factor of a hollow-core slab floor component?*
   A decision support model can be a solution for determining the reuse potential factor of the hollow-core slab floor components. Based on the information from the previous sub-questions, the model can be developed. The model can help to make the right decision for reusing the existing structural building component or opting for a manufactured structural building component and discarding the existing structural building component.

4. *Does the decision support model lead to realistic results with regard to the reuse potential factor?*
   The decision support model can be verified based on testing of different situations for reusing the hollow-core slab floor component. The results of the tests can give information about the sensitivity of the decision support model. This involves verifying the turning point when it is no longer possible to reuse the components.

Every chapter will cover one sub-question (see figure 4). The thesis will be divided into four parts including this first part. Part 0 is the introduction (chapter 1 and this chapter). Part I will explore the current situation about the reuse of hollow-core slab floor components and the reuse possibilities for these components (chapters 3 & 4). Part II will elaborate on the decision support model for the measure of the reuse potential of the hollow-core slab floor components (chapters 5 & 6). Part III will derive the conclusion and recommendations of this research thesis. Part I and II are the main parts of this research.

2.3 Research methodology

This study will be researched from the perspective of the Building Engineering field. To answer the research sub-questions and the main research question, a mixed method of the study from Creswell (2009) will be used; a method that "involves combining or integration qualitative and quantitative research and data in a research study". Information and data from literature or other studies will be used, as well as information from experts' opinions by interviews.

This thesis is divided into four parts. These parts are also the basis for the structure of this report. The research is structured in three different phases: the analysis phase (the explorative research), the synthesis phase (the development of the decision support model), and the verification phase (testing of the decision support model). The phases are arranged in order so that each phase provides information for the next phase. The multiple phases influence the development of the model and together they will answer the main research question. However, new findings may occur at a later stage of the research, which may require further analysis.

PART I: Explorative research about the reuse potential of HCS

The **analysis phase – explorative research** introduces the field of interest using a *literature review* and *expert interviews*. Based on this information a theoretical framework is conducted in this phase. Kumar (2011) explains that there are two main data collection methods for this first phase, the collection of primary data – *the literature study* – and the collection of secondary sources – *expert interviews or case studies*. A literature study is giving information about prior research and serves to enhance and consolidate your own knowledge base. Expert interviews are a form of qualitative research in which opinions or perceptions towards an issue are explored and professional knowledge is obtained (Kumar, 2011). For the theoretical framework, the main focus relies on research, wherein the end the basic knowledge for the model is formed. Therefore, the current situation of the hollow-core slab floor components related to the reuse of these components is elaborated on. Also, the available methods and knowledge related to the qualification and quantification processes that are required to reuse a hollow-core slab component are explained. These methods and knowledge are important to understand the issue of measuring the reuse potential factor of these structural buildings components. The information for these analyses is based on *a literature study* and *expert interviews.* The analysis phase will end with a performance framework that is required for the decision support model in the next phase. The first and second sub-questions are answered in this phase.

PART II: Decision support model for assessing the reuse potential

The **synthesis phase – decision support model** translates the conclusion of the analysis phase to a new approach of thinking about the reuse of hollow-core slab elements. The relevant aspects from the analysis phase are included in this phase and these aspects are the basis to create the decision support model. The decision support model is created by using *Excel-program*. The structure and method of the model are described and illustrated in this phase using a *literature study*. Based on the method for the model, the model is developed to measure the reuse potential factor of the hollow-core slab components. The Excel-model is set up on the basis of the qualification and quantification data from the previous phase. Therefore, the third sub-question has been answered.

The **verification phase – testing the model** elaborates on the model by verification and testing the model based on a reference project. The model is verified based on the assumption that is made earlier in the research. Thereafter, three different reuse situations for the hollow-core slab floor component – each situation is related to different requirements and wishes that must be met in that situation - are explained. These situations are tested by the model of the previous phase. By comparing the different outcomes of the tests, it is possible to see where the limit lies to what extent the structural building components are reusable. Important of this phase is to give insight into how it is possible to determine the reuse potential for the hollow-core slab floor components by a sensitivity-analysis. This phase provides an answer to the fourth sub-question by illustrating the usability of the model.

This research is based on many other types of investigation, but the strength is to develop a new decision support model based on the other studies and the outcomes of the research model. The mixed methods that are used and the different research phases are presented in figure 4. Finally, a conclusion will be described and, therefore, the conclusion answers the main research question and provides recommendations for future research.

2.4 Research outline

For each section of the research, the contents of each chapter will be explained. The core of the research is divided into four chapters and the conclusion will be discussed in the last chapter. The first part of the research is the description of the introduction (*PART 0: Introduction*), this is described in the previous chapter and this chapter.

PART I: Explorative research about the reuse potential of HCS

Chapter 3 answers the first sub-question: *What is the current state of regarding the reuse of hollow-core slab floor components?* This chapter combines literature study and expert interviews in order to create a view of the current situation towards the reuse of hollow-core slab floor components. Also, the opportunities and barriers of the reuse of these components, and the life cycle of the building component have been conducted. This results in an overview of the current situation that asks for a better sustainable solution for the reuse of the hollow-core slab floor components.

Chapter 4 gives information about the reuse potential and the related factors to measure this potential. This chapter answers the second sub-question of the research: *What methods and knowledge are currently available to be able to assess the reuse of hollow-core slab floor components?* Using literature study and expert interviews, a systematic approach to the reuse potential has been established. First, the definition of the reuse potential has been considered. The existing methods for measuring the environmental and economic impact related to the reuse potential have been proposed such as the theory combining these two impact categories. To measure the reuse potential, we must start from the assessment of the building component based on various quality factors. Therefore, the qualification factors have been established. Subsequently, the quantification factors for determining the value of the building component have also been established. Finally, the performance framework has been illustrated for describing the program of requirements for the decision support model to measure the reuse potential. For the aim of the research, it is highly important to consider the factors that are relevant to make an important decision about the reuse potential factor of these components.

PART II: Decision support model for assessing the reuse potential

Chapter 5 includes the development of the decision support model for measuring the reuse potential of the hollow-core slab floor components. The third sub-question of the research is answered in this chapter: *How is it possible to measure the reuse potential of a hollow-core slab floor component?* In this chapter, a literature study has been done to create the structure of the model and to develop the method of the decision model. The core objective of this research is to have access to a model for assessing the reuse potential (RP) factor. The intention is to indicate the RP-factor value, including the environmental and economic impact, of an existing hollow-core slab component and a manufactured hollow-core slab component. Therefore, these values can be compared to make the right decision of reusing the structural building component or not. Thereafter, the decision support model has been explained in detail.

Chapter 6 presents the last sub-question that will be answered: *Does the decision support model lead to realistic results with regard to the reuse potential factor?* Therefore, the verification of the decision support model based on a reference project will be elaborated. Also, the model will be tested in three different situations. Thereafter, the decision support model has been evaluated using the three different situations and the sensitivity of the reuse potential of the building components has been determined. Finally, the limitations of the decision support model are discussed.

The last part of the research describes the conclusion and recommendations of this research, the finalization part (*Part III: Finalization*). Chapter 7 includes the most important research conclusions and will give an answer to the main research question. Afterward, recommendations and future research have been discussed.

Figure 4 presents an overview of the chapters of this thesis, together with the sub-questions, content and the methods used for this study.

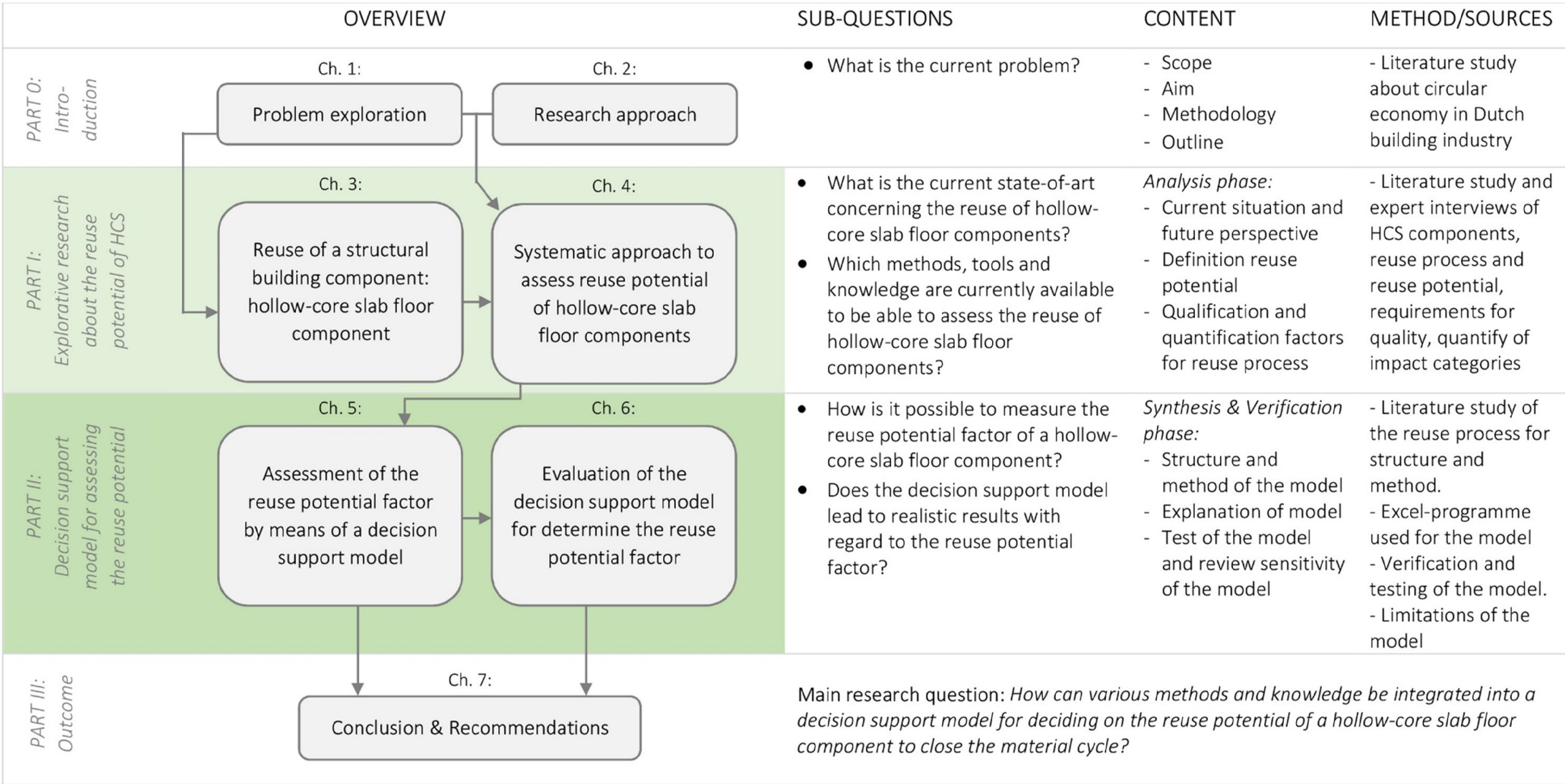


Figure 4. Overview of the research methodology.

PART I. Explorative research about the reuse potential of HCS

The reuse of hollow-core slab floor components is currently not being conducted regularly because companies are worried about the risks involved and to the limited certainty surrounding the requirement needs for 'new' components. However, due to the scarcity of resources in the future, the need to reuse components and to reduce the use of these resources is imminent.

In general, a component is designed situation-specific based on the existing preconditions of any given specific situation. It is therefore important that the matching of supply and demand is carefully done to reuse a hollow-core slab floor component in varying situations. For this purpose, the existing component should be checked qualitatively to see if it meets the new requirements. In order to take advantage of reuse, it is important that the impact on the environment and economic costs are as low as possible when reusing these components.

Chapter 3 discusses the concept of the hollow-core slab floor component whereby the current situation and the future perspective are discussed. Chapter 4 describes the reuse process for reusing a structural building component. Also, the critical factors for measuring the reuse potential factor will be elaborated.

3. Reuse of a structural building component: hollow-core slab floor component

3.1 Introduction

The current method for the demolishing of a building involves stripping the building and reusing the viable parts of the building left remaining. However, the main concrete structure of the building is not yet reused but most of the time crushed and recycled for the use as a foundation under the roads or as gravel in new concrete. As a result, the amount of waste is reduced in this case, but it provides limited environmental benefits, using a large amount of energy (van der Wal, n.d.).

It would be more viable to reuse the whole structure of a building to avoid energy losses and limit landfill disposal. From both economic and environmental perspectives, the idea of reusing structural building components becomes more popular throughout the world. In particular, the reuse of precast concrete components, because such elements are relatively easy to dismantle and to take away for the next use (Dawczyński, Brol, & Adamczyk, 2013).

The hollow-core slab floor component components (from now on to be referred to as 'HCS') is a structural precast building component and therefore is suitable for reuse. The transition to the circular economy requires the reuse of these components and the current situation should be adjusted to this change. Therefore, the key question to be answered in this chapter is:

What is the current state-of-art concerning the reuse of hollow-core slab floor components?

In this chapter, first, the current situation towards reusing the HCS components will be investigated and also what it means when these components are reused. Thereafter, the opportunities and barriers for the reuse of the HCS components will be discussed. At least, the life cycle of the component will be elaborated, in particular, the demolition and reuse phase of the component and the future perspective for the reuse of HCS components will be discussed.

3.2 Hollow-core slab floor component as a structural building component to be reused

For the building industry, the ambition of the Dutch Government regarding the transition to a circular economy in 2050 is one of the most important priorities. The question is, can we develop an economy in which raw materials never run out because they are efficiently used without harmful emissions to the environment? In order to be able to translate the idea of the circular economy into building from a circular perspective, the demolition and design of a new building require consideration of the use of existing building components (Buunk & Heebing, 2017).

Nowadays, non-structural building components, such as doors, windows, ceilings, etc., are already being reused. Buro BOOT *Ingenieurs* has developed an online 'marketplace' for reusable non-structural building components. These components are tested and it is investigated as to whether it is possible to reuse these components. The damage to the component and therefore also the quality of the component is considered (Drok, 2019).

‘Marketplace’ for reusable building materials/components – Buro BOOT ingenieurs

The knowledge of demolition companies and a visible ‘marketplace’ of various building materials contribute together to the accelerated acceptance and application of reusable building materials. The method requires close cooperation between the building parties.

Figure 5. Circular Café at Buro Boot Ingenieurs.

Buro BOOT, located in Veenendaal (NL), has established an innovative, circular platform: Insert. It is a collective of demolition companies that offers used building materials for reuse via an online marketplace. The aim is to reuse building materials from renovation and demolition projects in other new buildings due to be constructed. In this way, reusable building materials from one project can be used in another. The Circular Program manager, Peter Kreukniet, indicates that ‘the goal is to bring architects, contractors, and other building parties into contact with each other, to give reusable building materials that are still of excellent quality a new purpose’ (Vissers, 2018).

According to Drok (2019), a component is assessed on the basis of knowing whether the component can be reused. A specialist can check the quality and dimensions of the component and enter this in the developed app. If the specialist has indicated good quality, it is possible to reuse the component. However, it is important to compare the standards and requirements. The current standards can be different from the standards the door had to meet before for example. Buro BOOT focusses only on the reuse of non-structural components, such as doors, windows, ceilings, etc. The costs of the reused components consist of the transport and disassembly costs, but these are limited according to Drok. There is little attention paid to the environmental costs because it has already been stated that reusing components within the Netherlands is more sustainable than having new components transported from neighbouring countries (Drok, 2019).

By way of contrast, structural building components are more complicated to test and investigate and, therefore, to sell at a ‘marketplace’. Investigating these components takes more time because many tests have to be done for checking the quality of the component as well as for the guarantee of their safety. In addition, the specialist has to approve the safety and functionality of the component. Accordingly, these components are not commonly chosen for reuse (Drok, 2019). When in fact a building consists mainly of structural building components instead of non-structural building components. Glias (2013) has already done research on the concept of ‘Donor Skelet’ by reusing existing structural elements to reduce the environmental impact. These structural building components consist of many raw materials, more than non-structural building components. Therefore, it is more efficient to reuse the structural building components and reduce the impact on the environment in terms of exhaustion of raw materials (Glias, 2013).

A structural building component to be reused could be the HCS component (see figure 6) because this component is currently available in many existing buildings that will be demolished. The reason is that in 1970 a lot of buildings were constructed with prefab concrete components. In recent years, the use of prefab concrete systems has grown rapidly. Building with prefab concrete components is faster and cheaper, it could offer a counterbalance to falling house prices and make new-build homes more affordable. Interestingly, the wide floor plate and the hollow-core slab floor together dominated the market in this period. The HCS component is the structural prefab building component that was used in utility buildings and residential buildings (Lichtenberg, 2001). From the point of view of the circular economy, these released HCS components could be reused in new building projects otherwise, in the current economy, these components will be thrown away and become waste.

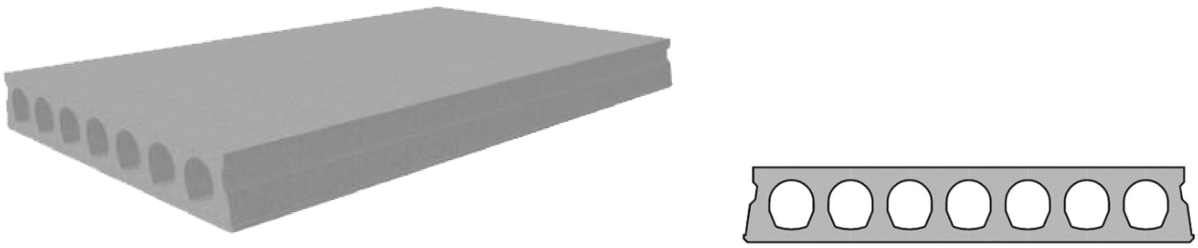


Figure 6. Hollow-core slab floor component, 200 mm thickness [Right: 3D-model; Left: cross-section].

3.2.1 The current situation of waste versus reuse of structural concrete building components

In the Netherlands, the building industry produces 18 million tonnes of waste per year (VROM, 2001). In the case of concrete building structures, reuse of existing structures is confined to crushing the structure and obtaining aggregates and steel in the form of scrap. The obtaining aggregates will be reused in civil engineering as granules for new road constructions or as replacement of gravel for making new concrete structural elements. Nowadays, this phenomenon currently solves the problem of 'concrete waste', but it is not a permanent solution due to the minimal environmental benefit. For example, 97% of the amount of CO_2 released during the manufacture of concrete with the obtaining aggregates is determined by the production process (Dawczyński et al., 2013);(Naber et al., 2013).

The recycling of concrete structures as granules for the replacement of gravel in concrete has become more extensive due to increased knowledge regarding quality. However, the type of recycling used is called down-cycling because the granules do not have the same quality anymore as the concrete it was part of. When using the granules as aggregate for making new concrete structures, the material will achieve approximately the same quality as its previous application. In addition, a lot of energy is also required for the recycling of concrete, as the concrete must be crushed, sorted and wasted. Moreover, most of the energy within the process of fabricating concrete is used for the production of cement. For the production of concrete with the granules of the crushed concrete, cement is still needed (Naber, 2012). Research has shown that 90% of the building materials and components are recycled by 'down-cycling'. However, this scenario is the least beneficial for the environment, because of the degradation of materials and loss of embodied energy (Durmisevic, 2006).

In order to prevent the impact on the environment over the coming years, research should be done into a better alternative. Instead of down-cycling, up-cycling could be a better choice. In this case, the quality of the component does not decrease but gets even better. Therefore, an existing structural building component - but not used any more - could be upgraded and used as a new component for a new building project. So, the structural concrete building components, such as the HCS components, from dismantled reinforced concrete structures offer the potential for the recovery of components in order to reuse (Dawczyński et al., 2013);(Naber et al., 2013). As a result, the waste will become less and have therefore less impact on the environment.

3.2.2 The waste management hierarchy for the hollow-core slab floor component

The current situation of crushing the concrete for recycling provides a little environmental benefit. To change the impact on the environment, it is necessary to prevent the amount of waste. Therefore, a waste prevention ladder can give more insight into the relationship between the amount of waste and the environmental benefit (Naber et al., 2013). An order for waste treatment is based on the Ladder of Lansink and describes the waste hierarchy with disposal at the bottom and prevention at the top as most preferred, see figure 7 (Macozoma, 2002). The highest step of the waste management hierarchy is the goal of waste prevention because this causes no impact on the environment. Whenever prevention is not possible anymore, the next highest step is the reuse of components and materials if the components or materials of a building can be recovered in a high-quality condition. It is not always possible to reuse the components or materials and, therefore, recycling is an option. The waste management hierarchy is about reducing the amount of waste destined for landfill to a minimum value and to fulfill the aim of resource efficiency (Couto & Couto, 2010).

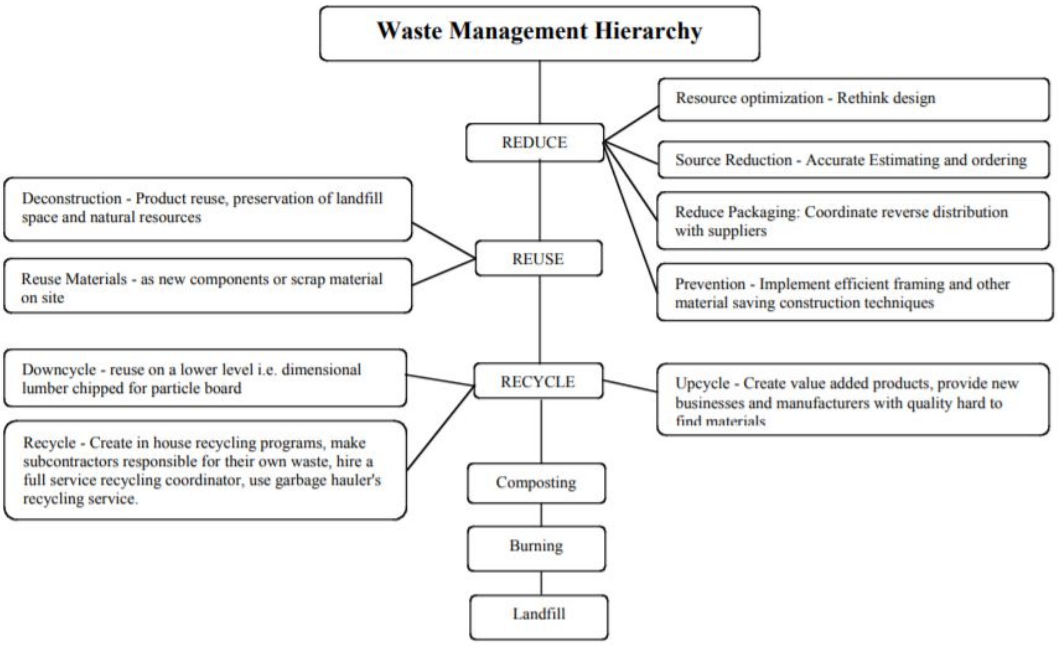


Figure 7. Waste management hierarchy based on the Ladder van Lansink (Macozoma, 2002).

If a building is due to be demolished, it is no longer possible to reach the highest step of the Ladder of Lansink. To limit the amount of waste, it is therefore important that the structural building components are reused. The process of reuse will limit the landfill disposal of materials that can be reused, thereby the contamination of the environment is reduced and this has a positive effect on the sustainable development of the building industry including the environmental aspects. The sustainable development, related to the circular economy, should cover the entire life cycle of the building, from the design through the utilization phase until the demolition phase. For each of these phases, the impact of buildings on the environment should be minimized and the use of building materials should be optimized by reusing the HCS components. The reuse of these components results in saving more energy and natural resources (for the production of new materials) and the less the costs will be for the disposal or storage of waste (Dawczyński et al., 2013).

3.3 Opportunities and barriers for reuse of hollow-core slab floor components

As mentioned before, the HCS floor components are often used in both utility buildings and residential buildings. The HCS component has many advantages that can be seen as opportunities for the reusability of the floor component. Also, the component has some disadvantages that can result in barriers for reuse of the component.

3.3.1 Opportunities for reuse hollow-core slab floor components

The advantages for using these HCS components and therefore the opportunities towards the reuse of these components are:

- The HCS component is a *standard product* with a standard width of 1.2 meters [1216 mm], see figure 8. Due to the standard product, the component is placed in many different building types. Also, the component has a standard thickness, a variation of a few different sizes, and therefore it is easier to obtain in the desired thickness for the new building (Naber, 2012).

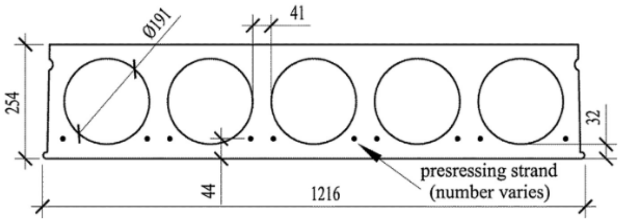


Figure 8. Cross-section of a HCS component with a standard width of 1216 mm (Adawi et al., 2015).

- The components have longitudinal voids in the cross-section which ensure a *reduced self-weight* of the floor component and the voids may be used for the electrical and mechanical runs without unsightly surface mounted conduit (Buettner & Becker, 1998).
- The floor component is a *prefab building component* and research has shown that it is technically possible to dismantle a building with prefab concrete components instead of demolishing it. The first building that was partly disassembled instead of demolished, was the residential building in Middelburg in 1986. The 7 top floors of the residential building in Middelburg have been deconstructed and a large part of the components of this building were reused in a new building project; 114 new houses were built with the reused components (Coenen, Lentz, & Prak, 1990).
- Also, it is possible *quick and easy to install and take out* the component of the construction in an easy way and therefore little energy is needed. This is because the joints and components are poorly bonded to other building components (Naber, 2012).
- The floor component is an *efficient floor system*, because the top surface can easily be prepared for the installation of the floor covering and the underside of the component can be used as a finished ceiling (Buettner & Becker, 1998).
- The HCS component provides the efficiency of a *prestressed member* for load capacity, deflection control and span range (Buettner & Becker, 1998).
- The *fire resistance* of an HCS component is excellent when the right thickness is calculated (VBI, n.d.-a). Depending on the thickness and the cover for the strands, fire resistance up to a 4-hour endurance can be achieved (figure 9). The required fire-resistance rating should be clearly specified in contract documents. The fire-resistance rating should be considered for determining the component thickness (Mydin & Ramli, 2012).

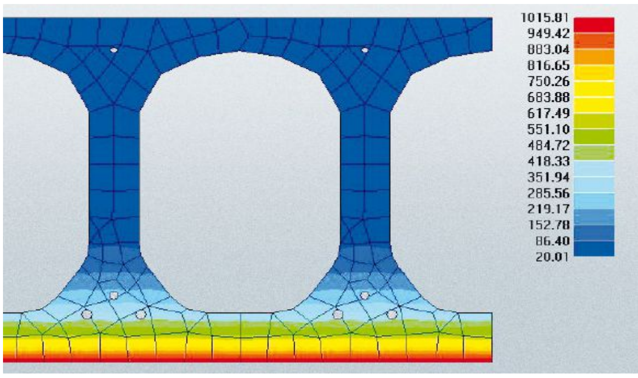


Figure 9. Fire-resistance of the floor components up to 180 minutes (Nordimpianti System SRL, n.d.).

- The *sound transmission* characteristic of the floor component is good for utility buildings. The sound transmission rating ranges from about 47 to 57 dB and with a topping it is even better (Buettner & Becker, 1998). However, the sound transmission requirements for a residential building, and especially the apartment buildings, are highly strict and the component is too light in weight so that it cannot meet the requirements. Additional adjustments must be made to meet these requirements.

- In addition, the *technical lifespan* of an HCS component is longer than mostly the functional lifespan. The manufacturer of concrete products, Holcon, notices in a presentation of 2013 that “prefab concrete lasts at least 200 years and we only use it 15 to 30 years on average” (Bartels, 2013). Also, the European Concrete Platform ASBL mentioned “Internal concrete structures are everlasting as there are no mechanisms that will damage indoor concrete in normal condition. Their service life is assumed to be 200 years” (Jacobs, 2009). Therefore, in many cases, the technical lifetime of an HCS component is many times longer than the service life of the building in which it is used (Naber, 2012).
- As mentioned before, the *environmental impact* for reuse an HCS component is much lower than for crushing and recycling the HCS component. If the component is reused, the use of energy and the emission of CO_2 during the production phase is not needed anymore (Dawczyński et al., 2013).
- The HCS component is widely known as an *economical* floor system (Iacovidou & Purnell, 2016).

These many advantages are the reason why this floor system is used in both residential and non-residential structures. However, the use of the components in both residential and non-residential structures asks for more HCS components to be manufactured. According to de Lange (2018), it becomes increasingly common that not enough HCS floor components can be supplied within the desired time due to the high demand. This creates a scarcity of the HCS floor components and the prices of the components will rise (de Lange, 2018). A reaction to the scarcity is to use more reused HCS components. And, the many advantages of the HCS floor components have a positive effect on the reuse of these components.

3.3.2 Barriers for reuse hollow-core slab floor components

In contrast to the advantages, there are also some disadvantages to the HCS component. These disadvantages could be barriers to the reuse of these components. The major barriers of the HCS component related to the reuse of the component are:

- The hollow-core slab floor components are usually *grouted* and in many situations *covered with a concrete topping* (figure 10). For the deconstruction process, this sometimes requires small alterations to the design to keep it intact (Iacovidou & Purnell, 2016).

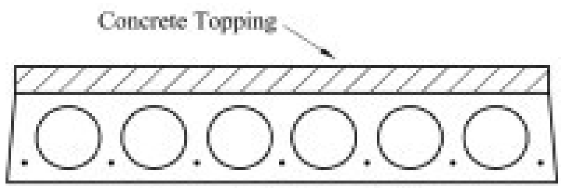


Figure 10. Concrete topping on top of the HCS (Adawi et al, 2015).

- The *bonding between the floor component and the supporting wall or column* is a restriction for the reuse of HCS components. The component can be connected to the supporting wall or column with coupling reinforcement (a so-called hammerhead [in Dutch: *hamerkop*] recesses with coupling reinforcement is used to transfer the shear stress) and by filling some cores with mortar, see figure 11. This could be a restriction for the reuse of the HCS components because some cores cannot be used anymore for a new connection of the reused component with the supporting wall or column in the new building project (Naber, 2012).
- The *bonding between the floor components itself* is also a restriction because reinforcement is used to connect the floor components. The reinforcement is mounted in head slots [in Dutch: *kopsleuven*] and the floor components are connected to each other, see figure 12. The reinforcement is needed for transferring the horizontal forces and for the cohesion and stability of the floor. If a floor component is reused, the floor components should be decoupled and the function of the reinforcement will disappear. The cohesion of the components through the reinforcement is also considered important for the fire resistance of the structure (Kraus et al., 2006).

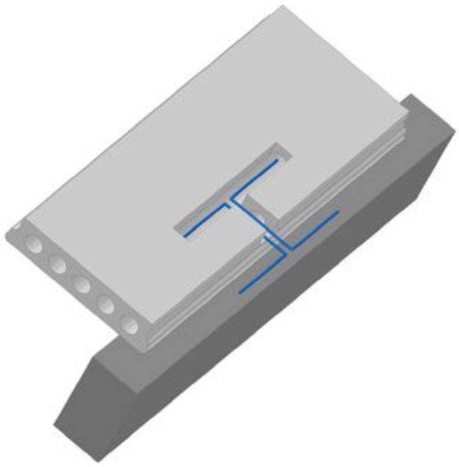


Figure 12. Hammerhead (Dutch: hamerkop) recesses with coupling reinforcement (Fingo, 2015).

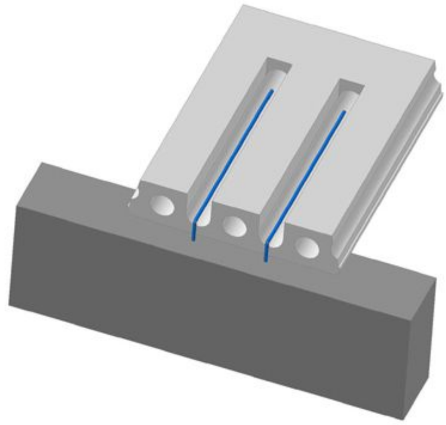


Figure 11. Head slots (Dutch: kopsleuven) for connecting the components to each other (Fingo, 2015).

- Sometimes it is possible that there is no documentation present about the condition of the component, such as cover thickness to the reinforcement, diffusion coefficient for the concrete cover, etc. (Naber, 2012). However, the municipality maintains an archive for the storage of building plans from 1900. These building plans can be requested by anyone. It could be that the plans only consist of overview drawings of the building and the detailed drawings could be missing (Gemeente Hilversum, 2019).
- The prices of the HCS component are low (Peters, 2016). However, research has shown that the costs of existing elements can be 26% less than building with new elements. But, the deconstruction of elements that are not planned for reuse has an increase in costs for the process of deconstruction. This results in a competition between the manufactured components and the components to be reused (Glias, 2013).
- For the different characteristics of the HCS component, such as sound transmission, insulation quality, fire resistance, etc., additional adjustments should be done to meet new requirements and wishes. However, there are not yet norms about the reuse of buildings and the adjustments to be made. To make (re)use of these concrete components possible, norms should be added in the current Eurocodes. Engineers can secure the required quality to the client if they follow the regulations on constructing with reused components by the Eurocodes (Naber, 2012).

The disadvantages are mainly related to the absence of regulations regarding the construction of reused components and documentation of the buildings. It will be a challenge to deconstruct the components because these components are mostly not designed to be dismantled due to their connections.

3.4 Life cycle of the hollow-core slab floor component against reuse

In the Netherlands, there are three major suppliers of HCS components: VBI, BetonSon, and Dycore. All of the three suppliers provide the HCS components independently with their own properties. The components are manufactured at the suppliers' factory and transported from the fabrication plant to the construction site. At the construction site, the component will stay as long as possible to fulfill the required function until it is not needed anymore or the building will be demolished (Naber, 2012). These are all different phases the component will follow. This is also called the life cycle of the component, see figure 13.

According to Ngwepe & Aigbavboa (2015), there are six life cycle stages of buildings and their components. These stages are divided into raw material extraction and manufacturing, construction, operation and maintenance, demolition, and disposal, reuse or recycling. Buildings are responsible for a great quantity of the environmental impact due to the long life cycle stages of the building components. A considerable amount of materials and energy is consumed and therefore most of the impact is created during two major life cycle phases: construction and operation stage. The reuse of existing components may reduce the impact on the environment, because of the excluding of the construction phase (and production stage). While the reuse of these components is not without certain impacts of its own. For example, some of the components may need to be re-painted and this will have an impact on the environment through paint. And fuel is also required for the transportation process (Ngwepe & Aigbavboa, 2015).

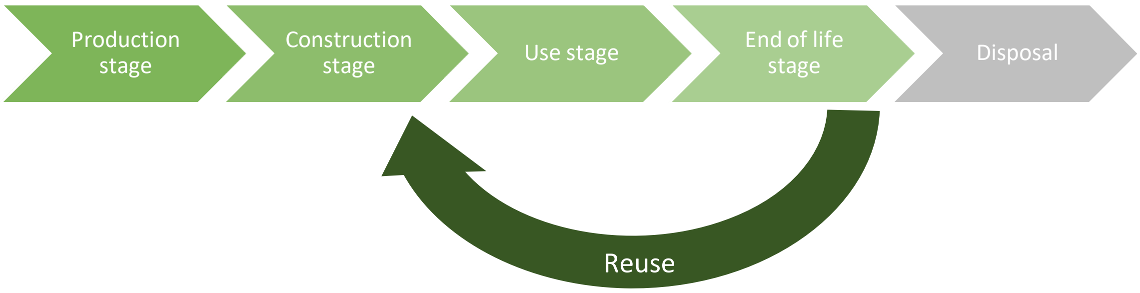


Figure 13. Life-cycle stages of the reuse of a hollow-core slab floor component.

Since reuse can limit the impact on the environment, it is important not to demolish HCS components but to use them again. Therefore, the demolition phase should be addressed in a different way and more attention is needed for the reuse stage of the life cycle.

3.4.1 Transition of the demolition phase towards the reuse phase

The most important life cycle stages for reusing HCS components are the demolition and reuse phase. At the end of the lifespan, the building has reached its functionality and the demolition phase will start. The demolition process has two stages (Durmisevic, 2006):

1. The reusable components are stripped from the building. Those are the non-structural components such as glass components from the window frames, radiators, sanitary fixtures, etc. Thereafter, the whole building is stripped and only the concrete construction frame remains. The waste is transported to a sorting plant and there the waste is recycled, burned, or used as landfill.
2. The demolition of the rest of the building is the next stage. The building is demolished floor by floor. Cranes and breaker shears are used to demolish the building structure. The rubble that is left is crushed by the crusher plant and the steel is removed.

In this case, nothing is left over to be reused after the demolition process. For this reason, another way of demolishing a building is preferred to make it possible to reuse the HCS components. The approach of disassembly could be a solution instead of the demolition process. Disassembly is about separating the structure into its different parts and does not demolish the components. This process helps to avoid the removal of building components and the waste production will be minimized (Guy, 2015). However, the disassembly process is difficult because designers conceptualize their buildings to be timeless and not to be deconstructed. The two stages of the demolition process will change into stripping the building with the result of reusable components at the end and disassemble these components from the structure (Kibert, 2001).

The reason for rarely applying the method of disassembly instead of demolition is because of economic reasons. Contractors want the cheapest way to bring down a building. The disassembly process is more time consuming than the demolition process and therefore the costs could be higher (Naber, 2012). Although, there is a lack of space for waste and that results in high disposal costs and therefore alternatives to traditional disposal should be more accepted (Kibert, 2001).

3.4.2 Disassembly process of hollow-core slab floor components for reuse

According to Luiken (2001), it is possible to disassemble and reuse components if these are constructed by assembly construction systems, because the components are only attached at the joints. Also, the larger these components are, the better for the environment to reuse. As a result, less energy is required for breaking and re-establishing the connections and potential energy is therefore retained. Figure 14 shows that more potential energy is retained if prefab components will be reused. Therefore, the reuse of HCS components is needed instead of recycling or demolishing (Luiken, 2001); (Naber et al., 2013).

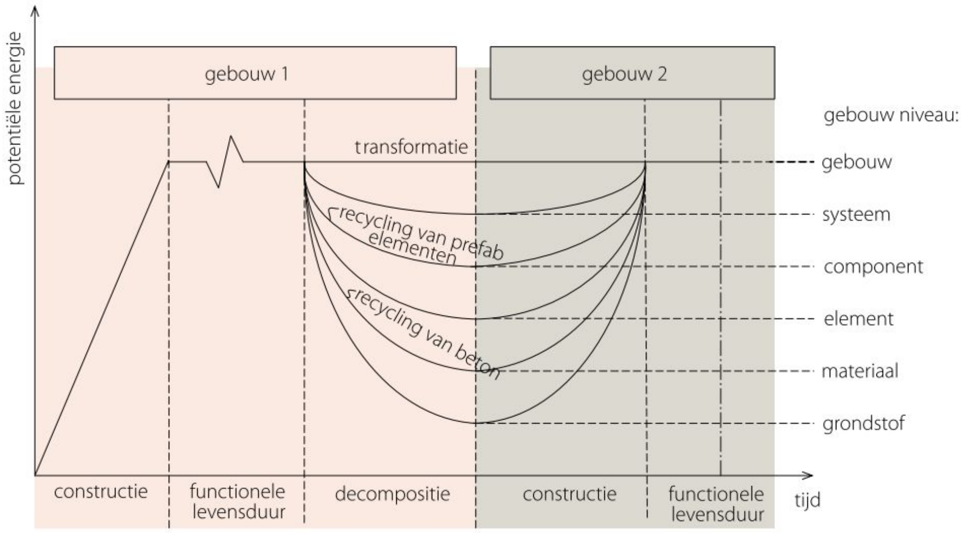


Figure 14. Potential embodied energy related to different building levels (Durmisevic, 2006).

However, the disadvantage of the disassembly process for the reuse of building components is that it is a more time-consuming process instead of demolition of a whole building. First, a constructive analysis of the components is needed to determine the possibilities for reuse of the components. This is based on the existing drawings of the building. Besides, an inspection on the building site has to be done because it could happen that a building is not built according to its drawing due to changes at the last moment of the building process (Glias, Pasterkamp, & Peters, 2014). After it is known which components could be reused, techniques are used to disassemble the building for the reuse of building components. It is important that these techniques cause as little damage as possible to the components so that the components can be reused. These techniques are (Luiken, 2001):

- The diamond saw is useful for dismantling the concrete structure. With this technique, the component can be taken out of the construction without any damages. It is also the most economical alternative for taking out the components.
- The jackhammer and/or chipping hammer can be used for breaking the unreinforced or slightly reinforced concrete, especially for the joints.
- And a crane is needed to take out the components of the building to be demolished.

3.5 Future perspective of reuse the hollow-core slab floor components

One of the major suppliers, VBI, has done research about the future perspective of the HCS component. According to Bouwwereld (2018), ‘at the end of the lifetime of a building, the HCS component could certainly also be used for a second time’. The future perspective is to make re-mountable HCS components. Therefore, VBI is a leader with a future sustainability principle to ensure that components are designed in such a way that they can be reused in the future (Bouwwereld, 2018). The temporary court in Amsterdam is an example of the future perspective of demountable and re-mountable structures.

The temporary court in Amsterdam

The court of Amsterdam's temporary building is a demountable building with traditional building materials. When the permanent court is ready, the temporary is deconstructed and rebuilt elsewhere, using the same materials and components (see figure 15) (Danschutter, Noomen, & Oostdam, 2017).

An important design principle is that the building must be demountable and should be able to be reassembled at another location. The building is constructed with a steel main supporting structure that can be built quickly. A dry building system is possible with bolted connections and is easy to dismantle and reconstruct. Various systems have been studied for the floor. Hollow-core slab floor components prove to be the most suitable for this building. In a short period of time, a large span can be realized with this flooring type. The HCS component is combined with integrated beams. Due to disassembly, a concrete topping is unsuitable and a special connection between the HCS component and the girder has been devised (Danschutter et al., 2017).

Deviations during the construction phase can be noticed on a digital platform in order not have some surprises during the deconstruction phase. Inspection of building materials and components, and especially the administration of the components, require the necessary attention. The registration and documentation of components offer the opportunity to guarantee disassembly and reassembly (Danschutter et al., 2017).

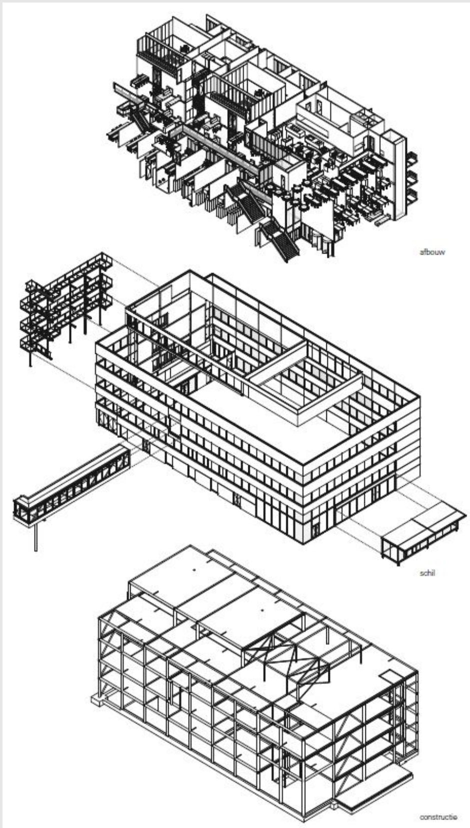


Figure 15. Disassembly process of the temporary court building (Danschutter et al., 2017).

Attention should be paid to the regulations that can change. In the case of structural reuse, the HCS component should comply with the then applicable regulations. It may happen that the regulations have changed in the meantime and that an HCS component no longer complies with the regulations. In this case, the floor component should be upgraded. For example, the requirements for the strength of the floor due to the fire resistance are increased. Then the fire resistance of the HCS component can be increased by treating it or by increasing the coverage of the concrete (Buunk & Heebing, 2017).

3.5.1 A new way of designing by using the material bank

In the coming years, several buildings will be designed and built. The buildings could be designed as transformable buildings with reusable building components. Therefore, these buildings create the potential to utilize the built environment in the future as a material bank for new buildings. This new design approach should focus on two main concepts that are important to meet the vision of reusing the building components in the future (Durmisevic et al., 2017). These two concepts are (Durmisevic et al., 2017):

1. After a few years, there could be new requirements to be met. The buildings and their building components should be designed to have the capacity to transform the building- and the component structure to meet the new requirements.
2. The potential to reuse the physical structures and components in new buildings has to be achieved.

The basis of the two concepts is to close the material cycle by making most of the building components reusable. The building becomes a material bank with an extensive material passport (Economic Board Utrecht, 2018)(Alliantie Cirkelregio Utrecht & Economic Board Utrecht, 2018). The reuse of building components is only possible if the materials in the buildings are identified and documented. Each component or material should have a document with the relevant information. A material passport should be updated during the whole lifetime of the component. The information in the passport should reflect the current state of the component (Romnée & Vrijders, 2017). A database that shows the available components and materials in the building and their corresponding material passport can give an overview of the building as a material bank. If the building does not fulfill its function anymore, the building components could be sold on a market place based on the database that is created for the building (Leising, 2016).

At this moment, the demolition companies are asked to invest more time in the preparation to identify which materials/components are suitable for reuse, how to remove them and when they could be available. However, this takes a lot of time and can have adverse consequences for the quality of the implementation due to the lack of time (Economic Board Utrecht, 2018). For this reason, it would be essential in the future to use the buildings as a material bank and to have documented all components/materials in advance after the construction phase. Nowadays, BIM-models are used to design buildings and to be able to properly document everything about the new building.

3.6 Results

Currently, the reuse of structural building components, such as the hollow-core slab floor components, is not yet accepted as a standard approach to building our building stock. The reuse of structural building components is difficult and uncertain due to the complexity to test and investigate the reuse possibilities of these components. However, the reuse of the components has a positive effect on the environment. The components are upcycled instead of downcycled. Therefore, the quality of the component will not decrease, less energy will be lost, and the amount of waste will be limited.

The HCS floor component has many good properties for both residential and non-residential buildings, such as the standard prefab component size, the quick and easy installation/de-installation of the component, the assured quality, and the long technical lifespan of the component. This results in opportunities for the reuse of these components. However, there are some barriers to the reuse of HCS floor components, like the concrete topping on the floor, the bonding between slaps and supporting walls, and the increasing costs for deconstruction.

The transition from the demolition phase to the reuse phase can limit the impact on the environment and economy because the production and construction stage will then be excluded. And these stages have the most impact on the environment. However, the current building industry is not yet ready for this change because designers have conceptualized their buildings to be timeless and not to be deconstructed. By way of contrast, research has shown that it is already technically possible to disassemble the structures of large prefab concrete elements. Therefore, the properties of the components should be well documented to verify the possibility to reuse the component.

The focus for the rest of this research is on the reuse of the HCS components and to tackle the issues of the current economy towards the reuse of the structural building components. The principle is that the floor components can technically be reused, but the more insight and feeling has to be gained in determining the possibility of reusing these components.

4. A systematic approach to assess the reuse potential of the hollow-core slab floor component

4.1 Introduction

It is technically possible to reuse hollow-core slab -HCS- floor components, but this is not a regular practice. Since it is a structural building component, it is important that its quality is good and companies will not be worried about the risks for reuse. In chapter 3 *Reuse of a structural building component: hollow-core slab floor component* the current situation of the reuse of HCS components is described. This chapter will show how to assess the potential for the reuse of an HCS component. Many different aspects are involved in the reuse of structural building components. From a circular economy point of view, the potential of reuse components is that it can lower the environmental impact and also the economic impact. However, there are methods to measure the environmental and economic impact, but these methods are not creating some trust compared to the quality potential to reuse structural building components. Hence, there should be developed a decision support model to assess the reuse potential of the HCS components.

Therefore, more information is needed about the current methods and knowledge about assessing the potential of reuse of these components. So, the following key question will be answered in this chapter:

Which methods, tools and knowledge are currently available to be able to assess the reuse potential of hollow-core slab floor components?

To assess the potential of reuse of the HCS components, it is necessary to investigate the background information of the reuse potential and the related aspects. Therefore, a definition of the reuse potential will be given first. Following on from this, some currently used methods related to calculating the environmental and economic impact of a component will be explained. Then, the process of reuse will be elaborated to provide insight into which steps are important when a component is reused. Afterward, all the factors that are needed to assess the reuse potential should be investigated. These factors can be used for the decision support model to assess the potential to reuse the HCS component from an existing building. Finally, the program of requirements for the assessment of the reuse potential will be described.

4.2 Definition of the reuse potential

The transition towards a circular economy is asking the current building industry to change their building process by reusing existing building components instead of using new building components. However, before reusing the existing building components, it is necessary to know whether the existing building components are still of good quality to be used for another lifetime. Therefore, the reuse potential of the existing building components has to be investigated.

According to Iacovidou and Purnell (2016), the reuse potential is "a *measure of the ability of a construction component to retain its functionality after the end of its primary life*". For every building component, it is difficult to define the reuse potential because it depends on many various factors. For example, the reuse potential for bricks depends on the time allowed for dismantling, the care taken that there will no damage and the materials used for binding (Iacovidou & Purnell, 2016). Also, it is important that the reused building component should have the same quality experience as new building components. The fact that reused building components are used for the new building project should not be an identification for lower quality, but it should instead provide added value (Economic Board Utrecht, 2018).

The quality of building component could become less, because of the changing requirements or damage during its primary lifespan. Also, the disassembly potential should be assessed to characterizes the quality of the building component. If the component of a building does not have a disassembly potential, this component cannot be dissembled without damage and therefore the quality of the building component will be less. So, in order to be able to determine the reuse potential of this building component, it is necessary to assess the quality of the existing building component; the higher the quality potential, the higher the reuse potential (Durmisevic et al., 2017).

Sometimes, the reuse of existing building components requires many adjustments to upgrade its quality, but this requires extra economic costs. There is tension between sustainability, price, and quality. Reuse of components after modification is not necessarily cheaper than purchasing new building components. It has also an effect on the environment due to the extra energy use and the extra pollution caused by the modification. Still, the quality of an existing building component should meet the quality requirements of a new element (Economic Board Utrecht, 2018).

To conclude, the reuse potential depends on the quality potential of the building component after the end of its primary life. The quality should be in balance with the price and sustainability of the building component. Therefore, the environmental and economic impact should be acceptable for the use of a new building component. So, three main factors should be in balance for the assessment of the reuse potential, see also figure 16:

- *Quality potential factor*, the quality of the existing building component should meet the requirements of a new building component.
- *Environmental impact factor*, the effect on the environment should be less, also after modification of the existing building component to upgrade the quality.
- *Economic impact factor*, the financial effect should be in balance with the costs of a new building component.

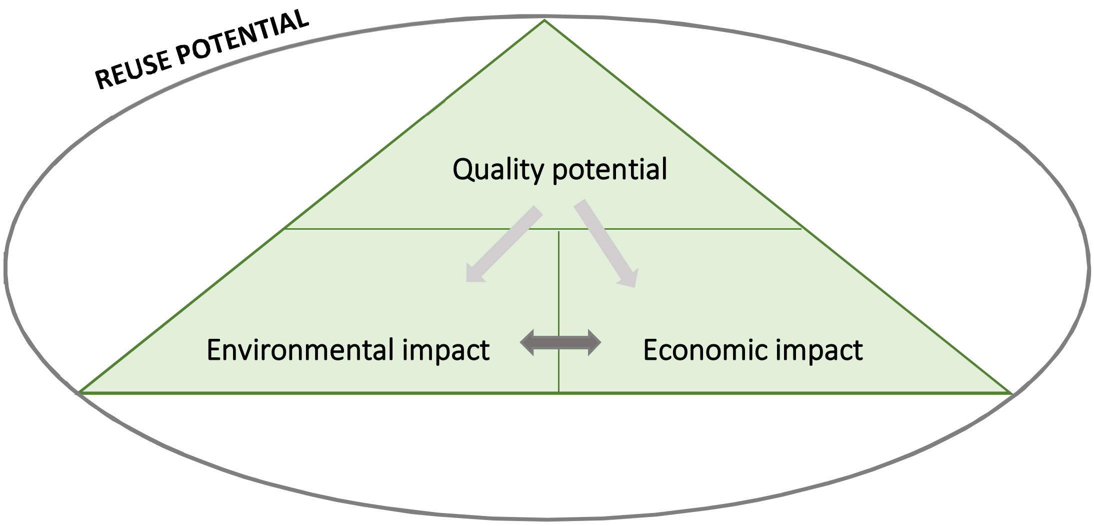


Figure 16. Three factors that have an effect on the reuse potential of the existing building component.

4.2.1 Measuring the reuse potential factor of a building component

A high reuse potential means that the reuse of the component is done in an environmentally friendly and cost-effective way. For assessing the reuse potential it is also important to analyse the function and characteristics (e.g. dimensions, load capacity, etc.) of the reused component, and then evaluate the "costs" – environmental and economic – of the treatment required for the reuse (e.g. painting, cleaning, testing etc.) transportation and construction (Iacovidou & Purnell, 2016). Therefore, the reuse potential can be determined based on two steps:

- **Reuse analysis**: this refers to the *qualification* of the required function and characteristics for the reused component and whether the required function and characteristics are met. It could be possible that some functions or characteristics are affected during the first life-cycle of the component. This will have to be treated before the element can be reused.

- **Reuse evaluation**: this refers to the *quantification* of the environmental and economic impact of the whole process of the reused component. If the element has to be treated to meet the required function and characteristics, this has consequences for the 'costs'. The 'costs' are expressed in environmental costs and economic costs.

After the evaluation of the different costs for the reuse of the component, it is possible to indicate the reuse potential. The 'reuse potential factor' could help to assist decision-making to manage waste as resources. The factor is based on creating value, waste moves around different 'regimes of value' by gaining and losing value. A low reuse potential can arise because the component contains a large amount of damage that is costly to be removed. By measuring the environmental and economic impact due to reusing the component and compare it with the value of a new component, the reuse potential factor expresses the usefulness of the component by a real value between 0 and 1, see figure 17. The component is discarded if it equals 0 and the component can be definitely reused if it equals 1 (Park & Chertow, 2014).

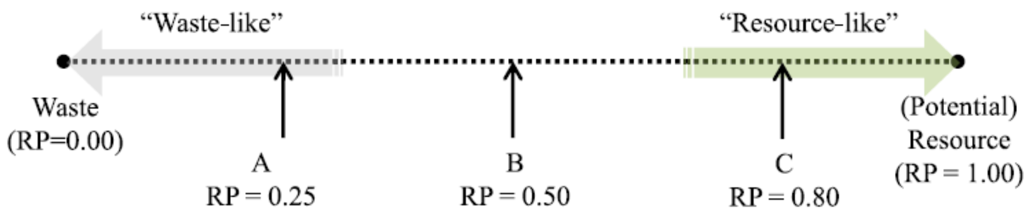


Figure 17. The value of the reuse potential from waste-like to resource-like (Park & Chertow, 2014).

4.2.2 Reuse potential factor determined by existing models for the building industry

As mentioned before by Iacovidou & Purnell (2016), a system for better decision-making for the reuse of components is required whereby efficient tracking and archiving to provide information relevant to the environmental and economic savings is important. There is a lack of qualitative and quantitative information restricts to demonstrate the real advantages of the reuse of building components. Research should better highlight the economic, environmental, technical and social benefits of reuse and, therefore, designers and contractors would be enabled to get a better understanding of deconstruction and reuse (Iacovidou & Purnell, 2016). There are already some models or methods that are used to determine the reuse potential to facilitate the decision process.

For example, the ARP-model of Langston *et al.* that is developed in 2008. It is a model to identify and rank the adaptive reuse potential in existing buildings. It is an intervention strategy to ensure the optimization of social value and future redundancy is planned. The model requires an estimation in years of the expected physical life of the building and the current age of the building. Also, an assessment of physical, economic, functional, technological, social, legal and political obsolescence is required (Langston, 2012). According to Langston (2012), "the obsolescence is advanced as a suitable concept for the objectively reduce the expected physical life of a building to its expected useful life" (Langston, 2012). An index of the reuse potential (the ARP score) is calculated and expressed in a percentage, see appendix A.1. The model is based on a 'discount rate'. This is an annual rate based on the sum of the obsolescence factors. Therefore, buildings can be ranked according to the potential they offer for adaptive reuse at any time, see figure 18. Building with a high index has the highest reuse potential, while buildings with a low index have almost no reuse potential (Langston & Shen, 2010).

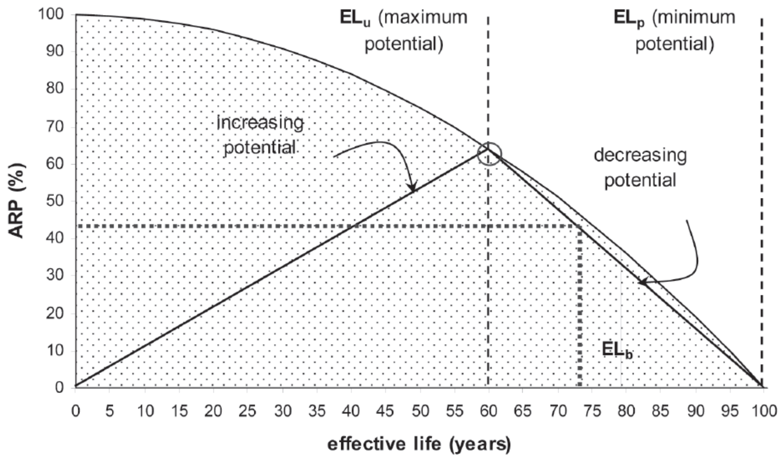


Figure 18. Concept of the ARP-model for measuring the reuse potential of existing buildings (Langston & Shen, 2010).

According to Iacovidou *et al.* (2018), there is also a model to track and trace information about construction components to boost the reuse of these components. The RFID technology – a wireless sensor technology operating that transmitted data via radio frequency signals – can communicate the designed physical and technical characteristics of a construction component throughout the lifecycle and their sustainability to be reused after the *n*-th life cycle. Based on the rich information streamed by the RFID, it has the potential to boost the reuse. Therefore, it can create multiple values like technical value, economic value, environmental value, and social value. So, the RFID technology can transform useful information about the components' characteristics, properties and performance into valuable knowledge compared to the lifecycle of the component (Iacovidou, Purnell, & Lim, 2018).

The ARP-model and the RFID technology are both focussed on collecting data about the building's or building component's properties or quality. The ARP-model can calculate the reuse potential of existing buildings based on the obsolescence factors but does not take into account the environmental and economic impact of the reuse of the existing buildings. The RFID collected data about the structural building component and create value. However, in this case the reuse of the components is only based on the data and no consideration is given to the amount of impact it could have on the environment and economy. It is already assumed that economic and environmental value is created through reuse. However, it is important to not only look at the quality but also quantify the impact on the environment and economy to mention the sustainability and reusability of a component.

4.3 Existing methods and tools for the quantification of the life-cycle of a component

In a circular economy, they are not only focused on the environmental aspects, but also on the business aspects of the required transition (Scheepens, Vogtländer, & Brezet, 2016). The quality of components during its life-cycle in terms of environmental impact and economic impact is a strategy to mention the sustainability of a component. This indicates that the environmental and economic impact should be in balance for reusing a component compared to the market value of a new component.

Different methods based on the life cycles of a building are based on the prediction of when a building component deteriorates to a moment where intervention is needed, and what the environmental impacts and economic costs of each intervention are (Durmisevic, 2006). For the calculation of the quantitative data as the environmental and economic impact, some existing tools can be used. The assessment method Life Cycle Assessment (LCA) has been developed to assess the environmental effects of building materials and components to determine to what extent one or another choice contributes to an improvement of the environmental impact (van den Dobbelsteen & Alberts, 2001). The economic dimension is based on the Life Cycle Costing (LCC) method, the assessment of all costs associated with the life cycle of the building materials/components (Petrillo et al., 2016). Therefore, the key to a sustainable way of reusing components – according to the circular economy - is a life cycle approach that integrates the requirements for efficient use of resources and market activities into the building life cycle phases (figure 19) (Durmisevic, 2006). A balance between the economic and environmental dimension is required, this is explained by the current Eco-cost value (EVR) model (Scheepens et al., 2016).

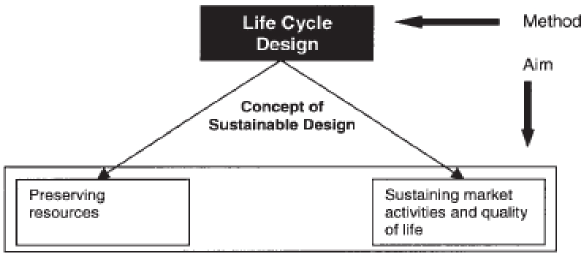


Figure 19. A sustainable way of reusing is the combination of limit the environmental impact as well as the economic impact (Durmisevic, 2006).

To determine if a building component can be reused in a sustainable way, it is necessary to investigate the economic and environmental impact. The current methods describe the basis of the measurement of the environmental and economic impact. Therefore the current LCA and LCC method is described and the EVR model is expressed in this section.

4.3.1 Life Cycle Assessment analysis

The Life Cycle Assessment (LCA) is a scientific tool to analyse the entire scope of the environmental impacts of a product, process or activity, from the extraction of raw materials, manufacturing and operational phase to the final disposal of the material (Guinée, 2002). The main goals for using the LCA are the identification of the environmental contribution in the different life cycle stages of the product and the life cycle stage contributing most of the total environmental impact. The collected information of the LCA is used for defining an Environmental Product Declaration (EPD) of a product and to compare the environmental performance of products with similar functionality (Jonkers, 2018). According to the ISO 14040 standard (2006), the definition of the life cycle assessment is "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of product system throughout its life cycle*". The LCA is divided into four phases according to the ISO 14040 (2006):

1. **Goal and scope definition**: defines the initial choices made for the outline of the entire LCA. The definition of the goal gives an explanation about the reason for the assessment, the intended application, and the audience. The scope comprises the definition of the functional unit, the system boundaries, the number and types of environmental impact categories, and the allocation procedures. The functional unit is important as it defines the performance characteristics of a product and is therefore important for the comparison between products. The system boundaries define which processes and product-related materials and equipment will be included, as well as the life cycle stages to be included (Jonkers, 2018).

2. **Life Cycle Inventory (LCI) analysis**: represents quantification of the environmental relevant inputs and outputs in all of the life cycle stages.

   The relevant in- and outputs of the involved life cycle stages are listed and drawn in a process flow diagram. The life cycle stages considered in an LCA study are production stage (A 1-3), construction stage (A 4-5), use stage (B 1-7) and end-of-life stage (C 1-4), including transportation for each stage (see figure 20). Also, category D can be included in case the product still has value at the end of the functional service life. This category gives information about the reuse, recovery or recycling of the product (Jonkers, 2018).

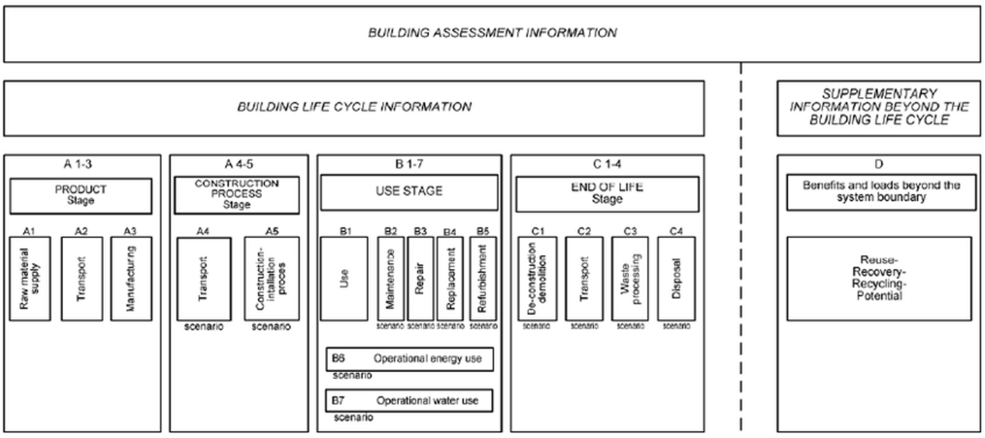


Figure 20. The life cycle stages EPD (ISO 14040,2006).

3. **Life Cycle Impact Assessment (LCIA)**: assigns the collected data of the inventory table to the environmental impact.

   The LCI data is assigned to a number of chosen environmental impact categories and indicators, see table 1. The environmental effects of the required raw materials including the energy as the input and the occurring emissions as the output of the products in all the life phases are estimated. The environmental value is calculated per environmental impact category and is expresses in a category indicator result. The category indicator results of the chosen impact categories can be represented as the environmental profile of the product In the Netherlands, the environmental data of materials, products, and processes are included in the 'Nationale Milieu Database (NMD)', managed by the 'Stichting Bouwkwaliteit – SBK' (Jonkers, 2018).

Impact Category	Description of Impacts
Global Warming	Contributes to atmospheric absorption of infrared radiation
Acidification	Contributes to acid deposition
Eutrophication	Provision of nutrients contributes to biological oxygen demand
Photochemical Oxidant Formation	Contributes to photochemical smog
Aquatic/Terrestrial Ecotoxicity	Contributes to conditions toxic to flora and fauna
Human Toxicty	Contributes to conditions toxic to humans
Energy Use	Contributes to depletion of non-renewable energy resources
Abiotic Resource Use	Contributes to depletion of non-renewable resources
Biotic Resource Use	Contributes to depletion of renewable resources
Ozone Depletion	Contributes to depletion of stratospheric ozone

Table 1. The environmental impact categories commonly used in the LCA method (Pelletier et al., 2007).

4. **Interpretation**: evaluates the results of the environmental impacts obtained in the LCI and LCIA phases.

   This last phase describes a discussion about the results obtained in the LCI and LCIA. Also, possible limitations and sensitivity of the methods should be discussed and conclusions and recommendations are also included (Jonkers, 2018).

So, the LCA could help to make an environmentally conscious choice of building materials/components by comparing the environmentally score relative to each other (van den Dobbelsteen & Alberts, 2001).

The calculation of the LCA of a building will make it possible to make more informed decisions and achieve real sustainability (Bruce-Hyrkäs, n.d.). To classify the environmental impact categories into one indicator, the environmental cost indicator (in Dutch: Milieu Kosten Indicator - MKI) is used in the Netherlands. With this indicator, the various environmental impact categories are weighed against each other and translated into a number that reflects the social costs for these impacts in euros [€] (for the region or Europe) (Kok & Damman, 2018). The environmental costs are also associated with the terms shadow price or prevention costs. The shadow price of emission is determined by the costs of the last measure needed to achieve an emission target. This price reflects the costs that society wants to pay for it to achieve the target. The prevention costs are the costs of preventive measures that can prevent a certain environmental impact. The total environmental costs are created by adding up all the environmental costs of each environmental effect based on all the life cycle stages, see figure 21 (NIBE, 2019). The lower the MKI value, the lower the environmental impact (Scheepens et al., 2016).

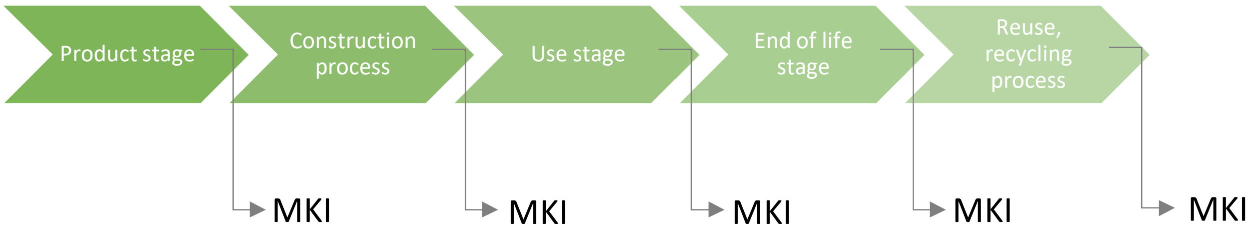


Figure 21. The building phases related to the total environmental costs; the environmental impact - LCA.

The environmental cost indicator is already measured for many different products and materials. In the Netherlands, the environmental impact data of building products and materials are provided by the National Environment Database (in Dutch: Nationale MilieuDatabase – NMD) (Schut & Leeuwen, 2018). The NMD is a universal database with the environmentally relevant performance information – environmental profile – of products used in the building industry. The database concerns LCA environmental data that is translated into an environmental product declaration. This data is supplied by the building industry. The database should be checked on the actuality from time to time and then adjusted if necessary (SBK, 2019). The European standard EN-15084 describes the rules for the preparation of environmental product declarations. The NMD has been developed for the controllability of the environmental data declared by the producer and its clarity in its use (Stichting Bouwkwaliteit, 2014).

However, the NMD is only based on the building materials or processes and has not yet incorporated building components into the system. NIBE (2019) has already developed, before the NMD existed, a database that provides information about the environmental and health properties of building components, such as HCS components. This database is called the environmental classification database and based on the TWIN2011-model of NIBE. The advantage of the model is that not only the qualitative data are coped but also the less quantitative data to allow for a broader assessment (Naber, 2012).

4.3.1.1 Life cycle stage for the circular economy - Module D: Reuse / Recovery / Recycling potential

The building industry should be thinking about the circular economy to comply with Dutch policies. According to Gervasio & Dimova (2018), "to comply with European policies related to the efficient use of resources and waste production, the reuse and recycling of the material resulting from any construction and demolition activities are crucial aspects in the life cycle analysis of buildings" (Gervasio & Dimova, 2018). The LCA-method includes already a life cycle stage for the reuse and recycling of components and materials; *module D*. This life cycle stage is based on evaluating the benefits or burdens resulting from potential future reuse of components of the building which are otherwise disposed of as waste (Lowres & Hobbs, 2017). In case secondary materials are created during the life cycle process, credits should be allocated in this module D due to the recycling or reusing processes between the primary life cycle and the secondary life cycle. Therefore, if building products are designed for reuse or recycling, the life cycle analysis of buildings has a positive result with respect to the environmental impact (Gervasio & Dimova, 2018).

So, the advantage of a reused building component is no waste production at the end of the first lifecycle. Therefore, the credits can be allocated in module D of the first lifecycle of the component. For the second lifecycle of the component, the production stage can be skipped and the component no longer needs to be produced compared to a new building component. Therefore, no energy is needed for the production process and there are no emissions of harmful substances for the environment. The building component can be used directly in the construction stage with an MKI-value of zero [MKI ≈ 0] (see figure 22) unless adjustments have to be made to the component that requires energy and causes emissions.

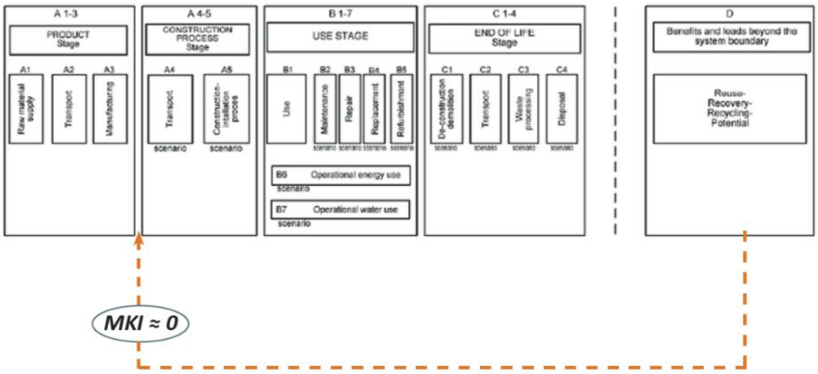


Figure 22. Module D of LCA for a circular approach with less environmental impact.

Despite the LCA and module D within it, there is currently no complete comparability in the calculation of the environmental impacts of reused components with each other and with 'virgin' materials. The main underlying cause is that an exact formula for allocating and quantifying the environmental impacts and benefits for recycling and reuse among the various links in the production process (e.g. reprocessing, application, etc.) has not yet been established within module D (Levels-Vermeer, van Ewijk, Scheepmaker, & de Vries, 2015). It is necessary to determine more about, for example, the disassembly of a product in order to be able to know the extra energy or materials are needed to reuse it (Schut & van Leeuwen, 2018). Better comparability of primary and secondary materials and components from the construction sector will ensure greater acceptance of environmental performance and sustainable use of circular products (Levels-Vermeer et al, 2015).

4.3.2 Life Cycle Cost analysis

The Life Cycle Costing (LCC) is the process to assess the life cycle of a product based on economic analysis (Petrillo et al., 2016). It summarizes all costs incurred by the owner of the product during the entire life cycle of that product (Kloepffer, 2008). The purpose of life cycle costing is to help by making the decision on the exploitation, rehabilitation, and disposal of assets. It is an instrument for realizing value from assets. LCC is important for obtaining a long-term and healthy balance between the performances of the asset, risks, and costs (van den Boomen, Schoenmaker, Verlaan, & Wolfert, 2017). According to Van den Boomen, Schoenmaker, Verlaan & Wolfert (2017), the objectives of an LCC are:

- The identification of major cost drivers;
- The evaluation of the economic viability of the investments;
- The comparison of alternatives;
- The financial planning of the long-term.

LCC includes all costs involved in the life cycle of a product; purchase, use, maintenance, and disposal. Therefore the costs for the design, development, manufacture, maintenance, replacement, demolition, disposal, etc. are included. The aim of LCC is to minimize the costs of the life cycle without affecting the inherent properties of the object. LCC can be described as follows (Coorens, 2001):

LCC = (L + O + M + A) * P + I + RD

L = cost of production

O = operational costs

M = maintenance costs

A= demolition and disposal costs

P = factor for the net present value during the lifetime of the building, including interest and inflation.

I = investment costs

RD = cost of research, development, and design

LCC gives insight into the total costs and cost structure and is expressed in euros [€] (for the region of Europe). LCC is a tool to make strategic decisions not only for purchasing but also when managing and reducing costs during the lifetime of the product, component or material (Coorens, 2001). It is a useful method complement to LCA because sustainable products should be profitable and not unreasonably expensive. However, decisions by consumers are often based on the price of a product but LCC will help to make a better decision towards the needs of future generations. LCC is useful for stand-alone assessment, but also the complementation of LCA is important (Kloepffer, 2008).

The life cycle costs of building components are the costs throughout its life cycle while fulfilling the performance requirements. Generally, the cost is divided into the cost for construction (design and engineering), operation, maintenance and end-of-life (demolition and disposal). The life cycle costing methodologies are used to compare new design and redesign alternatives (Straub, 2015).

LCC relies on predicting the building components when it will deteriorate to a level where intervention is needed, and what the cost will be for each intervention. LCC calculations depend on several assumptions, and therefore it is all subject to a degree of uncertainty. It is an estimation of the cost of a certain building component during its life-cycle (Clift, 2003). Every building phase is related to the costs incurred during the specific phase. The sum of all these costs together determines the total costs related to the life cycle of the building component. See figure 23 for the relation of the costs and the building phases. The costs depend also on the lifespan of a building component. The longer a component lasts, the higher the cost of the component because the element does have to be upgraded to continue to satisfy. Talking about the costs, it is important that the benefits are always higher than the costs. As soon as this changes, it makes no sense to continue using the component.

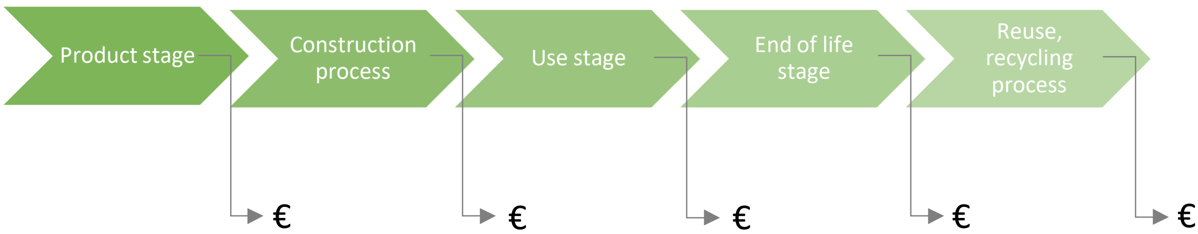


Figure 23. The building phases related to the total economic costs; the economic impact - LCC.

4.3.3 Limitations of the LCA and LCC

The LCA and LCC are two separate analyses to express the value of a product in two different ways; environmental perspective and economic perspective. The LCA is an important tool for assessing a circular economy because it is related to the impact of products on the environment. On the other hand, the LCC is also an important analysis for showing the economic impact of products. The reuse, recycling and recovery of products in a circular economy should be profitable and harmless for the environment. However, the LCA only focuses on the environmental issue and not on the economic issue. The eleven mentioned impact categories are all measurable and quantifiable and express in environmental costs, but not related to economics. By way of contrast, the LCC only focuses on the economic issue. The use and reuse of a product are only analysed from an economic point of view.

According to Norris (n.d.), the question is; "why have economic analysis not yet been well-addressed by LCA?" The possible reason is that the two analyses, Life Cycle Cost analysis (LCC) and Life Cycle Assessment analysis (LCA), have a lot of methodological differences. Both analyses provide answers to very different questions. The LCA evaluates the relative environmental performance of products that accomplish the same end-use function, from abroad, societal perspective. The LCC evaluates the relative cost-effectiveness of investments, from the perspective of an economic decision-maker. The different purpose of the analysis leads to a different scope and method (Norris, n.d.).

The separation of the life cycle environmental assessment from the economic analysis has at least three consequences. First, the separation has limited the relevance and influence of the LCA for decision making. A company cannot afford to make decisions only based on the LCA analysis, without concerning the economics, performances, etc. Even in the scenario where the environmental performance is the only objective for the selection decision, economics should be part of the analysis because there are only limited resources to reach this objective. Second, the important trade-offs and relations between economic and life cycle environmental performance of decision scenarios are uncharacterized due to the separation. At least, the economic relevance for companies can be influenced by the results and perspective of the LCA, which are missed when the economic analysis is neglected (Norris, n.d.).

So, it is important to fully bridging the gap between the LCA and LCC analysis. Especially to qualified the reuse potential of a building component based on both the environmental perspective as the economic perspective, it is necessary to combine both analyses. A combined analysis can be based on an existing model, the Eco-cost value ratio (EVR) model.

4.3.3.1 Eco-cost value ratio (EVR) model

The Eco-cost value ratio (EVR) is a model to analyse the environmental problem compared to the value of the product. To select the best solution for sustainability to achieve the circular economy ambition, the issue is to create maximum value for the end-user at a minimum environmental impact (Vogtländer, 2010). At the end-of-use of a building component, the components have a negative market value (price). The activities to reuse these components in an environmentally correct manner have a positive added value for society. Therefore, the 'value' of components in the end-of-use stage should be determined. The value is related to the market price and environmental impact costs (Vogtländer, Brezet, & Hendriks, 2001).

The basic idea of the EVR model is to link the 'value chain' to the ecological 'product chain', see figure 24. The added value (in terms of price) is determined for each phase of the building life cycle and based on the costs calculated by the LCC. Similarly, the ecological impact of each phase is also expressed in terms of money, the eco-costs or the MKI of the LCA (Vogtländer et al., 2001). The aim is to compare two products and concluded which one is more sustainable. There is a misunderstanding that the product with the lowest eco-costs is the best choice in terms of sustainability. If the eco-costs and costs are lower for the new product and the quality is better, it can be concluded that the new product is more sustainable. However, if the eco-costs or costs are higher or the quality is lower, it is important to make a proper assessment of which product is better to choose in terms of sustainability (Vogtländer, 2010).

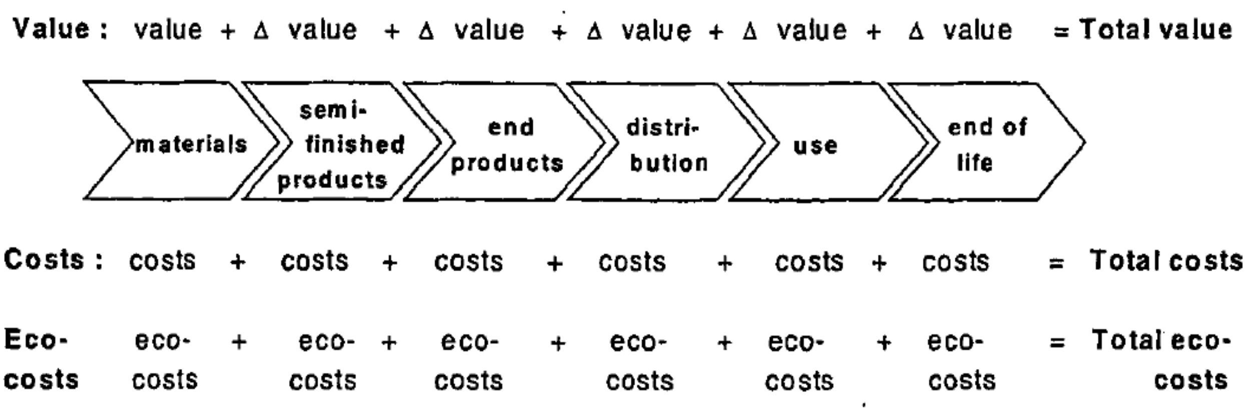


Figure 24. The basic concept of combining the economic and environmental chain - EVR model (Vogtländer et al., 2001).

Finally, the value of an existing building component - for this research, the HCS component - should be weighed against the combination of the economic and environmental impact to give a realistic outcome of the value of the product against the 'costs'.

4.4 The reuse process for determining the reuse potential factor

The reuse of structural building components fits very well with the aim of closing the material cycle and reducing CO_2 emissions. The reuse of structural building components prevents waste from being released and requires less energy than recycling. In order to reuse structural building components, it is important to know whether the building component can still meet the requirements set for the component when it is reused in a new building project. Therefore, the process of reuse is necessary to be elaborated for knowing all the effects that could influence the potential to reuse the component.

According to the research of Glias,(2013), the process of reuse can be divided into a number of steps (Glias, 2013):

1. *Inventory*. This is the start of the process of reusing components. The inventory should provide an overview of the properties of the various structural components of a building. An inventory can be done by inspection of original drawings and calculation sheets. The properties of the structural building component have to be defined. If there are no building drawings or calculation sheets, visual inspection has to be done. Therefore, a destructive test will have to be done to be able to collect all data from the element. One of the elements in the building can be used for the destructive test, in order to determine the properties for the other building components that performed the same function as the tested component. However, this does result in additional costs.

   Due to changes during the construction process, the structural building components might have different properties then the properties are mentioned in the original drawings. So, it is always important to do a visual inspection to check whether what is on the drawings actually matches the reality. And therefore, a complete overview of the properties is identified. This can be done by a specialist.

2. *Quality check*. The condition of the structural building component is investigated during the quality check. This quality check is preferred to take place when there is the intention to deconstruct the building. When the building can no longer fulfill its function, it is demolished or the building becomes vacant. At that time, it may still be that the lifetime of the component in terms of technical and aesthetic is still good.

   So, it is important to reassure that the components are safe to be used for more years and fulfill the required performances and requirements to be reused. The quality check is to reassure the possibility to reuse the component by indicating that the component complies with the performances and requirements for the new building project or needs some specific upgrades.

3. *Deconstruction process.* The deconstruction process should be carried out very carefully in order to recover as many elements as possible with the highest possible quality and as little damage as possible. In order to characterize the building as suitable for deconstruction, it must have a sufficient number of reusable components. The economic costs can be high for the deconstruction of a building. Good planning is needed and as many components as possible have to be reused.

   The deconstruction process is not affected by the size, weight or volume of the component, but it is affected by the number of components and the connections of the components. The more reusable components exist in the building, the less will be the deconstruction costs per component. Moreover, the connections are most important for determining the economic costs because one type of connection makes it easier to remove the component from the building than the other type of connection. And if connections should be destroyed to remove the component from the existing building structure, then new connections have to be created.

4. *Modification process.* The structural building components has to be adapted in order to be able to reuse these components in a new building. This concerns, for example, filling up the old recesses, cutting the element to the requested length, drilling new recesses, etc. The aim is to use components with less modification as possible. In order to achieve the maximum reuse of components with less modification, the performances of the existing component should meet the required requirements and performances for the new building structure. The architect and the engineer have to work closely together from the beginning of the design of the new building project to consider the use of the existing building components.

   It could be hard to reuse the existing building components without modifications to the component. The best moment to modify the components is during the removal of the building. However, sometimes the new project is not yet known and therefore the dimensions, performances and requirements are unclear. At that moment, the component should meet the highest requirements and performance so that it can be applied in any building. This will result in additional modification and the maximum economic and environmental costs for the modification.

5. *Storage.* If a structural building component cannot be constructed immediately in the new building project, it will first have to be stored at a storage site or to leave the existing building standing and use it as “virtual” storage – an existing empty building stored with the components to be reused. The storage site has the advantage of more flexibility, fixed costs and a better quality risk while the “virtual” storage is better in terms of the environmental impact, solutions, transportation costs and modification costs. However, from an economic point of view, the

fixed costs of an empty building are more than the extra transportation costs and the modification costs of a storage site. On the other hand, from an environmental point of view, fewer emissions are emitted due to the transportation of the components straight to the new construction site.

For the transition towards a circular economy, a market of reused components can be created to achieve the goal of closing the material cycle (see also *3.5.1 A new way of designing by using the material bank*). In this situation, buildings will be deconstructed and the reused components will be stored in a storage site. Then, the storage site can be seen as an outlet for the reused components. Currently, this transition has not yet taken place, but it can be a future solution.

6. *Transportation.* The structural building components to be reused have to be transported from the current location of the building component to the location of the new building, or from the current location to the storage location and from the storage location to the location of the new building. Also, eventually waste production should be transported to the recycling plant. Transport could have a great environmental impact within the process of reuse and determines a large part of the total cost price. Therefore, it is important to organize the transportation process as efficiently as possible in order to minimize costs and CO_2 emissions.

7. *Construction process*. This phase is the last phase of the reuse process. The use of reused components for the construction process has to be the same when building with new components. Finally, the structural building components are assembled in the new building project. It is important to bring the components to the new construction site as prefabricated components so that they are ready for reuse and immediately suitable for assembly as prefabricated components.

The steps in the process of reuse are set up in chronological order by Glias (2013). However, one more step that applies to the process of reuse is missing. A component that has been assessed to be able to use for the second lifetime should also be assessed whether additional maintenance is required.

8. *Maintenance*. A structural building component from an existing building can be affected by external influences. These influences can have an effect on the condition of the component. The more deterioration caused by these influences, the more maintenance is required for the component. It is better to have less maintenance because it costs less from both an economic and an environmental point of view.

For all the steps in the process of reuse, it is necessary to make a proper assessment of the economic and environmental impact of each step. Every step influences the economic and environmental costs. Therefore, the environmental and economic costs should be quantified during the whole process of reuse.

Figure 25 illustrated all the steps of the process of reuse. The combination of the economic impact, environmental impact and the steps of the process of reuse can conclude about the potential to reuse an existing structural building component.

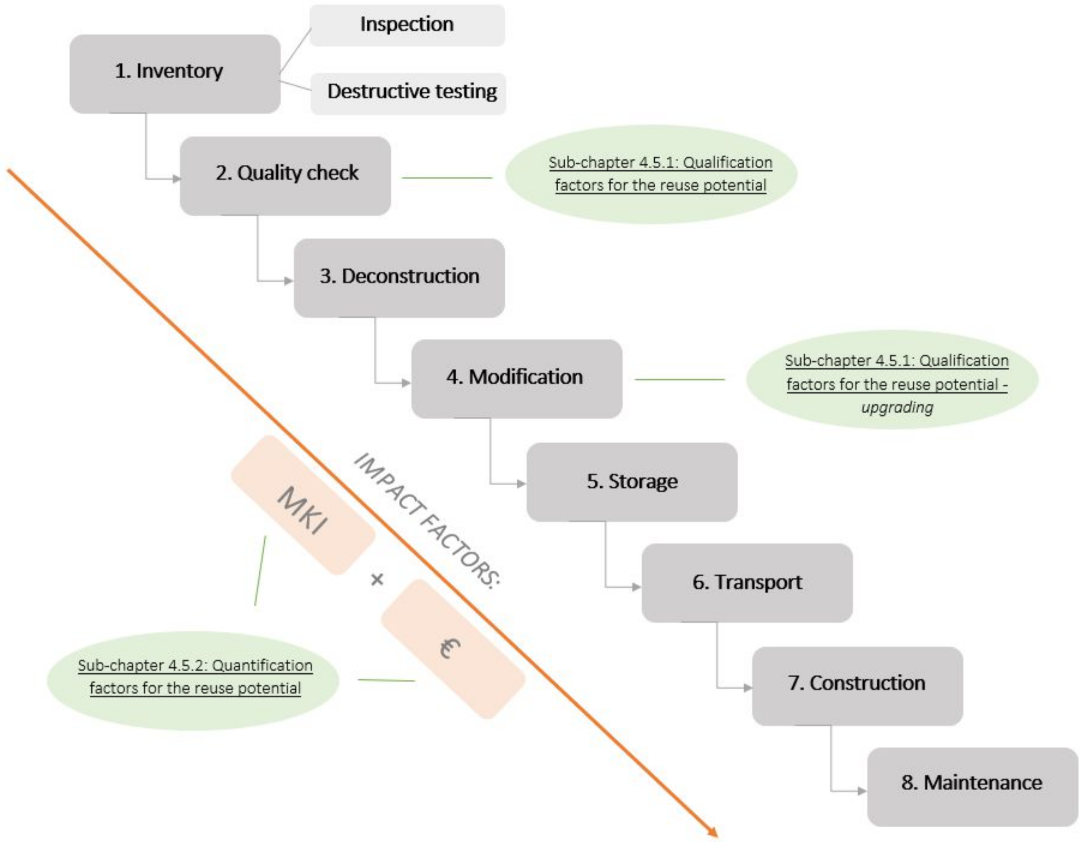


Figure 25. The diagram of the reuse process and the relation with the next sub-chapters.

In this research, it is assumed that the new building project with the required dimensions, performances and requirements is already known. Good cooperation between demolishing the existing buildings and designing the new buildings is important to be able to determine whether the existing component can be reused for the new building. The moment there is more market for reusing the existing components, it is also possible to look at creating a store where all various secondary HCS components can be sold.

4.5 Factors to be measured related to the reuse potential

Research has shown that there are challenges of affecting the reuse potential of building elements: the mismatch between quantity and quality – the data of the quality of the building component compared to the economic and environmental impact –, the market is not convinced to reuse – reluctance to use products without certification of tested performance and environmental impact is a barrier to reuse – and the value of a building component can be a barrier or an opportunity (Hobbs & Adams, 2017). The current methods, models and tools are either not focused on assessing reusability on quantitative values such as economic and environmental costs – ARP-model and RFID technology – or they can assess quantitative values but not yet for the reuse of components – LCA and LCC. Therefore, a new model based on the concepts of these current models, methods, and tools should be developed for calculating the reuse potential.

As mentioned before (see paragraph 4.2 D*efinition of the reuse potential*), the assessment of the reuse potential factor is based on three main factors; quality potential factor, environmental impact factor, and economic impact factor. These factors should be assessed separately from each other to see if they do not reach the limit indicated (Durmisevic, 2006). The limit, in this case, means that the quality should reach the level of the required quality for the new building project and the 'costs' (economic and environmental) should not be higher than the costs for creating new building components.

Each factor that plays a role in the reuse of the building components is linked to the effect – the reuse potential - and to each of the other factors. This is a 'circular process' or a 'feedback loop'. One loop will dominate and the other loops will then take over (Durmisevic, 2006). Figure 26 shows that the qualification factors are the first loops to be tested. If all the qualification factors meet the requirements and do not reach the limit, the reuse of the building component for the new building project is possible – 'reuse loop'. However, the last two loops of the quantification factors – environmental and economic system – has an influence on the 'reuse loop'. If the environmental system or economic system reaches the limit, it is possible that the reuse of the building component is not feasible.

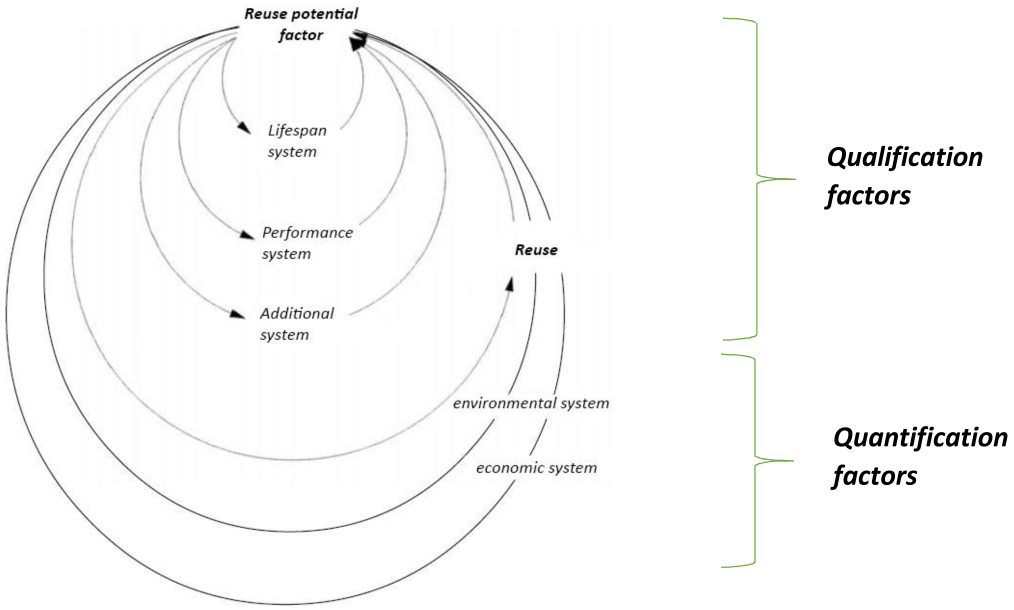


Figure 26. A feedback loop of the relations between the qualification and quantification factors and the reuse potential factor.

So, according to the reuse of the HCS components, the critical factors related to the quality and quantity needed to be determined for testing the reuse potential factor. The related qualification factors and quantification factors will be elaborated in the next two sub-paragraphs.

4.5.1 Qualification factors for the reuse potential

A range of factors governs to some extent the potential of structural building components to be reused. To assess the reuse potential factor of the HCS component, the first step to do is *the reuse analysis* (see paragraph *4.2.1 measuring the reuse potential factor of a building component*). This is about testing the reusability of the floor components based on *qualification factors*.

According to Iacovidou and Purnell (2016), the qualification factors are including the type and quality of the components, its durability, function, fatigue loading, and projected lifetime, and the construction and demolition methods used. One of the main factors is the lifetime of the construction component because the lifetime provides knowledge about the way this component can be reused – for a long period or a short period depending on the lifetime of its primary lifespan. A fundamental factor in determining the component's reuse potential is the technical feasibility, but also the functional feasibility of the component (Iacovidou & Purnell, 2016).

Therefore, the qualification factors are divided into three systems (see also figure 26):

- Lifespan system; each building component has its own lifespan - the period a building component can fulfill the required performance. If the reused building component still has a long remaining lifespan for a second lifetime, the reuse potential will become a positive factor.

- Performance system; the building component should meet different performance requirements before it can be used in the new building project.
- Additional processes system; there are also requirements not related to the performances that should be met. These additional requirements can be related to the maintenance, storage possibilities, transportation process etcetera.

These three qualification systems are explained below in the three sub-paragraphs.

4.5.1.1 Lifespan system of the reused component

Buildings are functional products with a certain performance. The performance should meet the requirements prepared in advance. On the moment a building is taken into use, the performance of the building will continuously change over time due to the influence of use, maintenance, climate and the quality of the building. The performance changes should be transparent and efforts should be made to keep the building in shape and to meet the established requirements. The building owners and users will agree about the minimum performance a building component has to deliver during a certain period related to the requirements, see figure 27 (Hermans, 1999).

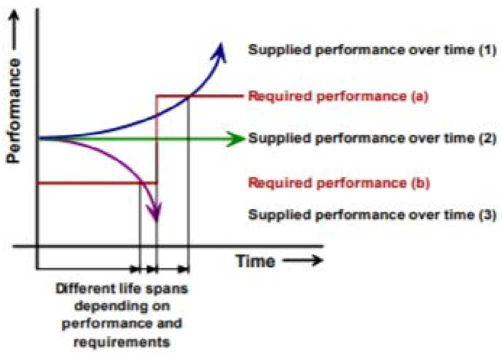


Figure 27. Lifespan vs performance and requirements of a building component (Hermans, 1999).

According to Polder (2012), the lifespan of a construction is the period in which it functions safely and reliably. The duration of the lifespan of a building depends on various factors, like the technical and functional obsolescence, economic circumstances and expectations and requirements. Therefore, the lifespan can be subdivided into four different types of the lifespan – the technical lifespan, the functional lifespan, the and aesthetical lifespan, and the economic life span (Paesschen, 2011). The economic lifespan is excluded in this research because the economic value is only to reflect and communicate about the urgency of different materials and is time depending (Verberne, 2016). For the reuse of components, the remaining lifespan should be determined. The remaining lifespan of the HCS component for a second lifecycle can be determined by calculating the difference between the technical lifespan of this component and the functional or aesthetical lifespan of the existing building. If the technical lifespan has a longer time duration than the functional or aesthetical lifespan of the existing building, the component can be reused in a new construction project with a certain remaining lifespan.

However, degradation mechanisms can lower the remaining lifespan. The function of the component is based on the *use of the element*, *the material from which it is made* and the *environment that affects it*. The degradation mechanisms affect the functioning of the component and these mechanisms should be carefully investigated before it causes aging and damage. Therefore, the timeframe or period that is indicated when talking about the remaining lifespan has to do with the fact that degradation can occur (Polder, 2011).

The three different types of lifespan and the possible degradation should be investigated for the assessment of the reuse potential factor (see figure 28). See appendix A.2 for more information about these different types of lifespan and the degradation mechanisms.

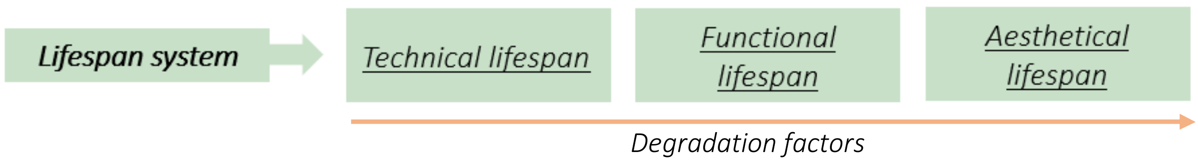


Figure 28. Lifespan system for measuring the reuse potential factor.

4.5.1.2 Performance system of the reused component

The opportunity for reuse of building components is the fact that building components have different life cycles and the durability of their functions is less long than the durability of the component itself. Therefore, the dominant issue for the decision to reuse the component is to know the specification of the building components. It is important to understand and evaluate the performance of the component to know the remaining quality the component still has. The performance requirements define the boundaries within the different performance levels of the existing building component are intended to operate (Durmisevic, 2006).

The reuse potential level of a component is related to the circular indicator that is expressed into values/performances. Whereby the goal is to minimize the virgin materials, to keep the materials infinite in the material cycle, and to lower the environmental impact (Verberne, 2016). Verberne (2016) indicates in his research three perspectives of dividing the value/performance:

1. *Technical value (performance)*: the value of technical information and technical solutions.
2. *Functional value (performance)*: the value of flexibility and adaptability.
3. *Aesthetical value (performance)*: the value of the impact on identity and image.

In this research, it is assumed that the circular indicator from the research of Verberne (2016) is related to the concept of the reuse potential. Therefore, the reuse potential factor is influenced by the technical, functional and aesthetical performances. Each performance has its own characteristics. For the HCS component, these three performances will be elaborated to know which requirements the floor component should meet in order to be reused.

1. **Technical performance**
   The reuse of building components is about the inspection to verify the technical performance and refabricate of the reused components to the requirements of the new project (Hobbs & Adams, 2017). A building element that is reused with a high quality of technical performance will cause less environmental impact than an element that needs to be changed for the next life cycle (Schut et al, 2015). The technical performance of an HCS component should be investigated before the floor component will be reused. Therefore, the constructor of the new building project will calculate if the existing floor component satisfies the requirements of the technical performances for the new building project.

2. **Functional performance**
   The possibility to reuse an HCS component also depends on the functional performance of the floor component. The functional performance is related to the physical properties of the building component. According to Naber (2012), these important properties concern *fire safety, sound insulation, block-outs in the floor components* and *the finishing of the ceiling of the floor component*. These properties of the reused HCS component should meet the requirements for the floor system of the new building construction. The requirements for a residential building are usually different from those of a non-residential building and primarily the function of the building creates other functional requirements. Due to the different requirements, sometimes adaptations are necessary before reusing an HCS component (Naber, 2012). The Dutch Building

Decree 2012 (Dutch: Bouwbesluit 2012) contains requirements with regard to the functional performance for various building functions. It is useful to know the requirements related to the new building function to check if the existing floor component properties can meet the new requirements or has to be adapted to meet these new requirements.

3. **Aesthetical performance**
   The aesthetics of an HCS component are also useful to criticize to estimate the reuse potential of the component. According to Glias (2013), the aesthetical performance is related to visual distress, deterioration, and damage. It can be investigated by means of a visual inspection of the structural components. The specific critical points of the existing structural floor component should be investigated and critical problems have to be located (Glias, 2013). If the floor component does have some damage or aesthetical issues, the component will not be reused before the aesthetical damages are resolved to be able to use the component for a second lifetime. Another aspect related to the aesthetical performances is the type of connections. The design of connections between components and the adjacent structure contributes to the increased or decreased disassembly possibilities. The interfaces define the degree of freedom between components. As a result, one type of connection will be easier to disassembly without causing much damage while the other type of connection causes a difficult process of disassembly where a lot of damage will be made to disconnect the floor components from each other and from the adjacent structure (Durmisevic, 2006). So, the aesthetics of the HCS components will be lowered if the disassembly process is difficult due to the type of connection. Hence, a visual inspection, before the component will be reused, could be helpful to notice if it could be possible to disassemble the component carefully without little damage as possible.

These performances of the component should be investigated for the assessment of the reuse potential factor (see figure 29). The performances influence the quality of the HCS component and all the performances should be tested if they meet the new requirements related to the new building construction. Appendix A.3-A.5 show more detailed information about these performances and gives also more information about the related requirements for different building functions.

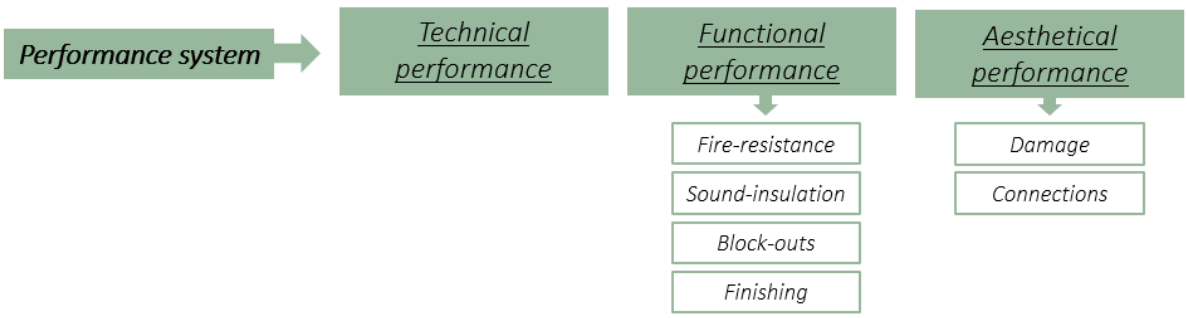


Figure 29. Performance system for measuring the reuse potential factor.

4.5.1.3 Additional processes system for the reused component

Before an HCS component could be reused, it is important that all the steps after the disassembly and modification process will not lower the reuse potential factor of the floor component. According to Glias (2013), and also described in paragraph 4.4 *The reuse process for determining the reuse potential factor*, the last steps of the reuse process are:

- Storage
- Transport
- Construction
- Maintenance

It should be investigated if these steps can influence the performance of the component and, therefore, the potential to reuse the HCS components. The components should be prepared for reassembly in the new construction, after which the component will be transported to the new construction site. It could be that the component cannot directly be used but will first have to be stored. The maintenance affects the 'additional' performance of the component because the risk and uncertainty of using the existing HCS component will be higher if more maintenance is needed in the second lifetime. So, the additional processes to be investigated for the assessment of the reuse potential factor are the *maintenance process*, the *reassembly process*, the *transportation process*, and the *storage process*. These processes can have an effect on the extra time and equipment that is needed for the reuse of the HCS components. The extra time and equipment can increase the environmental costs and economic costs. Therefore, it is useful to know the additional performance and to know what is extra needed for the reuse of the components.

The additional processes should be investigated for the assessment of the reuse potential factor (see figure 30). All these processes can provide an obstacle to reusing the HCS components. See appendix A.6 for more detailed information about the additional processes.

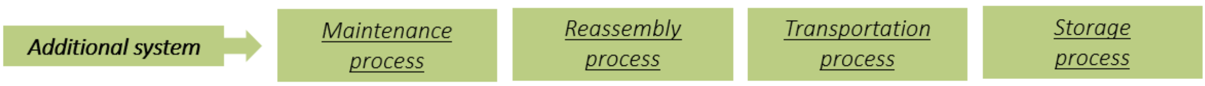


Figure 30. The additional processes system for measuring the reuse potential factor.

4.5.2 Quantification factors for the reuse potential

In addition to the qualification factors to be tested for investigating the quality of the HCS component compared to the requirements of the new building construction, it is also essential to assess the qualification factors. Therefore, the second step of measuring the reuse potential factor is *the reuse evaluation* (see paragraph *4.2.1 measuring the reuse potential of a building component*). This step is about calculating the 'costs' involved in reusing components. The 'costs' are expressed in environmental costs and economic costs. These are the *quantification factors* related to the environmental and economic impact of the reuse process of the floor components. It may be that the reuse process can become expensive - the economic impact - of the process can cause a lot of harmful emissions – the environmental impact – due to changes to improve the quality of the component.

During a decision-making process, the type of floor component is chosen based mostly on economic issues. However, the environmental indicator should also have a place in this process of decision-making by clearly evaluating the environmental consequences of a proposed activity before action is taken. According to Gilpin (1995), "the sustainable development depends on protecting the natural resources which are the foundation for further development" (Verberne, 2016);(Gilpin, 1995). For the reuse of HCS components, it would be relevant to balance both economic impact and the environmental impact.

4.5.2.1 Environmental impact factor

Sustainable building and achieving the goal of the circular economy means that the impact of the entire building process on the environment should be kept as limited as possible. According to Coelho & de Brito (2012), the concept of reuse does bring environmental benefits and has a positive effect on the impact. The purpose is to quantify the environmental effects of the reuse process against the environmental impact compared to the Life Cycle Analysis perspective (see paragraph *4.3.1 Life Cycle Assessment analysis*) (Coelho & De Brito, 2012). Therefore, the method of the LCA could be used for determining the environmental cost indicator. The environmental impact categories are expressed in equivalents and multiplied by the shadow price number per environmental impact category (€/unit), see table 2 (NIBE, 2019).

Impact category	Unit	Shadow prices (€/unit)
Global warming (GWP100)	kg CO2-eq.	0,05
Ozone layer depletion (ODP)	kg CFC-11-eq.	30
Human toxicity (HT)	kg 1,4-DB-eq.	0,09
Ecotoxicity, fresh water (FEATP)	kg 1,4-DB-eq.	0,03
Ecotoxicity, marine water (MAETP)	kg 1,4-DB-eq.	0,0001
Ecotoxicity, terrestrial (TETP)	kg 1,4-DB-eq.	0,06
Photochemical oxidation (POCP)	kg C2H4-eq.	2,00
Acidification (AP)	kg SO2-eq.	4,00
Eutrophication (EP)	kg PO4-3-eq.	9,00
Abiotic resource depletion	kg Sb-eq.	0,16
Biotic resource depletion	mbp	0,042202

Table 2. Shadow prices of the environmental effects (NIBE, 2019).

The environmental impact data of products, materials, components, and processes are available in the database of the NMD and NIBE. The environmental impact can be multiplied with the general shadow price to calculate the exact shadow price per product, material, component or process (NIBE, 2019). In this research, the database of NIBE will be used for the environmental impact information for the HCS components and other components needed for the upgrading of the qualification factors, and the NMD will be used for the environmental data of the building materials and processes to be used during the reuse process. The choices of the products, materials, components or processes for the upgrading of the performance of the component are based on the environmental class (see table 3).

Klasse	subklasse	omschrijving	milieubelastingsfactor
1	a	beste keuze	1,00 - 1,10
	b		1,10 - 1,32
	c		1,32 - 1,58
2	a	goede keuze	1,58 - 1,90
	b		1,90 - 2,28
	c		2,28 - 2,74
3	a	aanvaardbare keuze	2,74 - 3,28
	b		3,28 - 3,94
	c		3,94 - 4,73
4	a	minder goede keuze	4,73 - 5,68
	b		5,68 - 6,81
	c		6,81 - 8,17
5	a	af te raden keuze	8,17 - 9,81
	b		9,81 - 11,77
	c		11,77 - 14,12
6	a	slechte keuze	14,12 - 16,95
	b		16,95 - 20,34
	c		20,34 - 24,40
7	a	onaanvaardbare	24,40 - 29,29
	b	keuze	29,29 - 35,14
	c		35,14 - 42,17

Table 3. Environmental class related to the environmental costs factor (NIBE, 2019).

The shadow costs are translated into an environmental class. The best product/component from an environmental point of view receives environmental class 1a. To determine the environmental class for other products within the same product group, the classification is based on the environmental costs of the reference (product with the environmental class 1a). Up to and including class 3a, the products are considered acceptable. After that it evolves from good to unacceptable (class 7c), these are the more chemical products and materials. In this way, an environmental class can be determined for all products on the basis of environmental costs, see table 3 (NIBE, 2019);(Willaert, 2013).

Appendix A.7 shows all the shadow prices for the products, materials, and processes that are required for the process of reuse of the HCS components.

4.5.2.2 Economic impact factor

One of the main reasons why reuse of building components is not yet a common solution is the uncertainty about the extra amount of costs. It is important to calculate the costs, to get a clear view of the feasibility of reusing HCS components. Therefore, it is necessary to make a comparison between the costs for disassembly and reuse on the one hand, and the production of new components on the other hand based on the Life Cycle Cost analysis (see paragraph *4.3.2 Life Cycle Cost analysis*). The costs of the reused component consist of the disassembly costs (only the extra costs that are needed for the disassembly compared to the costs of demolition - Δ€) plus the modification, the transport, the storage, and the reassembly costs. The costs for a new component is related to the purchase price – depending on the production and transportation costs - of a new HCS component (Glias et al., 2014).

According to de Haan (2019), the costs from the economic point of view should be calculated for the reused components and compared with the economic costs of a new building component. The costs should be calculated before the whole reuse process will start because the reuse process should be profitable against the use of newly manufactured components. The costs can be divided into five costs-phases. The different costs-phases are (de Haan, 2019);(Glias, 2013):

- *Disassembly costs*: these are the costs of removing the component from the building and the common costs, as the various costs, project costs, general costs, profit, and risk. The cost for removing is the extra costs required for the disassembly compared to the demolishing costs and, therefore, the Δ€ is calculated. The best way to disassembly the building is layer by layer. First, the concrete topping and finishing layer should be removed. The finishing layer can be removed faster and cheaper for 3,5 €/m^2 than a concrete topping with the function of a compression layer with a cost of 7 €/m^2. A compressor with hammers can be used for removing this topping. Second, the HCS components can be removed in four steps: support the columns and walls, remove concrete between HCS, saw the connected joints between the HCS and the walls, beams, façade and other HCS, and lift the HCS with a crane from the building. The various costs are the costs for extra road plates or extra lifelines for safety, etc. The project costs are the costs for site huts, toilets, etc. and these costs depend on the time required for the disassembly process. At least, the general costs will be 7% of the total costs. Normally the profit and risk costs are together 5% of the total costs plus the general costs. However, for second-hands components an extra factor is needed due to the uncertainty about the deconstruction. To cover unexpected situations, the profit and risk costs will be 8% for the reuse process.

- *Modification costs*: these are the costs for the preparation of the component for reuse. The HCS components should be modified in such a way that the components could use directly in the new building as a prefabricated component. For the modification process of HCS components, there are four steps to do: (1) sawing the component to the required size [35 €/m^1 for a 200mm thickness floor, for another thickness a factor should be used], (2) remove fixings [2,5 €/m^2], (3) fill the holes with concrete or mortar [0,8 €/m^2], and (4) create openings for the connection in the new building [4,5 €/m^2].

- *Transportation costs*: these are the costs for the transportation of the reused HCS component to the desired place. As mentioned in the previous sub-chapter (*4.5.1.3 Additional processes system for the reused component*) there are several routes for the reused component to go to the construction site. Sometimes, the component will travel several routes and the travel distance expressed in kilometers will be longer. The price per cargo per day is estimated at around 600 €/cargo for one day for cargo with a load of 30 tonnes. The company that is responsible for the demolition/disassembly process is also responsible for the transportation of the components and debris.

- *Storage costs*: these are the costs for the storage of components. If it is possible to reuse the HCS components but the components can not immediately be placed at the new construction site, a storage location should be found. The storage costs depend on the length of time that the floor components should be stored and the number of square meters needed to store all the components. The costs are estimated around 12 €/m^2/year.

- *Construction costs*: the final stage of the reuse process is the construction of the new structure and using the existing HCS components. The construction costs can be excluded because these costs are the same for the construction process with the reused components as with the newly manufactured components.

The total costs for a reused HCS component is a summation of all costs described above. These costs still have to be weighed against the costs of a new HCS component. The costs for a new HCS component are estimated for 47,5 €/m^2 for a slab with a thickness of 200 mm, including the transportation costs. An overview of the costs is shown in Appendix A.8. The estimation of the costs is done with the aid of cost advisor Pieter de Haan from Coen Hagedoorn Bouwgroep. The aim of the cost analysis is to examine the feasibility of the reuse process for the HCS component.

4.6 Results and the program of requirements for the assessment of the reuse potential factor

Before a hollow-core slab floor component from an existing building can be used in a new building project, it is necessary to investigate if the component has some potential to be reused. For the assessment of the reuse potential, three factors should be balanced: *quality potential factor*, *environmental impact factor* and *economic impact factor*. The outcome of the assessment will be the reuse potential factor – an indicator to expresses the usefulness of the component by a value between 0 ("waste-like") and 1 ("resource-like"). This reuse potential factor should be determined by a decision support model to make the right decision towards the reuse of HCS components. Research shows that a decision support model has not yet been developed. However, the existing ARP-model and RFID technology could determine the reuse potential of existing buildings or building products, but these models were only aimed at determining the quality potential factor of the buildings and neglected the quantitative performance of the building. Therefore, the factor of the impact on the environment and economy is not calculated and only one factor in the assessment of the reuse potential has been assessed.

Currently, there are existing methods for determining the environmental impact factor and the economic impact factor. The Life Cycle Assessment (LCA) analysis is a tool to analyse the environmental impact of a product, component or material during its whole lifetime. The Life Cycle Cost (LCC) analysis focuses on the economic costs of a product, component or material during the entire life cycle. These important tools are not linked to each other due to the methodological differences and the lack of information about allocating the impacts for the reuse process. A combination of these two analyses is done by the Eco-cost value ratio (EVR) model. The principle of this model - to link the value of a product to the economic and ecological costs – will be used to express the reuse potential of an HCS component.

So, for determining the reuse potential factor of HCS components by a decision support model, the quality potential factor and the environmental and economic impact should be determined. The first step is the reuse analysis to analyse the quality of the component by testing the different performances – lifespan -, technical -, and additional performance – of the HCS component. The second step is the reuse evaluation to evaluate the quantification factors – environmental and economic costs – of the HCS component. To conclude, the reuse potential factor of the HCS component can be assessed by comparing the environmental and economic costs for the reused HCS component with the necessary upgrades and the new fabricated HCS component. Therefore, the higher the qualification factors, the lower the quantification factors should be and the higher the reuse potential factor is (see figure 31). So, if the performances scored high then fewer materials, tools and equipment are needed for the upgrading of the component and therefore the costs will be lower. The assumption in this research is that the level of reuse potential capacity, that relies on the qualification and quantification factors of the HCS component, has a direct relation with the level of building components' circularity. Higher reuse potential capacity means lower negative economic and environmental impact and therefore a higher circularity.

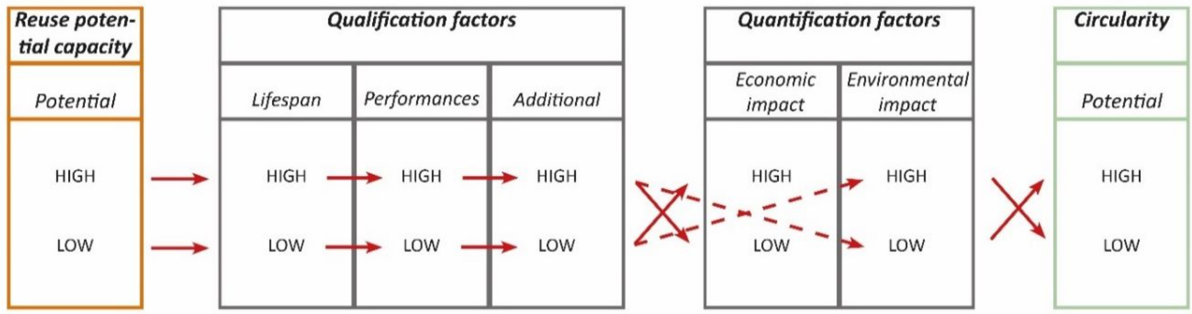


Figure 31. High reuse potential capacity = high circularity.

Accordingly, the existing building components can be divided into three groups based on the reuse potential factor:

1. Building components with low reuse potential capacity, a RP between 0 – 0.3 ("waste-like"). In this case, the component is for less than 30% reusable because, for example, too many changes have to be made to the component to meet the required requirements, as a result of which the economic and environmental costs become too high.
2. Building components with partial reuse potential, a RP between 0.3 – 0.7. This means that the component is reusable for between 30% and 70 %.
3. Building components with high reuse potential, a RP between 0.7 – 1.0 ("resource-like"). In this case, the component is for more than 70% reusable and little changes should be made to the component. Therefore, the environmental and economic costs will be as low as possible.

If the qualification factors of the existing HCS component scored high and the quantification factors scored low, it can be guaranteed that the reuse potential factor will be high.

The focus for the second part of this research is about the developing of the decision support model for calculating the reuse potential factor based on the quality of the component as well as the economic and environmental impact of reusing this component. The concepts of the existing models, methods, and tools will be combined in the developed decision support model to get an overall view of the reuse potential of the HCS components.

PART II. Decision support model for assessing the reuse potential

Before a hollow-core slab floor component will be reused, it is important to know if an existing building component has the potential to reuse it for a second lifetime. Therefore, the quality of the existing building component should still be satisfactory or the quality should be upgraded by making adaptations to the existing component. Though, there are (environmental and economic) costs associated with upgrading the component and these costs can be too high that it is no longer profitable to reuse the existing hollow-core slab floor component.

A decision support model can help to determine the potential to reuse an hollow-core slab floor component. Therefore, qualification and quantification performances should be tested. In the end, the (environmental and economic) costs for reusing the floor component should be compared with the costs of a new fabricated floor component in order to determine the concern factor.

Chapter 5 discusses the assessment of the reuse potential factor based on the decision support model. The structure, the method and the outline of the model are explained. Chapter 6 verified the results of the decision support model. Different situations for the reuse of the HCS component are compared. Also, the sensitivity of the model to assess the reuse potential factor is discussed.

5. Assessment of the reuse potential factor by means of a decision support model

5.1 Introduction

In order to be able to assess the potential to reuse the hollow core slab -HSC- floor component, a decision support analysis could be a solution. In chapter 4 *Systematic approach to assess the reuse potential of hollow-core slab floor components*, the process of reuse and the related performances to be tested are explained. The HSC component can be reused if it delivers certain performances after its primary lifecycle. These performances should meet the requirements for the new building project in order to place the component in the new structure. The reuse potential of a component is in this study regarded as the measure of the ability of this component to retain its functionality after the end of its primary lifecycle – the quality of the component should be sufficient. However, the reuse of the floor component is only possible if it becomes not too expensive in terms of environmental and economic costs. Therefore, the reuse potential factor is a factor to indicate if the reuse of an existing building component is feasible and profitable. Feasible in terms of its performance and profitable in terms of "costs". The assessment of the reuse potential factor for a component can be done by the decision support model that evaluates the qualification performances and quantification performances of the reused floor component. So, the following key question will be answered in this chapter:

How is it possible to measure the reuse potential factor of a hollow-core slab floor component?

First, attention will be paid to the purpose and structure of the decision support model. Second, the method to assess the reuse potential factor according to the economic and environmental impact and compared to a manufactured HCS component will be explained. Finally, the decision support model will be clarified by the outline of the Excel-model to quantify the reuse potential factor.

5.2 Purpose of the decision support model

A decision support model should be used to determine the potential of reusing HCS components. Therefore, the reuse potential factor should be measured by this model and based on this factor a decision can be made about the reuse of this existing HCS component or not. A high reuse potential factor means that it is definitely possible to reuse the existing floor component for the structure of the new building. As mentioned in chapter 4, there is not such a decision support model that could determine the reuse potential factor for structural building components. Therefore, it is time to develop a decision support model to make a better decision in times of the transition to a circular economy. The reuse potential factor is the factor to measure the quality of the existing HCS component after its primary life related to the economic and environmental impact of reusing this component.

Therefore, the first step to measure the reuse potential factor is to analyse the quality of the existing floor component – qualification performance. The following step is to evaluate the reuse of the component. Therefore, it should be investigated whether the impact on the environment and economy is too high - quantification factors. Figure 32 shows the steps to reach the goal.

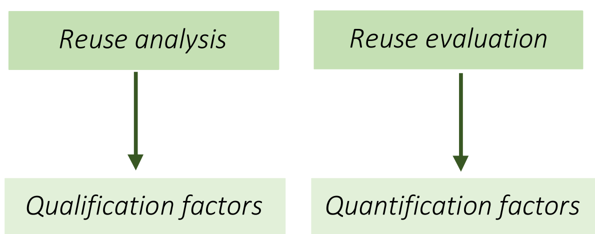


Figure 32. Steps of the decision support model.

5.3 Structure of the decision support model to measure the reuse potential factor

At a certain moment, an existing building cannot fulfill its function anymore and the building can become empty. A decision is made to demolish the building, but it is also possible to opt from a sustainability perspective to reuse components of the building. The process of reuse is described by Glias (2013) (see chapter 4 *Systematic approach to assess reuse potential of hollow core slab floor components*) in different steps; from the moment that there is an intention to reuse the components of an existing building till the construction of the reused component in the new building. However, before all these steps of the reuse process are done, it is important to know whether the component has the quality *potential* to be reused and whether it is feasible from an economic and ecological point of view to reuse the component.

The decision support model to estimate the reuse potential factor of the HSC component can help the designer of the new building project to find out if it is possible to reuse the HCS components for its project. All the chronologically steps of the process of reuse should be evaluated to check if it is feasible and profitable for each step to reuse the floor component.

The steps of the reuse process are based on the physical process whereby an inventory is made of the quality of the component to subsequently remove the component from the existing building and after the modification of the component, it can then be constructed in a new building project. It is important that this entire physical process is mapped out earlier, before the component is removed from the existing building, in order to determine whether it has a positive effect to reuse the component from both an economic and environmental point of view. Therefore, all the steps in the process of reuse should be quantified according to the economic and environmental costs. So, to measure the reuse potential factor of the HCS component by means of a decision support model all the steps of the process of reuse should be involved and investigated, see figures 33 & 34.

Therefore, the structure of the decision support model is based on the process of reuse and it is divided into four different phases:

1. *Inventory phase*. The properties of the existing HCS floor component and the properties for the required HCS floor component are investigated and described in the inventory list. This is the basis for the testing of the quality of the component.
2. *Quality performance test phase*. The condition of the HCS floor component is estimated by a specialist or based on the existing drawings. These estimated conditions can be compared with the required condition of a “new” component for the new building project. The condition of the HCS floor component is checked on the basis of the lifespan, technical, functional, aesthetical and additional performances.

These first phases describe whether the component meets the qualitative requirements for reuse. This is based on a comparison of the qualitative performances of the existing HCS floor component and the required qualitative performances for the new building project. If the performances of the existing component cannot meet the required performances, the component can be upgraded or already be excluded by a specialist. For the upgrading of the component, the component should be adapted to meet the requirements. The next two phases will quantify this process.

3. *Modification phase.* The adaptations needed to be done to meet the requirements of the new building project are indicated. Sometimes it can be suggested that the component does not have to completely meet all the requirements of the new building project. At that moment, it can be discussed with the specialist and the designer of the new building project which adaptations are necessary and which may be left behind. An adaptation list can give an overview.

4. *Quantity performance test phase.* To measure the reuse potential factor of the component, the economic and environmental costs should be quantified. These costs are related to the adaptations done in the modification phase. The total costs of the environmental and economic impact are the summation of all the costs for the adaptation process and the disassembly process of the HCS component.

Figures 33 & 34 illustrate the process of reuse and the structure of the decision support model to measure the reuse potential factor based on the steps of the process of reuse.

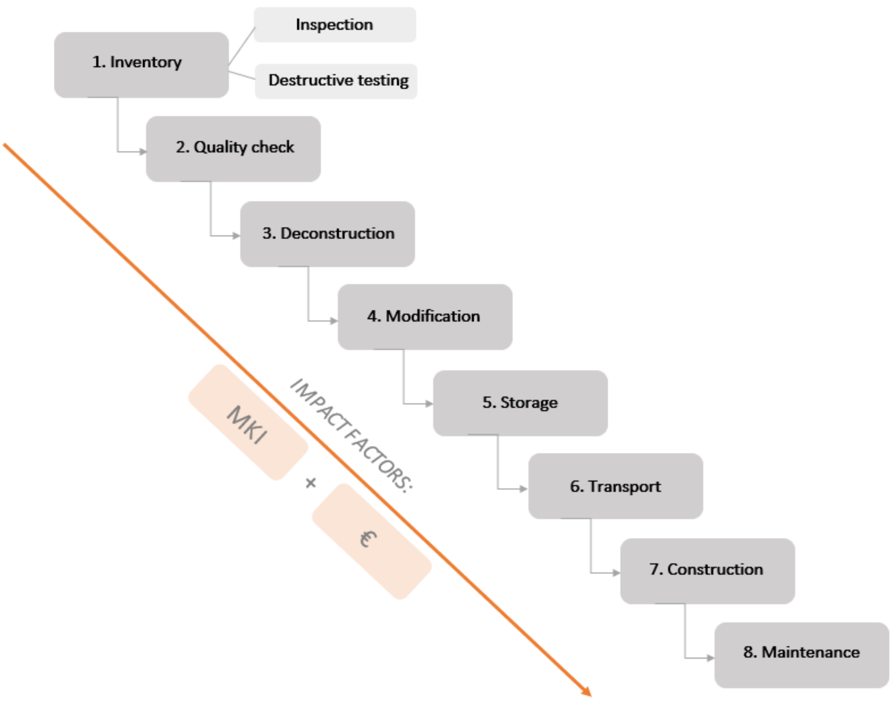


Figure 33. Steps of the process of reuse based on the method of Glias (2013).

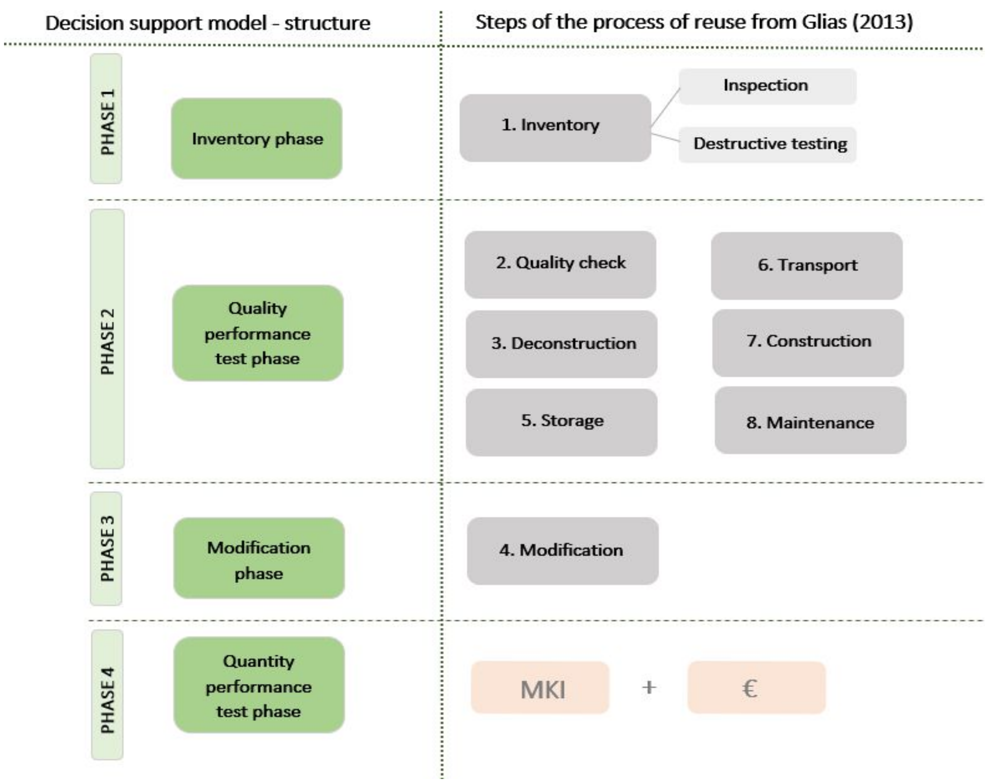


Figure 34. The structure of the decision support model compared with the steps of the process of reuse by Glias (2013) to estimate the reuse potential factor.

5.4 Method for the decision support model to measure the reuse potential factor

The measurement of the reuse potential is difficult to define as it depends on many factors. The factors are divided into the qualification and quantification factors for determining the reuse potential factor. The qualification factors are based on the performances of the reused floor component from a qualitative point of view. The quantification factors are related to the impact performances to measure the values of the economic and environmental costs. The comparison between the economic and environmental costs for the reused floor component and these costs for a new fabricated component is important to measure the reuse potential factor. Therefore, the reuse potential is defined as a factor measuring the ability of a component to retain its functionality after the end of its primary lifecycle compared to the economic and environmental costs to reuse the component. The reuse potential factor can be measured with the help of the decision support model. The method of the model will be discussed below and relation of the method with the existing methods described in chapter 4 *Systematic approach to assess reuse potential of hollow-core slag floor components*.

5.4.1 Description of the method for the decision support model

The method describes the relationship between qualitative and quantitative performances, see figure 36. The method is divided into checking the performances of the reused floor component compared to the performances of the new fabricated floor component. If the performances do not fulfill the requirements, then upgrading is needed. This upgrading has an effect on the environmental and economic impact. The comparison between the impacts of the new fabricated component and the reused building component will be determined at the end to give advice about the reuse potential of the existing floor component. The different steps of the method are as follows:

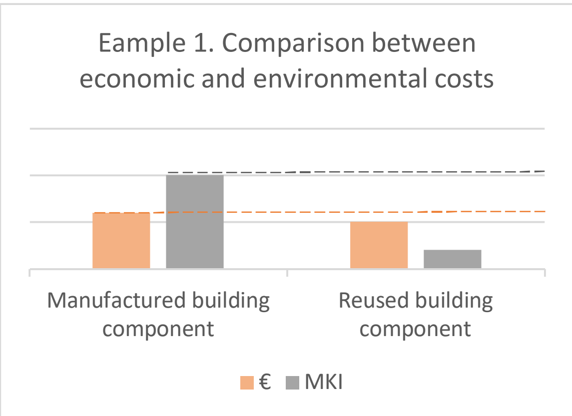
- **New fabricated building component:** The new fabricated HCS component should always meet the performance requirements of the new building project. Therefore, a percentage of 100% for all the qualitative performances is included for the new fabricated component (see the *red box* in figure 36). This percentage of 100% indicates that no upgrading is needed because a new fabricated component is already fully satisfactory. However, various steps and processes will have to be done to fabricate the floor component. These steps and processes contribute to the impact on the environment through the use of raw materials and the CO_2 emissions of the production process. In addition, producing a product has also an economic impact. There is a price associated with the purchase of a new fabricated component due to the production costs incurred. Therefore, the economic costs and the environmental costs could be calculated for the new fabricated component.

- **Reused building component**: The reused building component should also satisfy the required qualitative performances to be able to place the component in the new building structure. However, it may occur that the reused component does not meet the requirements and the component should be adapted to upgrade its performance. For example, one of the performances of the reused component only meets 60% of the required performance for the new building project. It can be determined what adaptations are needed to upgrade this performance of the reused floor component so that the component then meets the requirement of 100% (see the *blue boxes* in figure 36). It is also possible to choose not to upgrade the component to 100%, but it can be considered that it is sufficient to upgrade the component up to, for example, 90% if the designer of the new building project agrees. In addition, there is also the option not to upgrade the component and maintaining the same performance percentage. The percentage required is determined based on the situation scenario. One new building project has a different function and therefore different requirements than the other new building project. So, per situation scenario, another upgrade percentage is needed.

The upgrade of the qualification performances results in economic and environmental impact. Therefore, after upgrading the economic and environmental costs can be calculated for the reuse of this floor component. Some additional factors, such as the disassembly process, transportation, storage, etc., can also result in economic and environmental costs and these should be included as well.

- **Comparison:** For the various situations, it has been determined what the economic and environmental costs are for both the new fabricated HCS component and the reused HCS component. These quantification factors can be compared with each other to verify which component is better to use for the new building project. If the economic and environmental costs for the new fabricated floor component are higher than for the reused floor component, it has a more positive effect to place the reused floor component in the new building project. Therefore, the reuse potential can be set as 'high'; RP = 1.0. The "costs" limit for the reused floor component is the total economic costs and environmental costs of the new fabricated floor component. So, if the "costs" are higher for the existing HCS component than for the new fabricated HCS component, it is not profitable to reuse the existing HCS component.

  The following two figures (figure 35a+b) describes two different examples for the comparison of the economic and environmental cost. The first example shows the upper limit line for both the economic (*diagram colour: orange*) and environmental costs (*diagram colour: grey*) of the reused floor component-based on the "costs" of the new fabricated floor component. These costs for the reused building component do not exceed the upper limit line and therefore it is definitely possible to reuse the existing floor component. The next example shows the upper limit line and the different costs as well but, in this case, the costs for the reused floor component are high and therefore exceed the upper limit line. Therefore, the advice will be to not reuse the existing floor component, because it does not yield a positive result in terms of economic costs.



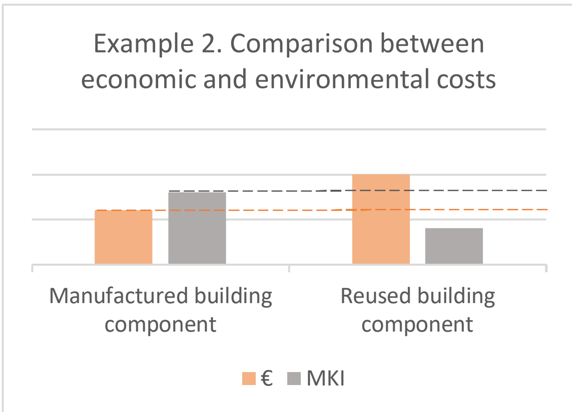


Figure 35. The comparison of the economic and environmental costs of the new fabricated component and the reused component. The "costs" of the reused component should not exceed the upper limit (dashed line).

The method gives a good overview on which the reuse potential factor is based. The decision support model is based on this method to give relevant *advice* regarding the choice to use an HCS component from the factory or to reuse an HCS component from an existing building for the new building project. The decision support model is in this study an advice model to make a substantiated choice.

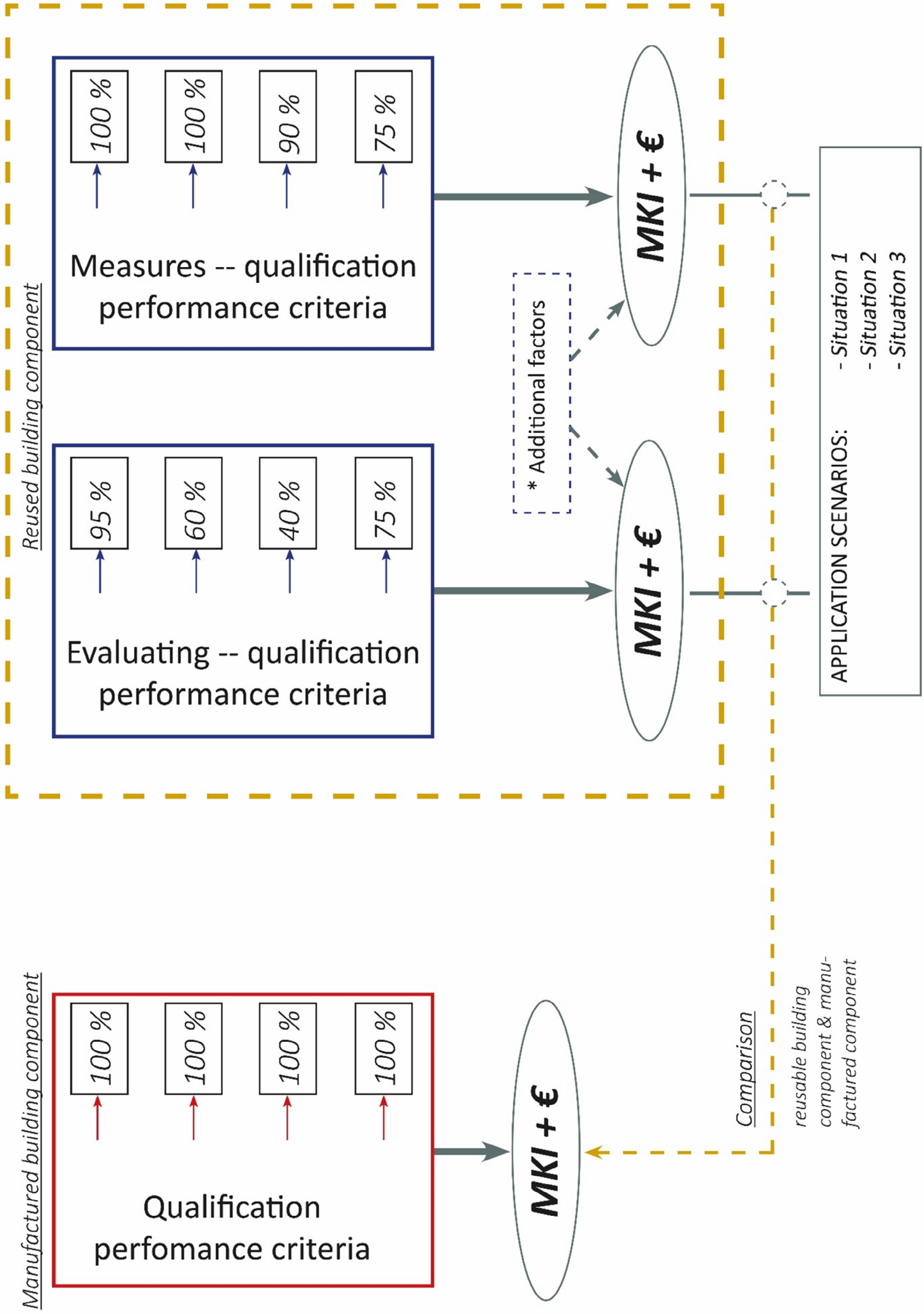


Figure 36. The method of the decision support model.

5.4.2 Method related to the life cycle of the building component

The method is used for the last stage, the end-of-life stage, of the life cycle of a building. In this stage, it should be determined for the existing building component whether it will be reused or demolished. The decisive factors are the quantitative factors of the model. These quantitative factors are based on the two existing methods for the quantification of the life-cycle of a building component; LCA and LCC analysis (see paragraph 4.3 *Existing methods about the quantification of the life-cycle of a component*).

With the LCA analysis, the environmental impact can be determined for the building component during the different stages of the life cycle. The environmental impact is translated into a value indicator, the environmental cost indicator (*abbreviation: MKI*). As mentioned before, the environmental benefits of reuse, recycling, and energy recovery are calculated in the additional stage of the life cycle, module D. For this module D an environmental indicator could also be mentioned to realise the positive effect of using an existing building component for a new building project. This approach is used for the method of the decision support model whereby the environmental cost indicator is determined for the additional stage of the life cycle of the floor component to be reused. However, the reuse potential factor can be measured at the end of the life cycle of a floor component. Nowadays, module D is used to estimate at the beginning of the life cycle of a product the positive effect of reuse of the component. A product can get some credits if it is assumed that the product can be reused at the end-of-life stage. However, the many factors that are involved during the process of determining the reuse potential factor show that it is not yet easy to determine the number of credits.

Moreover, with the LCC analysis the economic impact can be defined for each stage of the life cycle of a building component. For the LCC analysis, module D can also be used to determine what the economic benefits are for reusing a component. The value of the economic impact is the economic cost indicator. For this additional stage, the economic costs could be clarified to have a better understanding of what it means to reuse a component from an economic point of view.

5.5 Outline of the decision support model to measure the reuse potential factor

Based on the method and the structure for the decision support model described in the previous subchapters (5.1 *Structure for the Reuse Potential decision support model* & 5.2 *Method for the Reuse Potential decision support model*) the decision support model is created in the Excel-program. In this Excel-program different tabs/spreadsheets have been developed for the four phases of the model. Different tabs have been designed for each phase to provide information for that phase. The outline of the model in the program Excel is described below based on the structure of the model - the four different phases.

The outline of the decision support model is as follows, see also figure 38:

<u>PHASE 1. Inventory phase</u>

1. *Situation – scenarios new structure (NS)*
   The first step of the model is to describe the three possible function situations for the new building design. The relevant information about these three different situations can be entered into the model. With all this information, the type of HCS component required in the new building structure can be determined per situation. This first spreadsheet provides the data required for the following step.

2. *New structure information*
   2.1 *Inventory list – new structure (NS)*
   The second step of the model is to establish the requirements for the HCS floor component in the new building structure. Therefore, one situation should first be chosen to elaborate. The general, technical and functional requirements for the HCS floor component that will be installed in the new building structure will be examined. Most of

the information will be entered by the constructor of the new building. The requirements for the floor component are determined and the properties for the selected HCS component can be calculated.

2.2 Results – new structure (NS)

The third step is to calculate and determine the properties of the selected HCS component. The properties are calculated based on the requirements of the previous step. However, the technical properties are further elaborated with the help of the structural calculation tool of VBI.

3. Existing structure information

3.1 Inventory list – existing structure (ES)

The next step is to investigate the properties of the existing HCS component. Therefore, the general, technical and functional information of the existing floor component should be entered in the model. The requested information can be obtained through archive information and calculations or visual inspection.

3.2 Results – existing structure (ES)

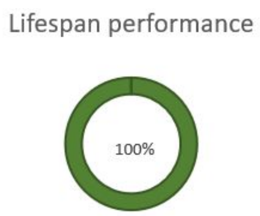
The properties of the existing HCS component are determined and the technical properties are calculated with the help of the structural calculation tool of VBI.

PHASE 2. Quality performance test phase

4. Quality test

The quality of the existing HCS component should be tested by comparing the properties of the existing HCS component with the required properties for a component to be placed in the new building structure.

4.1 Quality test – Lifespan system

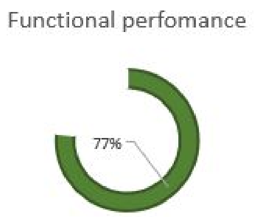


First, the lifespan performance is tested. The remaining lifespan of the existing floor component will have to be compared with the required lifespan for the component in the new building structure. Therefore, the remaining technical lifespan and the remaining functional lifespan of the existing floor component are tested. The remaining technical lifespan is influenced by the degradation mechanisms and the amount of damage to the component. The remaining functional lifespan is about the function the component can still perform for a particular building function. A lifespan performance percentage is estimated based on the difference between the remaining lifespan for a second life of the building component and the required lifespan for the component in the new building structure. If the lifespan performance percentage is lower than 100%, it is <u>not</u> possible to reuse the component. The reason is that it is not possible to upgrade the component to extend the lifespan.

4.2 Quality test – Technical performance

Second, the technical performance of the existing floor component is tested. Therefore, the structural properties of the existing HCS component should be compared with the structural properties required for a floor component installed in the new building structure. Also, general technical properties such as length, height, width, etc. should be tested and compared. Finally, the technical performance percentage is estimated. The percentage indicates to what extent the existing floor component meets the technical requirements for the new building structure. If the percentage is lower than 100%, it is <u>not</u> possible to reuse the existing HCS component. The reason is that it will not be possible to upgrade the technical performance, for example the length of the component cannot become longer.

4.3 Quality test – Functional performance



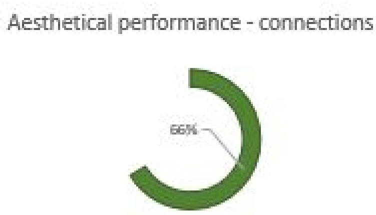
Third, the functional performance is tested. The functional properties of the existing floor component are compared with the required functional performance of the new building structure. The fire-resistance, the sound-insulation, the number of block-outs and the finishing layer are tested. If the properties of the existing HCS component does not match the required properties for the new structure, then the existing component should be adapted to achieve the requirements. The functional performance percentage is estimated based on the percentages the existing component achieved for its performance of all functional properties compared to the required performance.

4.4 Quality test – Aesthetical performance

4.4.1 Quality test – Aesthetical performance 1: damage

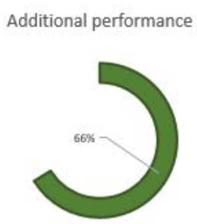
The aesthetical performance related to the damage of the existing HCS component is tested. A visual inspection is needed to locate the visual distress, deterioration, and damage to the existing component. The amount of damage can be entered by changing the sliders for every damage factor. Therefore, the 'reusability factor' – percentage it is possible to reuse the component – can be indicated. Finally, the damage performance percentage is estimated. The percentage will be lower if the component is more damaged and then the component should be adjusted before it is reused.

4.4.2 Quality test – Aesthetical performance 2: connections



The aesthetical performance related to the connections between the existing HCS and the supporting walls/columns are tested as well. The type of connection influences the possibility to disassemble the existing HCS component from the existing structure without damaging the component. A visual inspection is needed to indicate the type of connections. The 'disassembly factor' can be calculated based on these types of connections. The higher the disassembly factor, the easier it is to disassemble the existing component without damaging the component. Lastly, the connection performance percentage is estimated. If the connections make the disassembly process difficult, then the percentage will be lower and more equipment and tools are needed for the disassembly of the components.

4.5 Quality test Additional system



The last step of the quality test is testing the additional performance. The additional performance is divided into the maintenance -, reassembly -, storage -, and transport performance. The more maintenance inspections are required for the second lifetime of the existing HCS component or the more difficult it is to reassemble the existing component in the new building structure, the less profitable it is to reuse these components. Also, the longer the components should be stored before they can be used in the new building structure or the longer the distance for the transportation of the components compared to a reference factor, the less profitable reuse is. The additional performance percentage is estimated based on the amount of maintenance inspection are required, the number of modifications needed before reassembly is possible, and the influence of the transportation and storage process.

PHASE 3. Modification phase

5. ***Evaluation of the qualification performances***

All the qualification performances are tested and the results are the performance percentage for each qualification factor. The percentages show the degree of performance the existing HCS component can deliver relative to the required performance for the new building structure. An overview is given of these percentages. In addition, sliders in the spreadsheet can be used to indicate the extent to which they want to upgrade the existing component – 0% to 100%.

6. *Modification of the component*
   6.1 *Adaptation list – upgrade*
   Sometimes it is required to adapt the component before it can be reused in the new building structure. The upgrade percentage is indicated in the previous step. The percentage for the upgrade determines the number of adaptations required. An adaption list can be developed to indicate which part of the component should be modified and what is required for this modification.

   6.2 *Influence of the adaptation – Environmental performance*
   Every modification made to the component influences the environmental performance of the component. The reuse of a component has no impact on the environment unless additional materials have to be added to the component for repair work before it is reused. Also, the equipment and tools needed for the disassembly process have an impact on the environment. The impact on the environment is quantified in this step. Therefore, the shadow costs (€/m^2) for each modification or for the disassembly tools are calculated.

   6.3 *Influence of the adaptation – Economic performance*
   The modifications made to the component and the disassembly process also influences the economic performance. Therefore, the costs (€) for these processes are calculated. The costs per material, tool or process can be found in the database and this information is used for the calculation of the costs.

PHASE 4. Quantity performance test phase

7. *Evaluation of the reuse potential factor (RP-factor)*
   Finally, the reuse potential factor is measured based on the results of the quantification performances. The total of the shadow costs and the economic costs The total costs for the existing component to be reused are compared with the total costs for a new manufactured HCS component. The RP-factor is calculated by the following formula:

$$RP = 1{,}0 - (\Delta\, percentage\, 'costs'\, of\, the\, modified\, existing\, HCS\, component/100)$$

The range of the reuse potential factor is shown in the following figure:

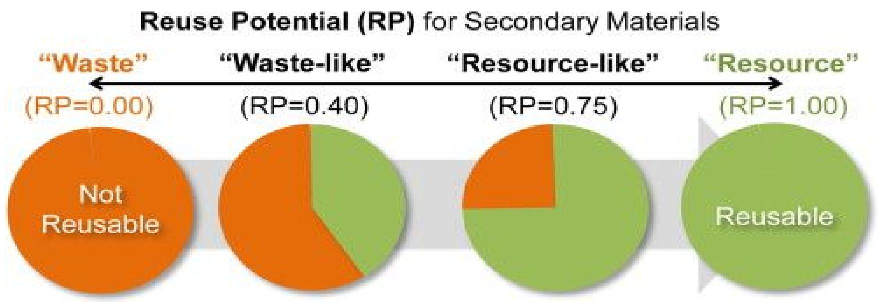


Figure 37. The value of the reuse potential from waste-like to resource-like (Park & Chertow, 2014).

Appendix B explains the outline more in detail and per spreadsheet/tab of the model an extensive explanation is given.

Remark: The model works on the basis of filling in requested aspects (the *yellow* parts in the model) and data processed in the model. This data is described in a database and the model is therefore linked to this database. The data is related to information that is needed to calculate the properties and performance of the HCS component and is based on the literature obtained in Chapter 4 *A systematic approach to assess the reuse potential of the hollow-core slab floor component*.

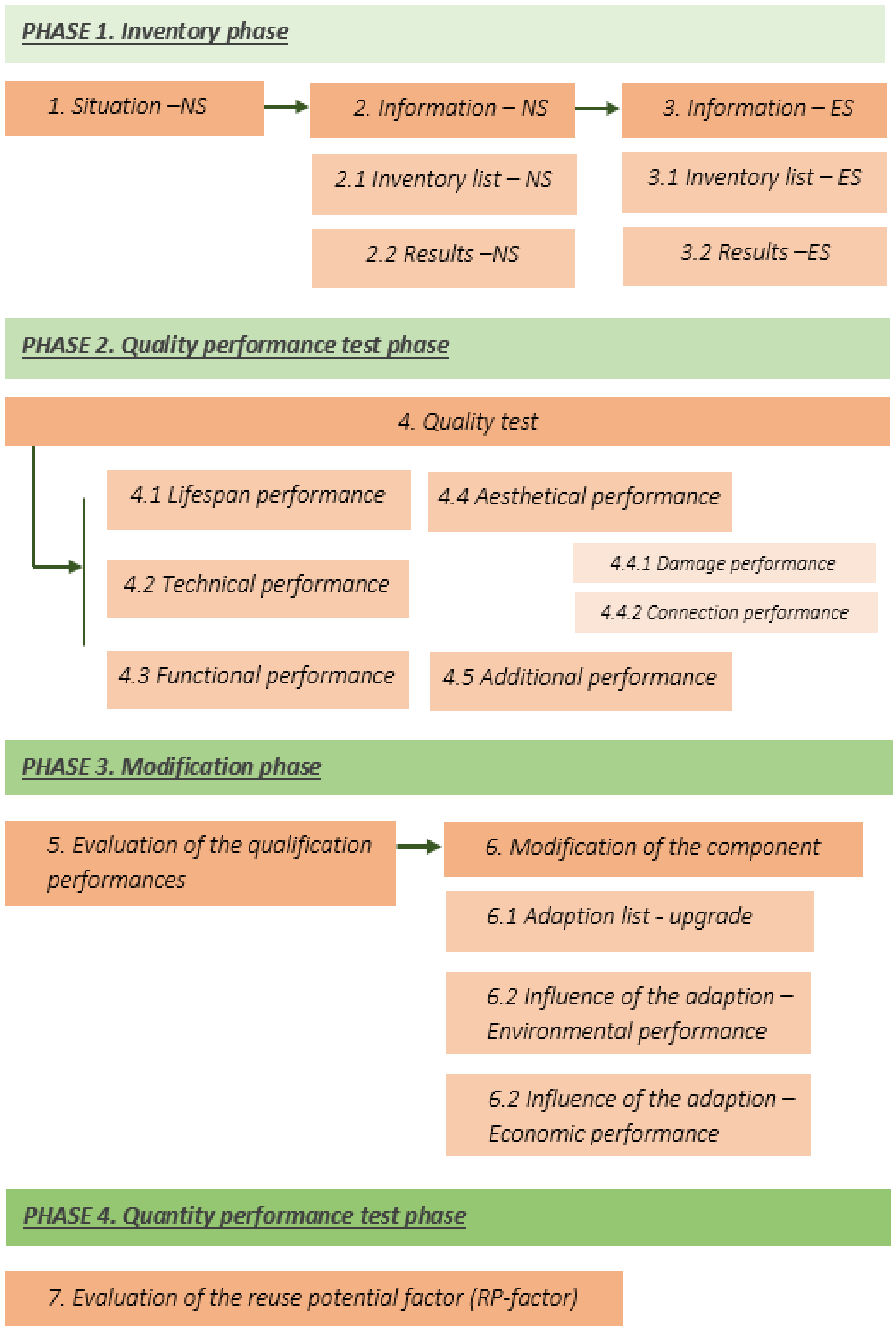


Figure 38. The overview of the outline of the decision support model to measure the reuse potential factor.

5.6 Results

The decision support model can measure the reuse potential factor of an HCS component. The decision support model is an advice model to make a substantiated choice of reusing the existing HCS component or use a new fabricated HCS component for the new building project. It can help the designer of the new building project to find out if it is possible to reuse the existing HCS components for its project.

The structure of the decision support model is based on the process of reuse. All the chronologically steps of the process of reuse should be evaluated to check if it is feasible and profitable for each step to reuse the floor component. Therefore, the structure of the decision support model is divided into four different phases: *inventory phase, quality performance test phase, the modification phase,* and *quantity performance test phase*. The quality performance test phase is to qualify the performance of the existing HCS component compared to the required performance for the new building structure. The quantity performance test phase is based on quantifying the environmental and economic costs of the existing floor component and the environmental and economic costs of a new fabricated floor component.

The method of the decision support model on the relationship between the qualitative and quantitative performances whereby the new fabricated floor component and existing floor component are both tested if they meet the required performance. If the existing floor component did not meet the requirements, the performance of the component should be upgraded by adapting the component. The upgrade percentage can be chosen by the designer and constructor of the new building project. The adaptation will have an effect on the “costs” of the existing floor component. The comparison between the “costs” of the existing floor component should not exceed the upper limit of the “costs” of the new fabricated component.

The reuse potential factor can be measured by comparing the environmental and economic costs of an existing HCS component and these costs of a new fabricated HCS floor component. The reuse potential factor is expressed by a real value between 0 and 1. The component is discarded if it equals 0 and the component can be definitely reused if it equals 1. Therefore, the reuse potential factor is a factor to indicate if the reuse of an existing building component is feasible and profitable. Feasible in terms of the performance/condition of the HCS component and profitable in terms of “costs”.

6. Evaluation of the decision support model for determining the reuse potential factor

6.1 Introduction

In this chapter, the decision support model for calculating the reuse potential factor of the hollow-core slab -HCS- floor components are evaluated. In the future, our current economy should become a more circular economy whereby buildings will not be demolished but building components will be reused for a second lifetime. Therefore, it is important to know whether the HCS floor components from an existing building can be reused for another specific new building. The decision support model can help to find out if it is possible to reuse the existing HCS component. This is based on the amount of impact on the environment and the economy due to the adjustments to be made to the component to meet the qualification requirements for the new structure.

There are several different buildings with HCS components as the structural floor type. Each building has its own characteristics and requirements. Therefore, the type of HCS component is different for each building. Each HCS component has its own properties. The properties of the HCS component should meet the characteristics and requirements of the new building structure to reuse this component. The decision support model has been developed to perform this analysis. To test the decision support model, a reference project of IMd Raadgevende Ingenieurs is used. See paragraph 6.3.1 *Existing building and various scenarios as input for the decision support model* for a detailed explanation of the reference project. The decision support model investigates the quality of the floor component and the economic and environmental costs are evaluated if these are still acceptable or certainly lowers the reuse potential factor. The following key question will be answered in this chapter:

Does the decision support model lead to realistic results with regard to the reuse potential factor?

The first step to evaluate the decision support model is to verify the assumptions made about the model. The assumptions made should be verified to assess whether the model achieves realistic results. Thereafter, the 'sensitivity' of the decision support model is elaborated. Furthermore, the model can be used to test an existing HCS component for several different situations. It will be indicated for which scenario it is feasible or not feasible to reuse the component by calculating the reuse potential factor. Also, the parameters of the qualification factors are evaluated for some situations and the demountable building situation is further elaborated. At last, the limitations of the decision support model are investigated.

6.2 Verification of the decision support model to measure the reuse potential factor

It should be investigated whether the model gives results that are also expected. Therefore, the assumption made about the decision support model should be discussed and verified. During a verification process, the model is forced to re-examine assumptions made during the research process (Verberne, 2016). In this research, assumptions have been made for the relationship between the qualification factors and quantification factors to estimate the reuse potential factor, see also 4.6 *Results and program of requirements for the assessment of the reuse potential factor.* It is assumed that if the qualification factors have a <u>high</u> score, the quantification factors score <u>lower</u> and this results in a <u>high</u> score for the reuse potential factor.

The qualification factors should be compared with the quantification factors to calculate the reuse potential factor. The qualification factors influence the quantification factors and not the other way around. Therefore, the qualification factors should be investigated to verify the workability of the model. These factors are divided into the functional performance, aesthetical performance with regard to the damage and the connections, and the additional performance related to the transportation and storage process. The technical and lifespan performance are excluded from the verification process because these performances do not influence the quantification factors. If these performances do not meet the 100% performance than the component cannot be reused and adjustments are not even possible due to the extreme adjustments that should be made.

Verification of the functional performance
The functional performance includes four variables; the fire-resistance, the sound-insulation, the number of block-outs, and the type of finishing layer. These four variables have been issued by means of a low and high number of influences in order to indicate the impact on the environment and economy.

The fire-resistance and sound-insulation do influence the reuse potential factor, because if the fire-resistance or sound-insulation performance needs to be improved and an extra top layer and finishing floor should be applied. It is assumed that this will extremely increase the environmental costs. Based on the environmental class of materials (see subparagraph 4.5.2.1 *Environmental impact factor*), the costs of the component will become 3-4 times higher than the modified HCS component due to the harmful materials required for the modification of the component. However, the economic costs will not be raised extremely, because the materials are not expensive for the extra top layer and finishing floor. Also, the number of block-outs and the finishing layer will not have a major impact on the costs, because less material is needed for the upgrade. It is assumed that the costs will become 10-20% higher.

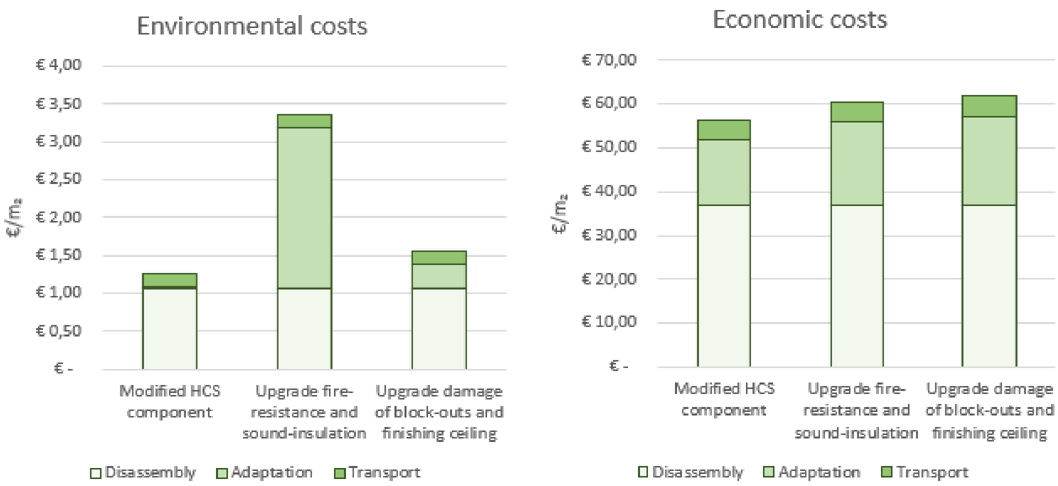


Figure 39. Verification of the functional performance; the effect of the upgrading relative to the costs.

Figure 39 shows the result of adjusting the fire-resistance, sound-insulation, damage to the block-outs, and the finishing ceiling. It can be concluded that the environmental costs become extremely higher due to the upgrade of the fire-resistance and sound-insulation and therefore the reuse potential factor will become lower.

Verification of the damage performance (aesthetical performance)
The damage performance of the component is based on the factor of the reusability. The reusability can be determined based on the damage rate of each damage that will occur. It is assumed that the higher the damage rate, the higher the costs will be due to the extra materials and equipment needed for the upgrading of the floor component. However, the environmental costs will rise faster because the required materials have a higher impact on the environment.

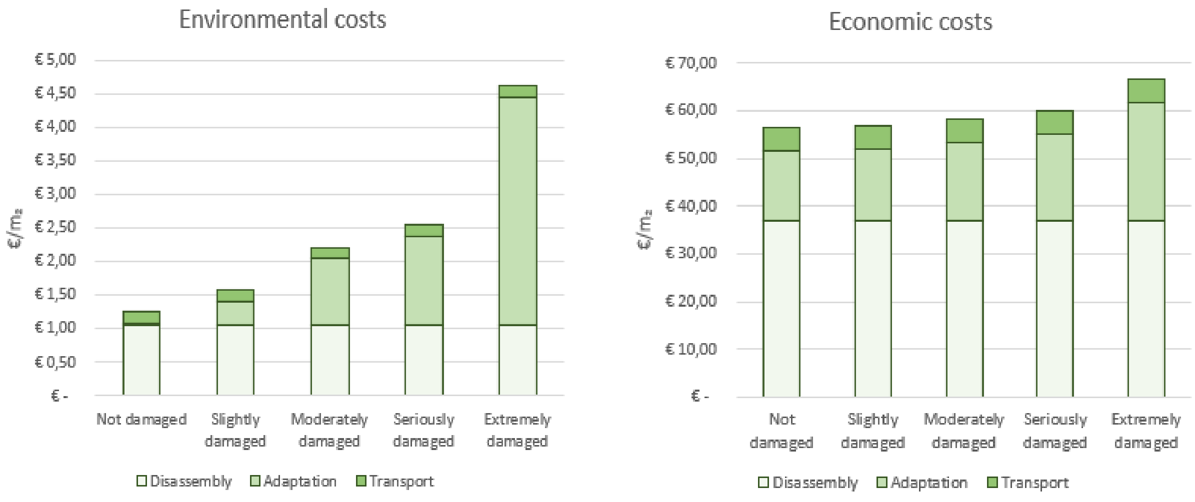


Figure 40. Verification of the damage performance; the effect of the upgrading relative to the costs.

Figure 40 shows the economic costs and the environmental costs compared to the damage rate. The environmental costs for the extremely damaged component are high compared with the other environmental costs. The reason for this is that harmful materials are required for the modification of the component to resolve the extreme damage caused by the fire and the damage of the steel reinforcement. The many required materials to solve this damage increase the costs. However, the economic costs have not risen that fast because the materials needed for the upgrade of the extremely damaged component are not too expensive per m^2.

Verification of the connection performance (aesthetical performance)

The performance of the connections is related to disassembly possibilities. If the component is easier to disassemble, the less energy and equipment are required for the disassembly process. Therefore, the environmental and economic costs will become lower. The costs compared to the disassembly rate will be verified.

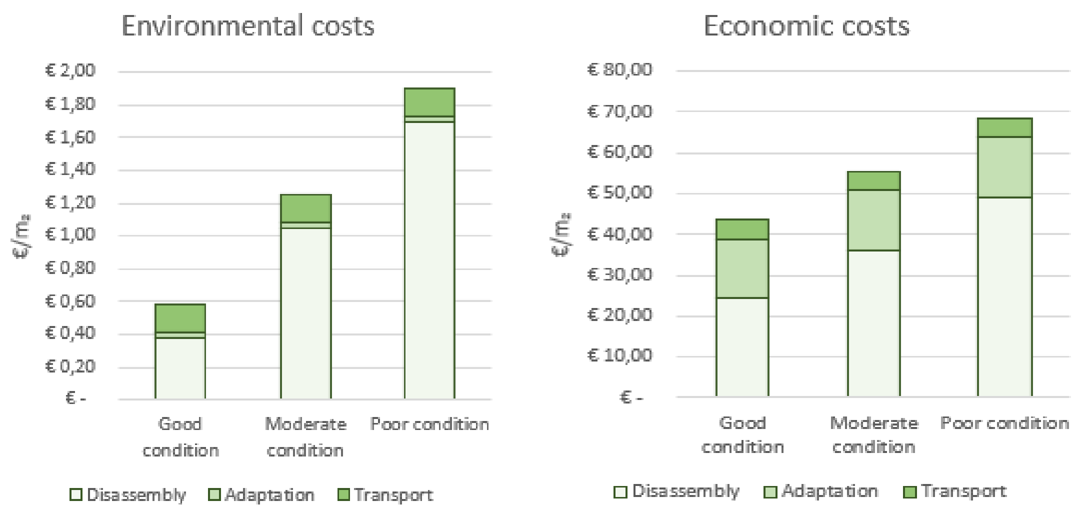


Figure 41. Verification of the connection performance; the effect of the upgrading relative to the costs.

Figure 41 shows the influence of the condition of the connections on the disassembly process. Both the environmental and economic costs rise because more connections should be sawn and more building workers and extra equipment are required. The economic costs rise faster in percentage than the environmental costs, this is because the economic costs for sawing the connections are very high per m^2. The reuse potential factor is lower for the poor condition of the connections. This was also assumed and it can be concluded that the model gives realistic results.

Verification of the transportation process (additional performance)

The costs for the transportation process will be influenced by the number of kilometers and the number of tons to be transported. This should be indicated by the model as well. The assumption is that the number of kilometers will influence environmental costs extremely. The emissions of the trucks will be more than doubled for a distance of 100 kilometers compared to the distance of 50 kilometers. The economic costs per kilometer for transportation will not rise a lot.

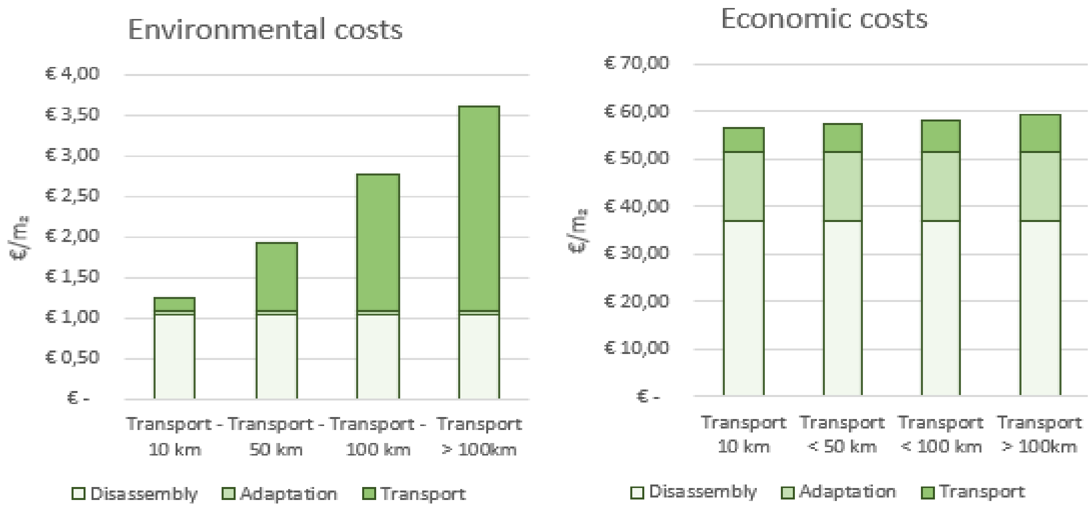


Figure 42. Verification of the transportation performance; the effect of the upgrading relative to the costs.

Figure 42 shows that the transport distance has a large share of the emissions. The transportation of the HCS components over a distance of 50 km caused even more than half of the environmental costs of transportation over a distance of 10 km. The economic costs are almost not influenced by the number of kilometers. However, the reuse potential factor calculated by the model is lower when the transport distance increases.

Verification of the storage process (additional performance)

The storage process is about the number of years for the storage of the components. It is assumed that the storage area costs €12,- per m^2 per year (de Haan, 2019). The costs for the storage area is one of the losses for the component, but also the capital loss of the component should be investigated. The interest rate is 3.0 % (de Haan, 2019). Therefore, the economic costs for the storage of the components should become every year higher per slab due to these losses. The storage process does not have an influence on environmental costs, because no materials or equipment is required that can harm the environment.

Figure 43 shows the economic costs for the storage of the components. The more years the component will be stored at a storage location, the higher the costs will be. The model shows that the reuse potential factor became lower as the component should be stored for more years.

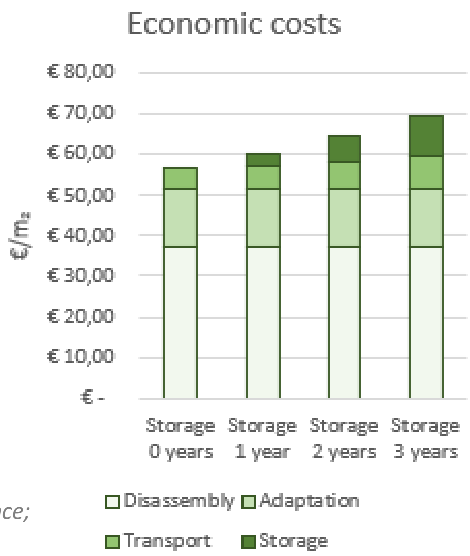


Figure 43. Verification of the storage performance; the effect of the upgrading relative to the costs.

6.3 'Sensitivity' of the decision support model

The decision support model can be used to measure the reuse potential factor. This factor is influenced by many different quality factors. These quality factors provide information about the possibility of reusing the existing component. The performance percentage of the quality factors can be determined by the decision support model. The 'sensitivity' of this performance percentage is indicated by the decision support model and it is concluded whether the component can still be reused with a few adjustments that should be made or the component can no longer be reused. The required adjustments will have an effect on the economic and environmental impact and thus influence the reuse potential factor. Therefore, the 'sensitivity' of the model is related to the quality factors.

1. *Lifespan performance*

The lifespan performance is divided into the technical lifespan performance and the functional lifespan performance. A building and its building components are designed for a specific lifespan – design lifespan – related to the function of the building. If the building no longer meets the functional requirements and expectations of the user, the building will no longer be used by the user/owner. There will be two options for the building, using the component for the same function or using the component for a different function. If the component will be reused for the same function, then it is important to investigate the remaining functional lifespan. The difference between the design lifespan and the number of years the building has been used is the remaining functional lifespan. The decision support model indicates that it is possible to reuse the HCS component if the remaining lifespan of the HCS component is longer than the design lifespan for the 'new' design with the same function. Figure 44 shows the different results about the reuse of the component or when it is not possible to reuse it.

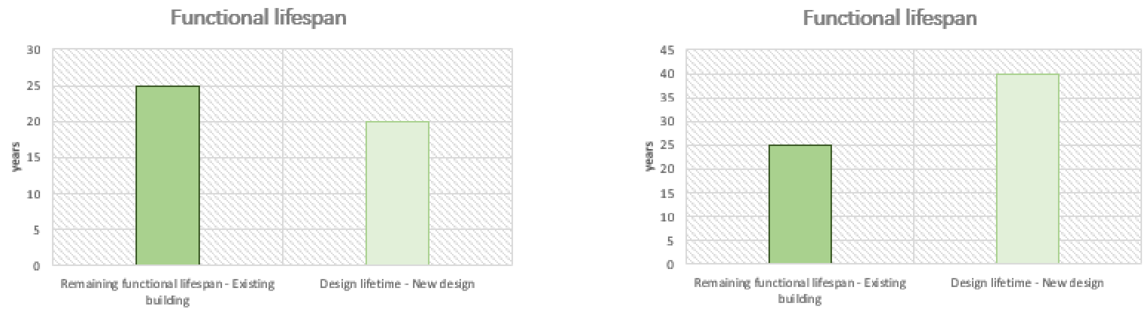


Figure 44. The 'sensitivity' of the functional lifespan for the reuse of the HCS component [Left: the existing building component can be reused; Right: it is not possible to reuse the component].

If the function of the new building is different from the function of the current building, then it is important to know whether the component is technically sufficient to be reused. The remaining technical lifespan of the HCS component is determined by the difference between the functional lifespan and the technical lifespan of the component. This remaining technical lifespan is compared with the design lifespan of the new building. Figure 45 shows the different results from the model about the possibility to reuse the component related to the remaining technical lifespan.

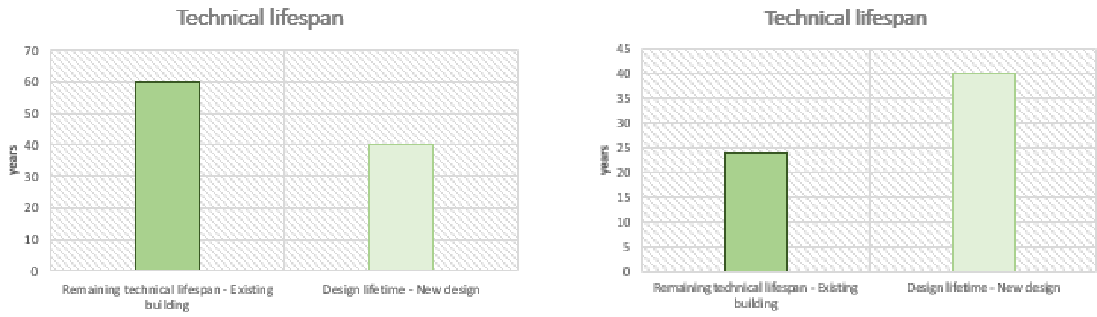


Figure 45. The 'sensitivity' of the technical lifespan for the reuse of the HCS component [Left: the existing building component can be reused; Right: it is not possible to reuse the component].

2. *Technical performance*

The technical performance is calculated based on the technical information of the existing HCS component and the newly fabricated HCS component. The technical performance is influenced by the general technical properties and the structural properties of the component. The general technical properties are the length, height, width, weight, amount of reinforcement, and the quality of the concrete. These general properties have an effect on the percentage of technical performance. Figure 46 shows the general properties of the existing HCS component (colour: *dark green*) that are set to 100 percent because these are the properties the element can provide for the new construction. The general technical properties required for the new floor construction are also included (colour: *light green*). If the required general technical properties are within the lines of the general properties for the existing HCS component, then the properties of the existing component are sufficient for the new construction (figure 46 - left). However, if the required general properties are not within the lines and will become outside the octagon, then the properties of the existing component will not be sufficient for the new construction and the component cannot be reused for the specific new building construction. For example, if the length of the existing HCS component is shorter than the length required for the new floor construction, the floor component cannot be reused for this specific new floor construction. And this is mentioned in the decision support model.

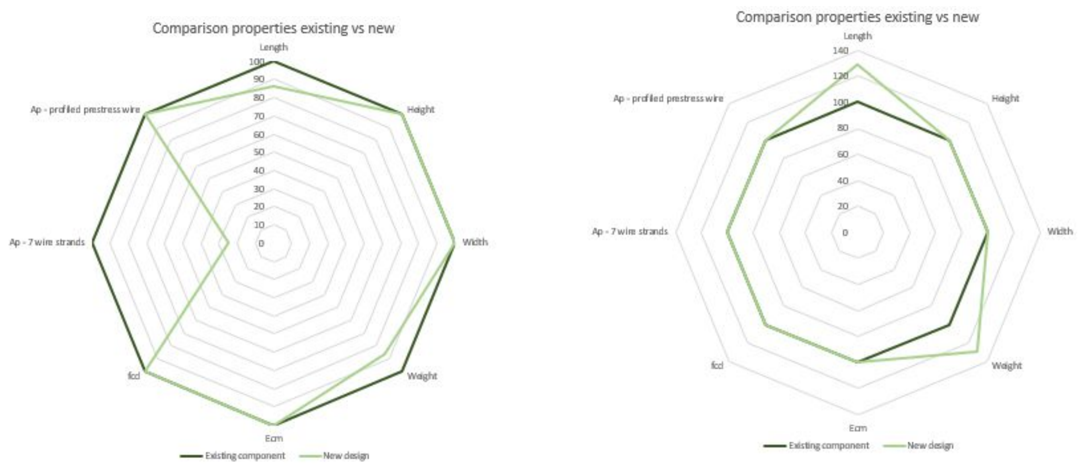


Figure 46. The 'sensitivity' of the general technical properties of the HCS component [Left: the existing building component can be reused; Right: it is not possible to reuse the component].

Also, the structural properties for the existing HCS component and the required structural properties for the new construction are determined based on the technical information. The structural properties of the existing HCS component are set to 100 percent. The model shows that if the required structural properties percentage for the new construction scored lower (or at the same level) than the percentage of the existing HCS component, the component can be reused otherwise it is not possible to reuse the component, see figure 47.

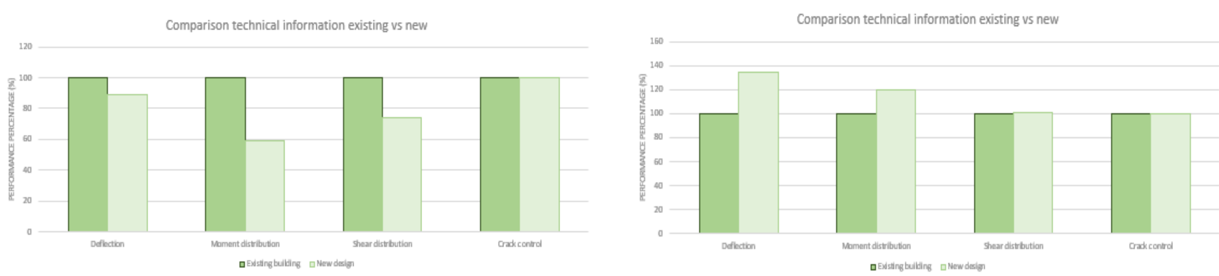


Figure 47. The 'sensitivity' of the structural properties of the HCS component [Left: the existing building component can be reused; Right: it is not possible to reuse the component].

3. *Functional performance*

The functional performance can influence the possibility to reuse the component as well. If the functional performance of the existing HCS component do not fulfil the required functional performance for the new construction, some adjustments to the component will have to be made before it can be reused. The decision support model explores the fire-resistance, sound-insulation, amount of block-outs, and the finishing performance. It applies that if these performances of the existing component have a higher level than the required performance, the component can be reused without having to make adjustments to the component, see figure 48 from the decision support model. An exception is the impact sound level and camber. For the impact sound level, it is known that the lower the impact sound level, the better the sound insulation will be. For the camber, it is assumed that the camber of the existing component should be lower than the maximum allowable camber for the new construction. Therefore, the performance of the impact sound level and camber of the existing component should be lower than the required performance for the new construction. The difference between the functional performances of the existing component and the required performance for the new structure has been calculated. If the difference in percentage is positive, then the model indicates that it is possible to reuse the component otherwise the component can only be reused after adjustments have been made.

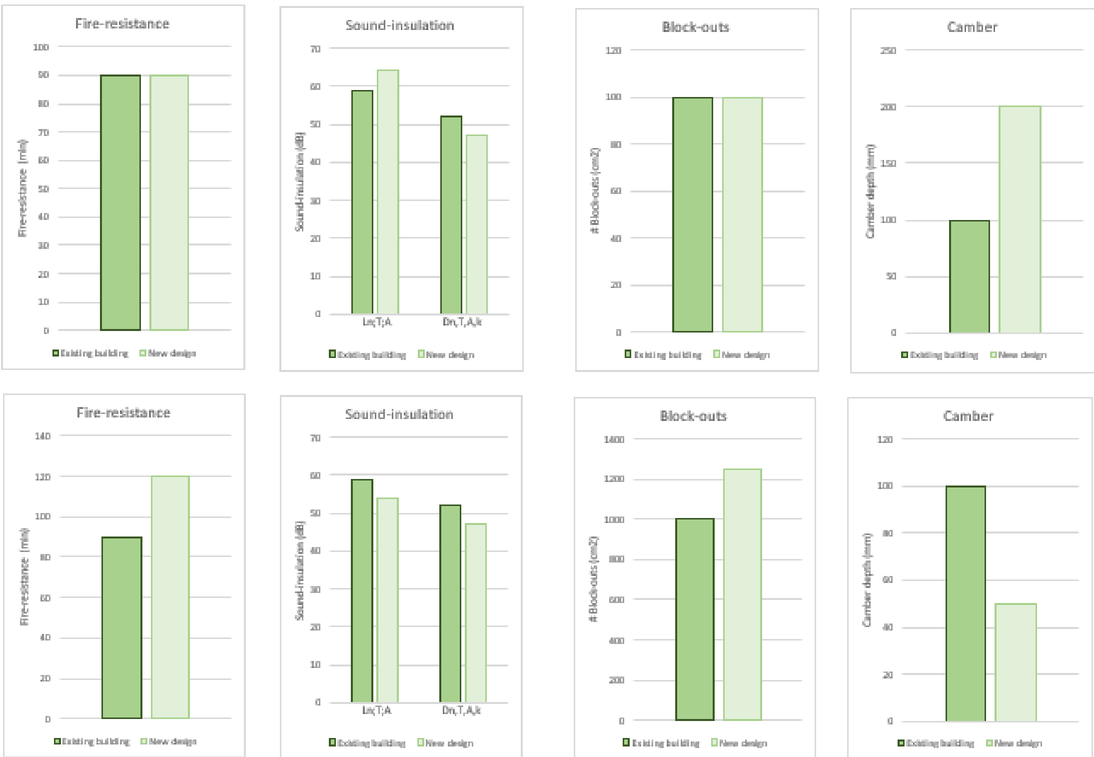


Figure 48. The 'sensitivity' of the functional performance of the HCS component [Above: the existing building component can be reused; Below: it is not possible to reuse the component].

4. *Aesthetical performance (damage)*

The aesthetical performance is influenced by the damage to the component. A component can be damaged during its lifecycle. The more damage to the HCS component, the more influence it has on the choice to reuse the component. If the component has a lot of damage, more will have to be repaired and the environmental and economic costs will become higher as a result. The decision support model shows a graph that indicates the reusability factor – the possibility to reuse the component related to the amount of damage – of the HCS component. The higher the percentage of the reusability factor for 'definitely', the fewer adjustments that have to be made to the component in order to be reused. Figure 49 shows the 'sensitivity' of the reusability factor related to the amount of damage. Based on this data, the model mentioned a percentage for the aesthetical performance and indicates whether adjustments are needed.

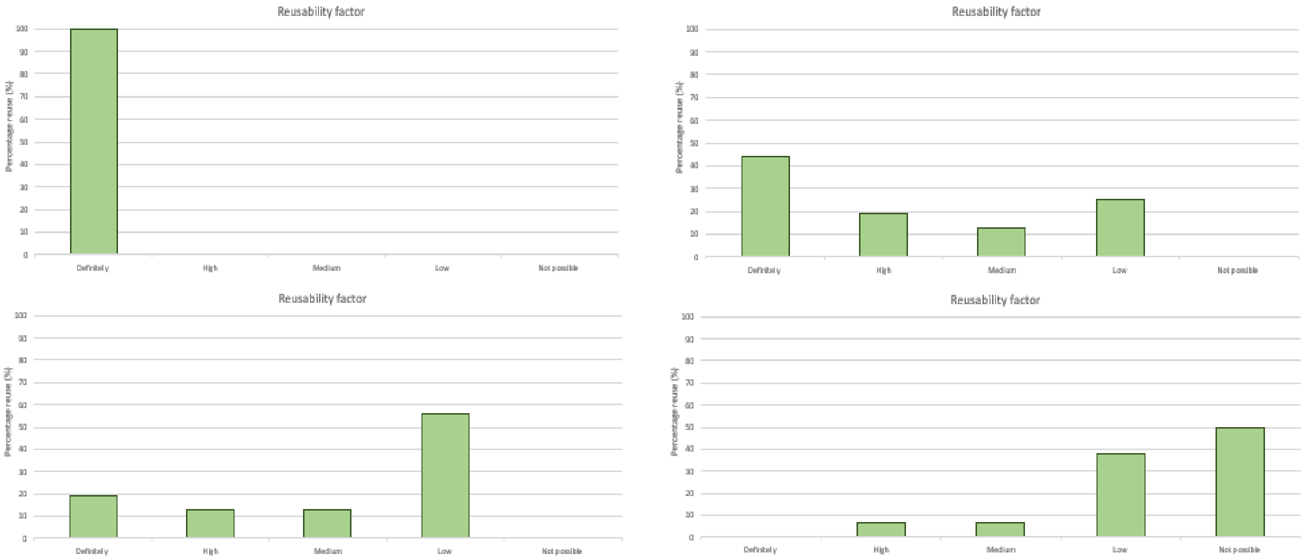


Figure 49. The 'sensitivity' of the aesthetical performance (damage) of the HCS component [Above left: no damage (100%) - definitely reusable; Above right: slightly damaged (70%) - reusable with some adjustments; Below left: moderately damaged (50%) - reusable with many adjustments; Below right: seriously damaged (20%) - almost not reusable anymore].

5. Aesthetical performance (connections)

The aesthetical performance related to the connections influences the disassembly process if the component will be reused. The type of connection(s) of the HCS component says something about the difficulty of the disassembly process. If the disassembly process is not so easy, more equipment, tools, materials, and effort are needed and it possible that the component will be more damaged. The disassembly factor – the possibility to easy disassembly the component related to the type of connections – of the component can be determined based on the information entered about the connections of the HCS component. The more dry and flexible connections the component has, the easier the disassembly process will be. The decision support model shows a graph that indicates the disassembly factor of the component. The higher the percentage of the disassembly factor for 'definitely', the easier it is to disassemble the component from the existing structure. Figure 50 shows the graph of the decision support model that indicates the 'sensitivity' of the disassembly factor related to the type of connections. Based on this data, the model mentioned a percentage for the aesthetical performance and indicates whether adjustments are needed.

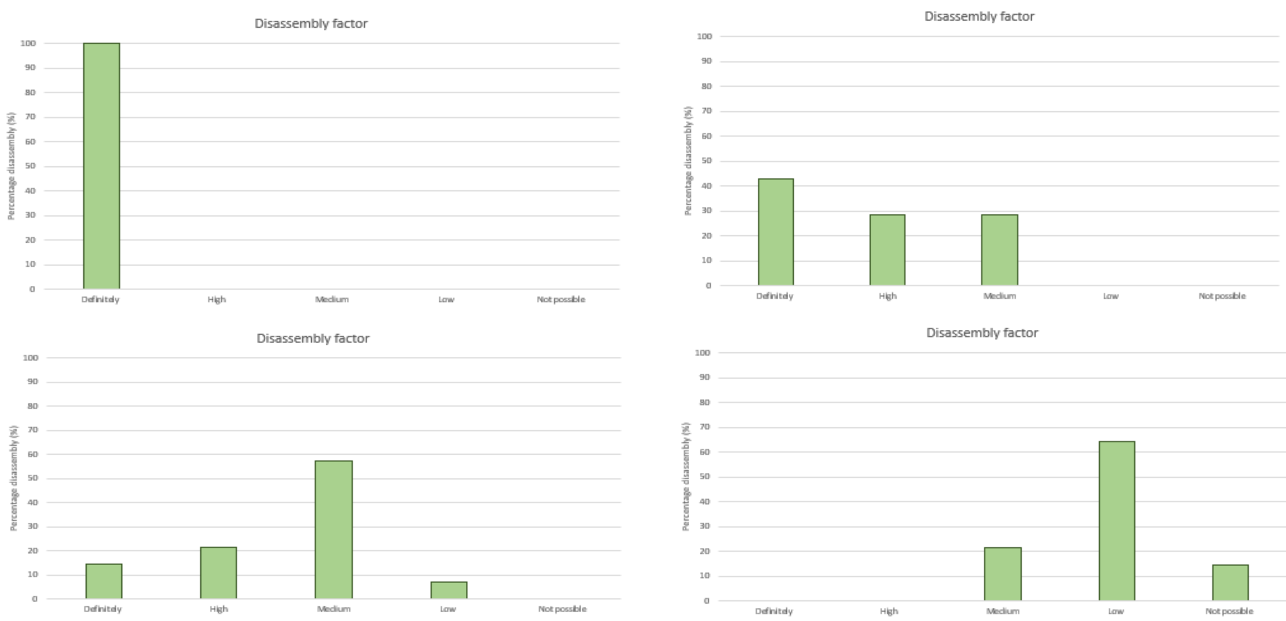


Figure 50. The 'sensitivity' of the aesthetical performance (connections) of the HCS component [Above left: dry/flexible connections (100%) - definitely possible to disassemble; Above right: less dry/flexible connections (70%) - disassembly possible but the component should be a little bit damaged; Below left: dry/flexible and wet connections (50%) – disassembly is difficult; Below right: no dry/flexible, but wet connections (20%) - disassembly almost not possible without damaging the component].

6. *Additional performance*

The additional performance is influenced by maintenance performance, reassembly performance, transport performance, and storage performance. The decision support model shows that the more the component is damaged, the more inspection should be needed during the second lifecycle (see figure 51). Also, the decision support model shows the influence of the transport performance. The longer the distance for the transportation of the components or the more routes the transport consists, the more effect it will have on the reuse potential factor, see figure 52. Research has shown that a transport distance above 50 km will have a big influence on the environment and economy. Therefore, a transport distance of more than 50 km will lower the additional performance. The number of transportation routes has also an effect. The best situation is when the component does not have to be transported – none transportation routes. The normal situation – the reference situation – is that the component is transported one time to the desired location. If the truck still has to travel several more routes, then it will lower the additional performance.

Figure 51. The 'sensitivity' of the inspection related to the maintenance performance.

Figure 52. The 'sensitivity' of the additional performance related to the transportation process [Left: the transportation performance are lower than the reference situation – the impact is low; Right: the transportation performance are higher than the reference situation – the impact is high and the reuse potential factor will be lower].

The reassembly of the component is most influenced by the sawing process to cut the component to the right size. The floor plans for every building is different and, therefore, the costs for sawing of the slabs are also different. The cost of sawing the HCS floor component of 4,8 meters is around **€** 9,05 per m^2. If the length of the floor component increases, the costs will decrease. This is because less sawing is needed per m^2 of the floor component. Naber (2012) did also some research on this phenomenon and concluded the following figure 53. The extra costs of the reused floor component differ from 18 % to 29 % compared to a fabricated HCS floor component (Naber, 2012). So, to reach a high reuse potential factor, the length of the component should be as long as possible.

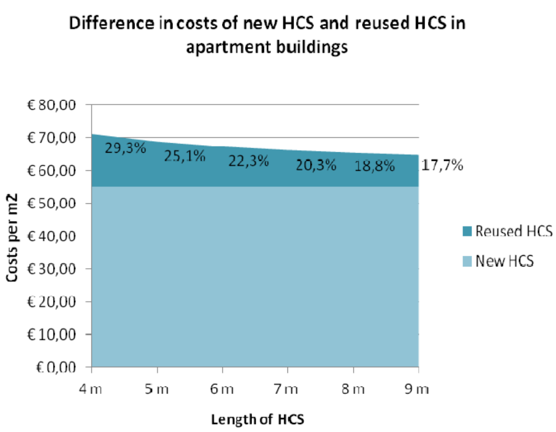


Figure 53. Difference in costs of new HCS component and reused HCS component (Naber, 2012).

6.4 Results of the decision support model to measure the reuse potential

The HCS floor component from an existing building can probably be reused in a new building structure. However, the question is whether the existing floor component can meet the requirements set for the new building structure. These requirements differ per building project because it depends on the function of the building. A new building project can be designed for the same function as the existing building or for a different function. Specific requirements should be met for each function. Therefore, the function of the existing building and the possible scenario functions for the new building project influences the potential to reuse the existing HCS component. The reuse potential factor of an HCS component from an existing building project has been tested.

6.4.1 Existing building and various situations as input for the decision support model

One of the most common buildings constructed with HCS floor components are office buildings (non-residential) (Naber et al., 2013). Therefore, the function of the existing building is an office building. A reference project of IMd Raadgevende Ingenieurs is used as input for the decision support model as the existing building type. Three different function situations are elaborated as input for new constructions.

Existing building - Office building (non-residential)

The office building is two-story high and has a floor construction that consists of HCS floor components. The type of HCS floor component is an HCS component with a thickness of 200 mm and it is fabricated by VBI. The strength property of the floor component is C45/55 and for the reinforcement is FeP1860. The strength class of the concrete topping is C20/25.

The floor components are divided into two groups because of the span. There are approximately 82 HCS floor components with a thickness of 200 mm and a span of 5560 mm. Also, there are approximately 35 HCS floor types with a thickness of 200 mm and a span of 4890 mm. All these HCS floor components are finished with a concrete top layer and a finishing layer. The general information about loads on the floor component is given in table 4.

	Dikte (mm)	Permanent – q_p (kN/m^2)	Distributed load - q_k (kN/m^2)	Instantaneous factor		
				Ψ0	ψ1	Ψ2
HCS component	200	3,20				
Concrete top layer	50	1,25				
Finishing	70	1,40				
Ceiling and pipes		0,25				
Distributed load			5,00			
Total		6,10	5,00	0,4	0,7	0,6

Table 4. General information about the loads on the hollow-core slab floor component of the office building (IMd Raadgevende Ingenieurs, 2019).

The HCS components are placed on a THQ beam when it is adjacent to a supporting wall and placed on an IPE200 when it is adjacent to another floor field. A THQ beam with one flange is used at the edges of the building. The beam is placed between the lower and upper supporting wall and the floor component is placed on the flange of this beam. A bar of 1 Ø 16 per plate is used for the anchoring (*in Dutch*: hamerkopsparing) of the component. See Appendix C.1 for more details of the connections of the floor components.

For the office function, the Dutch Building Decree 2012 has described the requirements of the fire-resistance and sound-insulating. The requirement for the fire-resistance performance of the floor component is 90 minutes (for a non-residential building lower than 25 meters). The requirements for the sound-insulation of this floor component are 59 dB for the impact sound level and 52 dB for the airborne noise level. Some of the floor components only have a few block-outs, because most of the pipes and wires are transported via a vertical shaft. A suspended ceiling ensures that the horizontal pipes are not visible.

Figure 54. The reference office building of two-story high.

It is assumed that the office building (see figure 54) will no longer be used as an office function after 25 years. The question is whether the non-damaged HCS components can still be reused. Remark: this information of the office building is based on the information of a building project of IMd Raadgevende Ingenieurs. This building project can be found in Appendix C.1 and the details about the project as well. The functional requirements are based on general information from the database of the model. This general information for the database is from the Dutch Building Decree 2012 and can be found in Appendix A.3-A.5.

It has to be investigated whether it is possible to reuse the HCS floor component from the existing building. The reuse potential of the floor component depends on the function of the new building project. Therefore, different function situations are elaborated and these should be compared with the variant of the existing building. The situations are discussed with a construction project manager, E. Bleuel, to get realistic values to be entered as input in the decision support model (Bleuel, 2019).

Situation 1: New building project with the same function

The HCS components of the existing building can be reused in a new building project that has the same function as the function of the existing building. If the function of the buildings is the same, then the existing performance and the required performance for the new building project will almost match. This could be an advantage for the reuse of the floor components because there are not many adjustments to be made to the component.

Input for the decision support model

The new building project will become a new office building. For the reuse of the HCS components, technical quality, fire safety, and sound insulation quality are the most important criteria (see table 5). The performance of the floor components should meet these requirements or the performance should be lower than these requirements.

Building height	Design load	Fire safety	Sound-insulation	
			impact sound level	airborne noise level
< 5 m	2,5 kN/m2	60 min	≤ 64 dB	≥ 47 dB
5-13 m	2,5 kN/m2	90 min	≤ 64 dB	≥ 47 dB
> 13 m	2,5 kN/m2	120 min	≤ 64 dB	≥ 47 dB

Table 5. Design load (VBI, 2019), fire safety (Boot-Dijkhuis, Eggink-Eilander, Ruytenbeek, & van den Berg, 2014), sound-insulation requirements (Bouwbesluit, 2012) for HCS floor component in an office building.

An assumption has been made for the new design of the office building. The new office building should be designed for a lifetime of 50 years. The highest floor of the office building is approximately 14 meters above the ground. The grid designed for this building project is 5200 by 1200 mm. The floor components will be supported by two supports at each end of the component. For this office building it is important that the reused floor component is completely restored and, therefore, it looks like a 'new' component. The construction site of the new building project is about 50 km from the deconstruction site.

Situation 2: New building project with a different function
The new building project can also be designed for another function than the function of the existing building. If the HCS component will be reused in a building with another type of function, the performance and the requirements of the new building project will be different. Therefore, some adjustments to the component will probably have to be made to meet the requirements set for the new building project.

Input for the decision support model
A residential building like a single-family house or apartment building could be the new building project and it is designed with a floor construction of HCS components. The required technical quality, fire safety and sound-insulation quality for this type of function are described by the Dutch Building Decree 2012 and it is shown in table 6. If the performance of the floor component is lower than the requirements of the new building project, then some adjustments to the floor component will have to be made. The ceiling of a residential building is almost always visible. Therefore, the bottom of the floor should be properly finished before it is reused.

Building height	Design load	Fire safety	Sound-insulation			
			impact sound level		airborne noise level	
			Single-family house	Apartment building	Single-family house	Apartment building
< 7 m	1,75 kN/m2	60 min	≤ 59 dB	≤ 54 dB	≥ 52 dB	≥ 52 dB
7 - 13 m	1,75 kN/m2	90 min	≤ 59 dB	≤ 54 dB	≥ 52 dB	≥ 52 dB
> 13 m	1,75 kN/m2	120 min	≤ 59 dB	≤ 54 dB	≥ 52 dB	≥ 52 dB

Table 6. Design load (VBI, 2019), fire safety (Boot-Dijkhuis et al., 2014), sound-insulation requirements (Bouwbesluit, 2012) for hollow-core slab floor components in a residential building.

An assumption has been made for the new design of the single-family house and low-rise apartment building. The residential building will be designed for 50 years with the highest floor approximately 6 meters above the ground. The grid designed for this building project is 4800 by 1200 mm. The floor component will be accepted if it aesthetically performs. The construction site of the new building project is about 50 km from the deconstruction site.

These two situations described different possible functions of the new construction and the existing building is a general building. However, there are also already buildings that are designed to be a demountable building and this will also be a future perspective. This situation should also be tested. Therefore, it is assumed that the reference project of IMd Raadgevende Ingenieurs is a demountable building with demountable HCS components. All the dimensions, load cases, and functional performances are the same.

Situation 3: Future perspective of a demountable building
The existing building consists of demountable floor components. Therefore, the connections between the components and the surrounding supporting walls are demountable connections and the floor component can be easily removed from the existing building and reassembled in the new demountable building structure.

Input for the decision support model
The assumption of the new design of the new demountable building will be a store building of two stories high. Table 7 shows the technical quality, fire-safety and sound-insulation requirements for this type of building. Since the components are demountable, the disassembly process will be easier because the connections do not have to be cut. However, it is necessary to check if the component meets the requirements for the new function.

Building height	Design load	Fire safety	Sound-insulation	
			impact sound level	airborne noise level
< 5 m	4,0 kN/m2	0 min	≤ 64 dB	≥ 47 dB
≥ 5m	4,0 kN/m2	90 min	≤ 64 dB	≥ 47 dB

Table 7. Design load (VBI,2019), fire safety (Boot-Dijkhuis et al., 2014), sound-insulation requirements (Bouwbesluit, 2012) for HCS components in a store building.

The assumption is that the store building will be designed for a lifetime of 15 years. The grid designed for this building project is also 5560 by 1200 mm. The floor component should not be too damaged before it will be placed in the new store building. The component does not have to be sawn to length, because the required length is the same as for the existing component.

6.4.2 The comparison of the various situations

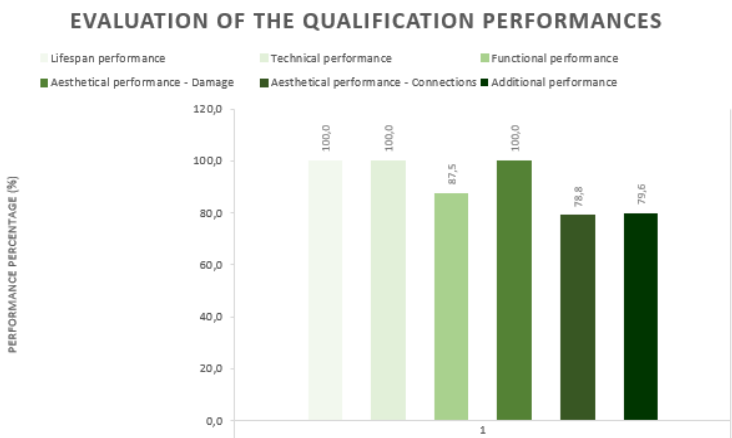
The data of the existing building and the data of the different situations can be compared by the decision support model. As a result, the reuse potential factor of the HCS floor component can be determined. The data of the existing building has already been processed in the model. The results of each situation are described below.

Situation 1: New building project with the same function

The HCS component of the existing building will be used in a newly designed office building with a dimension of 5200 x 1200 mm. Therefore, it is known that the reused HCS component should be sawn to size after it is taken out of the existing building. The information about the newly designed office building is included in the decision support model. As a result, the requirements of the newly designed office building and quality of the existing floor component is tested and compared with the required quality performance.

Quality performance test

The quality of the existing floor component is tested and compared with the required quality performance of the newly designed office building. As a result, the decision support model calculates the percentage of the quality of the existing HCS floor component for each performance. Therefore, the database included in the model and the data entered about the existing and new building is used. The outcome of the quality performance test of the decision support model is shown in figure 55.



	1
Lifespan performance	100,0
Technical performance	100,0
Functional performance	87,5
Aesthetical performance - Damage	100,0
Aesthetical performance - Connections	78,8
Additional performance	79,6

Figure 55. Evaluation of the qualification performances for scenario 1.

Both the lifespan and technical performance has the highest score of 100%. This score should also be achieved for these two performances, otherwise, it is not possible to reuse the component. The functional performance has a score of 87,5% - due to the low fire-resistance performance -, the aesthetical performances related to the connections has a score of 78,8% - due to the indirect connection and some wet connections at the position of the column -, and the additional performance has a score of 79,6% - due to the transportation and reassembly process. These three performances should be upgraded to 100% because the aim of the new office building structure was to have completely restored floor components.

Modification
For the functional performance, the fire-resistance of the floor component should be adapted. The concrete top layer should become thicker, and a concrete top layer of 70 mm will be sufficient. For the reassembly performance, the component is sawn to size, a new protective layer is applied to the exposed reinforcement, and the damage to the core and ceiling is restored. For the disassembly of the existing floor component, the component can be sawn to size directly at the deconstruction site by means of a diamond saw. A crane and building workers are required for lifting out the floor components from the existing building.

Environmental impact
The modification and disassembly phase influences the impact on the environment of the modified floor component. By comparing the process of the reusable floor component against the fabricated floor component, it becomes clear what the impact is of adapting the existing floor component to be prepared for reuse. Figure 56 shows the kg 1,4—DB equivalent per HCS floor component [dimensions: 5,2 x 1,2 m] and the kg CO_2 equivalent per HCS floor component [dimensions: 5,2 x 1,2 m].

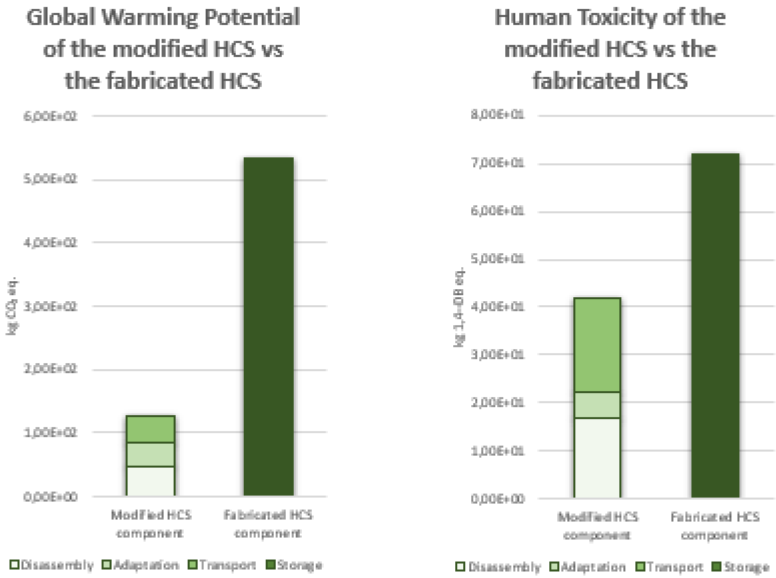


Figure 56. Comparison of the modified HCS component versus the fabricated HCS component for scenario 1.

From these comparisons, it becomes clear that the emissions for the fabricated HCS component are high compared to the emissions produced by the modified floor component. The share of the adaptation process for the modified HCS floor component is low with regard to human toxicity. The global warming potential of transport is relatively low.

The total environmental impact is based on the shadow price of the floor component. The shadow price for a new fabricated component depends on the building type of the new building – residential or non-residential –, the height of the building, and the designed grid dimensions. The shadow price for the new fabricated floor component for this new office building will be 45,67 €/per slab (incl. top layer). The shadow price for the modified floor component will be 14,36 €/per slab (incl. top layer). Figure 57 shows the shadow price of the modified HCS floor component and the fabricated HCS component, see also Appendix C.2.

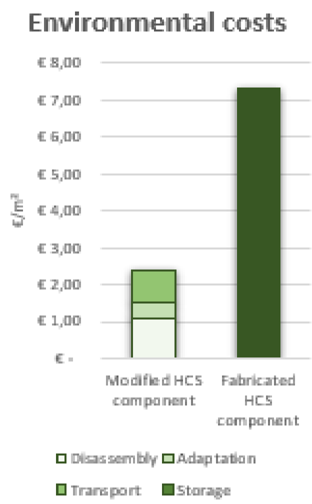


Figure 57. The shadow price per m2 for scenario 1.

The shadow price of the modified HCS floor component is relatively low relative to the fabricated HCS floor component. This is possible because the production process (incl. transportation) of a new HCS component costs a lot of energy. And as a result, a lot of harmful emissions will be produced during this process.

Economic impact
The adaptation of the floor component to the required performance also has an impact on the economic costs. The tools and equipment required for the modification and disassembly of the component influence the economic costs for the reuse of the existing HCS component. The production process of a newly fabricated HCS floor component also leads to economic costs. Figure 58 shows the economic costs of the modified HCS floor component compared to the economic costs of the fabricated HCS component (see also Appendix C.2).

Figure 58. The economic costs per m2 for scenario 1.

The economic costs for the new fabricated floor component are about € 296.40 per slab [47,50 €/m2]. To reuse the modified floor component from the office building, the costs are about € 350.37 per slab [56,15 €/m2] including the construction of the reassembly and disassembly process. This means that the modified HCS component is 18,2% more expensive than the new floor slab to be used.

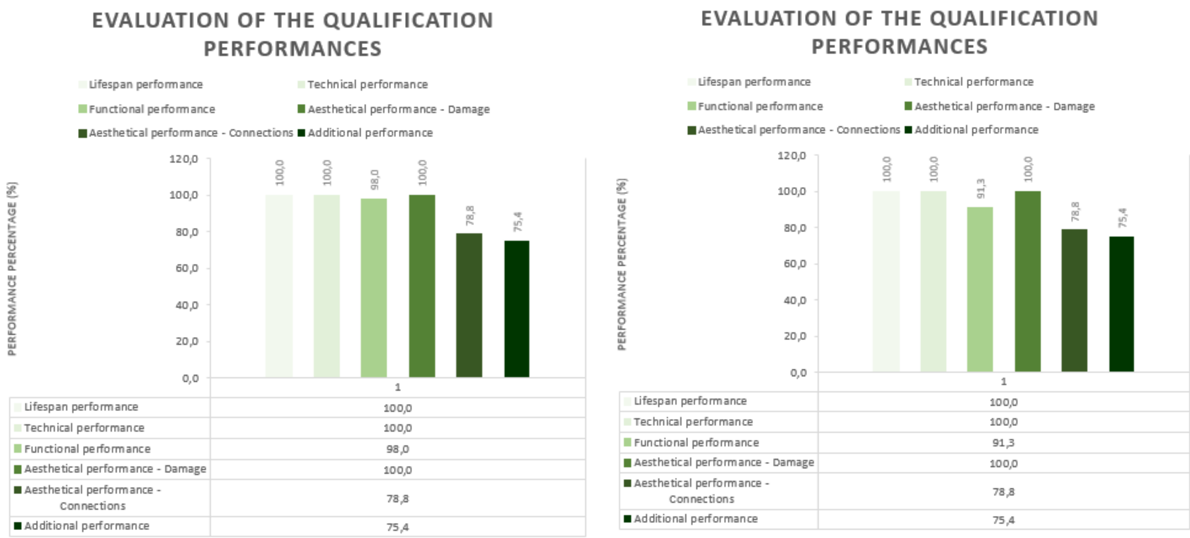
Reuse potential factor
As a result, the reuse potential factor for the hollow-core slab floor component from the existing office building is **0.82**.

$$RP = 1 - \left(\frac{18{,}2\% + 0\%}{100}\right) = 0{,}82$$

Situation 2: New building project with a different function
This situation describes the reuse of the existing HCS component in a new designed single-family house or a low-rise apartment building - both a residential function. The dimension of the floor component for both new buildings should be 4800 x 1200 mm. Therefore, the existing component should be sawn to size after it is disassembled from the office building. The data of the new designed single-family house and the low-rise apartment is entered in the decision support model. As a result, the requirements of the new designed single-family house and low-rise apartment building are known and the performance of the existing floor component can be compared to these requirements.

Quality performance test
The qualification performances of the existing floor component are tested and compared to the requirements for the new designed single-family house and low-rise apartment building. The outcome of the quality performance test is shown in figure 59.

For both cases - the single-family house and the low-rise apartment building - the lifespan and technical performance have reached the highest score of 100%. The functional performance differs per building type; the single-family house scores 98% - due to the finishing ceiling requirement – and the low-apartment building scores 91,3 % - due to the low sound-insulation level and the finishing ceiling requirement -. For both building types, the aesthetical performance related to the connections has a score of 78,8% - due to the indirect connection and some wet connections at the position of the column- and the additional performance has a score of 75,4% - due to the reassembly and transportation process. These performances should be upgraded to 100% because the aim for the single-family house and the low-rise apartment building was to reuse completely restored floor components.



	1
Lifespan performance	100,0
Technical performance	100,0
Functional performance	98,0
Aesthetical performance - Damage	100,0
Aesthetical performance - Connections	78,8
Additional performance	75,4

	1
Lifespan performance	100,0
Technical performance	100,0
Functional performance	91,3
Aesthetical performance - Damage	100,0
Aesthetical performance - Connections	78,8
Additional performance	75,4

Figure 59. Evaluation of the qualification performances for scenario 2 [Right: single-family house; Left: low-rise apartment building].

Modification

The modification process of the floor component for the low-rise apartment building is important and a floating floor is required for the upgrading of the sound-insulation performance. A floating floor with ΔLlin ≥ 14 dB is needed for this type of HCS component to reach the required sound-insulation level (see also appendix A.4). The floating floor consists of a finishing floor, an EPS layer, and a concrete topping. The bottom of the floor component should be sprayed because the bottom of the component will be visible in the apartment building. For the single-family house, the bottom of the floor component should be sprayed as well. The reassembly process, such as sawing the component to size, will be done directly at the deconstruction site. A crane and building workers are required for lifting out the floor components from the existing building. Trucks with a maximum load of 30 tons will be used for the transportation of the components.

Environmental impact

The modification phase has an impact on the environment because of the floating floor that is required for the low-rise apartment building and the sawing process to cut the component. The impact on the environment can become clear by comparing the process of reusing the floor component with the process of manufacturing the floor component. Figures 60 and figure 61 show the kg CO_2 equivalent per HCS component and the kg 1,4—DB equivalent per HCS component [dimensions: 4,8 x 1,2 m].

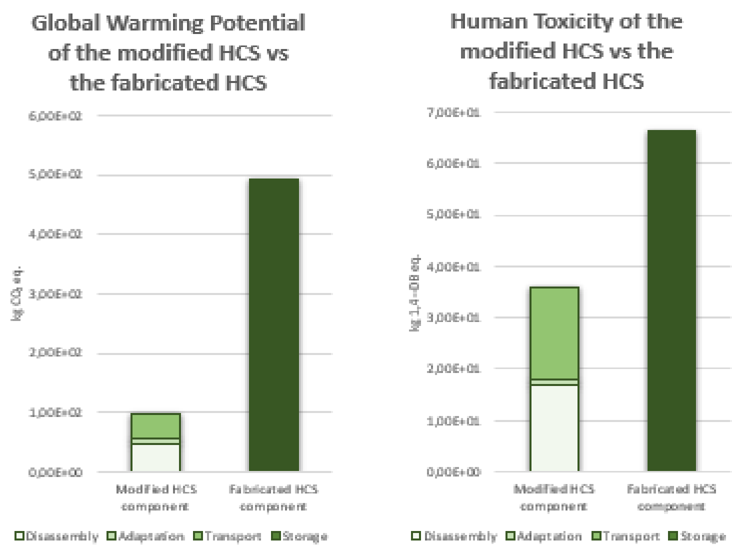


Figure 60. Comparison of the modified HCS component versus the fabricated HCS component for scenario 2 - single-family house.

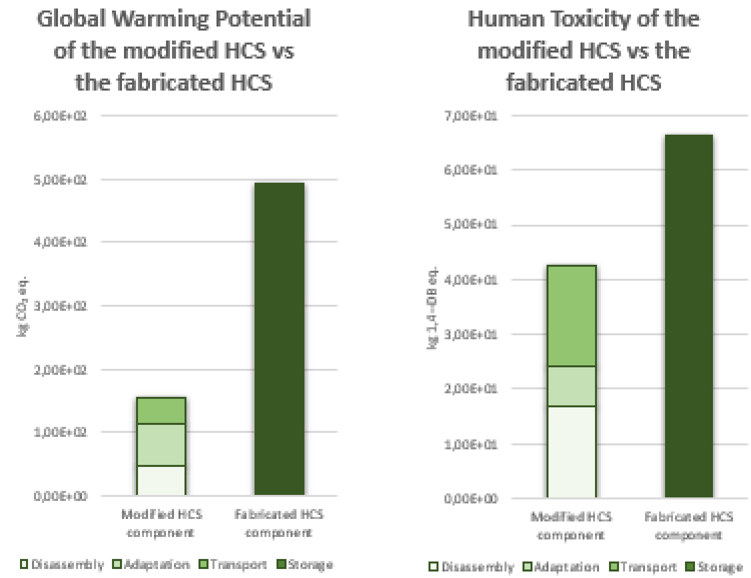


Figure 61. Comparison of the modified HCS component versus the fabricated HCS component for scenario 2 - low-rise apartment building.

For the global warming potential, the modification process to upgrade the sound-insulation has a large share in the emission compared to the disassembly and transportation process. However, the modification process only has a small share in the number of human toxicity emissions produced. The modification process of the floor component for the single-family house has almost no influence on the environmental impact. The shadow price for the fabricated component for both the single-family house and the low-rise apartment building will be 42,16 €/per slab (incl. top layer). The shadow price for the modified floor component will be 11.91 €/per slab (incl. top layer) for the single-family house and 16.42 €/per slab (incl. top layer) for the low-rise apartment building. Figure 62 shows the shadow price of the modified HCS component and the fabricated HCS component (see appendix C.3 & C.4).

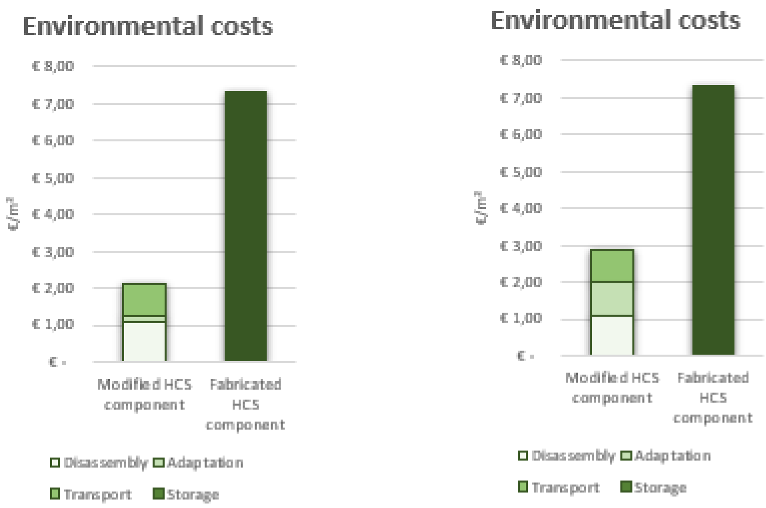


Figure 62. The shadow price per m2 for scenario 2 [Right: single-family house; Left: low-rise apartment building].

The shadow price of the modified HCS floor component for the low-rise apartment building is most influenced by the adaptation process of the floating floor. As a result, more harmful emissions will be produced during this process.

Economic impact

The modification process of the floor component to the required performance also has an impact on the economic costs. Figure 63 shows the economic costs of the modified HCS floor component compared to the economic costs of the fabricated HCS component for both building types, see also Appendix C.3 & C.4.

Figure 63. The economic costs per m2 for scenario 2 [Right: single-family house; Left: low-rise apartment building].

The economic costs for the newly fabricated floor component are about € 273.6 per slab [47,50 €/m2]. To reuse the modified floor component from the office building, the costs are about € 342.56 per slab [59.47 €/m2] for the single-family house and € 374.92 per slab [65.09 €/m2] for the low-rise apartment-building including the construction of the finishing floor, the reassembly, and disassembly process. This means that the modified HCS component is 25.2% more expensive than a newly fabricated floor slab for the single-family house and the component is 37 % more expensive than a fabricated slab for the low-rise apartment building.

Reuse potential factor

As a result, the reuse potential factor for the hollow-core slab floor component from the existing office building is **0.75** for the single-family house and **0.63** for the low-rise apartment building.

$$RP = 1 - \left(\frac{25.2\% + 0\%}{100}\right) = 0{,}75$$

$$RP = 1 - \left(\frac{37.0\% + 0\%}{100}\right) = 0{,}63$$

Situation 3: Future perspective of a demountable building

The last situation is about the future perspective of a demountable building. For this situation, it is assumed that the existing floor components are demountable HCS components. Therefore, the floor components can be disassembled from the existing building in an easy way. The connections of the floor components are made in such a way that the components do not have to be cut first, but the components can be lifted out directly from the building. The dimensions of the floor components for the newly designed building are the same as for the existing building. The new design will be a store building. The data of this new building is entered into the decision support model. As a result, the requirements of the newly designed store building are known and can be compared with the performance of the existing floor component.

Quality performance test

The qualification performances of the existing floor component are tested and compared with the requirements for the floor component of the newly designed store building. The outcome of the quality performance test is shown in figure 64.

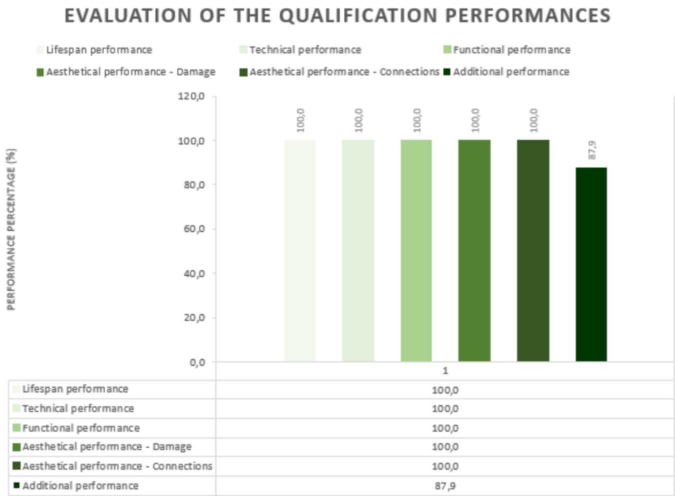


Figure 64. Evaluation of the qualification performances for scenario 3.

In this case, almost all qualification performances scored the highest score percentage. This is because the connections are demountable and, therefore, no extra equipment or building workers are needed to cut the components. The functional requirements of the newly designed store building are lower than the functional requirements for the existing office building. Therefore, the functional performance is met and reached a score of 100%. The technical performance is also sufficient despite the fact that it is a storage building that normally has a higher design load than an office building. In this case, the office building is charged with a higher design load than normally because this was already chosen during the design phase of this office building. Only the additional performance has a lower score of 87,9% due to the reassembly and transportation process. This performance should be upgraded to 100% to make it possible to reuse the component.

Modification

Only the additional performance needs to be addressed. Some fixings should be removed and some little holes due to the removing of the fixings should be recovered. The disassembly process will be easier because the components can be taken out directly from the building. However, this will take extra time because it should be done carefully. A crane and building workers are required for lifting out the floor components from the existing building. And trucks with a maximum load of 30 tons will be used for transportation.

Environmental impact

The disassembly phase and the transportation of the components have an effect on the impact of the environment. However, the modification of the component has less effect on the impact. The impact on the environment can become clear by comparing the process of reusing floor component with the process of fabricating the floor component. Figure 65 shows the kg 1,4—DB equivalent per HCS floor component [dimensions: 5,56 x 1,2 m] and the kg CO_2 equivalent per HCS floor component [dimensions: 5,56 x 1,2 m].

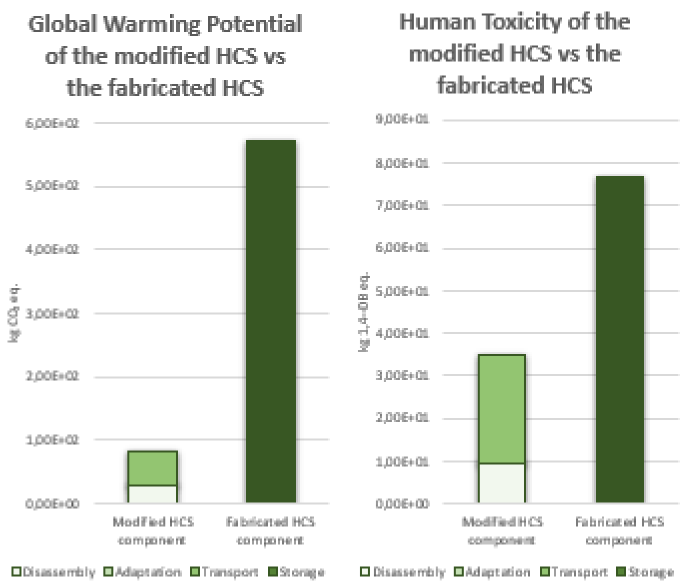


Figure 65. Comparison of the modified HCS component versus the fabricated HCS component for scenario 3.

The modification process has almost no influence because little has to be done for the modification of the component. The transportation of the component has the most impact on the environment, for both the global warming potential as for human toxicity. The shadow price for the newly fabricated floor component for this new storage building will be 48,83 €/per slab (incl. top layer). The shadow price for the modified floor component will be 10,32 €/per slab (incl. top layer). Figure 66 shows the shadow price of the modified HCS floor component and the fabricated HCS component, see also Appendix C.5.

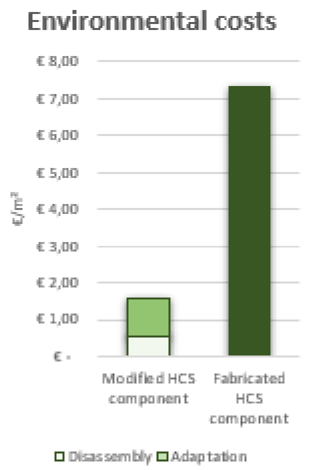


Figure 66. The shadow price per m2 for scenario 3.

The shadow price of the modified HCS floor component has hardly been affected by the adaptation process. Only the preparation for the reassembly of the component is still important in the modification phase. The transportation of the components will have the most impact on the environment in this case.

Economic impact

The adaptation of the floor component to the required performance also has an impact on the economic costs. Figure 67 shows the economic costs of the modified HCS floor component compared with the economic costs of the fabricated HCS component, see also Appendix C.5.

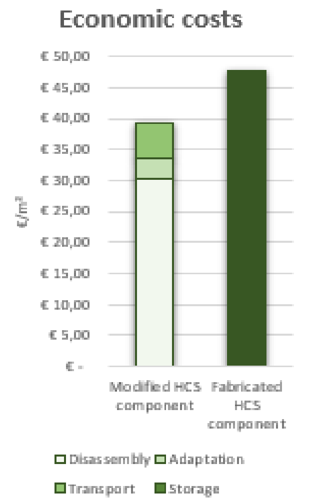


Figure 67. The economic costs per m2 for scenario 3.

The economic costs for the newly fabricated floor component including the construction of the finishing floor cost about € 316.9 per slab [47,50 €/m2]. To reuse the modified floor component from the office building, the costs are about € 258.79 per slab [38.79 €/m2] including the transportation costs, the adaptation costs, and the costs of the reassembly and disassembly process. This means that the modified HCS component is 18.3% cheaper than the new floor slab for a storage building.

Reuse potential factor

As a result, the reuse potential factor for the hollow-core slab floor component from the existing office building is **1.0**. And therefore it is definitely possible to reuse the modified HCS component.

$$RP = 1 - \left(\frac{0\% + 0\%}{100}\right) = 1.0$$

6.4.3 Changing parameters in the decisions support model

The reuse potential factor has been calculated for the three different situations. In chapter 4 *A systematic approach to assess the reuse potential of the hollow-core slab floor component* it was explained that if the reuse potential factor is between 0.7 – 1.0, it would be beneficial to reuse the floor components. The lower the reuse potential factor, the less likely it is to reuse the component in relation to the economic and environmental impact. The environmental and economic impact is affected by the quality performance of the existing component. In previous situations, the degree of quality of the existing HCS component has been assumed. However, the quality of the component can be different and this can have consequences for the reuse potential factor.

The reuse potential factor for the new office building scored well. However, the reuse potential factor may change if the parameters of the qualification performance change. It was assumed that the existing building components are not damaged, the transportation distance to the new construction site was only 50 kilometers, and no storage location was required. Changing these parameters in the decision support model will have an effect on the environmental and economic costs. The parameters are changed for scenario 1 - the new office building - to investigate the effect of these changes with regard to the reuse potential factor.

- *Damage performance*

The damage of the component influence the aesthetical performance of the floor component. It is important that the floor component is repaired before it is reused in the new structure. However, the modification of the floor component will have an effect on the economic costs and environmental costs. If the floor component is slightly, moderately or extremely damaged, it will have different influences on the reuse potential factor of the reused floor component.

The model made an estimation of the number of materials required to repair the damage. As a result, the economic costs and environmental costs could be calculated by using this data. The following figures (figure 68 & 69) show the economic and environmental costs of the floor component that is slightly, moderately or extremely damaged.

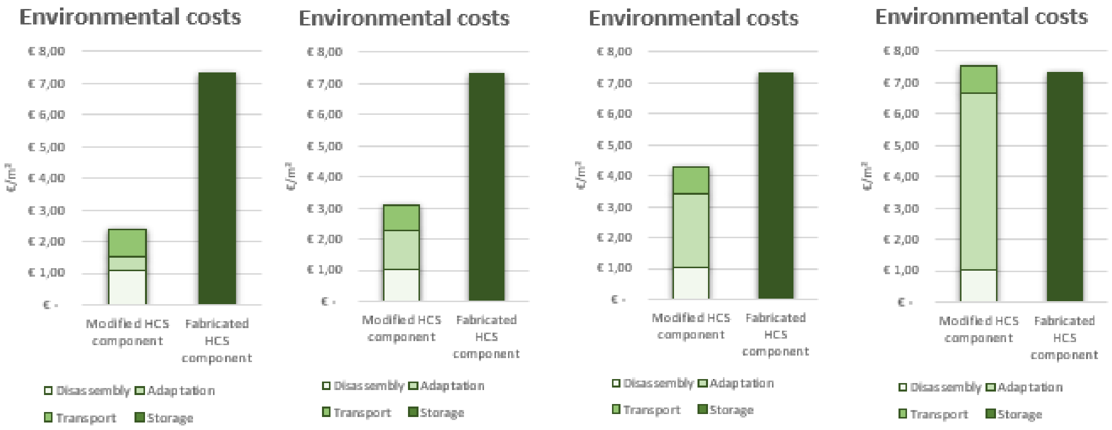


Figure 69. The environmental costs of a none damaged, slightly damaged, moderately damaged, and extremely damaged floor component.

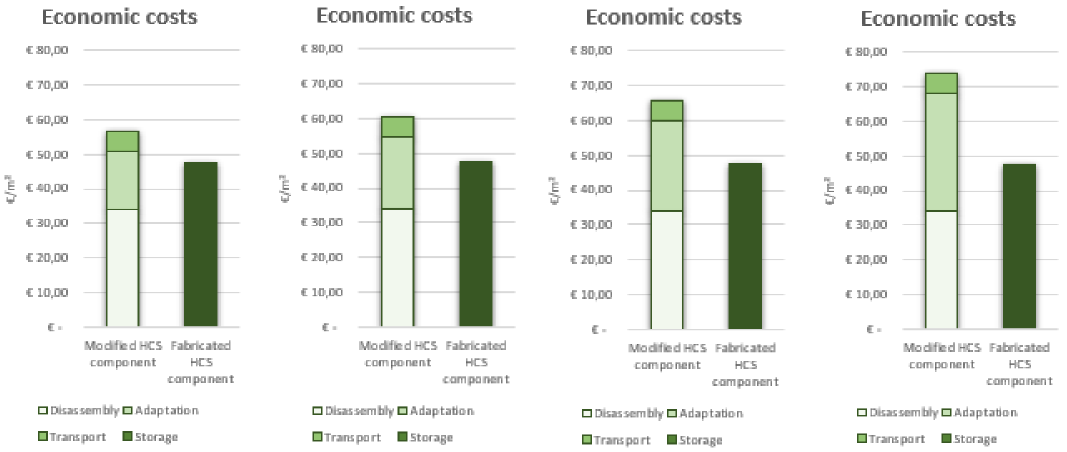


Figure 68. The economic costs of a none damaged, slightly damaged, moderately damaged, and extremely damaged floor component.

It can be concluded that the more damage the floor component has, the less favourable it becomes to reuse the floor component. The materials needed for the adaptation process cause a lot of harmful emissions. Both the economic and environmental costs for an extremely damaged floor component are higher than for a fabricated HCS floor component. These are major interventions and, as a result, a lot of harmful emissions are released and a lot of economic costs are incurred. In this case, it is definitely not possible to reuse the floor components. The reuse potential factors of the floor component related to these four variants of damage are **0.82** (none damage), **0.74** (slightly damaged), **0.62** (moderately damaged), and **0.0** (extremely damaged).

- *Transport process*

The transport of the floor components from the deconstruction site to the construction site also contributes to the economic and environmental costs. The costs depend on the distance to transport the floor component to the new construction site. For this scenario, a distance of 10 km, 50 km, and 100 km have been considered. The figures (figure 70 & 71) below show the differences in costs for transportation distances.

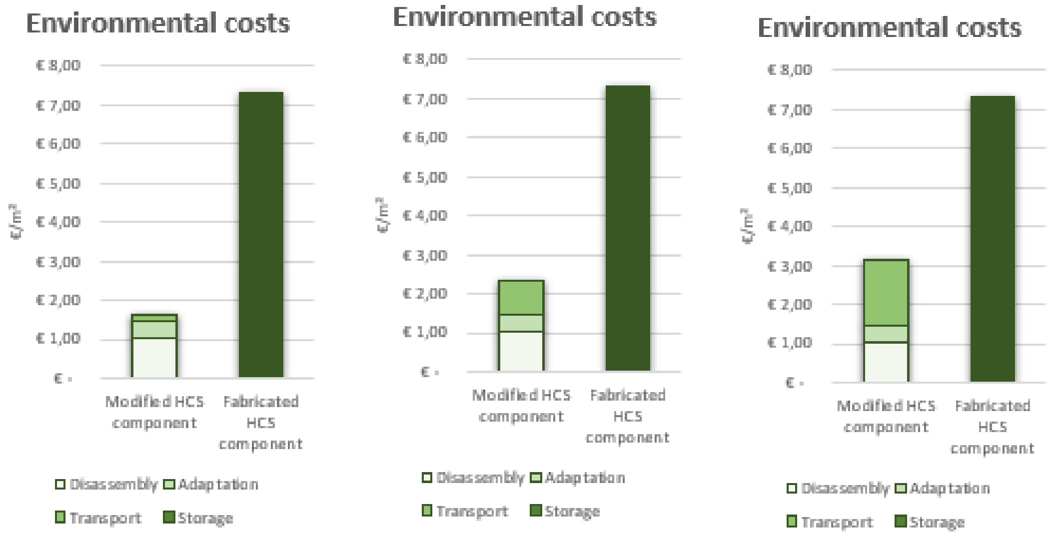


Figure 70. The environmental costs for the different transportation distances: 10 km, 50 km, and 100 km.

Figure 71. The economic costs for the different transportation distances: 10 km, 50 km, and 100 km.

The transportation process to transport the floor components from the deconstruction site to the construction site influences mainly the environmental costs. The environmental costs for the transportation distance of 100 km are more than doubled compared to the distance of 50 km. Therefore, the longer the distance to the construction site, the more extreme the impact is on the environment. The economic costs increase less rapidly. The reuse potential factors of the floor component related to these three various transportation distances are **0.83** (distance of 10 km), **0.82** (distance of 50 km), **0.79** (distance of 100 km).

- *Storage process*

The floor components will be stored at a storage location before the components can be constructed in the new office building. The economic costs are influenced by storing the components. The environmental costs are not affected by the storage process, because no harmful emissions will be released when storage the components. However, the components should be transported to the storage location and this will have an impact on the environment. The components should be transported to the storage site and after the storage time to the deconstruction site. Therefore, the transportation distance will be longer and the trucks will have to transport the components twice. This will higher the costs, both economic and environmental. It is assumed that the storage location is approximately 20 km from the construction site. The figures (figure 72 & 73) below show the environmental and economic impact of the storage process.

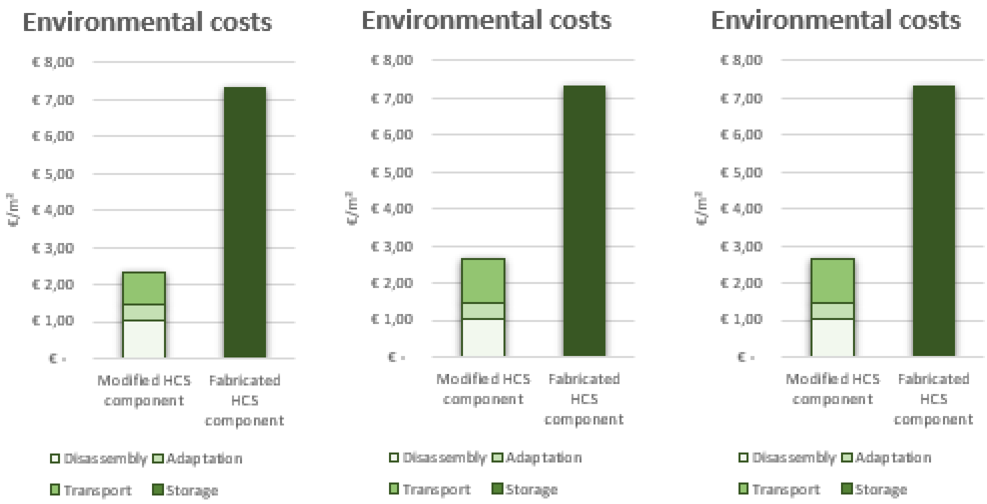


Figure 72. The environmental costs for the various storage times: 0 years, 1 year, and 2 years.

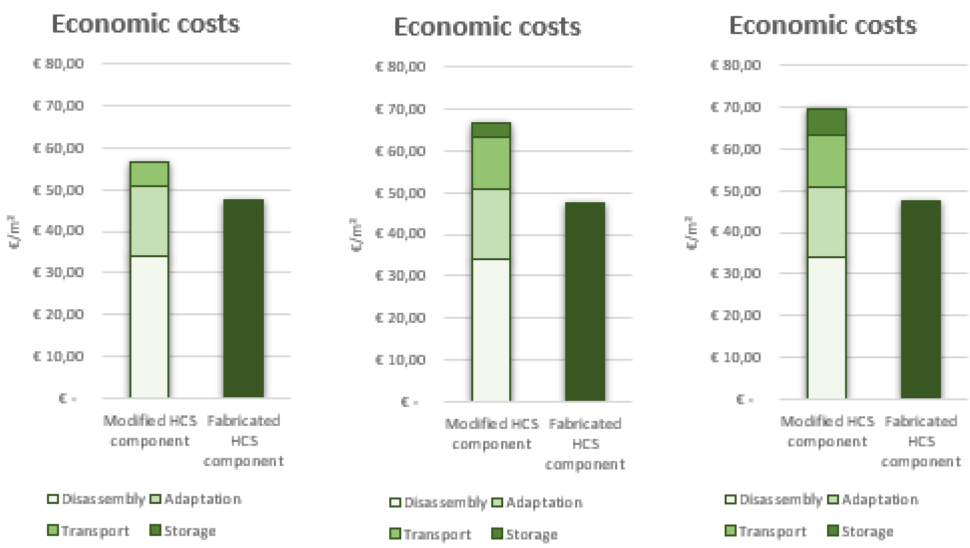


Figure 73. The economic costs for the various storage times: 0 years, 1 year, and 2 years.

The impact on the environment is only influenced by the extra transportation distance. On the other hand, the economic costs will rise due to the costs of the storage location, the interest rate for the storage process, and the extra transportation distance. The reuse potential factors of the floor component related to these three various storage duration times are **0.82** (no storage), **0.61** (storage duration of 1 year), **0.55** (storage duration of 2 years).

6.4.4 'Turning point' of the reuse potential factor by means of the decision support model

A reuse potential factor of 1.0 was determined for one situation; the future situation of the demountable building. This factor means that the component can certainly be reused without incurring additional economic costs or affecting the environment worse than purchasing a new component. However, if the component was more damaged, or if the connections were not so easy to disassemble, etc., this should influence the reuse potential factor. At a certain moment, the adjustments that have to be made to the component cause too much impact on the economy and environment. As a result, the reuse potential factor will change to a factor lower than 1.0. This is the 'turning point' of the reuse potential factor. The 'turning point' for situation 3 - the demountable building - is determined below.

The economic and environmental costs are lower than the 'costs' of a fabricated HCS component and, therefore, the reuse potential factor is 1.0. However, the factor is mainly influenced by the economic costs that are incurred. The economic costs consist mainly of disassembly costs. These disassembly costs are relatively high compared to the costs for the modification and transport of the HCS components. The combination of the disassembly costs, the adaptation costs and the costs for the transportation of the floor component do not reach the total costs for the production of a new floor component. However, if a few adjustments have to be made to the component, the economic costs will exceed the upper limit - the total production costs of a new fabricated HCS floor component -, see figure 74 (the red dot line is the upper limit). If the upper limit is reached for the environmental or economic costs, then the 'turning point' of the reuse potential factor is also reached.

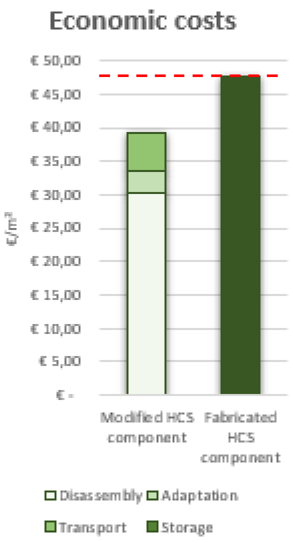


Figure 74. The upper limit [red dot line] of the economic costs for the modified HCS component.

The disassembly and reassembly process for the existing demountable HCS components influence the economic costs. If a few adjustments have to be made to the floor component, the environmental and economic costs can become higher. The difference between the economic costs for the modified HCS component and the new fabricated HCS component is small. Therefore, the upper limit will probably be reached quickly if a few adjustments have to be made to the component. To determine the 'turning point', the performances related to the quality of the existing component were examined and compared with the required quality performance for the new demountable building.

The results of the different situations show that applying a floating floor helps for the sound insulation but also has a certain effect on the costs. If the acceptable sound level of the floor component is not achieved for the new building, a floating floor can be installed on top of the existing demountable HCS component. Figure 75 shows that the upper limit of the economic costs will almost be achieved through this adjustment to the component.

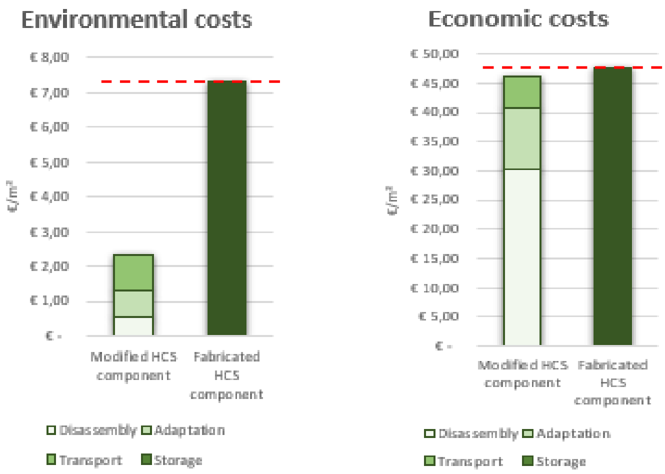


Figure 75. The environmental and economic costs if a floating floor is installed on top of the demountable reused HCS component.

It is also possible that the demountable floor component cannot be reused directly. The component should be stored first before it can be transported to the construction site of the new building. The results of storing the demountable component for a year at a storage location is shown in figure 76. It shows that the storage process and extra transportation distance influence the costs and the upper limit of the economic costs is achieved. Therefore, it can be concluded that it is possible to store the demountable floor components for a year, but the longer storage time will result in more economic costs and lower the reuse potential factor.

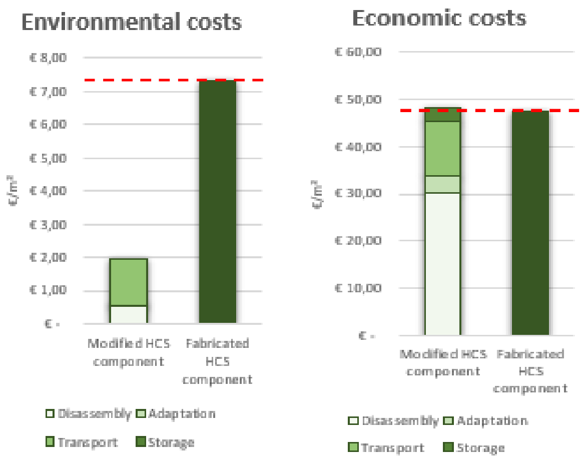


Figure 76. The environmental and economic costs if the demountable components are stored for one year at a storage location.

It is also possible that the demountable components have some damage. The performance of the damage is also investigated, see figure 77. If the component is slightly damaged, the economic costs remain below the upper limit. If the floor component is serious damaged, the upper limit has been exceeded and the reuse potential factor has been turned below 1.0.

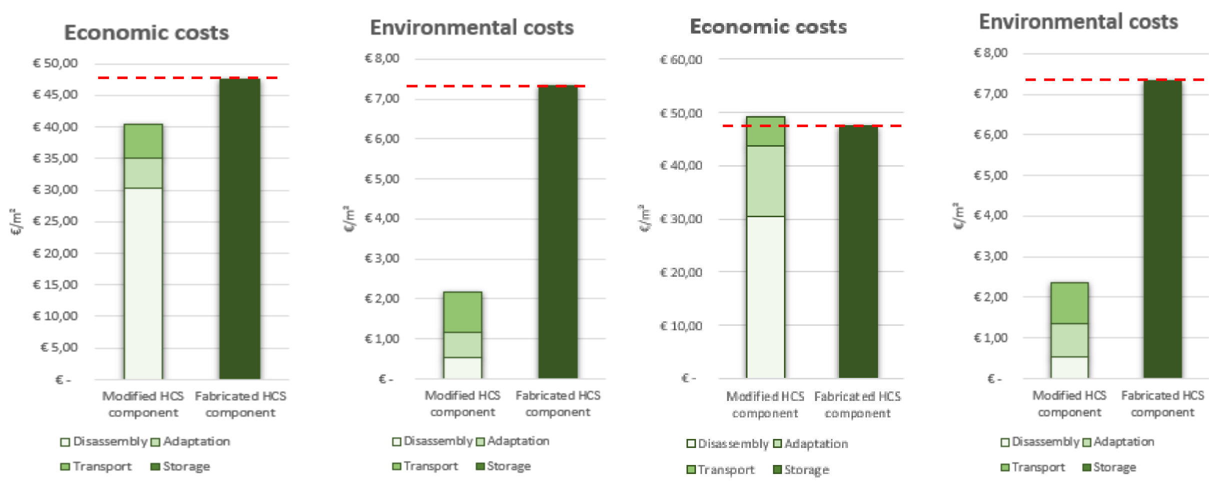


Figure 77. The environmental and economic costs if the demountable floor components are damaged [Right: slightly damaged; Left: serious damaged].

6.5 Limitations of the decision support model

As mentioned before, the decision support model can be used for determining the reuse potential factor for a certain HCS floor component. The results from the decision support model show the reuse potential factor for different situations. However, all the factors included in the model can also be approached in other ways and additional research should be done. Therefore, the limitations and reliability of the model should be evaluated.

Qualification performance categories

An important aspect of the decision support model is to test the performances related to the quality of the floor component. These performances have an effect on the reuse potential factor. However, not all the performances can directly be calculated by the model or the performances are treated equally while there are indeed differences. Therefore, the qualification performances should be discussed to determine the usability and reliability of the model.

Lifespan performance

The lifespan performance of the HCS floor component is based on the lifetime of the HCS component and the degradation mechanisms that can occur. The lifetime of the floor component can be determined based on the information about the lifespan of the building itself. The degradation mechanisms can influence the lifespan of the floor component at the moment the component has been located in an outside environment (e.g. a parking garage). As described in paragraph 4.5.1.1 *Lifespan system of the reused component*, the components can be affected by these degradation mechanisms and, as a result, aging occurs. These degradation mechanisms should be demonstrated and it should be investigated whether they have an effect on the lifespan. This can be done by a specialist. However, it is not possible to calculate the remaining lifetime through degradation mechanisms in the decision support model by means of a visual inspection and a calculation. Due to the complex factors involved in this process, a specialist should always be needed to determine the remaining lifespan and to complete the model. Therefore, the model calculation of the lifespan performance is limited because external information is required.

Technical performance

The technical specifications of a floor component are important for determining the technical performance of the HSC component. These specifications can be obtained from existing technical drawings and structural calculations. If there are fewer technical drawings and calculations available, the component should be inspected visually. The visual inspection of the HCS components will take more time and energy. The extra time and energy have an impact on the economic and environmental costs. As a result, the total 'costs' will increase and the reuse potential factor will be affected. That is why it might be interesting for this research to add the costs for the visual inspection for a more detailed examination because these costs are now being neglected.

Functional performance

The investigation of the quality of the HCS component related to the functional properties is based on the four characteristics of the floor component: fire-resistance, sound-insulation, amount of block-outs and the finishing of the component. As described in paragraph 4.5.1.2 *Performance system of the reused component*, the fire-resistance and sound-insulation requirements are important to examine. If the fire-resistance or the sound-insulation of a building component did not meet the requirements, the structural building component cannot be reused or should first be adapted. Major adjustments should be made to optimize the fire-resistance or sound-insulation of the component. On the other hand, the amount of small block-outs and finishing of the component has less effect on the reuse of the component, because the component can probably be reused with these characteristics or the improvement only takes little time and effort.

These contradictions of the functional characteristics are not reflected in the determination of the functional performance. If the requirements for the fire-resistance and sound-insulation were to be counted more heavily, the functional performance percentage would be more balanced. A weighting factor of 50% more for both the fire-resistance and sound-insulation performance results in a reduction of approximately 30% of the functional performance percentage.

Damage performance
The damage performance can be calculated by entering the occurring damage on the HCS component in the model. The possible occurring types of damage have been described in paragraph 4.5.1.2. However, these various possible damage types are the most common types of damage for all structural products. Therefore, these types of damage can occur with the HCS component, but this means that specific damage that occurs with the floor component is probably overlooked.

The calculation of the damage performance is based on the occurring degree of the type of damage. In the model, it is possible to indicate to what extent the damage occurs with the HCS component. However, no distinction is made as to which damage type has more impact on the component and, therefore, on the reuse of the component. In the calculation of the damage performance, every possible damage type has the same weighting factor to determine the damage performance percentage. However, one damage is more serious than the other, regardless of the extent of the damage. For example, the damage to the floor component by honeycombs is less harmful to the component than a crack that has occurred. These effects are neglected in this research but might be interesting for a more detailed study.

Connection performance
The performance of the connections between the HCS component and the supporting structure or other slabs can be determined based on the type of connection. The more flexible the connections, the easier it is to remove the HCS components from the existing building. This flexibility of the connections in relation to the disassembly process is tested using the model. The degree of the flexibility of the connections is estimated and, therefore, the effect on the disassembly process as well. However, the type of connections can be entered and the extent to which a connection type occurs but the weighting factor for the flexibility of the connections cannot be determined. There is not enough information to indicate to what extent a certain connection is more flexible and advantageous for the reuse of the component. In the model, the least flexible connection has the lowest rate and for every more flexible connection, the rate is one step higher. However, it does not always mean that a flexible connection has fewer challenges. It is recommended to do more research on the type of connections.

As mentioned before, the type of connections influence the disassembly process and based on only this information the impact of the disassembly process on the economy and environment is explored. However, the disassembly process is also influenced by many other factors, such as the removal of the concrete topping, the size of the building that needs to be disassembled, the devices that are available, etc. These factors are neglected in the model due to insufficient information about the effects of these factors.

Additional performance
The maintenance process is one of the factors that influence the additional performance percentage. For the maintenance of the floor component, the degree of damage is evaluated and thus the number of inspections during the second lifetime can be estimated. The physically maintaining of the HCS component is excluded in this research because research has shown that HCS components do not require maintenance. Also, there is no information about the physical maintenance of reused components. So, the maintenance only consists of inspections that should be carried out. Therefore, the number of inspections required is only calculated by the model and the maintenance is excluded.

Adaptation possibilities

The qualification performance of the existing HCS component should be upgraded to meet the performance requirements of the newly designed building project. Therefore, adjustments to the floor component will have to be made. Different materials, tools, equipment, and products are required to adapt the floor components. However, not all possible upgrading options are included in the model for the adaptation of the component. The most common solutions for upgrading the quality of the HCS component are determined based on literature review and expert interviews and included in the model. Therefore, the most common upgrading techniques can be chosen but more specific adaptations options cannot be chosen in this model. The database of the upgrading techniques should be larger so that it also contains the specific adaptation techniques.

The type of equipment, tools, materials, and products required for the disassembly and adaptation process are determined based on the literature review and some people working in the field of demolition branches. The amount of time a tool is needed or the number of materials or products required for the disassembly and reassembly process of the component cannot be estimated by the decision support model. A specialist from the construction sector should help to determine the numbers to be able to enter them in the model. Therefore, the model is not yet complete to be able to estimate these numbers.

Impact categories

Environmental costs

The environmental costs are determined based on the standard 11 impact categories that are taken into account. The data of the 11 impact categories for each product, material or process was found using two databases; NIBE.INFO and NMD. However, other aspects that have a significant impact on the environment in terms of sustainability are not taken into account because of the lack of methods to quantify these other impact categories.

The disassembly process has a major impact on environmental costs. Though, not all environmental impact data for the disassembly process could be found in the databases. Some values were estimated. For example, the pneumatic hammer was not found in the databases, but the breaker could be found. The breaker is larger than the pneumatic hammer, and a reduction factor of 4.0 has been applied to give realistic results of the environmental costs for the hammer.

Economic costs

The economic costs of products and materials indicated by external companies are actual prices they ask for their products or materials. The costs of the disassembly process are high compared to the costs of the other process. A project-cost engineer, P. de Haan, estimates the economic costs but he indicated that the costs differ per building project. Therefore, a percentage of 15% is calculated for the uncertainty. Also, the costs highly depend on the organization of the disassembly and adaptation process. If the process is very well organised, then it can make a difference of about 30% of the costs. Also, the economic costs can be reduced if the same company that is selling the slabs does the sawing of the slab. The costs can be reduced to 30% (Naber, 2012). Therefore, these factors should also be investigated to make a good estimate of the economic costs.

6.6 Results

The decision support model calculates the reuse potential factor based on the quality of the existing HCS component and the required performance for the new building structure. If the qualification factors scored lower than 100%, the existing HCS component should be upgraded to the desired performance percentage. The model shows that if the quality of the HCS floor component is improved, the economic and environmental costs are increased. The environmental costs often increase more in proportion than the economic costs.

The five qualification performances – lifespan performance, technical performance, functional performance, aesthetical performance, and additional performance – have their own contribution to the reuse potential factor. Therefore, the qualification factors indicate the 'sensitivity' of the model. The qualification performances of the existing component are compared with the requirements for the new building structure. As a result, the model demonstrates whether it is possible to reuse the component or whether the component should be adjusted before it can be reused or whether it is not possible to reuse the component.

It appears that in many situations the reuse potential factor of 1.0 (definitely reusable) is not achieved. Every situation is different due to the function of the building. The function of the building is important because the function describes the requirements for the new building structure. For each different situation, other requirements should be met and, therefore, other or no adjustments should be made to the existing HCS component. The modification process and also the disassembly and reassembly process have a large impact on the economic costs and do therefore lower the reuse potential of the component. The economic costs upper limit is almost reached due to these processes. However, a demountable floor component has reduced disassembly costs. As a result, the upper limit of the economic costs is not yet reached and the reuse potential factor is RP=1.0, see table 8. An RP-factor between 0.7 and 1.0 means that it is acceptable and possible to reuse the component.

	Adaptation required?	*RP -factor*
Situation 1: same building function	Yes, few adaptations.	RP = 0.82
Situation 2: other building functions	Yes, a lot of adaptations.	RP = 0.75 or RP = 0.63
Situation 3: demountable building	No.	RP = 1.0

Table 8. The reuse potential factor with regard to the adaptations required due to the reduced qualification performance.

The quality of the existing HCS component is assumed. However, the quality of the component may be different and the reuse potential factor will chance. The qualification performance parameters may change to see the effect on the ability to reuse the component. Table 9 shows the reuse potential factor for the various performances compared to the extent to which these performances occur.

	None (almost)	More	Even More	Most
Damage performance	RP = 0,82	RP = 0,74	RP = 0,62	RP = 0,0
	100 %	90,2 %	75,6 %	0 %
Transportation performance	RP = 0,83	RP = 0,82	RP = 0,79	RP = < 0,79
	100 %	98,7 %	96,3 %	< 96,3 %
Storage performance	RP = 0,82	RP = 0,61	RP = 0,55	RP = < 0,55
	100 %	74,3 %	67,1 %	< 67,1 %

Table 9. Changing the parameters of the qualification factors results in different RP-factors for one specific situation.

The RP-factor indicates the possibility of reusing the HCS component, but also the extent to which it has an impact on the economy and environment. If the RP-factor becomes lower than 1.0, the upper limit of the environmental or economic impact is reached. This is also the 'turning point' of the RP-factor. The component with an RP-factor up to 0.7 can be accepted by the contractor to use this component. As it appears, for most situations it is mainly the economic costs that cause a lower RP-factor. Therefore, the transition to a circular economy requires more money to be made available or more buildings should already be designed in such a way that the building component can be reused for a second lifecycle.

The decision support model is a useful model for assessing the reuse potential of building components. However, the model also has some limitations that can be further developed. The model cannot calculate some qualification performance without a specialist. Also, all performances are treated equally, although there are differences. And the database can be expanded even further.

7. Conclusion & Recommendations

7.1 Introduction

This research shows that the developed decision support model can help to investigate the reuse potential factor of the existing hollow-core slab floor component for various new design situations. The main research question is: "*How can various methods and knowledge be integrated into a decision support model for deciding on the reuse potential of a hollow-core slab floor component to close the material cycle?"* This chapter will provide an answer to this main research question. The setup of this chapter is as follows. In section 7.2 the main conclusions will be presented. In section 7.3 an evaluation of the validity and reliability of the decision support model will be described and also the relation with the building industry is elaborated upon. Subsequently, recommendations for future research will be listed.

7.2 Conclusion

The current economy motivates to develop a decision support model for analysing the reuse potential factor of structural building components, such as hollow-core slab - HCS - floor components. The transition to a circular economy becomes more important and, therefore, the reuse of building products, components, and materials as well. However, the reuse of structural building components has not yet been adopted due to the uncertainty and risks involved when reusing these components. It is important to know how good, reliable, and useful these existing HCS components still are, if the reuse of these components has a positive effect on the environment, and if it is feasible from an economic point of view. Therefore, a model should be developed and supported by efficient tracking and archiving to provide information relevant to the environmental and economic savings and to enable better decision-making concerning the reuse of building components. Currently, there is still no model to decide on the reuse potential of structural building components. There are already technologies and models – the ARP-model and RFID technology – to determine the quality potential of an existing building or building component to reuse it, but the impact on the environment and economy is neglected.

As a result, a decision support model is developed to measure the reuse potential factor of existing HCS components and to stimulate making better decisions about either the reuse of existing components or the use of newly fabricated components for a new construction. The reuse potential factor is the factor for measuring the ability of a component to retain its functionality after the end of its primary lifecycle compared to the economic and environmental costs to reuse the component. To determine the reuse potential factor, the factors related to the quality of the component – qualification factors – should be tested and compared with the required quality of the new construction. Also, the factors related to the environmental and economic costs – quantification factors – should be determined for the reused component based on the Life Cycle Assessment tool and Life Cycle Cost tool and should be compared with the quantification factors of a newly fabricated component. The environmental and economic costs for the reused component will become higher when adjustments have to be made to this component, because the quality of the existing HCS component does not meet the requirements for the quality of the new building structure. Results of the model shows that the reuse potential factor of HCS components becomes lower due to the high economic costs. The costs for the disassembly process are fairly high. Therefore, the reuse of demountable HCS components is definitely possible because these disassembly costs are low. So, based on current knowledge, the reuse potential factor will be higher if the qualification factors are high and the quantification factors are low, and therefore the circularity factor of the component is assessed to be high (see figure 78).

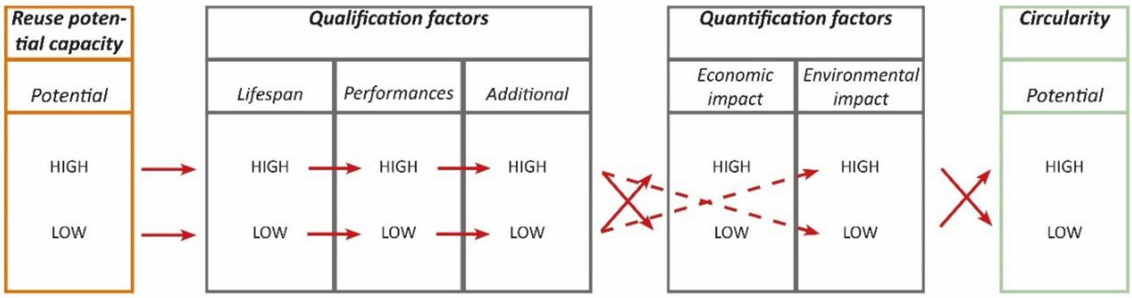


Figure 78. The steps to measure the reuse potential factor in the decision support model.

The decision support model can help to determine whether the hollow-core slab floor components can be reused or not, and whether it is better to use a reused component or a newly fabricated component in terms of economic and environmental impact. With the decision support model it is possible:

- *To test the quality of an HCS component*: the performances of the HCS component can be tested and compared to the requirements for the new building structure. The lifespan performance, technical performance, functional performance, aesthetical performance, and additional performance are the performances to be tested to measure the quality of the component.
- *To quantify the 'costs' of reusing an HCS component*: the reuse of the HCS component will incur some environmental and economic costs. These costs can be calculated by the model to express the impact on the environment and economy.
- *To decide about the use of a reused HCS component or a new fabricated HCS component*: a reused HCS component and a new HCS component are compared based on their environmental and economic impact. The component with the lowest impact on the environment and economy is the one to use for the new building structure.
- *To compare different situations*: the existing HCS component can be reused for various functions of the new building structure. The function of the new structure is important for determining the requirements the reused HCS component should meet. Different situations can be compared to find out for which situation the component can best be reused.
- *To indicate the required percentage for the upgrading of the HCS component*: the quality of the reused component can be lower than 100%. Therefore, the component should be upgraded to a required percentage. This percentage can be entered in the model and indicated by the contractor or designer of the new building structure. The required percentage influence the number of adjustments. If more adjustments are required, the 'costs' will become higher.
- *To select the adaptation techniques required for the upgrading*: if the component should be upgraded, various upgrade options are integrated into the model and the right modification technique can be selected. Most of the adaptation techniques are integrated in the database.

Within the decision support model it is not possible:

- *To calculate the reuse potential factor of other structural building components*: the model is not generalised and, therefore, only to be used for the HCS components. This is because the database provides only data about the HCS component.
- *To determine the quality in itself*: the quality of the existing HCS components can be tested by the model based on the information entered. However, sometimes a specialist is needed to investigate the quality of the existing HCS component. For example, the calculation of lifespan performance affected by the degradation mechanism should be done by a specialist.
- *To distinguish which qualification factors have more influence on the reuse process*: all quality factors are counted on the same level in the model. For example, the various damage possibilities are all considered to have the same impact that they can cause. However, in practise one damage case is much more harmful to the component than the other case.

Thus, the decision support model can serve as a tool to achieve the ambition of the Dutch Government to switch from a linear to a circular economy. The model gives the government and the building industry a better view of how to close the material cycle of concrete by reusing hollow-core slab floor components.

7.3 Discussion

The input of the decision support model was determined by using databases and literature review. The reliability, validity, and usability of the research and the decision support model is important to investigate.

Reference building component

The calculations for the reuse potential factor are related to one chosen structural building component: the hollow-core slab floor component. As described in chapter 3 *Reuse of a structural building component: hollow-core slab floor component*, many companies are worried about the risks involved to reuse structural building components. It could be useful to investigate the reuse potential of structural building components. However, for this research, it is particularly important to have a constant reference structural building component to refer to and to set up the requirements for the decision support model. Therefore, the input for the model would not be influenced by the use of different building components and their requirements. As a result, the model will be reliable.

Database

For the environmental costs calculations, two different databases – NIBE.INFO & NMD – are used. The database NIBE.INFO is used for the environmental data of construction products and the National Milieu Database (NMD) for the environmental data of materials and processes. The use of these two databases also has its disadvantages in this research. Firstly, not all data is traceable as not all materials, processes and construction products have yet been processed in the databases or the data is not public. Some of the data can be found in the database of NIBE.INFO or the NMD, but in other cases there is no exact data of the materials, processes, or construction products. Therefore, it is recommendable to use materials, processes and construction products with an environmental profile when calculating the reuse potential factor.

The second disadvantage is that the available data in the databases is still limited and some data has not been tested yet. The data of the database comes from producers that can include their products in the database, but they have to pay for it. The costs for including their products are not affordable for all producers.

Type of building component

This research is focussed on the hollow-core slab floor components. However, other structural components are equally important to investigate whether they can be reused. Due to the ambitions of the circular economy, all components in a building should preferably be reused. The decision support model is only made for measuring the reuse potential of hollow-core slab floor components. The model cannot be used for measuring the reuse potential of other structural building components – such as steel components or wooden components, etcetera –, because the database and requirements are related to the HCS component. The decision support model should be reconstructed in order to be able to test other structural building components for their reuse potential. For the building industry, it could be advantageous if the model becomes a more generalised decision support model, able to measure the reuse potential factor for all types of building components.

The concept of the decision support model, however, also applies to other structural building components. It is expected that the reuse potential factor of other structural floor components should be tested on the same performance indicators as the HCS component. To determine the reuse potential factor of other structural building components, the same steps as in the decision support model for the hollow-core slab floor component should be investigated.

Generalisation
It is not possible to use the developed decision support model for measuring the reuse potential factor for other structural building components. However, some conclusions about the reuse potential factor of the hollow-core slab floor component are valid for other structural building components. The results from the model can be used to substantiate that the function of the new building is important to know for assessing the reuse of structural building components. If the function of the new building project is the same as the function of the existing building, there is a greater chance that the structural building components can be reused. However, the requirements that may differ between a floor of 30 years old and a floor that is now being constructed in the building should be carefully considered.

The transportation and storage performances will give the same effect for other structural building components with regard to the reuse potential factor because the transport or storage of components is not dependent on the type of the component. However, the damage performances and especially the disassembly performances may differ for other structural building components. It may depend on the type of structural component in which adjustments must be made to the component. The connections for each type of structural component are also different and this requires a different disassembly process than for the hollow-core slab floor component.

The customized sawing process also has the same consequences for the other structural building components as for the hollow-core slab floor component. The costs of this process are based on the ratio between the number of square meters of the component and the cutting length. Almost all components are sawn off on the short side, which makes a longer component cheaper to cut compared to the number of square meters.

The scientific and practical contribution
This research showed the necessity to develop a model for measuring the reuse potential factor. The building industry aims to be circular in 2050 and, therefore, the reuse of building components is important. The major contribution of this research is the preparation of a decision support model. The reuse of building components has been discussed for a long time, but no earlier studies have been developing a decision support model for measuring the reuse potential factor based on the quality of the component and the environmental and economic impact. The building industry can use this model for preparing on the circular economy concerned with reusing building components. This model will also stimulate the building industry to think about reuse of other structural building components, such as steel or wooden components. Therefore, research is required about the reuse of these components to measure their reuse potential factor.

Some outcomes of the model showed a major impact on the economy when reusing components. Whereas buildings are not designed to be able to reuse its components, it is often difficult to remove these components from an existing building without damaging the component. This research makes the building industry aware of this disadvantage and the building industry should think more about the economic contribution. It could be that in the future more money should become available for the disassembly of the components or that future designs should already take into account the careful disassembly process for reusing components.

7.4 Recommendations for future research
This research can be used to determine the reuse potential factor of existing hollow-core slab floor components using a decision support model. The decision support model and the knowledge about the determining of the reuse potential factor can be used in a broader context to improve the reuse of existing structural building components to close the material cycle explained by the concept of the circular economy. So, for further development, it is important that the following research takes place.

Modifying the decision support model to be used for multiple structural building components
To limit the scope of this research, the developed decision support model is only focussed on determining the reuse potential factor of the hollow-core slab floor components. For other structural or non-structural building components, the decision support model cannot be used yet. Other structural components will have other specifications, such as steel components or wooden components. Therefore, the model should be modified to be usable for multiple structural building components. The concept of the model can definitely be used for determining the reuse potential factor of other structural components.

Application of assumed situations instead of practical situations
The verification and results of the decision support model are focused on assumed situations for the design of a new building project. These situations are not based on practical situations. Therefore, it is not exactly known if the model can be used in practice. Although the model can be useful for designers of a new building project, the model should first be verified and tested within practical situations.

More references projects
In addition to the importance of using practical examples, it is also important to have more reference projects. When the parameters are variated and the results of different reference projects are interpreted, more general conclusions can be drawn.

More information required about the performance parameters
The performance tested in the decision support model should be further investigated. In this research, we learned that the damage performance has a big influence on the reuse potential factor. However, the most general damage is taken into account and all the types of damage get the same rate. It is recommended to do further research on all the damage that could happen to a hollow-core slab floor component and the degree of the negative influence of the damage on the reuse potential of the floor component.

Also, the connections have a big influence on the reuse potential factor because the degree of difficulty of the disassembly process depends on these connections. More research will have to be done on the impact on the disassembly process of every type of connection that can occur for the hollow-core slab floor components.

Life Cycle Assessment analysis and Life Cycle Costing analysis
The analysis methods and the related database are not yet developed to take into account the reuse potential of a building component. More knowledge on how to integrate the reuse of components in the calculation of LCA and LCC analysis must be gathered and spread. In this research, it was difficult to calculate the reuse of hollow-core slab floor components and the impact of the disassembly process. It is necessary to develop tools and databases to take into account the reuse of products, components or materials.

Sustainable development
The sustainable development is about people, planet, and profit [3 P's] which should be harmoniously combined. These three elements together form an important principle for the sustainability of products. The reuse of hollow-core slab floor components is seen as sustainable development. The decision support model is testing the impact on the environment (*planet*) and the financial feasibility (*profit*) of the reused floor component. However, one of the elements of sustainable development has not been taken into account. The 'social' side of the reuse of building components should also be determined. For example, the vibrations and noise of the disassembling of the floor components could have a negative effect on the reuse process. As long as that has not been done, not everything can be said about the sustainability of the reuse process of hollow-core slab floor components.

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