Towards developing a tool for circular building elements in the construction and waste industry

Master Thesis – Mohammad Amini

Towards developing a tool for circular building elements in the construction and waste industry

The applicability of a Circular Construction Element Information System for existing building elements based on Circular Economy strategies to optimize the reusability

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Preface

This thesis is the final product of my graduation project at Delft University of Technology toward the completion of my master's degree in Construction Management and Engineering. Conducting this thesis research requires the application of all knowledge acquired from the different fields during the master's program.

Choosing a research topic is a major challenge that should be done with great care, because it has to be lived with for a long time. I enjoyed this interesting topic and worked on this research with passion. As, the transition to a Circular Economy still requires a lot of research in many different fields such as the construction and waste industry. The loop of finite materials and resources would be closed, the market of construction products would be more interested for various stakeholders, and governments should take more innovative measures to accelerate this aim. This research was carried out with the aim of improving sustainability and circularity and hopefully I can make a small contribution to that.

Firstly, I would like to extend my heartfelt thanks to the chair of my committee, Prof. Henk Jonkers for his clear and valuable feedback. His friendly attitude and critical remarks have motivated me and I have gained a lot of knowledge and information from his guidance. Then, I would like to thank my first supervisor, Dr. Sander van Nederveen for enriching my understanding of process modelling and describing how to start a large research like this and providing more other advices and feedback. Next, I want to thank Ben Visser. Ben, thank you for all the explanations, advices and experiences you shared with me in a very friendly way, I have received a lot of practical information from you beside this research. Also, thanks to the people of Oxand company with their friendly behaviors.

Furthermore, I want to thank all the interviewees from different companies who participated in this study and who took the time to share with me their valuable experiences and knowledge. I am grateful to all my friends and peers for being a part of this research.

Finally, I would like to specially thank my parents, particularly my dear mother, who always supported me, you were always patient in every step of my life.

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Executive summary

The construction and waste industry required more innovative, sustainable and efficient scientific research on various topics in the last decades. As, this industry produces more waste material and energy than any other industrial sector and this can affect the economy, society and environment remarkably. The materials and resources used in the construction industry are finite and the extracting of raw materials cannot continue forever. Therefore, the need of implementing Circular Economy (CE) strategies is highly recommended which can be adopted as a process aimed at preserving products, materials, equipment, components and also infrastructure for maximum value of time, efficiency, utility and productivity, with the main purpose of eliminating waste, hence improving the efficiency of these various resources.

In order to move towards CE strategies, it is important to maximize the reusability of the existing elements, as reusability is one the main aspects concerning achieving the CE strategies (10-R model) and sustainability goals. Additionally, according to the Dutch government the construction sector would be organized in such a way, with regard to the design, development, operation, management and also dismantling of different buildings, that the sustainable construction, use, reuse, preservation and dismantling of these objects is guaranteed, by 2050. On the other hand, reuse process of the existing elements encounters different social, economic and technological barriers such as high prices, difficulty of disassembling, lack demand and supply, norms and like that. Moreover, reuse requires a systematic deconstruction process which considers as the essence of transition to the Waste Management Hierarchy Model.

To move in line with the aim of waste management hierarchy model, it is needed to analyze the functional and technical aspects of existing elements. Analyzing the functional performance characteristics of existing elements in this research requires to know the level of quality of them. Thus, the remain value, i.e. the reuse potential value of a building element such as HCS floors and columns, should be measured which provides insight into the qualitative and quantitative factors of those elements. Measuring the reuse potential value contributes to have a better understanding concerning building products functional properties, and also an insight into the economic value of the elements.

This research was aimed to develop a ‘CCE Information System’, which is a combination of an import sheet and dashboard, that takes into consideration the functional performance characteristics of the existing elements and the main stakeholder issue, namely cost in the construction and waste industry. The proposed CCE Information System could ultimately be used as a tool to provide a method that maximizes the reusability of the existing elements through closing the loop of the reuse of the elements. Moreover, the developed tool would support different stakeholders involved in the deconstruction process to make the right decision regarding the reuse of the elements.

Functional performance characteristics: this research analyzed the functional features of concrete elements. Concrete is the most used material and product worldwide and it has various functional properties. The functional properties of concrete component depend on the functional properties of the substances used in it. For example, strength, fire resistance and sound insulation of concrete elements depend on the type of aggregate, amount of cement, w/c ratio, density and etc. Moreover, concrete structures become obsolete and deteriorate with time and these phenomena will affect the performance of the structures considerably, also external and internal factors can affect the functionality of concrete. To maximize the reusability of concrete elements it is required to deconstruct the building system instead of demolition. Deconstruction is a costly approach and consists of different processes with various requirements.

Stakeholder cost issues in the deconstruction process: There are a large number of stakeholders involved in the (de)construction and waste process, all with different ambitions, interests, opinions, and benefits. The client and the contractor (demolition company) considered as the two main actors in this process. The client decides whether the construction system would be deconstructed or even demolished. On the other hand, the reuse process includes some activities that makes the reuse practically uneconomic. So, it is important to calculate the reuse costs which includes deconstruction cost and other associated costs such as the cost of improvement and transport. Analyzing the reuse costs should contribute to understand which costs are allocated to which stakeholders. This makes possible to observe whether the contractor or the client has made a profit or even a loss. In addition, analyzing the reuse cost has also this advantage to perceive which processes in the deconstruction process are costly and have major impacts on the total reuse cost.

Business Process Model (BPM) and measuring the Reuse Potential (RP) factor: One of the most important challenges in the construction and waste industry is that in the case of aging a building system the object cannot fulfill its function anymore and it should be decided to deconstruct the building when the reuse is of the subject. Realizing and developing a Business Process Model (BPM) for the deconstruction process contributes to zoom more in details of each separate processes. Deconstruction is not a preferable process within demolition companies as it requires more time, manpower, equipment and also it is costly. Nevertheless, creating BPM will contribute to more insight into the measurement of reuse potential value of the elements.

In order to measure the reuse potential factor of the existing elements it is essential to carry out quality performance test that reveals the functional remain value of the elements. The RP factor of different functional properties of concrete elements such as strength, fire resistance and etc. would be estimated based on their technical information. Since the technical and functional features have an intense relationship with each other. This measurement indicates whether the components have sufficient functional ability for reuse or not. Thereafter, the influence of different processes such as improvement/modification and transport on the reuse cost should be analyzed in a real case, which ultimately contributes to measure the reuse potential value of the existing elements from an economic point of view.

Circular Construction Element Information System: The objective of this research was to realize and develop an enriched Information System, namely a combination of an import sheet and a dashboard that includes the analyzed functional properties of existing building elements and covers the cost-related issues of the stakeholders. The structure of this CCE Information System was based on the BPM developed for deconstruction processes. The import sheet serves as a platform of the data achieved from the interviews and other sources. Therefore, all the technical and functional data of an aged and newly designed building system would be implemented in the import sheet. Realizing and developing of the concept of this tool is based on an innovative way such that they include novel technological achievement.

To measure the RP factor from either a functional perspective or from economically point of view, a between tab (process and handling stage) has been realized for the tool. This will demonstrate the user how the procedure of calculation or measuring the RP factor is carried out. Once the RP values of all the existing elements have been calculated, decision-makers (contractor or the client) have a CCE Information System, i.e. dashboard, from which to prioritize reuse projects. In other words, all the results and outcomes of previous steps are shown in a dashboard. The dashboard should assist the parties, especially the contractor, in the reuse process to choose the proper element functionally and economically. However, the CCE Information System will act as a tool, therefore, this tool is able to optimize the options of the reuse element.

Applying* the CCE Information System in *practice: The applicability of the developed tool is based on its usability in real cases. Hence, a related project 'The City Post' has chosen which is located in the city of Zwolle and it functions as utility (office) building. After gathering and implementing the related data to the import sheet, some scenarios have been assumed which are needed for measuring the RP factor. The assumed scenarios have different functions, because a system is always designed for a specific purpose. The HCS elements gained various RP factor in different situations. For example, the strength RP factor was about 100% in both transformation and infrastructure project, while this factor reduced to 87% and 70% in sport and healthcare situations. It can thus be emphasized that the functional performance properties of the elements vary according to the functionality of the intended building system.

The discussed costs in the deconstruction process have been calculated to be able to measure the RP factor from an economically perspective. The only costs that negatively impacted deconstruction costs were the cost of stripping. On the other hand, the improvement and transport process is considered to be the most expensive processes in the reuse cycle, due to the high prices. These two processes affected the reuse costs in all scenarios approximately between 20% and 40%. The RP factor was then measured and it appeared that in no situation can the elements be economically reused, with the exception of transformation and infrastructure. However, the profit of the contractor from the reuse process in the infrastructure project depends on the salvage value (revenue) obtained from the selling of the elements.

The client and the contractor (demolition company) can deal with many costs uncertainties, including benefits and loss. These parties may face different uncertainties that can arise due to many reasons such as the exceedance of process time, additional labor costs, and uncertainties regarding salvage value. Because if the market has insufficient capacity to offer the contractor the sales market, the risk that he will make a loss is greater than the benefits. In addition, the collaboration between the stakeholders involved is not appropriate and the information and data often become exclusive to a company.

The CCE Information System would also serve as a tool to be able to choose the elements from different cases, analyze them, combine the scenarios and find the best scenario for the contractor. By analyzing the impact of different processes on both deconstruction and reuse costs, it can be concluded that which price can be an upper bound, this helps to find the tipping point of each scenario. After that, the tool will find the best case based on the profitability for the related actor. Ultimately, a method was presented in which all the ideas behind the concept of the CCE Information System were described. In other words, the method has been developed to close the loop of reuse of the existing elements by linking them to the best analyzed scenario and projects, making it even less of a cost-effective reuse procedure for the client or contractor.

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Abbreviations

ARP	An Index of the Reuse Potential
BPMN	Business Process Model and Notation
C&W	Construction & Waste
CCE	Circular Construction Element
CE	Circular Economy
CE-Mark	Conformité Européenne
DoP	Declaration of Performance
EBD	European Assessment Document
ECI	Environmental Costs Indicator
EoL	End-of-Life
ETA	European Technical Assessment
FPC	Factory Production Control
HCS	Hollow Core Slab
MKI	Milieu Kosten Indicator
NRC	Noise Reduction Coefficient
RFID	The Radio Frequency Identification
RP	Reuse Potential
Rw	Sound reduction index
W/C	Water/Cementitious ratio

CHAPTER 1 | INTRODUCTION

Chapter 1 – Introduction

1.1. Introduction

The construction and building industry has required more innovative, sustainable and efficient scientific research on various topics in the last decades. According to Osobajo et al. (2020), the construction industry produces more waste material and energy than any other industrial sector and this can impact the economy, society and environment significantly. However, the materials and resources used in the construction industry are finite and the extracting of raw materials cannot continue forever (MacArthur, 2013). Therefore, the need of implementing Circular Economy (CE) approaches is highly recommended which can be adopted as a process aimed at preserving products, materials, equipment, components and also infrastructure for maximum value of time, efficiency, utility and productivity, with the main purpose of eliminating waste, hence improving the efficiency of these various resources (Osobajo et al., 2020; Invernizzi et al., 2020). In other words, there is a relationship between Circular Economy strategies that can be applied in the building industry and the efficiency of building structure materials such as beams, concrete, bars and etc. Furthermore, Geißdörfer et al. (2017) have been explained that a circular economy utilizes reuse, sharing, maintenance, renovation, remanufacturing and recycling to form a closed-loop system, minimizing the use of different resource inputs (see figure 1.1) and also the creation of waste, pollution and carbon/CO_2 emissions.

According to (Akinade et al., 2015), deconstruction is a process in a building which disassemble the whole or some parts of buildings to facilitate component or products reuse and also material recycling to eradicate demolition through the recovery of reusable materials and products. This process will be carried out with the objective of rapid relocation of building, reduced demolition waste, improved flexibility and also retrofitting, etc. Moreover, Akinade et al. (2015) described that deconstruction not only contribute to divert waste from landfills, but this process also enables other environmental, social and economic benefits. In addition, functional performance characteristics and requirements of building products is one of the key factors in different phases of a building system and also play a major role in (de)construction phase which can contribute to the improving of decision-making, data transition and providing appropriate information for different stakeholders involved during deconstruction of buildings. A building as a system consists of many different subsystems, products and elements such as a prefabricated column, beam, bars, or in-situ concrete column, floor, roof, brick, doors from wood, window frames and more other elements which in some cases can be demountable. Therefore, knowing the functional performance of building products at the end of building life phase can provide more environmental, social and economic benefits for different public and private stakeholders involved.

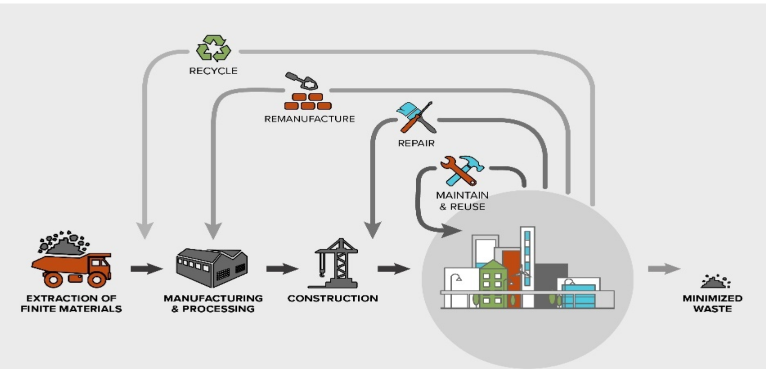


Figure 1.1: The Circular Economy as applied to the built environment (Retrieved from: Hickok Cole, n.d.).

Construction and deconstruction sector requires the participation of different stakeholders and parties to manage this sector effectively. It is undoubtedly important to manage this interdisciplinary industry significantly (Zhao, 2021). Additionally, the stakeholders involved often have different roles, interests, concerns, and objectives, resulting in different behaviors, awareness, and tendencies. For instance, governments and the public stakeholders are often concerned about regulatory and policy enforcement, as well as social and environmental impacts of construction and demolition waste management, clients are keen to pay more attention regarding economic viability, contractors generally emphasize cost and time savings and play an important role in minimizing C&D waste on site, and, waste recycling and demolition companies are eager to achieve the government subsidies and revenues from sales (Zhao, 2021). On the other hand, managing construction and waste sector requires application of new technologies methods such as building product databases and passports to increase the reusability of building products. Moreover, material or building product passports address different stakeholders needs, interests and benefits (Honic et al., 2019). Thus, a more circular building product passport, data platform can be used as a crucial decision-support and optimization tool.

The exponential increasing of using a unit platform in construction and waste sector achieved more attention from various actors and also had a large impact on the construction industry in the last decade. Many different databases and tools have been developed to address the problem of providing information related to building materials, products and elements such as Material Passports by Madaster or BAMB. A construction Material Passport includes various information about the functional performance requirement, characteristics and also origins of materials, the disassembling choices of the different products and also the current location of those products (Madaster, n.d.). By using material or building product passport, it is easier to recover and reuse them, in cases of renovation, restoration, maintenance and repair. Therefore, buildings function as a documented 'storage units' of different materials, products or elements (Madaster, n.d.). The Material Passports have this potential and possibilities to be adopted by many different stakeholders throughout the value chain of a building, additionally, through that provide a multitude of value propositions. One of these is the ability of building element data platforms to influence innovation and also the design of products (BAMB, 2018). Building element data platforms can be applied as a tool along the life cycle of a building, from the conceptual design phase, preliminary design phase, tendering phase, operation phase and also End-of-Life phase. Thus, developing a more circular building element information system which takes into consideration the functional performance characteristics of building products and also the needs and interests of various actors can be of great benefit in steering towards circular buildings.

1.2. Problem Description

1.2.1. Problem Context

Despite the great interest and ambition of both scholars and practitioners in the CE concept, the development and implications of CE are still progressing and the construction industry has not yet made considerable steps towards this approach. Moreover, the construction industry contributes largely to the economic, social and environmental aspects of people's life, however it accounts for the highest amount of total waste (100 Mtones/year) generated globally, using more natural resources (400 Mtons/year) than other sectors, and it also accounts for over 40% of the world's carbon/CO2 emission, while from the aforementioned statistics just approximately 30% of these materials and products are either reused or recycled (Osobajo et al., 2020). On the other hand, according to the Dutch government the construction sector would be organized in such a way, with regard to the design, development, operation, management and also dismantling of different buildings, that the sustainable construction, use, reuse, preservation and dismantling of these objects is guaranteed, by 2050. (Rijksoverheid, 2016). This can be a great challenge to build and construct without emissions, depletion, exhaustion and pollution of the living and built environment. Therefore, more research and guidance is required to attain the CE strategies, however the implementation of CE is very complex by nature.

Building product reusability is one of the major issues in the construction industry and the need to improve that can still be studied from different perspectives. Moreover, limited availability or scarcity of building raw materials may be major threat to the economy and number of jobs, and also the production processes of those building materials and products can influence environment significantly (Antti & Tarja, 2014). Novel studies have centralized on recycling Construction and Demolition Waste (C&DW) with little consideration on the reuse potential of building products, resulting in the decrease of reclaimed building products. Additionally, the design of current buildings is not appropriate for deconstruction, the importance of the concept of reusing their products after their End-of-Life phase should be considered in order to achieve higher levels of environmental performance with less material input, and also to provide benefit for different involved stakeholders (Kamel et al., 2021).

On the other hand, deconstruction is the procedure of dismantling a building to save the materials for recycling or reuse. In order to move more on a circular building process, it is needed that the deconstruction process of a project be handled as an essential factor as it would close the construction materials' loop. The construction and waste industry involves a large number of public and private stakeholders with divergent ideas in different phases. All those involved parties have specific perspective on how to make a significant benefit from each stage of a project. Furthermore, moving from a linear towards a Circular Economy in the construction industry requires more focus on systemic thinking that includes either the building life cycle or the construction value chain for stakeholders involved. The availability and redeveloping of different structured information on building product composition, various building stocks, material flow, and also the functional performance characteristics of building product is essential for supporting this alteration, however, the construction industry is still behind in the use of information technology and also technology sharing (Munaro & Tavares, 2021). According to (Kim et al., 2020), there is a lack of knowledge that generally examine the variables that form the evaluation framework of C&DWM performance with regard to key project stakeholders' perspectives, like owners, (sub)contractors, consultants and etc.

Furthermore, various material or product data platforms have been developed with different applications although, the Material Passport is not mainstream in the construction sector. Moreover, there are few studies handled the introduction of circular practices in the sector, one of the reasons can be either the lack of sufficient information about the available building stock, product or the effective management of End-of-Life products. Additionally, most of those information is often incomplete or inaccessible all of the time to the professionals and stakeholders involved (Munaro & Tavares, 2021). New building projects are generally well documented, although this is not the case for the building products. As buildings have a long longevity, they will face with many adjustments and adaptations all over their life-cycle, hence the original material composition might modify and will not comply any more with the actual state of the building (Honic et al., 2021).

1.2.2. Problem Statement

The transition from a linear to a Circular Economy is still a major challenge in the construction and waste sector. This transition will require close collaboration and cooperation within the stakeholders involved in the construction value chain, an alteration in mindset towards system-thinking, the introduction of new business models, regulations, legalizations and new technological advancements

(Carra & Magdani, 2017). In addition, this needs the application of a novel structured document for different building products including appropriate information regarding functional performance characteristics of them that takes into consideration the policies and business models for stakeholders involved.

Moreover, Osobajo et al. (2020) emphasized that the current view indicates that it is probably impossible to reuse materials or building products within the construction industry as buildings are often disposed of at the end of their useful life. Thus, the potential solution for the proposed problem can be figured out by applying the theory of implementing functional performance characteristics of building products in a data information system and the impact of it on the building circularity. Subsequently, analyzing the role of stakeholders involved and which of them would be needed to use of an element information system and of which they can make profit in the construction and waste industry can be of great contribution to stimulating reuse of building products.

The development and implementation of building product passports is led by the market. However, construction industry lags considerably behind other industrial sectors in its use of digital tools or other digital equipment and also technological advancement. The current landscape of building product tools includes several passport initiatives, all with their own approach and also confidentiality of information, with limited to no harmonization among building product data information systems. This will result in a situation where clients or users become cautious to implement building product passports due to of their experimental character and unproven added value. Therefore, governmental organizations provided more opportunities for building product passport implementation within experimental building projects in order to create the right framework from which building product passport can be realized on the basis of transparency, privacy, availability and governance (Transactionteam CBE, 2018). Utilizing material and product passport can facilitate the perception of the complex and multidimensional nature of different building products, building elements and also various systems used in a project (Munaro & Tavares, 2021). Building product passports would be comparable and also interchangeable for different involved parties to facilitate information flow and exchange along the value chain. However, the agreements among data passports/platforms developers are lacking and this will increase the risk that this will not be obvious and leads to limited implementation and less impactful adaptation (Platform CB23, 2019).

1.3. Research Gap

Different studies emphasized the necessity to explore the efficacy and influence of CE in the construction industry. Moving towards applying circular design strategies in the construction and waste management sector, and the implementing of functional perspectives of building products in a passport needs to be improved (Osobajo et al., 2020). According to Atta et al. (2021), most of material passports developed in the construction industry try to provide quantitative information such as the environmental efficiency, without taking into account other functional perspectives such as sustainability guidelines. On the other hand, as different involved actors are major decision makers regarding design, choosing building products, construction and assembly procedure, they have large responsibilities by defining the efficiency of resources over the whole life cycle. Given that the functional performance requirements will be determined in early design phase, and other constructive criteria in the construction phase and end of life stage, appropriate tools such as building element information systems for stakeholders involved, provide opportunities to assess the recycling potential are needed. Hence, there is lack of design-centric building product tools allowing such appraisals in different phases of a construction project (Honic et al., 2019).

According to Debacker & Manshoven (2016), building product passports developed by different platforms/companies will suggest opportunities to regain value from recovery and reuse of materials, building products and systems applied in buildings for different stakeholders between the value chain. Although, the needs of those stakeholders involved in the process to a circular building element data passport has not been researched enough in the current studies and which of them can make profit from that can be analyzed and explored. Therefore, a circular information system for existing building elements such as dashboard, that includes functional performance characteristics of building products beside taking into consideration the stakeholders requirements and profit from a proposed information system is lacking. The purpose of this research is to develop a more circular construction element information system for existing building products in such a way that it becomes more comprehensive than previous tools/platforms. Also, this research attempts to fill the lack of enough information to implement innovative sustainable and circular strategies by providing data and information that were not included in the previous tools. Additionally, the proposed information system will be aimed to support decision making on what quantity of building products will be recycled such that cost effective results achieved.

1.4. Research Objective

Many scientific research and articles have emphasized that CE play an important role in the construction industry and can contribute to achieving lowering the environmental impact, also to replace the End-of-Life concept with reducing, reusing, recycling and recovering and it helps simultaneously to creating environmental quality, economic prosperity and social equity in the building sector (Kirchherr et al., 2017). However, the implementation of the specific circular strategies will only result in incremental improvements at best and the CE principles in construction is still limited. Building product passports track the material composition of either a product or a building by the documentation of different quantity factors such as volume, weight, dimensions and location of building materials within a construction project. However, in order to function and implement as a more effective tool in measuring the potential of this building product supply for future reuse or recycling, supplementary functional information is equally essential (Heisel & Rau-Oberhuber, 2020).

The main objective of this research, which arises from the literature review, is to develop a 'Circular Construction Element Information System' (from now on to be referred to as 'CCE Information System') for building elements that includes the functional performance characteristics of those elements, the needs and benefits of different stakeholders involved based on a use case or case study.

Moreover, this research will try to develop a CCE Information System as a tool that become more comprehensive than previous tools. Also, the proposed tool will try to support decision-making in building sector, in addition to support different stakeholders in reaching their circular development goals while maximizing efficiency of recycling, namely; maximizing reusability, waste efficiency and the end circularity.

1.5. Research Questions

The research aim lead to the main and sub research questions. The goal of this research can be summarized as the development of a CCE Information System for building products which will be applicable in the building sector and will also support decision-making for different stakeholders involved to choose a more circular building product. To reach the aim of this research the following main research question is formulated:

How can analyzing the functional performance characteristics of existing elements and stakeholder challenges, improve the insight into the reusability of building products for decision-making in construction circularity issues?

Thereafter, to find the answer to this question, more information and knowledge needs to be gained and analyzed about different features of building products, the effectiveness of implementing functional performance characteristics of various building elements on building circularity, and the roles, requirements and benefit of stakeholders involved in the construction and waste management sector. The sub-research questions that can contribute to the finding of the solution for the main question are as follows:

- <u>Sub-research questions regarding literature study (chapter 2)</u>:

1- What are the challenges and obstacles in extending the life cycle of existing building elements in the EoL phase?
2- What are the functional performance characteristics of concrete building elements? and which external and internal factors affect those functional performances?
3- Which parties involved in the (de)construction and waste industry would benefit from better insight into the circular construction elements?
4- Which costs are included in the process of deconstruction for reuse?

- <u>Sub-research questions regarding the development of CCE Information System (chapter 3&4)</u>:

1- How is it possible to measure the Reuse Potential (RP) factor of a concrete element, and how this measurement contributes to optimizing its reusability?
2- What are the critical elements (functional requirements) to develop a CCE Information System for existing building elements such that maximizing the reusability, waste efficiency, and the end circularity of building elements, and also meet the needs of stakeholders involved?

- <u>Sub-research questions regarding the evaluation of the proposed tool (chapter 5)</u>:

1- Which cost issues and stakeholder challenges exist in the Dutch (de)construction industry?
2- How can information on functional performance characteristics of the building elements contribute to the improvement of building circularity?
3- How can information on cost-related issues of the stakeholders contribute to maximizing the reusability?
4- How could a CCE Information System maximize the reusability of the existing elements?

The first part of sub-research questions concerns different needed information from the literature. Different subjects related to the topic of this research would be studied from various sources, books, articles, and scientific journals. The first question of this part will handle the challenges, (dis)advantages, barriers in extending the life cycle of the existing elements in/after the EoL phase. Thereafter, the second question concerns the study about functional performance properties of concrete elements besides the factors which affect the functionality of those elements, as concrete can be deteriorated due to different external and internal factor. The next question analyzes the stakeholder circularity issues in the (de)construction sector. Therefore, it is needed to zoom more in which stakeholders are incorporated in the deconstruction process and which of them need and profit from a CCE Information System. Finally, the last question of this part concerns the study about one of the main stakeholder issues, namely costs, in the reusability of the existing elements, which reveals knowledge whether the reuse process is profitable for all the stakeholders involved.

The second part of sub-research questions covers the knowledge needed for the development of a CCE Information System. The deconstruction process is a complex and dynamic process thus it would be needed to analyze this process by using business models. It is substantial to understand whether the existing elements have sufficient remain value to be reused in a newly designed project. The first question arose because of the understanding of how this remain value can be measured. This question serves as a context to arrive to the requirements for developing an Information System that includes the functional properties and cost-related issues. Consequently, the second question in this part is drafted to provide a path for the realizing and creation of a CCE Information System for the existing building elements in the construction and waste industry. Therefore, the critical elements (functional requirements) of a proposed Information System will be handled which ultimately lead to the maximizing of reusability of the existing elements.

The last research questions have been formulated with regards to the evaluation of the proposed tool based on case study approach. The concept of tool will be applied in a related case study at the EoL phase. It is necessary to gain information and data from the (de)construction practice to understand which costs are included in the deconstruction process, the need of stakeholders from a Circular Information System, and the challenges they deal with in the building elements circularity. This learning experiences and constraints can be derived from real cases (case study) including data collection and interviews with different parties in the Dutch (de)construction and waste industry. The next sub-research questions provide more insight into the impact of implementing functional performance features of building objects, and also implementing deconstruction and reuse cost in a proposed CCE Information System on building circularity and on sustainability of building products. Ultimately, the last question addresses the role of the proposed tool in optimizing the reuse of existing elements by substantiating of a method from the results achieved.

1.6. Contextual and Geographical Scope

The construction industry is very large and complex, and consists of different type of sectors. It has to mention that the building and construction industry is known for its uniqueness of each project. Therefore, this research aimed to focus on the building projects, while the research will be further focus more on utility buildings in the Netherlands. Hence, the Dutch practices, rules, regulations and policies of the building projects will be taken into account. To test and validate the proposed tool, the data and information of some utility building, or even a simple building project, provided through Oxand Company will be applied.

1.7. Research Design

The research design would be geared to the research purpose and the formulated research questions. It should be the most efficient research path to find the most logical answer for the predesignated questions. The objective of this research is to investigate how can a CCE Information System be developed that includes the functional performance characteristics of building elements, and takes into consideration the needs and benefits of stakeholders involved from a more circular Information System for existing elements based on a case study.

1.8. Research Approach

In this research a process analysis model has been illustrated below (figure 1.2) as a flow diagram to demonstrate the development approach of the research. A process analysis provides more insight into the information and data needed for the research by defining the goal for the project. So in this case, the process analysis can reveal which data and information will be required for the functional properties analysis part, the stakeholder main issues, namely costs and collaboration, and the requirements for developing a CCE Information System. The proposed tool should be enriched from functional, technical and economical perspectives. As already mentioned, the aim of this research is to expand a more circular Information System which can support different stakeholders in decision-making regarding reuse of the existing elements and meets their circularity issues, based on a use case.

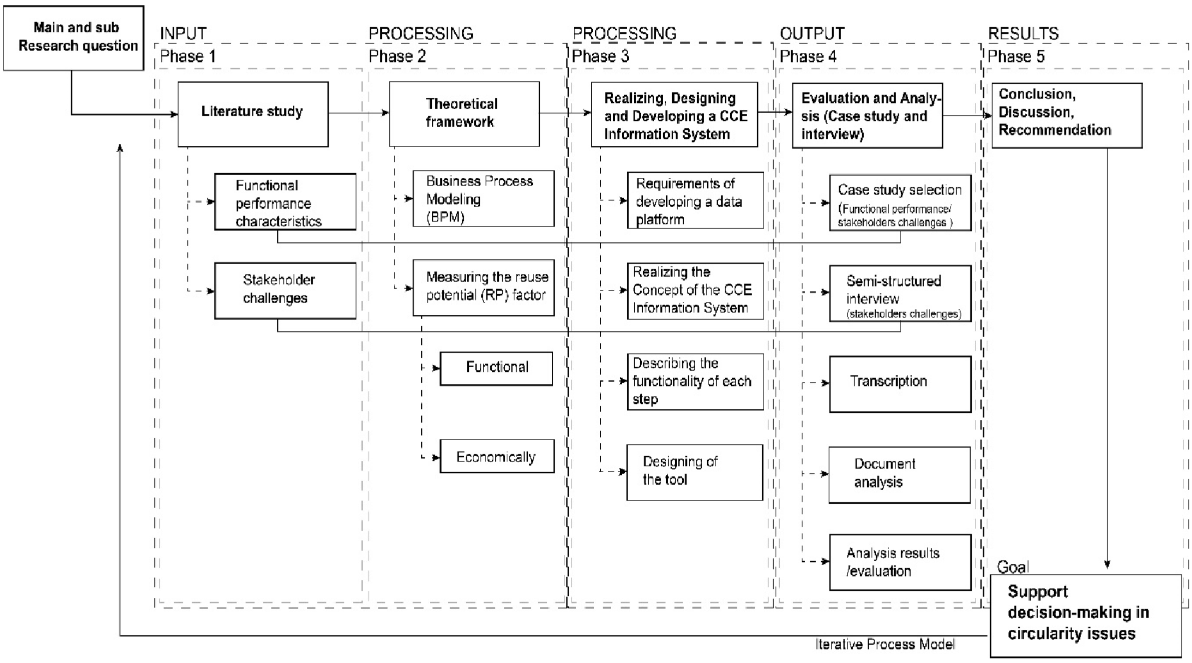


Figure 1.2: Process analysis model developed for the research (own illustration).

This research will be consisted of four complementary parts, literature review, theoretical framework, developing a CCE Information System, and ultimately a case study approach which includes interview with experts and stakeholders.

1.8.1. Literature Study

Primarily, in chapter two, a literature study will be conducted to gain information surrounding different subjects related to the topic of this study. Various articles, books, scientific journals and papers would be studied from the domain of (de)construction and waste industry, concrete building elements and materials, stakeholders involved in the deconstruction processes, and the reuse and other associated costs in the deconstruction process. Construction projects consists of a large number of products and elements which can be reused, recycled and remanufactured in different sectors depends on the product performance characteristics, in the End-of-Life phase. Knowing the functional performance features of each building object in the EoL phase can significantly increase the different circularity and sustainability aspects in the construction and waste circularity issues. Also, the interest, roles, responsibilities and benefits of different actors involved in the construction and waste process play a major role in optimization of reusability of building product and minimizing waste. Therefore, an analysis concerning those stakeholder issues would be of great importance that provides more insight into the advantages of inserting the needs of them from a circular Information System. Carrying out of a literature study will contribute largely to the development of a theoretical framework which can be used further. As already mentioned, this research focuses on the functional performance features of building elements, and the stakeholders involved in the construction and waste industry with the main concentration on the development of a CCE Information System as a tool for the existing building elements. In order to become acquainted with the available existing knowledge and information about the research subject, therefore, a literature review can play an important role.

1.8.2. Business Process Modeling approach

The next chapter concerns the development of a Business Process Model for the deconstruction process to zoom in more details of the advantages and disadvantages of different processes in the aforementioned sector. In this way, the obstacles, constraints and opportunities of each separate process will be revealed that affect various stakeholders. The model also provides insight into how different reusability issues of the existing elements can be tackled and thereafter be improved. The development and enriching of the above business model based on the knowledge obtained from the literature study, and also data and information gained from the practice.

Furthermore, this study will focus on the functional performance characteristics of the existing elements. These properties play a main role in decision-making regarding their reusability. Each of those characteristics would be analyzed and handled in such a way that the results can be applied and optimize the reuse ability significantly. Analyzing the functional features of the element is the first step of the understanding of the remain value. Subsequently, the remain value should be measured and this aim would be fulfilled by conducting a deep research into the related subjects. The measured reuse potential value contributes to the reusing of the existing elements, also enrich the data and information regarding the functionality and economically of the existing elements. The reuse potential factor should be measured from either a functional point of view or an economic perspective. Given that this research also analyzes the main stakeholder issues in the construction and waste industry.

1.8.3. Developing a CCE Information System as a Tool

In chapter four of this thesis, the critical elements for realizing and creating an enriched CCE Information System for the existing building elements will be analyzed. The developed tool would contribute to the maximizing of reusability, waste efficiency, and the end circularity of building products, and also meet the requirements of stakeholders involved. In this part of the research, the proposed tool and also the primary requirements for the development of such a tool will be discussed. The tool will be realized as a concept and thereafter will be designed and developed as a prototype in Microsoft Excel which can be fulfilled in a simple manner and also can be simply transferred to other information systems. The other reason is that Excel is well-known program which makes the tool even more accessible for various stakeholders and non-experts. In addition, in Excel different users can simply handle the design input and output sheets, and also when more proof will be needed, the sheets which provide the data can be analyzed as well. The output of the design tool will consist of two main columns which shows:

- First column: Functional performance features aspects
- Second column: Main stakeholder aspects

Each main column will also consist of sub columns in which the aforementioned aspects will demonstrate by various diagrams, charts and other modeling techniques. In addition, a list of functional requirements in combination with based on a use case example will be made for the tool to provide insight into the applicability of the Information System for different users. The tool would provide more extra information, context, and knowledge for various users and stakeholders involved in the construction and waste industry in decision-making regarding existing building objects in a simple manner. The proposed CCE Information System would be a proof of concept based on a use case/case study. In the last part, conclusion will be drawn by reflecting the results on the research goals and theory.

1.8.4. Case Study Approach

The last part, namely chapter five, is the most essential part of this research as it applies a case study approach which contribute to the expanding of a building element information system based on a use case, provided by Oxand company, in practice within the Dutch construction industry. A case study is an empirical qualitative research method that explores either a case or multiple cases to capture in-depth perspectives of practitioners and experts with a topic in its' natural context. This part elaborates on the development approach applied in this research to collect, contextualize and also analyze the learning experiences and obstacles encountered in practice with the building product circularity issues and stakeholder interpretation and meanings regarding construction and waste challenges. Therefore, analyzing the characteristics of building products in a real case can uncover novel knowledge that cannot be found in grey literature. In this thesis a qualitative and quantitative research approach will be applied to collect and analyze non-numerical and numerical data.

There are different methodologies that can be adopted in a qualitative and quantitative research by applying data analysis that is both inductive and deductive and establishes patterns or subjects. As limited information or knowledge can be achieved and shared with respect to the building product circularity issues within practice, this research will use inductive and deductive reasoning to, respectively; collect and recommend the knowledge of practice, and also with respect to available scientific literature on the issue.

- Case Study Selection

Finding an appropriate case study is an important and defining part of a research. To select the most relevant case study it is undoubtedly important to define criteria based upon certain characteristics that can be found within a construction project and also in accordance with the objective of the research. The criteria used to select the case study can be defined as follows:

- A project within civil and utility construction in the Netherlands
- The project would be in the use, End-of-Life, deconstruct or demolish phase
- The availability of products information used in the building
- The project involved different stakeholders, parties and actors
- Retrospective so that learning experiences and obstacles can be analyzed

The selection procedure of relevant case studies will be conducted later by Oxand company.

- Approach of Interviews

The theory of qualitative research shows that there are different approaches, namely structured, semi-structured and unstructured, for setting up interviews in qualitative research to collect and gather the data. Semi-structured approach can be a significant method in this research due to its comprehensive list of questions and topics to cover during the interview.

The focus of this research lies on developing a CCE Information System based on a case study, therefore, the learning experiences and obstacles in practice related to building product circularity issues and the challenges of stakeholders involved will be of great importance. This subject is largely unexplored among science and grey literature, and its implementation and expansion takes place in a construction project, which can be seen as a dynamic, complex and complicated context. In addition, there is intensive collaboration between many different stakeholders, all with their own culture, interests, benefits, goals and procedure. Therefore, a semi-structured interview approach can be applied which allows the researcher to objectively assess learning experiences and barriers among practices. The interviewees and participant are the stakeholders and actors involved in the construction and waste industry.

It will be tried to conduct face-to-face interviews with stakeholders and participants involved which can be recorded by audio recording, although due to COVID-19 circumstances the interviews can be done through online meeting which can also be recorded.

- Structure of Interview, Questions and Topics

The interviews with stakeholders and parties involved in the selected case study will be conducted in a logical manner such that the results achieved contribute significantly to the objective of the main research question. The questions and topics to be discussed with interviewees are based on the theoretical framework generated from the literature study. The two main topics of this research are functional performance characteristics of building elements and the needs and benefit of stakeholders from a circular product information system. Therefore, the formulated questions would be related to the aforementioned subjects and also would be varied depends on the stakeholders. The question topics can be related to legal, finance, technical and collaboration concerning building objects and stakeholder issues, namely cost.

- Document Analysis

Document analysis is a systematic and principled technique in which the researcher examines and explicates documents to better understand a topic and also extract different meaning to produce empirical knowledge and information. Prior to interviewing the participants, documentation of the case would be examined. By examining the documents of the project, relevant data is collected on the case in which an initial understanding of building products circularity loop and functional performance properties of them is obtained. Subsequently, the interviews are conducted to pose questions more in-depth about the already mentioned stakeholder challenges in the building product circularity subjects.

Data will be gathered on individual case by examining the following documents.

- Program requirements
- Material, products, elements in the drawing (detailed)
- Document analysis (Tender, purchases, planning, financial)

- Data Analysis

To analyze the data gathered through interviews these need to be transcribed into protocols and transcripts. The data analysis uses all the relevant and suitable data achieved in the respective interviews and the analysis of the documents. The interviews will be transcribed and thereafter different viewpoints, opinions and learning experiences will be analyzed along of the predefined interview and topics. Thus, reviewing and exploring the data will be needed to examine the data for patterns or repeated ideas that emerge. This will provide a more in-depth perception of the learning experiences and obstacles with respect to the different topics related to building products circularity and stakeholder issue within practice.

- Data Modeling

The models in a qualitative research do not particularly require mathematical formulism, but they are used to draw, diagram, plan, design or represent visually opinions, hunches, realized patterns or relationships among parts of their projects, explorations in their data and so on. Researchers frequently apply various qualitative models to provide support for hypotheses and also define new statements from collected data. Thus, a flow diagram or bar charts can be use in this thesis as a modeling tool which can evaluate the data achieved from previous steps and thereafter provide a logical context for developing a building product tool. However, the quantitative research concerns analyzing the numerical data obtained from various sources. Therefore, it will be attempted to use different related modeling approaches in a quantitative manner. Different quantitative models have long been identified as a beneficial method to manage and optimize economically flows. In addition, quantitative models contribute to achieve an appropriate comprehension in the interactions and dynamics and complexity of various systems.

1.9. Research Outline

A research strategy includes different choices that are made and from which new choices will be arisen (Verschuren et al., 2010). The structure of this research follows the structure of the research approach described in the previous part. Figure below (figure 1.3), shows the procedures applied in this thesis research in order to answer the main and sub research questions. The answer to each research question reflects the output of the phase concerned.

As can be seen in the figure below, the second chapter will be conducted to develop theoretical framework based on literature study. Next chapter, the third one, will focus on the process modeling using different relevant approaches such as Business Process Modeling (BPM), and also the focus lies on the analyzing and measuring the functional performance features and remain value of the existing elements from an economic perspective. The following chapter will be proposed a sustainable Information System which includes a combination of an import sheet and dashboard to stimulate the reusability of the elements. Chapter five focuses on the assessment of the proposed CCE Information System based on real cases in the Dutch (de)construction industry. In this chapter, case studies, interviews and collecting and analyzing data will be adopted to evaluate and validate the outcomes gained from the practice. Ultimately, the last chapter will provide conclusions based on the findings, discuss the results gained and also recommendations for future research in this field, other fields and for the practice.

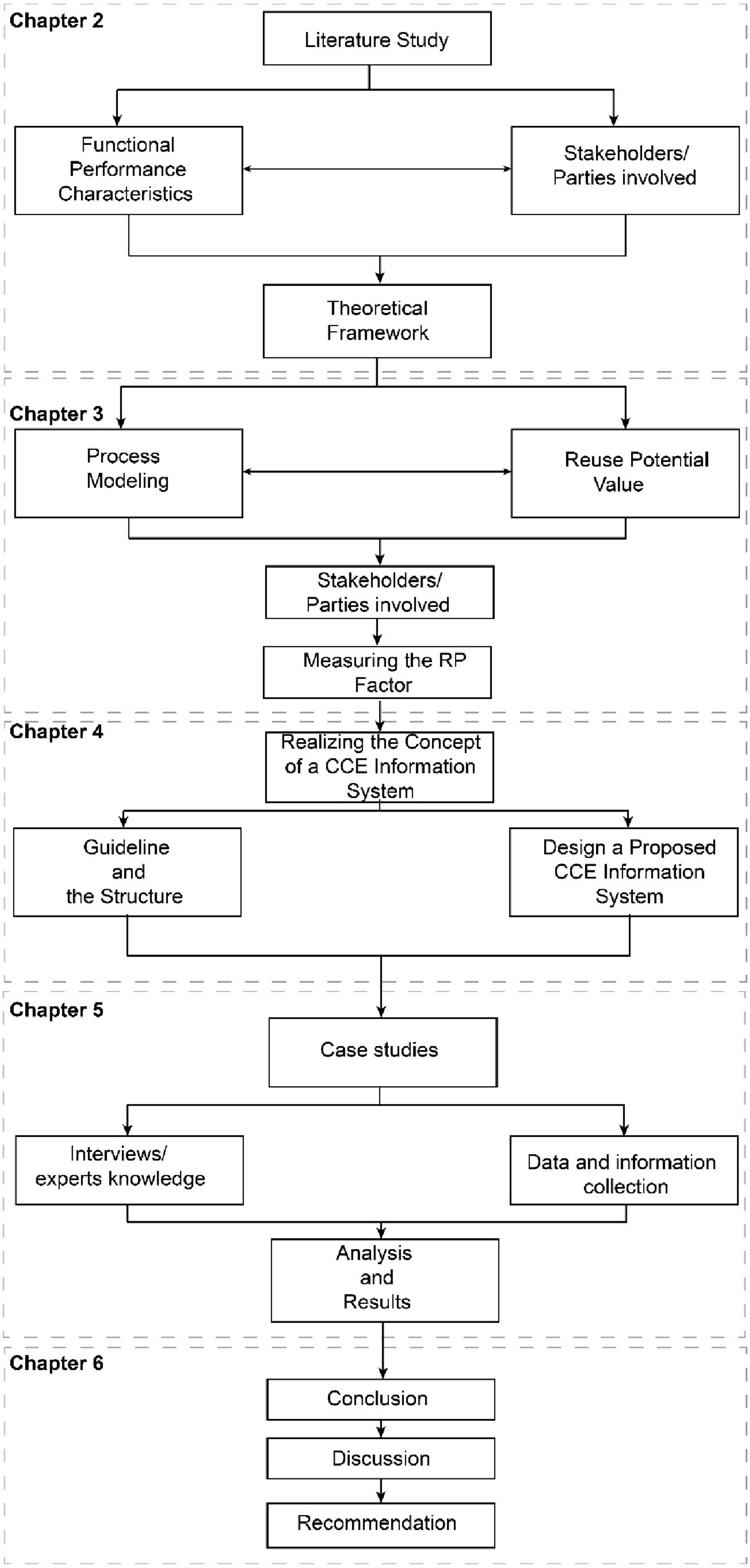


Figure 1.3: Research outline (own illustration).

CHAPTER 2 | LITERATURE STUDY AND THEORETICAL FRAMEWORK

Chapter 2 – Literature Study and Theoretical Framework

In this chapter, the two main concepts namely; functional performance characteristics and also stakeholder challenges will be analyzed using literature study. Thus, the chapter start with the explanation of different functional performance properties of concrete building objects in detail. Thereafter, an analysis will be carried out concerning various stakeholder's issue in the construction and waste sector. The theoretical framework forms the base for the next methods, developing a CCE Information System, and also using case study including interview.

2.1. Circular Design Strategies for Extending the Building Product Lifespan

2.1.1. Deconstruction Process and Design for Disassembly (DfD) Challenges and Benefits

Moving towards Circular Economy strategies (see Appendix A.1.1) and sustainability goals, requires appropriate adaptation of CE strategies at the related stages of the construction process. This research analyzes the functional performance properties of concrete building products at the end of life phase in order to maximize their reusability. Therefore, it is necessary to discuss the approaches such as the deconstruction process and Design for Disassembly (DfD), which largely contribute to the optimization of reusability at the End-of-Life phase of building products.

According to Rios et al. (2015), DfD is a practice to facilitate deconstruction processes and methods through optimal planning and design, this is also a main strategy to conserve raw materials. Deconstruction can be seen as the process of demolishing a building, on the other hand, it will restore the use of the demolished materials. These concepts are highly recommended to use by practitioners and scholars at the design phase. The main principles of DfD include (a) appropriate documentation of elements and procedures for deconstruction process, (b) design the connection to allow for their accessibility and joint approaches to facilitate disassembly, (c) separate different element and objects like non-reusable, non-recyclable, and non-disposal from each other, (d) design an ordinary structure and shapes that do not interfere with the standardization and dimensions of elements, (e) design in such a way that reflects work practices, productivity and also safety. It is undoubtedly clear that almost all the obsolete buildings have not considered these DfD principle. But this question may arise that what percentage of new building structures have taken these measures into account.

Despite the hype of the concepts of deconstruction and DfD between the practitioners, it has not yet gained enough success in the construction sector because of its impracticality imposed by standards, codes, and also professional practices. For instance, construction practitioners will find it a huge challenge to integrate the DfD concept into their designs as they do not have the freeness and control over the schedule and cost of the project, and they additionally confront the unavailability of materials. There are also many issues regarding the stakeholders and market ability which block the effort for using and adopting these concepts (Rios et al., 2015).

On the other hand, deconstruction and DfD has some environmental, social, economic benefits. For example, applying these concepts contribute to the closing the loops of materials. Therefore, the life of raw materials mines will be extended, the cost of materials will be reduced (if the supply chain is mature), and embodied energy and $CO2$ emissions will be significantly reduced. Apart from the potential savings, e.g. disposal costs, heavy equipment, re-sales value, deconstruction would encourage the creation of an entirely new market for the salvage building products, beyond the available facilities. The basic challenges the implementation of deconstruction can be overcome by the chances created by DfD, public and private involvement and also successful collaborations (Rios et al., 2015).

2.1.2. Expanding Building Products Life Cycle in/after EoL Phase

Reusability is one the main aspects concerning achieving the CE strategies (10-R model) and sustainability goals, as already explained in Appendix A.1.1. It is very important to increase the reusability of all building elements, thereby achieving environmental, social, economic and other benefits for the concerned stakeholders, residents and governments. However, applying CE strategies depends highly on the results gained from the research about the quality and other factors of building products at the End-of-Life phase (Morseletto, 2020).

Morseletto (2020) defined in his article "Reuse" as the second or further use (by another user/owner) of a product or finished goods that is yet in desirable condition and manages to carry out its principal function. In 2008, a waste hierarchy was introduced by 'The European Waste Framework Directive', as set forth by the European Union, which prioritizes waste reuse over recycling where technically and financially feasible. Moreover, in the field of construction, life cycle assessments of various building products have illustrated that reuse of structures has a considerable carbon saving potential. This is the fundamental asset that reuse of building elements has over new and recycled materials, although economic and social possibilities have also been identified. These include new business and employment opportunities, as well as the use of local resources (materials, labor). In the case of optimal application of reusability in the building demolition and waste sector, a cost saving of approximately 26% is estimated, a beneficial addition to new building methods (Huuhka & Hakanen, 2015).

On the other hand, reuse of building components, products and elements has not yet achieved ground in Western industrialized societies such as the Netherlands. The obstacles which hindering reuse of building products include cost, inconsistent quality and quantity, understanding and also trust between the stakeholder involved. As reuse has been considered labor-intensive, while high labor costs have been seen as the crucial obstacle for reuse in the Europe (Huuhka & Hakanen, 2015). Other issue is that the most aged building in e.g. the Netherlands, are not designed and suitable for methodic deconstruction. But the one of the building product reusability issues related to the objective of this research is the lack of secondary product dashboard. For reuse of structural products, it is imperative to realize and develop a detailed inventory of the products to share with that information with stakeholders involved. However, there is not yet a central passport for the available building stock. This makes it difficult to estimate the value of the secondary component.

Table 2.1: Economic, social, ecological and technological barriers to the reuse of building products (adapted from: Huuhka & Hakanen, 2015).

Economic barriers	**Social barriers**	**Ecological barriers**	**Technological barriers**
Higher price Lack of demand Lack of supply Difficulty of scheduling Attractiveness of conventional recycling Higher insurance fees	Norms Lack of awareness Bad image of salvaged components Bad image of the original product Health risks	Unclear environmental benefit Emissions from transport and reconditioning	Components not designed for deconstruction Inadequate material properties or damage Lack of applications and examples

In table above 2.1, other obstacles regarding the reusability of construction product have been tabulated. Construction industry, worldwide, must still take huge steps towards developing buildings designed with deconstruction ability. This backlog, makes the expansion of recycling technologies more likely than the development of Design for Disassembly (Huuhka & Hakanen, 2015). By analyzing the functional performance characteristics of concrete building products, more insight will provide into the level of quality of concerned products. Thereafter, the provided knowledge will show which strategies (i.e. Reuse, Recycle, Refurbish, Remanufacture or Repurpose) would be applied for the concrete building products. Finally, the stakeholders involved can make a logical decision-making for choosing the appropriate building products with a significant benefit.

One of the main challenges in the C&D industry is to model the process of a system after EoL phase. In other words, value recovery after EoL phase has not been taken into account as a common practice in construction. EoL planning has mostly been missed within the design and the use phase of a building system. Moreover, value recovery has not been included in the life cycle system of a building. Building life cycle information phases is provided in the European Norms guidelines (Figure 2.1).

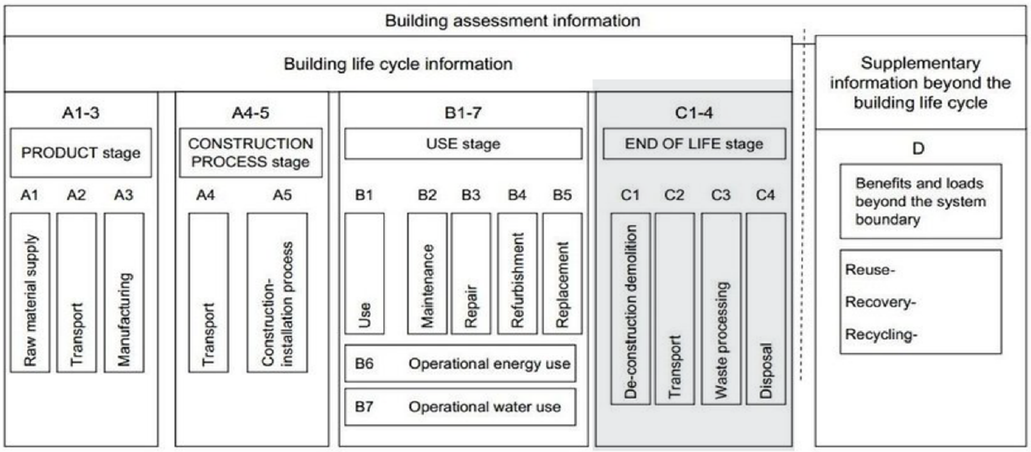


Figure 2.1: End-of-Life stage in the 'Building assessment information' model (adapted from; EN 15978).

As can be seen in the figure above, the last phase refers to the disposal of building/building components. Furthermore, as an apart phase or according to the guideline (supplementary information beyond the building life cycle) value recovery with "reuse", "recovery" and "recycling" has taken into consideration in module D which are outside the system boundary. Using the guideline above, has contribute to model the building life cycle with adding the supplementary module to the system (figure 2.2). In this model, it has been tried to add an alternative for demolition phase which is deconstruction. Because, when a building system is demolished in traditional way without recovering its elements value, then achieving the circular economic goals become a great challenge. Despite the difficulty of deconstruction process, but applying this process will contribute largely to close the material loops, it has also various environmental, economic and social benefits. Deconstruction process includes many different activities such as; permit, audit, inventory building components, planning, site preparation, performance test of building elements, removing components, modification, repair, storage, and transport again to the construction site. The performance test indicates the level of quality of building components of which can be reused, repaired, refurbished, remanufactured, or even recycled. Depending on the remain value from the building components, also using the 'van Lansink's' ladder (i.e. Waste Management Hierarchy Model), the reusability of building products can increase significantly.

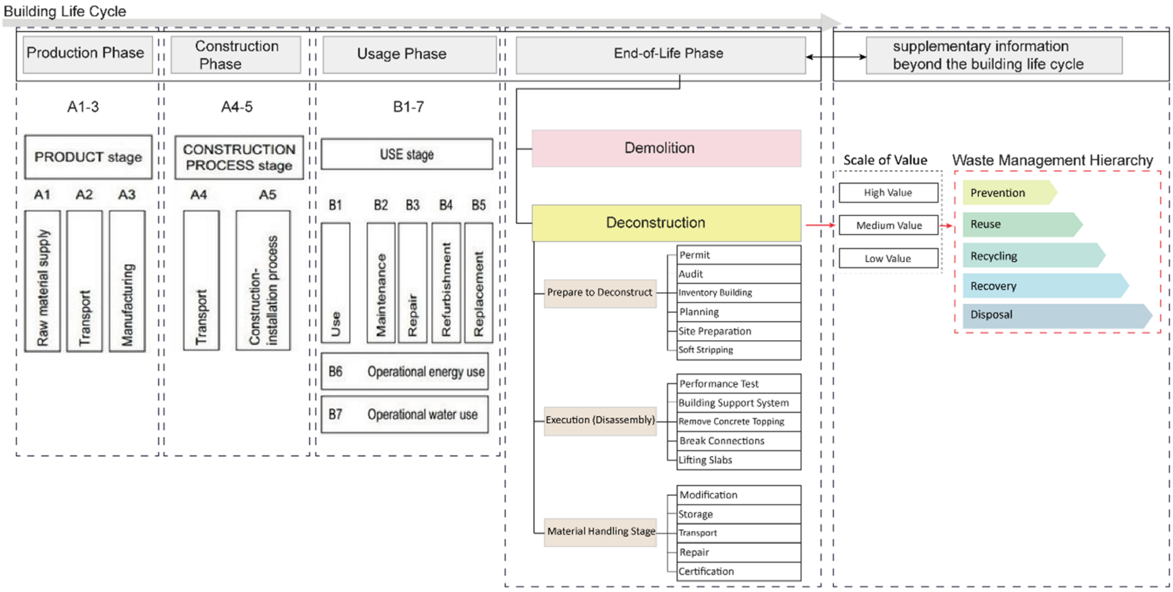


Figure 2.2: Improved Building life cycle process model (own illustration, adapted from: EN 15978).

Therefore, developing a CCE Information System for existing elements that contain functional performance properties of different components and analyze the problems of different stakeholders can largely contribute to the creating of more job opportunities, improving the ecological and environmental sustainability aspects, and closing the material/components loop. Developing this tool will allow the C&W industry to have a more dynamic economic cycle.

2.2. Measuring the Reuse Potential Value (Factor) of a Building Product

Moving towards a circular economy required an improvement in the process of current building industry by optimizing the reusability of existing building products. For reuse of the existing building elements, however, it is necessary to understand whether the existing building elements are still meet the required quality in order to last a lifetime. Thus, the reuse potential of the existing building components including their materials and substances should be investigated.

To achieve a high reuse potential, it is needed that the reuse of the component proceeds in an environmentally friendly and also cost-effective manner. Therefore, for evaluating the reuse potential, it is essential to analyze the functional performance characteristics of the reused component, and thereafter assess the environmental and economic costs of the treatment required for the reuse transportation and construction (Iacovidou & Purnell, 2016). The reuse potential of existing building products can be specified based on two steps, namely:

- Reuse analysis: This terms concerns the qualification of different required function and properties, i.e. functional performance characteristics, for the reused product and whether the desired function and characteristics have been met the requirements. Some functional performance characteristics may be affected during the use phase of the elements. This need to be handled and treated before the component can be reused again.
- Reuse evaluation: In contrast to reuse analysis, this method refers to the quantification of different environmental and economic impact of the entire process of the reused element. If the component needs to be recovered to meet the desired function and properties, this can

cause higher costs, e.g. modification cost. These costs can be considered as an indicator and will be expressed in environmental or economic costs.

Given that this research analyze the functional performance characteristics of concrete building products, and stakeholder challenges, therefore, both the aforementioned methods will be discussed. Thus, to understand that a component can be reused it is needed to conduct a reuse analysis and reuse evaluation. After applying the evaluation methods for the reuse of the building product, the re-use potential can be indicated. The 'reuse potential factor' can contribute significantly to make decision regarding managing waste as a resource. The factor is based on value creation, waste moves through different value regimes by obtaining and losing value. There may be a low reuse potential because the component contains a lot of damage which is costly to remove. The reuse potential factor can be indicated by assessing the environmental and economic impact because of reusing the component, and thereafter comparing it with the value of a new component. The reuse potential factor represents the efficiency of the component by a real value between 0 and 1 (figure 2.3). 0 indicates that the component need to be discarded and the component can certainly be reused if it shows 1 (Park & Chertow, 2014).

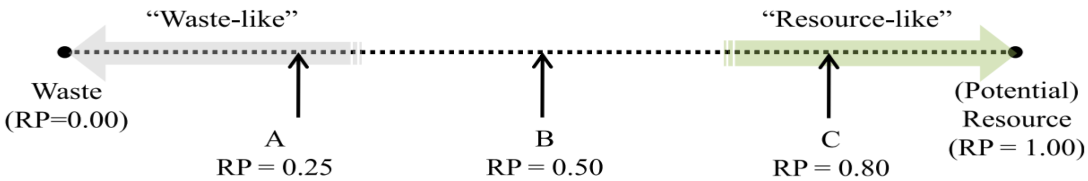


Figure 2.3: The scale of reuse potential (RP), between 0 and 1. (Park & Chertow, 2014, p. 47).

The reuse potential factors can be determined applying existing models and methods for the building sector which facilitate the decision process. ARP model developed by Langston et al. is a model which identify and grade the adaptive reuse potential in existing buildings. The model provides year estimation of the expected physical life of the building (component) and the current age of that. The model illustrates with an index of the reuse potential (the ARP score) the calculated percentage which is an annual rate based on the sum of the aging factors. High index buildings have the highest reuse potential, whereas low index buildings have almost no reuse potential (Langston & Shen, 2010).

Furthermore, there is also another model, RFID, which tracks and traces construction components information and data to enhance the reuse of those products. The Radio Frequency Identification (RFID) is a wireless technology that applies sensor technology that transmits data through radio frequency signals and can communicate the designed physical and technical characteristics of a structural component during its lifecycle and optimize their durability after the n-th life cycle (Iacovidou et al., 2018).

Both models have undoubtedly (dis)advantages, like; they do not take into consideration different environmental and economic impacts of the reuse of the existing buildings. These models can assess quantitative values but not yet for the reuse of building products. Therefore, it is required to zoom more in the details of building products functional performance characteristics and also analyzing the environmental and economic impacts in a real case. However, this research is aimed to implement the functional performance characteristics of concrete products in a dashboard.

2.2.1. Qualification Factors for the Reuse Potential

Different factors determine to some extent the reuse potential of structural building products. To evaluate the reuse potential factor of different concrete building components, it is essential to carry out the reuse analysis. It concerns testing the reusability of the concrete building products on the basis of qualification factors.

The qualification factors include component type and quality, durability, function, fatigue loading, project lifetime, and the construction/deconstruction/demolition methods applied. One of the most important factors is the lifespan of the building component, because knowing the lifespan provides more insight into the product reusability ways. A basic factor in determining the re-use potential of a component is the technical feasibility, however, the functional feasibility of the component play a key role (Iacovidou & Purnell, 2016).

The qualification factors for assessing the reuse potential of a building product can be divided into three systems:

- Lifespan system: All the different building products have their own lifespan. Lifespan refers to the period that a building component can perform the required performance. When a building component still has a long remaining lifespan to be reused, then the reuse potential considered as a positive factor.
- Performance system: The building products must meet various performance requirements before they can be reused in the new building project.
- Additional processes system: Some of the requirements are not particularly related to the performance that should be met. These additional requirements may relate to maintenance, storage possibilities, the transport process and etc.

Since this study takes into consideration the different functional properties of building products such as concrete in a newly developed dashboard, then it is substantial to analyze the performance system of reused concrete components in more details.

2.2.2. Performance System of the Reused Building Component

Building components have different life cycles and this fact provides the opportunity for reuse of them, in addition, the lifespan of their functions is shorter than the durability of the component itself. Thus, the main problem regarding reuse decision-making is to identify the characteristics of the building components. It is important to realize and assess the performance of the component and thereafter to recognize the remaining quality the component. The performance requirements describe the boundaries to be used within the different performance levels of the existing building component which intended to function (Durmisevic, 2006).

Furthermore, there is a relationship between the reuse potential level of a component and circular indicator which has been expressed in values/performances. The aim is to minimize virgin substances, keep the materials in the material cycle indefinitely (close the material's loop), and diminish the impact on the environment (Verberne, 2016). In the research of Verberne (2016), he analyzes the value/performance from three different perspectives, namely;

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

All the aforementioned performances have their own characteristics. In this research article, Functional value will be elaborated and discussed to realize which requirements the different concrete building products should meet in order to be reused, and technical and aesthetical performances are excluded in this research.

Functional performance:

The ability to reuse a concrete building component depends on the functional performance of that component. Therefore, it is very important to analyze the functional performance characteristics of a concrete component. On the other hand, the functional performance is also related to other factors such as physical characteristics of a building component. Naber (2012) explained that these main characteristics concern thermal, porosity, fire safety, sound insulation, block-outs in the concrete products, and the finishing of the ceiling of the roof component. These characteristics of the existing concrete components would meet different requirements set for the product systems of the new building. The requirements for various type of buildings such as residential, utilities, and industrial buildings are generally different, so the function of a building determines highly the functional requirements. Due to those various requirements, adjustments or modification are sometimes necessary before a concrete building component can be reused (Naber, 2012). The Dutch Building Decree 2012 (Dutch: Bouwbesluit 2012) includes the aforementioned requirements with regard to the functional performance for different type of building. Knowing the requirements related to the new building function can contribute to the updating of information regarding existing functional performance characteristics of a component. Because the existing components would meet the new requirements which allow them to be reused, recycled, refurbished or etc.

2.3. Functional Performance Characteristics of Building Products (Reuse Analysis)

Any construction and building system consists of a large number of different products each of which has been produced with different materials. Designing buildings (2022) defines building product as a material, substance or a set of collection thereof, which has been produced, refined, purified or even processed and declared by its manufacturer for a predesignated end use for interim and/or permanent incorporation into either a building or different civil engineering works, whether as part of new construction, renovation or preservation and maintenance. Construction products are processed and finished items that are presented for sale and also for end use. In other words, they are manufactured combinations of many different substances, materials or even the combination of other products, processed to make various items such as doors, windows, light fittings, and etc. Therefore, building products are generally distinguished from building materials which are raw and also unprocessed substances such as salt, sand, stone and etc. (Designing buildings, 2022).

Furthermore, building or construction products are the main requirement in this modern era of technology. There are many types of building products, materials and elements used for various structures. For a building product to be considered as building product, it would have required a large number of engineering, functional and also mechanical properties appropriate for construction works. These characteristics of building products are responsible for its quality and capacity and undoubtedly contributes to determine the applications of these products. Additionally, all the building materials, products or objects have different features such as functional characteristics which makes usage discrepancies among them. The characteristics of building products depends on various factors such as the composition of that product, deterioration and the use pattern (de Brito & Dekker, 2003).

In this research, the functional performance properties of building products such as floors, beams, columns, and walls which are made from concrete, will be handled and analyzed in the End-of-Life (EoL) phase. Since, concrete and (steel) are the most two building products that have been used in the construction industry.

2.4. Functional Performance Characteristics of Concrete Building Products

Each building consists of a large number of products such as beams, columns, floor, roof, foundation, wall, doors, windows and etc. that are made and constructed from different materials like concrete, timber, aluminum and etc. In this research the functional properties of concrete building products will be analyzed and handled. Therefore, to realize a CCE Information System for concrete building products such as floors and columns it is of great importance to provide significant information regarding functional characteristics of these products for the stakeholders involved in the construction projects.

2.4.1. Concrete Floor and Roof

Floors are one of the main components in the buildings and they provide strong level surface to support (resists) occupants, furniture, and other equipment (load). A concrete floor is usually a floor in which a flat slab is formed from concrete, which can be either poured in-situ or precast (prefabricated) in a factory. According to Westenbrugge-Bilbardie & Peters (2016), different types of floor systems have been applied in the floor and roof structure. Although, the most applied ground floor or floor systems integrated in the design tool are as follows; the combination floor, the ribbed floor, the hollow core slab floor and the in-situ concrete solid floor and precast concrete floor. In addition, all ground floor systems are designed and constructed of concrete. The aforementioned floor systems include products with different materialization and products used very common in the building sector. This research will analyze the two most common used concrete floor and roof, namely precast (prefab) and in situ, in the Netherlands.

Moreover, the functional performance characteristics of a concrete floor/roof can be summarized as;

- Strength and stability: The strength of the floor depends on the characteristics of substances and materials used to construct the floor's structure such as wood, concrete, reinforced concrete and steel used to construct the floor's structure. Design loads can be found in both Minimum design loads for buildings and other structures (also in Bouwbesluit). The strength of concrete components consists of compressive, tensile and flexural strength. With regard to the stability of the floor, the hardness of the floor must meet the predetermined requirements to keep the floor, and the level under its own weight and expected dead and live loads, stable.

- Durability and free from maintenance: In general, water tight ground floors based on solid foundations and story floors (roof) supported by walls would be durable for the life of the structure and in addition require not too much maintenance, repair or improvement. The durability and free from maintenance of floors depend on the nature of materials and substances (in the case of this research; concrete) used and the wear they are exposed to.

- Abrasion resistance: Abrasion resistance refers to the capability of the concrete surface to withstand wear forces from rolling steel wheels, scratches from pallet and stillage legs, fork lift truck tines, or even impact from falling different objects. The major factor controlling the abrasion resistance of concrete component is the compressive strength of the material used from (concrete). The higher the surface strength of the concrete, the better the concrete's resistance to abrasion. There are several factors, beside the concrete strength, that need to be taken into consideration that affect the abrasion resistance of concrete, such as the use of w/c less than 0.45, the use of dry shakes and toppings, finishing techniques, and adequate curing.

- Fire resistance: All the building components/elements/materials including floors, roofs, walls, columns and etc. must be sufficiently resistant to fire during which the occupant can leave the building. NEN-norms and Euro-codes (in Eurocode 3: NEN-EN 1992 part 1 & 2) determines the rating of fire resistance starting from an hour to 4 hours based on the types of aggregate and the thickness of concrete cover (see Appendix A.2.1, Table A´.2.9, Table A´.2.10, Table A´.2.11).

- Resistance to passage of heat (Thermal): Floors as the same as other concrete components must be able to withstand heat emission if there are large air temperature differences on both sides of the floor. Using different materials in floor, roof, and wall systems such as damp-proof membrane can contribute largely to the decreasing of heat transfer (see Appendix A.2.1, Table A´.2.16, Table A´.2.17).

- Resistance to passage of sound (Sound insulation): One of the functional properties of the floors, roofs and walls is to act as a barrier and prevent the transmission of sound. Therefore, it is needed to realize a suitable sound insulation layer in the floor, roof or wall systems to this functionality of the concrete component, by choosing an absorbent sound layer or panel finishes (see Appendix A.2.1, Table A´.2.9, Table A´.2.12).

- Precast (Prefabricated) Concrete Floor:

Precast concrete is a building product manufactured by pouring concrete into a reusable mold or form which will be thereafter cured in a controlled environment, and finally transported to the construction site and lifted into place for construction works. There are several types of precast concrete forming systems, in forms of floor, roof and wall, for architectural applications, varying in size, function, and cost (Elliott, 2016). In the figure 2.4, the four most common types of prefabricated concrete building products can be seen. Precast concrete systems have many potential advantages in comparison with onsite casting. Furthermore, off-site production, such as manufacturing precast concrete products and also an increasing use of self-compacting concrete on site (no need for vibration compacting) contribute to reduce noise pollution on construction sites. Precast concrete products provide faster and more effective construction process. additionally, this system has its own functional and physical characteristics that affect the layout, the length of span, construction depth, stability system and etc. to a greater or less extend (Georgopoulos, 2014).

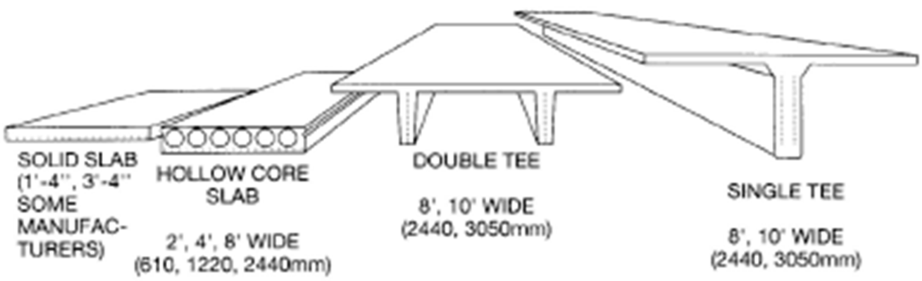


Figure 2.4: Different types of pre cast concrete floor/roof systems (adapted from: CRCA, 2020).

Applying precast concrete building products in different types such as hollow core slab or solid slab, TEE form or etc. can improve the sustainability of a project appropriately. On the other hand, one of the main processes in the prefabricated concrete elements is using reinforcement materials, mostly steel. Thus, reinforcing concrete with other substances like steel will improve strength and durability.

However, the compressive strength of concrete is largely significant, but lacks tension and shear strength can be subject to cracking with long-term loading. Steel helps concrete to achieve high tension and also higher shear strength to compensate the functional that concrete lacks. Reinforcement mostly will be applied in the form of rebar. Rebar has sufficient versatility to be bent or mount to support the form of any concrete structure. Some of the functional characteristics of precast concrete products can be seen in the table below.

Table 2.2: Functional performance properties of precast concrete floor/roof (own table).

Types of Concrete	functional performance characteristics
Precast concrete floors: **Hollow Core Slab Floor (HCS)** **Solid slab** **Double TEE** **Single TEE**	Quick and easy installation Excellent fire resistance High load capacity and rigidity Easy project implementation/structural movements Efficient span/depth-ratio leading to reduced storey height High durability and load resistance Long spans without the need of temporary supports Control light/radiation of heat/conduction of heat/sound Thermal & moisture expansion/contraction

Hollow core slab (HCS) floor is a kind of precast slab of pre stressed concrete which commonly used in the construction of floors in especially multi-story apartment buildings. This type of concrete floor system has been especially used in countries where precast and prefabricated concrete is the most useful production method for construction, including Northern Europe and also in the Netherlands (figure 2.5).

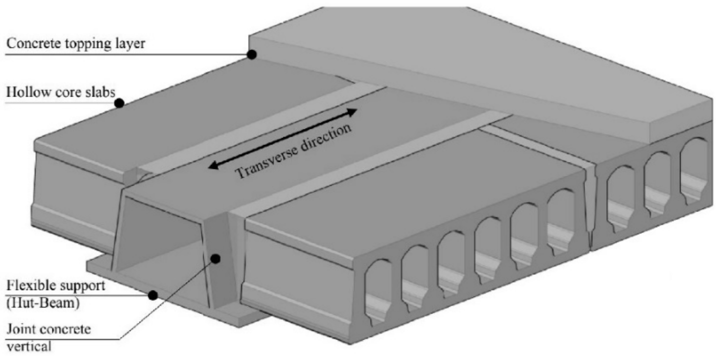


Figure 2.5: Floor structures with hollow core units (Derkowski & Surma, 2021, p. 2).

Furthermore, HCS units are mainly applied for floors and also roof systems of buildings and warehouses. They have high quality concrete as they are fabricated and manufactured under controlled conditions in precast factories (Al-Negheimish et al., 2018). A HCS is a prefabricated, pre stressed concrete member with ongoing voids provided to reduce weight, cost and as an added benefit, can be used for concealed electrical or mechanical conduits. As HCS is one of the types of precast concrete, these types of concrete can significantly use in low-seismic regions and it is also more economical constructions due to fast building assembly, lower self-weight (less material) and etc. Furthermore, precast hollow core elements are considered as the most sustainable floor-roof system and have much smaller CO_2 footprint. HCS has excellent span capabilities, reaching a capacity of 2.5 kN/m² over a 16m span. (Buettner & Becker, 1998).

- In-situ (Cast-in-Place) Concrete Solid Floor:

In situ concrete solid (cast in place) floor is a wet form of construction which requires the floor to expand its full strength, generally circa 28 days after it has been poured. Moreover, shuttering or formwork must remain in position for the required period of time, depends on the composition of materials used in the concrete, until the slab has reached enough strength. Cast in place floor is generally only economical over small spans of around 3m to 5m.

Usually, the simple type of this floor is a concrete slab that spans only in one way, i.e. the reinforcement acts lonely in one direction among two supports. Additionally, two-way spanning slabs can significantly be used for higher loads and longer spans. This type of concrete floor can also be applied in other forms such as flat plate floor, in situ T-beams floor, in situ hollow block floor, and waffle slabs (Designing buildings, 2022). Cast in place concrete floor can be thermally activated by including a water-carrying pipe network in the construction. This pipe network mostly has a heating function (underfloor heating system).

2.4.2. Concrete Columns (Precast and Cast-in-Place)

Columns are actually vertical structural components where the load can be transferred parallel to the longitudinal axis as compression and sometimes as tension. Concrete can be applied in different forms, shapes and types variability with different functionality, characteristics, and usability. Therefore, concrete can be considered in a construction as a column in different composition, forms, and also different manner of applicability namely prefabricated or casting it in the construction place. However, concrete columns will mostly be applied including reinforcement materials like steel (composed of concrete with an embedded steel frame) to achieve more strength ability.

The most functional performance characteristics of column is carrying the loads from the beams and slabs down to the foundations, and thus they are acting as a primarily compression members, although they may also have to withstand bending forces because of the continuity of the structure (Mosley & Bungey, 1987). Moreover, different types of columns will use in the structure of a building depends on many different factors. The columns such as tied, spiral, composite, column with uniaxial eccentric loading, column with biaxial eccentric loading, short column, long column, square or rectangular column, circular column, and more other types. It is estimated that approximately 95% of all columns in buildings are tied. As the same as concrete floor and roof, the functional performance characteristics of concrete columns depend also on its composition characteristics. For instance, the strength of a column depends on the strength of substances used, the geometry, the shape and size of cross-section, the length and position of column relative to the support position at both ends.

2.4.3. Concrete Walls (Precast and Cast-in-Place)

The construction of concrete walls plays a crucial and important role in building construction. It is constructed as a load bearing structure as well as column to transmit loads from floor to the underlying wall or to the foundation, also to dividing spaces in multi-story buildings. Moreover, there are various methods to construct the concrete walls such as prefabricated and cast in place which require different construction processes.

Functional performance characteristics of concrete walls, as the same as floor/roof, can be divided into strength of that, durability, permeability and porosity, and thermal properties of materials used in wall. For example, substances and materials used for the construction of concrete walls play an important role in improving the performance of the wall during its service life (Mosley & Bungey, 1987). However, these functional characteristics can also be applied for columns, roof and floor in a building.

2.4.4. Functional Performance Characteristics of Reinforcement Material (Steel)

When a high tensile strength material, such as steel, is placed in concrete, the composite material, reinforced concrete, can withstand not only compression but also bending and other direct tensile forces. A section of reinforced concrete where the concrete withstands the compression and the steel withstands the stress can be made into almost any form, shape and size for the construction industry (Mosley & Bungey, 1987).

Rebar (short for Reinforcing Bar) has high tensile strength and elasticity (figure 2.6). The thermal coefficient of steel bar is almost equal to that of concrete, i.e. respectively. This reinforcing material develops a good bond with concrete, and it is cheaply and easily available in bulk. Thus, the reinforcing steel - bars, rods or mesh - will absorb the tensile, shear, and sometimes the compressive stresses in a concrete structure. In the design phase of concrete products, it is undoubtedly essential to take some factors of steel into consideration such as yield strength, Ratio of tensile strength/Yield strength, percentage total elongation at maximum force, fatigue strength, bend performance, weld ability, bond strength, tolerances and dimensions (Elliott, 2016).

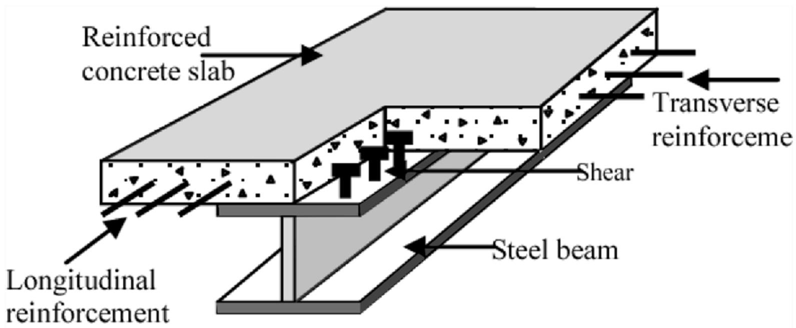


Figure 2.6: Rebar in reinforced concrete slab (own figure).

Given that this research analyze the functional characteristics of building products at the end of service life phase to maximize the reusability of them, therefore, it is needed to discuss first; the design characteristics of steel from a case document and thereafter an analysis will be carried out regarding the external factors that can affect the quality of steel during the use phase. for instance, the corrosion of reinforcement bars (Rebar) because of carbonization of hardened (cured) cement paste or chloride attack under moist conditions.

The functional performance properties of concrete floor, roof, column and walls depends largely on many external and internal factors such as the strength of material (concrete) used in a floor or column. Therefore, the quality of concrete floor, roof and etc. would be analyzed at the end of service life phase, and also analyzing the external and internal factors which could affect the functionality of these building products during the use phase. Because the results achieved from the analyzing these internal and external factors, indicate the level of quality of concrete floor, column and etc. which contribute to the maximization of the reusability of these concrete products.

Internal factors: composition of building products – durability of concrete – strength of concrete or eventually the strength of reinforcement martial – permeability and porosity – thermal factors

External factors: environmental conditions and effects such as moisture – temperature – sea water effects – bacterial corrosion – physical damage

2.5. Functional Performance Characteristics of Concrete as a Substance

2.5.1. Concrete

Concrete is one of most important man-made substances in the world used for several purposes either in the construction or in other industries. According to Gagg (2014), concrete is the second consumed material, after water, in the world, and it is the most commonly used building material. Concrete is considered as a composite material that consists of different substances namely; cement (normally Portland cement), sand, crushed stone or gravel (aggregate), chemical additives and water. When these substances have been mixed, the cement will be hydrated and finally becomes hard as a stone-like material. Moreover, concrete has been the main and most important building material in the modern times because of its longevity, durability, formability, and easiness of transport (Gagg, 2014).

In order to understand the functional performance characteristics of concrete, it is essential to analyze different types of this building material in the construction industry and thereafter various functional properties of concrete like the strength of concrete, durability and lifetime, permeability and porosity, thermal and acoustic insulation characteristics of concrete, and finally the reusability of this building material.

2.5.2. Different Types and Modified Concrete

Given that concrete can be considered as a human made material the in construction industry, therefore, it will be modified during the time to improve its characteristics, especially by growing the technology. There are many different types of concrete in the construction industry that can be used for different purposes.

Modern concrete, High-strength concrete, Stamped concrete, High-performance concrete (HPC), Ultra-high-performance concrete (UHPC), Micro-reinforced ultra-high-performance concrete, Self-consolidating concrete (SCC), Polymer concretes, Polymer Portland Cement Concrete (PPCC), Polymer-Impregnated Concrete (PIC), Vacuum concrete, Shotcrete, Lightweight Concrete, Pervious concrete, Cellular concrete, Roller-compacted concrete (RCC), Asphalt concrete, Rapid strength concrete, Rubberized concrete, Glass concrete, High-Early-Strength Concrete (HES), Micro silica Concrete, Limecrete, Sulphur Concretes (SC), Fiber-Reinforced Concretes, Air entrained concrete, Ferro-Concrete, Precast concrete, and Pre stressed concrete, are different types of concrete available in the construction industry (Surahyo, 2019).

All the aforementioned types of concrete have different functional, mechanical, physical, and chemical characteristics in two states, the plastic and the hardened state depending on the usability, environmental circumstances, materials used therein and other factors. This research analyze functional performance features of concrete applied in the Dutch construction sector, hence, it is substantial to provide more insight into the most used concrete building products in the Netherlands.

Concrete is also one of most used building materilas in the Netherlands as the same as other countries. Reinforced concrete was first applied in the Netherlands around 1880, after which the material was gradually used more and more for divers' construction works. From 1900 normal or reinforced concrete was applied increasingly in constructions such as bridges, factories, halls, silos, cooling towers and water towers. After 1900, more and more prefabricated and precast constructive concrete elements became available in the Dutch market, which could be used in different types of floor systems and roof panels. Moreover, at the beginning of the twentieth century, the first concrete floor buildings have been built in the form of a beam construction in the Netherlands. Most concrete structures were also poured on site, so that the various parts formed a monolith. Later, from 1930, pre-stressed concrete has been developed and applied largely. Thereby, fast-setting concrete with a high density and compressive strength and also a low shrinkage was used. From 1945, the Dutch constructors tried to adopt new techniques such as vibrate and shake, and also using plasticizers to increase the quality of prefab concrete elements (Rijksdienst voor het cultureel erfgoed, 2021).

According to (Bijleveld et al., 2013), total amounts of concrete products used in the Netherlands are known. The average use of concrete of approximately 13 to 14 million m³ corresponds roughly to 0.75 m³ of concrete per inhabitant, every year (Table 2.3). Given the table below, the most concrete products have been used in ground-road and hydraulic engineering sector (GWW; grond-weg en waterbouw), 41.5%.

Table 2.3: The total amount of concrete in the Netherlands (Bijleveld et al., 2013, p. 19).

	Betonmortel	Betonproducten	Totaal	Aandeel
	m^3 x1.000	m^3 x1.000	m^3 x1.000	
Woningbouw	2.975	1.020	3.995	28,5%
Utiliteitsbouw	2.575	1.620	4.195	30%
Civiel/GWW	995	3.360	5.810	41,5%
Agrarisch	905	Inbegrepen bij utiliteitsbouw		
Overig	550	n.v.t.		
TOTAAL	8.000	6.000	14.000	100%
Bron	Cement & Betoncentrum en VOBN (2011)	BFBN		

The using of different types of concrete products depends on various factors such as strength class. Therefore, rapid strength concrete, also known as fast concrete or speed mix, beside liquid concrete is probably one of the most commonly used types of concrete in the Netherlands. Due to its special composition and characteristics, this concrete can be hardened within 15 minutes. However, as already mentioned, in the most aged buildings from previous years in the Netherlands pre-stressed concrete as well as precast (prefab) concrete have been used.

2.5.3. Strength of Concrete

As already mentioned, concrete is the most used building material and products worldwide. The structure of building, columns, floor, foundation or other parts of any construction project can be realized at the design point to be constructed by concrete. Therefore, the concrete would meet its strength requirements to fulfill its function. The strength of cured cement paste is most crucial property of concrete (Surahyo, 2019). However, the strength of concrete can be affected by many different external and internal factors such as environmental conditions, temperature, curing and quality of substances used.

According to Hamidi et al. (2020), compressive strength of concrete is relatively high, while this element has a much lower tensile strength. Thus, concrete is generally will be reinforced with materials and substances that are stronger in tension, mostly with steel. Furthermore, Gagg (2014) describes that the compressive strength that a concrete can gain depends on different factors such as the water–cement ratio, the hydration improvement progress, the curing and environmental conditions and also the age and lifetime of the concrete. The strengths of concrete are determined by its function. Moreover, strength of concrete is usually given as a compressive value, declared in Mega Pascal (MPa) at 28 days of age (Gagg, 2014). The results of 28-day strength tests are typically applied for quality control and acceptance of concrete and also to determine that the concrete mix as supplied meets the requirements of the specified strength in the contract specifications (Surahyo, 2019).

The compressive strength of concrete is a complex non-linear regression issue for construction and structural engineering. Additionally, it is difficult to predict the concrete strength due to its nonlinearity (Deepa et al., 2010). Nevertheless, it is known that the compressive strength of the concrete will increase further after the characteristic strength is reached at day 28 (see figure 2.7).

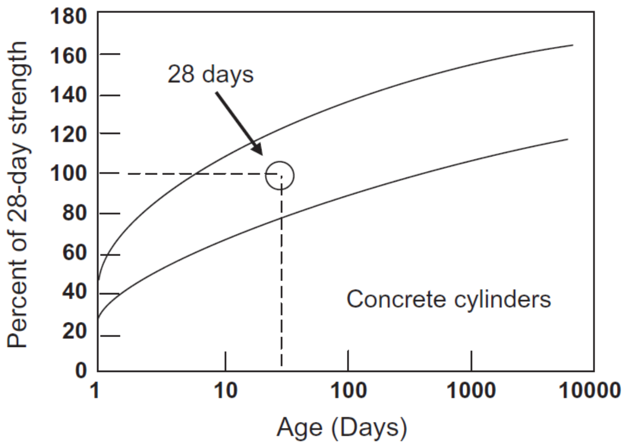


Figure 2.7: Increase of the concrete strength in the long term (Gagg, 2014, p.118).

Moreover, compressive strength of concrete differs from less than 10 N/mm², or in other words 14 MPa for lean concretes to more than 55 N/mm² for special concretes. For most common uses, 20 to 32 MPa (2,900 to 4,600 psi) concrete is mostly used. Also, concrete with 40 MPa (5,800 psi) strength is conveniently commercially available as a more durable, although more expensive, option. While, higher strengths up to and exceeding 70 MPa (10,000 psi) are sometimes specified for certain applications in e.g. the lower floor columns of high-rise concrete buildings to design and keep the size of the columns small (Surahyo, 2019).

It would be noted that the buildings aimed for deconstruction processes to reuse their components categorized under aged buildings with other strength classes. Therefore, those strength requirements need to be compared to the new codes (Euro code of 2012) to provide a clear picture of the development of the compressive strength of the concrete from 1912 up to the Euro code of 2012 (see table 2.4).

Table 2.4: Mean cubic compressive strength values of the highest strength classes from different standards (Zandbergen, 2016).

Standard	**Strength class**	**Mean cubic compressive strength in N/mm2**
GBV 1912	-	26.3
GBV 1962	K300	31.5
VBC 1974	B60	67.5
VBC 1995	B65	73.0
Eurocode 2012	C90/105	113.0

Table above shows various strength classes from previous years to 2012 which were defined in GBV (Gewapend Betonvoorschriften) of 1962 (classes of K160, K225, K300). Thereafter, eight new strength classes were defined in the VBC (Voorschriften Betonconstructies) of 1974 (B12.5 up to B60), and other classes (B15-B65) were introduced in the VBC of 1995. Nowadays, using Euro codes is common method which basically focuses on the cylindrical compressive strength values. These values, divided into C12 to C90, are 15 to 20% lower than cubic compressive strength values (Zandbergen, 2016).

2.5.4. Durability of Concrete

Durability is one of the major structural and functional properties of hardened concrete. The durable concrete can withstand the conditions considerably for which it was designed without any degradation and deterioration. So, durability can be seen as an important ability of concrete to withstand weathering action, chemical attack, and also abrasion while retaining its desired technical and functional properties (Surahyo, 2019). Therefore, knowing and improving the longevity of concrete can significantly contribute to the maximization of reusability of this building material at or after the end-of-life phase.

Furthermore, the durability of concrete can be affected by different external factors such as environmental condition, freezing and thawing, moistening and drying, abrasion, and also chemical attacks like sulfate attack. Also, by some internal factors like interaction among the constituent substances such as the reaction of alkali aggregate, volume changes, erosion, and corrosion of reinforcement. Hence, designing and using various types of concretes will require different degrees of durability depending on either the exposure environment or desired characteristics (Surahyo, 2019).

One the key objectives of this research is to maximize the reusability of building products and minimizing the waste in the end-of-life phase of a project. Also, moving towards Circular Economy strategies requires systematic thinking and handling building products issues such that different functional properties like durability optimize significantly. Because, durability plays a major role that contribute to the achievement of sustainability purposes. One of the ways to preserve natural and finite resources is to increase and optimize the service life of concrete by increasing the durability of concrete or even other building products. The key terms 'Service life' refers to the period of time that a building is expected to resist normal conditions, if appropriately maintained (European Concrete Platform, 2009).

Concrete can be considered as a long service life building material and element due to durability and low-maintenance requirements of its components. This building material can withstand weathering impacts, chemical attack, moisture and wear, while retaining desired technical properties. These specific characteristics of concrete make it sustainable in several ways; using concrete avoids contributing solid waste to landfills, diminishes the depletion of different natural resources, and also the production of water, air, and solid waste from substitute materials. Moreover, the most important characteristics is that when concrete designed properly, concrete structures and products can be reused or repurposed multiple times in the future (Shepherd, 2015). The design service life for concrete structures is set at a minimum of 50 years, however concrete can last for a maximum of 200 years. There is 95% probability that the intended and designed service life will be reached (European Concrete Platform, 2009). Therefore, to reuse the concrete products applied in a building project, it is required to analyze the aforementioned factors and the age of constructed building in the end-of-life phase.

2.5.5. Permeability and Porosity of Concrete

As already mentioned, concrete has different types of physical, mechanical and functional characteristics that play major roles in its functionalities and performances. Permeability is actually one the properties of concrete that allows liquids to pass through it, while porosity is the other characteristic of concrete that permits liquids to penetrate into it by capillary action, and it depends generally on the total volume of the spaces occupied by water or air among the solid substances in the hardened concrete. A higher permeability or porosity can cause damage and deterioration of concrete. Thus, permeability is one of the main characteristics of concrete that affect the durability and strength of concrete to the potentially harmful substances such as penetrate of water, oxygen, and carbon dioxide (Surahyo, 2019).

Therefore, some criteria have been defined that try to suggests the designers and engineers involved in the earlier phase making concrete with lower permeability (see table 2.5). In other words, for example proper water/cement (w/c) ratio followed by cautious placement, compacting, and curing are the best approaches to ensure high resistance to water ingress. Because excess water and water cause voids which reduce the permeability of concrete largely.

Table 2.5: Requirements for special exposure conditions based on American Concrete Institute-318 (Surahyo, 2019, p. 139).

Exposure conditions	Maximum w/c ratio (by weight)	Maximum compressive strength N/mm² (psi)
Concrete intended to have low permeability when exposed to water	0.50	28 (4000)
Concrete exposed to freezing and thawing in a moist condition or to deicing chemicals	0.45	31 (4500)
For corrosion protection: reinforced concrete exposed to chlorides from deicing chemicals, salt or brackish water, or spray from these sources	0.40	34 (5000)

The table above shows, the structural concrete would not have a w/c ratio of more than 0.50 for exposure to fresh water and also not have a w/c ratio more than 0.40 for exposure to seawater.

2.5.6. Thermal Characteristics of Concrete

There are different thermal properties, which may be remarkable in the performance of concrete such as thermal conductivity, specific heat, thermal diffusivity, and also coefficient of thermal expansion. Thermal conductivity and specific heat are needed in mass concrete to which insulation is applied to control heat loss through evaporation, conduction, and radiation. However, thermal diffusivity is considered as an index of the facility that allows the temperature to modify and the coefficient of thermal expansion play a major role in ordinary structural works (Surahyo, 2019).

- Thermal conductivity: This thermal property of concrete depends on the mixture of concrete and it also varies with the density and porosity of the material. The mean value of thermal conductivity of normal-weight 1:2:4 gravel concrete at normal temperature is equal to 10 British thermal unit inches per square foot per hour per F (1.44 W/m²/°C).
- Specific heat: It indicates the heat capacity of concrete and will increase with the humidity amount of concrete, and this thermal property varies with temperature. The specific heat values for normal concrete are between 0.2 and 0.28 BTU/lb/F.
- Thermal diffusivity: It is considered as a constant and it is also a measure of the rate at which temperature changes occur within the mass of hardened concrete. Its variability over a range of 0.020–0.080 ft.²/h (0.00186–0.0074 m²/h) will be controlled mostly by the composition of the mass and is largely similar in properties to the thermal conductivity.
- Thermal expansion: This thermal characteristics of concrete depends largely on the sort of aggregate and cement content used. Hardened concrete has usually a coefficient of thermal expansion ranging from 7 to 12x10^{-6} per °C (4 to 7x10^{-6}per °F).

2.5.7. Fire Resistance of Concrete

Several construction products, consisting of concrete as the main material, have significant fire-resistant characteristics, compared to steel (Mosley & Bungey, 1987). One of the best functional properties of concrete components is their ability to withstand fire or to provide protection against fire. This includes the ability of a concrete structural element to continue to either perform a particular structural function or to contain fire, or even both.

Furthermore, Surahyo (2019) explained that concrete is a porous material which is bound together by water containing crystals. The binding material can decompose and disjoint when heated to too high temperature (above 300°C), resulting in loss of strength. If the temperature increase constantly, the strength and modulus of elasticity for both concrete and steel reinforcement in it decrease. Although, the rate at which the strength and modulus of elasticity reduce depends largely on the rate at which the temperature of the fire increases and the insulating characteristics of concrete. The evaporation of moisture will cause shrinkage and increasing in temperature causes the aggregates to expand, resulting in cracking and spalling of the concrete. In addition, when the concrete products are exposed to fire, the cement mortar turns to quick lime at temperature of approximately 450 °C and causes scaling and cracking on the surface.

On the other hand, reinforcing steel (Rebar) used in the concrete products is much more sensitive to high temperatures than concrete. When the reinforcing steel is exposed through the spalling action, then the steel expands faster than the surrounding concrete, causing buckling and loss of adhesion to adjacent concrete, where the rebar is completely encased. Reinforcement (Hot-rolled steels) will retain about 50% of its normal yield strength up to 426°C, while for cold-drawn steels (pre stressing strands) this temperature is about 260 °C that they lose their strength (Mosley & Bungey, 1987; Surahyo, 2019).

Despite concrete can appropriately withstand fire, but concrete structures have yet to be designed for fire effects. The fire resistance of reinforced concrete products depends mainly on the type of aggregate, the thickness of the different parts that make up the element, and also the cover of concrete over the rebar. The fire resistance of concrete components is rated/expressed (from 0.5 to 4 hour) by the number of hours of effective fire resistance, e.g. utilities buildings require a four-hour rating. Thus, it is needed to analyze the technical fire requirements according to the Dutch Building Decree (in Dutch: 'Bouwbesluit') in which the fire safety measures have been determined for different type of buildings and their products (see Appendix A.1.2).

- The Ability of Concrete to Withstand Fire During its Lifetime:

As this research analyze the functional performance properties of concrete building products at the EoL phase to optimize the reusability of them, therefore, this question may arise; how does the fire resistance of concrete products modify during the service lifetime of the component? As explained before, the compressive strength of the concrete still increases during its lifespan, but concrete can be considerably weakened after many years by different forms of deterioration and this could affect the temperature effects as well.

There are many factors which playing important role in fire resistance ability of concrete components, and also affect this ability. The thickness, strength of concrete, type of aggregates, concrete cover used in floor systems, and some deterioration factors such as; corrosion of the reinforcement, carbonation, chloride and chemical attack, and physical deterioration (drying shrinkage and creep, frost and de-icing salt damage) (Wang et al., 2013).

The other parameter that influence the functional performance characteristics of concrete is the spalling of aged concrete. The concrete spalling can be influenced by large number of factors like moisture content, the porosity, the concrete strength and etc. In the aged buildings the moisture content of concrete seemed to be quite high which can increase the chance of spalling. The risk of spalling is relatively high in the early years of normal strength concrete, as the water content decreases with age due to drying and the effective water content of the pores close to the surface decreases over time. However, there are conflicting studies showing that aging increases the susceptibility of concrete to spalling, while, others suggested that concrete will not spall beyond a critical age. If the life time of obsolete concrete building structure is exceeded and the building system can meet its functional requirements under normal conditions by maintaining the structural defects, a fire safety evaluation should be performed by a fire engineer to provide information and solutions to address the fire resistance requirements (Wang et al., 2013).

Table 2.6: Performance of unprotected building materials (steel and concrete) in case of fire (Zandbergen, 2016).

Unprotected construction material	Fire resistance	Combustibility	Contribution to the fire load	Rate of temperature rise across a cross-section	Reparability after a fire
Steel	Very low	Nil	Nil	Very high	Low
Concrete	High	Nil	Nil	Low	High

Table above shows that concrete can be considered as a suitable building material due to its high fire resistance. Moreover, the characteristics that favorably influence the fire behavior of the material do not change in time. As Wang et al. (2013) also pointed out that novel types of concrete has a good resistance to the effect of fire by nature. However, for structures made of older concrete, the thermal characteristics should be taken into account to determine the actual fire resistance of the concrete structure, and it may be necessary to test sample material.

2.5.8. Sound Insulation of Concrete

Different materials with high density such as concrete are commonly used as external cladding tool to impede sound transmission into the property by reflection. The acoustic characteristics of concrete refers to its ability to diminish the transmission of sound across it. Standard concrete mixes with a density of 2300 kg/m³ can, in relatively small thicknesses, provide enough mass to reflect sound. Various studies emphasized that concrete can be consider as a good insulator which, because of its high density, is able to reflect up to 99% of sound energy. However, plain or ordinary concrete can be seen as a poor sound absorber that can lead to echoes in enclosed spaces (Holmes et al., 2014).

Furthermore, according to Fediuk et al. (2021), the behavior of concrete as a sound conductor depends on the different types, particularly dense compositions are great sound reflectors, while light ones are sound absorbers. Research revealed that the level of sound reflection in modified concrete depends on different factors such as the type of aggregates, the size and distribution of pores, and also depends on changes in concrete mix design constituents. Fediuk et al. (2021) also provided a table which shows acoustic characteristic of various type of concretes (Table 2.7).

Table 2.7: Acoustic property of different type of concretes (Fediuk et al., 2021, p. 9).

Type of Concretes	Maximum Coefficient of Sound Absorption	Level of Sound Reflection	Maximum Decrease in Sound Level at Frequencies, Hz
Normal concrete	0.05–0.10	High	3000–5500
Aerated concrete	0.15–0.75	Low	250–2500
Foamed concrete	0.13–0.50	Low	100–2000
Crumb rubber concrete	0.30–0.70	Medium	400–2500
Polyurethane concrete	0.08–1.0	Low	150–1400
Coal bottom ash concrete	0.05–0.31	Medium	500–3500
Coconut fibers concrete	0.42–0.80	Medium	1250–3200
Recycled aggregate concrete	0.01–1.0	Medium	1500–2000
Oyster shell waste aggregate concrete	0.43–0.53	Low	1000–1800
Polymer concrete	0.90–1.0	Low	64–1600
Glass-based concrete	0.20–0.37	High	250–3150

Table above is illustrated that the highest level of sound reflection is allocated to normal concrete followed by glass-based concrete. The sound absorption coefficient for normal concrete is approximately 0.02, which means that about 98% of the sound dynamism is a surface reflection. In the other words, if concrete be denser or heavier, then the sound insulation rate that can be detected will be higher.

Assessment of the sound related properties of the building (concrete) components such as floors, walls, and etc. allows the engineers to deal with the noise penetrating the premises and specify the degree of its impact (Fediuk et al., 2021). Below, different acoustic characteristics of concrete building products has been summarized as follows;

- Reinforced concrete wall system: Sound-insulating characteristics of a reinforced concrete is much better than a brick of the same thickness, because it is denser. A thick concrete wall is a better sound insulator than a thin concrete wall. Reinforced concrete wall with extremely high acoustic insulation ensure a sound reduction index of up to 60 dB.
- Concrete sandwich panels: There are different types of concrete sandwich panels made of various compositions with different thicknesses. Appropriate acoustic characteristics (Rw = 40 dB) are predicted for multi-layer sandwich panels with striped steel surfaces and a core of plain or reinforced foam.
- Reinforced concrete slab system: Traditionally, hollow core concrete slabs (HCS) are used to reduce the volume of concrete in the slab and also to minimize its own weight, in this case, however, the resistance to impact noise is decreased (Rw = 36 dB). Therefore, it is necessary to reduce the rate of impact noise through the use of different damping additives in the roof e.g. rubber. The transition of impact noise through hard-walled ceilings is increasingly optimized (Rw = 45 dB). Some other hollow composite reinforcing system can improve sound insulation performance up to (Rw = 43 dB). In addition, the constituent structural elements of the reinforced concrete slabs can improve the strength and performance of either the steel or the concrete as well.
- Steel-concrete composite flooring: Compared to reinforced concrete slab systems, composite floor systems providing a more economical solution. Therefore, it is needed to develop various modification of these composites to improve the acoustic characteristics of the floors. This will provide a more favorable sound insulation to the floor (Rw = 30-50 dB).

Meanwhile, to understand that the existing concrete building products meet the sound insulation requirements established in Euro codes or Dutch Building Decree (Bouwbesluit) at the EoL phase, it is important to carry out the performance test and evaluate the level of sound properties. The sound insulation requirements for different building parts e.g. outer walls or dividing walls will be noted in (Appendix A.1.3).

2.6. Concrete Degradation and Deterioration

Concrete structures become obsolete and deteriorate with time and these phenomena will affect the performance of the structures significantly (Wang et al., 2013). As already mentioned, this thesis will analyze the functional performance properties of concrete building products at the end of service life phase, with the aim of maximizing reusability. Concrete can be damaged and degraded due to large number of different internal and external factors such as; corrosion of reinforcement - incorrect selection of constituent materials - poor construction methods - chemical attack - hot and cold weather concreting - errors in designing and detailing and etc. (Surahyo, 2019). In any case, concrete is most commonly damaged and deteriorate by the corrosion of reinforcement bars because of either the carbonation of hardened cement paste or chloride attack under moist conditions (see figure 2.8). Therefore, when the concrete being damaged its two most important functional properties namely; strength and durability affected remarkably and hence the service life of the concrete will decrease (Felix et al., 2018).

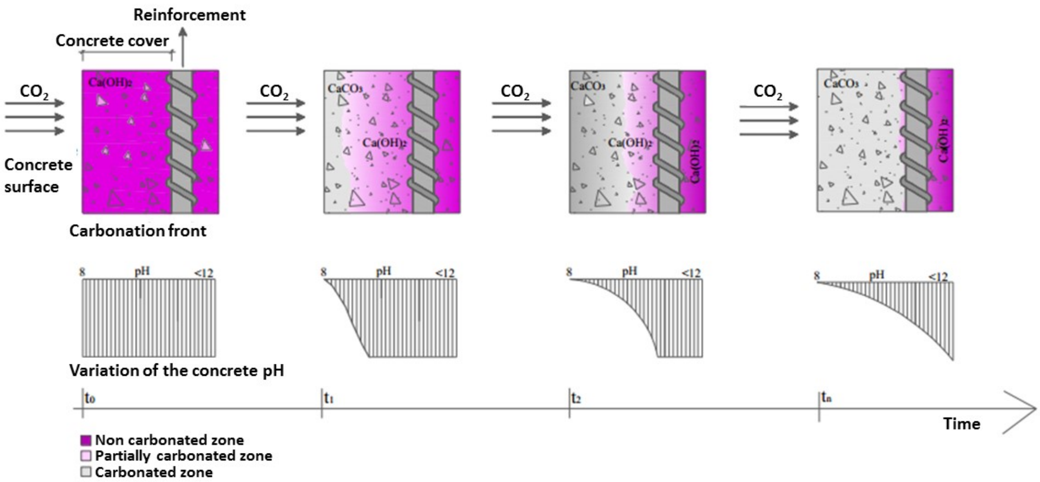


Figure 2.8: Advance of carbonation front vs pH reduction in concrete (Felix et al., 2018, p. 4).

Furthermore, some factors influencing the functional performance of concrete and concrete products would be considered at the design stage, and they are out of the scope of this research. According to Morseletto (2020), concrete building products related to design strategies (R3–R7) are stochastically uncertain in terms of their quantity or quality conditions. Therefore, to understand the level of quality of concrete (as substance) and the building elements made of concrete, it is needed to research about the environmental and different external factors (quality process phase) that affected the quality of concrete during the use phase, and also to provide significant information which shows the condition of concrete building products for recyclability, reusability, other purposes, or even for landfill at the EoL phase. Because, quality control within pre-demolition and also demolition stage would be taken into consideration, either in terms of occupational safety or recyclability/reusability of the C&D waste products (European Commission, 2016).

2.7. Deconstructing of Concrete Building Products

Deconstruction can be considered as different activities that systematically disassemble buildings, separate building products or even infrastructure elements, in order to regain the maximum amount of reusable and recyclable materials or components. Moreover, the aforementioned deconstruction activities close the loop of linear resource use, also diminish dependence on new substances, and decrease waste disposals in landfills. The deconstruction procedure is more complex and dynamic with increasing concerns about professional safety and environmental impact. Deconstruction is also recognized as green (sustainable) demolition, dismantling, or reverse construction (Tatiya et al., 2018). More insight into deconstruction process, its (dis)advantages and etc. can be found in Appendix A.1.4.

As the focus of this research lies on the concrete building products/components, therefore, it is essential to provide some knowledge about the deconstruction of its products. In other words, deconstruction is the main process of component management. It is a process that must be done very carefully to obtain the greatest amount of elements with the highest quality and the least damage. Thus, it is substantial to analyze this process which helps to have a clear picture of the process and also the calculation of the costs. More information regarding the correct deconstruction steps of a concrete building products can be seen in Appendix A.1.5. The technical steps of the deconstruction process can be summarized as follows:

- 1- Remove concrete topping: This topping is a concrete layer above the Hollow Core Slabs (HCS) and it has two functions; compression layer and finishing layer. A compression layer has about 50 mm thickness or more, contains reinforcement. This leads to a hard and slower removal process. Removing a concrete layer that function as a finishing is easier due to its 30 mm thickness and it contains no reinforcement, so it can be removed faster.
- 2- Remove Hollow Core Slabs: After removing the concrete layer, HC slabs can be removed. This process includes some activities/steps that would be done before deconstructing it, like; support walls and columns, remove concrete between the slabs, saw the concrete joint between beams/facades/walls and slabs.
- 3- Remove Façade Beams: After removing HCS, façade beams can be removed firstly. The façade beams are lied either on walls or on columns and they are joint with 1 dowel per side. In order to deconstruct them from other components, their junctions must be destroyed by; cutting the connection, drilling the connection, or sawing the connection.
- 4- Remove Beams: The next step that can be carried out after removing the façade beams, is removing the beams. The beams in most constructed buildings are actually supported on a corbel or at the edge of a wall, they are also joint with 2 steel dowels per side. The connections can be destroyed through lifting the elements.
- 5- Remove Columns: Thereafter, the columns can be removed. The columns are already supported with shores. It can that the columns are 2-4 storeys high, thus they will be deconstructed when their lower part has been reached. If the columns have a load-bearing function, then they can be removed as the last parts. The columns are connected to the columns of the ground floor with 4 reinforcing bars. The connection between them can be destroyed as the same as in façade beams.
- 6- Remove Walls: The walls as a load-bearing elements are the last standing products. Generally, they are the heaviest components between all the other structural elements. The walls are connected with steel reinforcing bars and a thin layer of concrete (2 cm) to the wall below, and the can be removed with the same methods as columns.

2.8. The Reuse of Concrete Building Products

As already mentioned, different existing building components/elements can be reused depends on their reuse potential, the remain functional, mechanical and technical values of those components and also depends on economic aspects such as creating a new market for secondary building components and providing more incentives for various stakeholders involved.

2.8.1. The Waste Management Hierarchy for Concrete Building Component

The current concrete crushing process for recycling does not have too much environmental benefits. The transition to CE strategies requires a major modification in different waste handling processes, and changing the impact on the environment, by preventing the amount of waste. A waste prevention ladder, 'Ladder van Lansink', can therefore provide more insight into the relationship among the amount of waste and the environmental benefit (Naber et al., 2013). According to Macozoma (2002), a waste management assignment is based on Lansink's Ladder and explains the waste hierarchy including prevention at the top as the most preferred and disposal at the bottom (figure 2.9). As can be seen in the waste management hierarchy, this model aimed to prevent the waste as much as possible, because it has no impact on the environment. On the other hand, due to the impossibility of prevention, the second highest step, namely reuse, will be prioritized if the components or materials of a building can be treated in a high-quality condition. Re-use of the components/materials is not always feasible, so recycling can be the next alternative. The waste management hierarchy was designed to reduce the amount of landfill waste and also achieve the goal of resource efficiency (Couto & Couto, 2010).

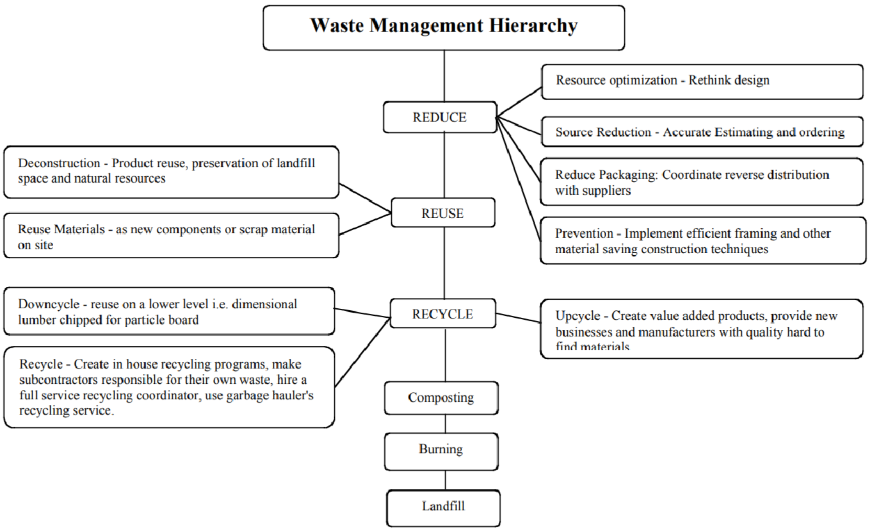


Figure 2.9: 'Waste Management Hierarchy' based on the 'Ladder van Lansink' (Macozoma, 2002, p. 58).

Demolishing a building system will make it difficult to reach the highest step of the ladder van Lansink. In order to limit the amount of waste, it is substantial that the structural components will be reused. The reuse process will contribute to the limitation of material/component landfill which has the reuse potential, thereby the environmental pollution will reduce appropriately. This can positively affect the sustainable development of the building sector, including different environmental aspects. The sustainable development in line with circular economy goals, should cover the whole life cycle of a building system, from the design point through the use phase and demolition phase. Therefore, the impact of buildings (incl. building components) on the environment should be minimized and the reusability of (concrete) building components should be optimized. Increasing the reuse of concrete components will result in saving more energy and finite natural resources, and also reduces the costs for the disposal/deconstruction or storage of waste (Dawczyński et al., 2013).

2.8.2. Reusability of Concrete Building Products after Deconstruction

Concrete products can also be reused at their end-of-life phase. For example, hollow-core concrete slabs are easy to disassemble, the span is generally constant and making them suitable for reuse. Furthermore, precast concrete pieces are also possible for reusability through selective demolition, because selective demolition allows such pieces can be disassembled and collected for further use at other construction sites. Concrete prefabricated constructions are the prerequisites for structures that can necessarily be taken apart. Therefore, implementing functional performance characteristics of different building objects such as concrete floor or etc. can highly contribute to the optimization of product circularity. Deconstruction process (Word Breakdown Structure) diagram of concrete building components is illustrated as follows (Figure 2.10).

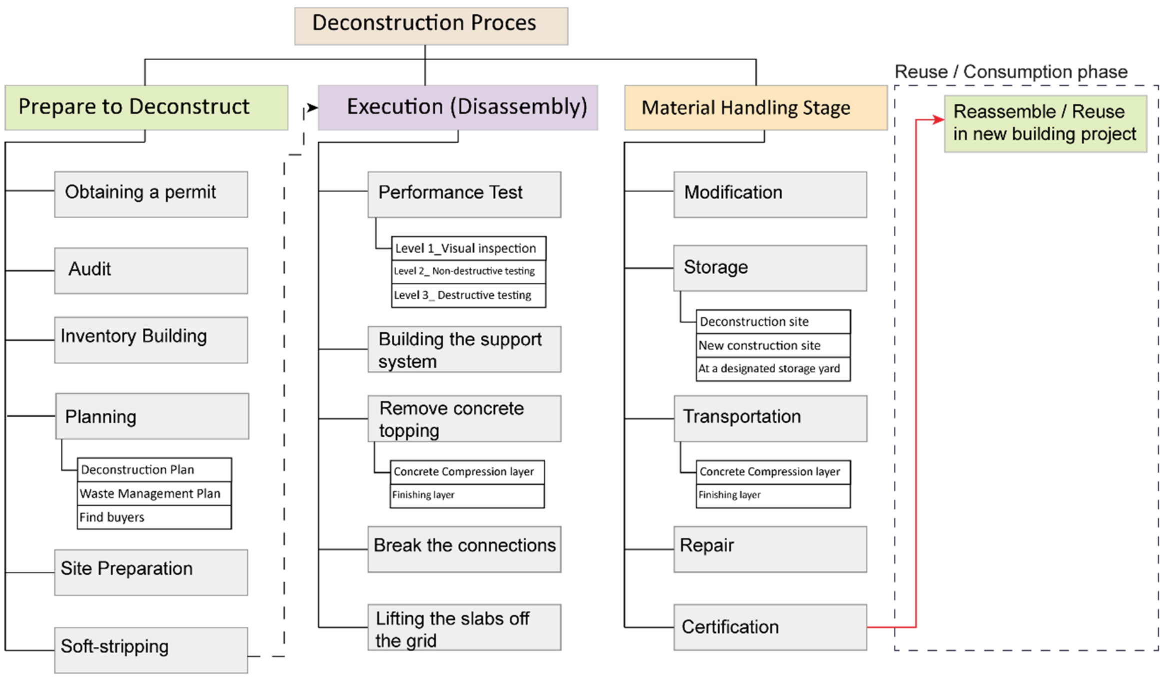


Figure 2.10: The deconstruction process model for reuse (own illustration, adapted from: Glias, 2013).

The reuse of existing building products has not been guaranteed after deconstruction process and it requires sometimes different adjustments to boost its quality, but this bring additional economic costs. There is challenge among sustainability, price, and quality. Reuse of existing building products after modification is not necessarily cheaper than purchasing the new one. The modification process can also affect environment significantly due to the extra energy consumption and extra pollution. Nevertheless, the level of quality of an existing component must meet the quality requirements of a new product. (Economic Board Utrecht, 2018). Therefore, there is a direct link between the reuse potential and the quality potential of a building component after the-end of its primary lifespan. The quality, in addition, should be in balance with the price and sustainability of the component.

As this research analyze the functional performance characteristics of concrete building products at EoL phase of a building, which will be implemented in a database later. Therefore, it is needed to take into consideration some aspects related to the execution (disassembly) stage. Because the first stage of the deconstruction process is the same as the traditional demolition process. Recent studies have been shown that there are some issues affecting the reuse potential of building products, namely; the mismatch among quantity and quality. Therefore, this have negative effects on the reuse market. In other words, the market is reluctance to use components without certification of performance test.

- Performance test: It consists of technical, functional, and aesthetical performance. After the building has been stripped down to its structural skeleton, performance tests would be performed to ensure that the concrete structural elements are durable enough for reuse. Tests are also carried out to confirm the stability of the design on the drawings and the as-built on site. This process can be done by first part conformity assessment method or second party conformity assessment approach. In first-party conformity evaluation method, a person or an organization fulfill in-house test elements while in the other conformity assessment method the evaluation will be done by the end-user (ISO, 2004). Concrete building components can be affected by different internal and external fators:
    - Internal causes: Effects of salt in the constituent substances, interaction among the constituent materials and substances such as alkali-aggregate reaction, volume change, absorption, and permeability
    - External Factors: Restraint against movement - exposure conditions (weather conditions - effects of salts from soil, ground, or seawater - freezing and thawing - wetting and drying - Leaching – abrasion) – overloading – settlement - fire resistance.

  This approach will be applied in the case study part of this research.

- Modification: After testing the performance of an element, sometimes it is required to carry out some change to a demounted component before reusing it. This is particularly needed when the components are not designed to be reused or disassembled. Fewer adjustments are required in prefabricated elements because they are standard dimensions than in cast-in-place slabs that are not designed to be deconstructed for reuse. There are different types of modifications to which a component can be subjected. The term 'No modification' means that the building part can be properly reused without any modification. For example, HCS can be reused without any changes because the elements are standardized (Bleuel, 2019).

- Repair: Again after testing or in case of damages or cracks, the component need to be repaired. For precast concrete products, it is not recommended to reuse components with signs of localized corrosion, section loss, and frost damage, etc. Some damages can be occurred by (external factors) like: entrapped air - spalling-off corners - honeycombs - scaling (by frost) - fire damage - delamination surface - discoloration of concrete - craquelé (small hairline cracks) - exposed reinforcement - moisture (Bleuel, 2019).

- Certification: According to ISO (2014), certification can be defined as an attestation of the products by a third party, i.e. a third party issuing a decision stating that the product meets the specified requirements. Moreover, the third party would be an appraisal body with the recognition of its ability to certify the building product by another independent party. A product will be considered as a certified product to ensure that it meets not only the performance test, but also the qualification criteria laid down in standardized guidelines and regulations.

In the Netherlands, a high percentage of approximately 95-98% of the C&D wastes will be recycled essentially minimizing landfill costs. This means that demolition has undoubtedly economic benefits by minimizing landfill costs and also environmental benefits by recycling construction and demolition waste. But It is an already established approach and technique and all the stakeholders involved have been experienced this process. On the other hand, literature studies and research done by practitioners and scholars emphasize that economic benefits of deconstruction would be more appropriate through the sale of the salvaged components and environmental benefits through the reuse of the products. It must be mentioned that these advantages also depend on the existence of new market for those secondary products, developing different information systems, and more other factors that discussed already.

2.9. Stakeholders Analysis

The (de)construction and waste projects involve a large number of stakeholders including public and private organizations, companies, consultant and etc. of various characteristics that may have different opinions on CCE Information System and benefits. Also, the participation and input of various stakeholders and parties in (de)construction projects play a key role in achieving sustainable waste goals (Kim et al., 2020). These stakeholders generally refer to the organizations (public-private) or individuals involved in C&W sector (Zhao, 2021). Therefore, analyzing their roles, responsibilities in this sector and also their needs and benefit from a CCE Information System can optimize the reusability of any building component significantly.

2.9.1. Stakeholders-Network in Deconstruction Process, Their Roles and Responsibilities

As already mentioned, deconstruction industry includes many different public-private stakeholders, parties and actors, in contrast to the traditional demolition. In traditional demolition method, the owner of the building hires a contractor who has the responsibility to demolish the facilities, then the debris will be transported to the waste collector for treatment. However, deconstruction process contains many different actors (see figure 2.11) who either directly or indirectly affect the process. The dialogue and collaboration between these stakeholders can be crucial to make reuse feasible.

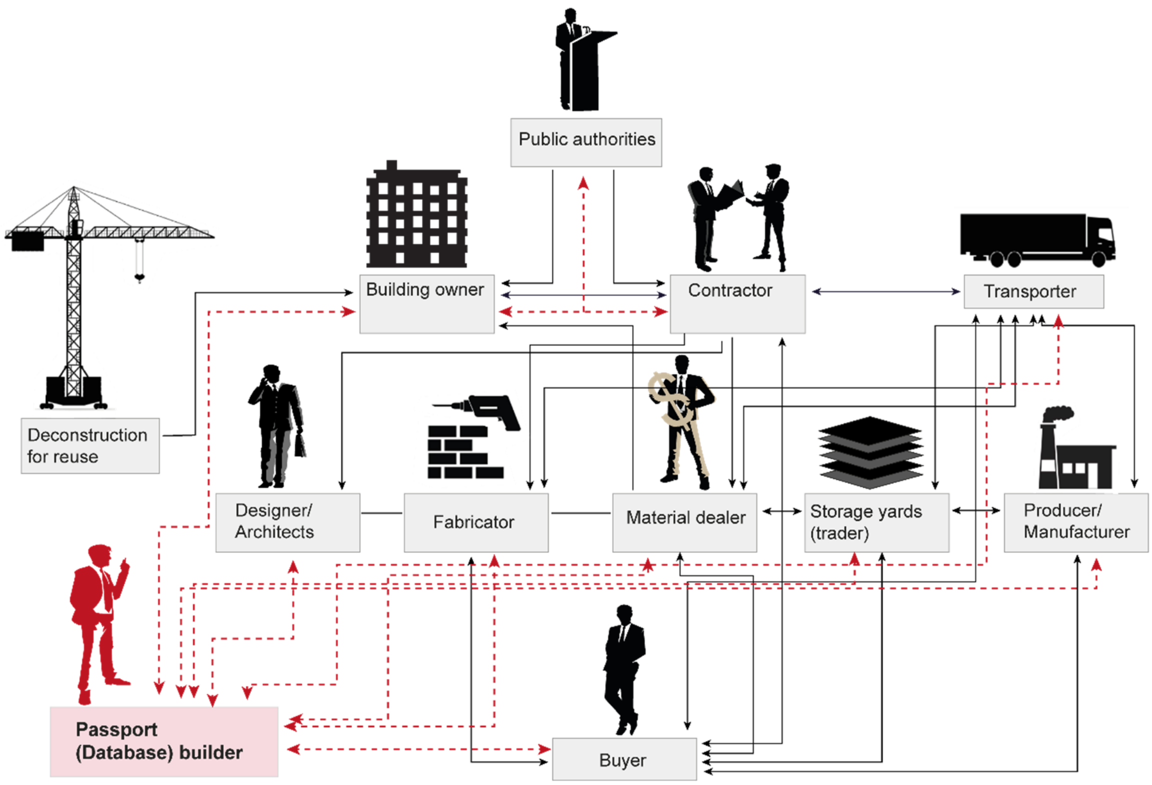


Figure 2.11: The networks model of stakeholders involved in the deconstruction for reuse process, implementing passport builder to the model (own illustration, adapted from: Jabeen, 2020).

The stakeholders involved usually tend to have different roles, concerns, and purposes, resulting in different behaviors, knowledge, and tendencies and make it challenging to implement building product passport (Zhao, 2021). Furthermore, some other actors involved in the deconstruction for reuse process can consider as; Passport (dashboard) builder, public administrations, consultancy firms, non-governmental organizations, and technology providers. All the aforementioned stakeholders have different responsibilities.

- Public authorities: Public authorities including governmental organization, municipalities, and provinces play a fundamental role by providing grants, permits, regulations, subsidies and tax relaxations to pilot project. In the cases that no subsidies or tax relaxation was offered by government, it becomes difficult to have a beneficial business case. Thus, all the risks ended up with the housing association and the contractor (Dorsthorst & Kowalczyk, 2005). Government policies on waste disposal and resource recovery can significantly affect the reuse costs. Moreover, there should be specific and predesignated guidelines for material/product grading and performance testing of secondary components.

- Building owner (Client/Investors): The owner of a project (a building, infrastructure, etc.) can be an individual, real estate (project) developer, municipality, etc. The incentive and willingness of the owner to deconstruct a project for reuse is a precondition in reusability process, as the client is the main actor. In the other words, the owner is the main decision-maker for either deconstructing a building or demolishing it. The client can be involved in all the phases, however his role in the tender stage is crucial. Although the owner is an active actor, but the owner's responsibilities is not too much when it comes to finding buyers and also potential clients for the secondary elements (Hradil et al., 2014; Platform CB'23, 2019).

- Contractor: The main contractor or subcontractor is usually responsible for the C&D waste management. The aim of the contractor is to keep the disposal cost as low as possible. The contractors (incl. demolition companies, waste companies, etc.) are instructed to either completely or partially demolish, in case of deconstructing; selective or partly-selective deconstruct the building for reuse by the project owner. So, the contractor becomes the main responsible actor for carrying out the demolition or deconstruction of a building and handling of the released EoL products. No contractor takes the initiative to deconstruct a project, when asked to demolish, as this costs more time and money (JRC, 2012; Zhao, 2021; Platform CB'23, 2019).

- Architects and designers: The other major roles in the D&W process are Architects and designers. Their role is particularly involved in the design phase. So, they must design the buildings according to the DfD principles and also with the information of existing building stocks in such a way that secondary components achieved from deconstruction can be reused. They need to be kept informed about the supply of secondary products, their functional performance and etc. and this can be done using passports (dashboards) (Hradil et al., 2014).

- Material dealers: They are also known as retailers. They purchase secondary products from contractor (demolition) and after sorting, grading, batching, they sell those components to end-users or selling back to the manufacturers. However, their activities include soft strip products not the structural elements (Hradil et al., 2014).

- Transporters: The transport companies are also involved in the C&W process. The recovered components for reuse are transported by them to a project site, a secondary product end-user or even to a storage yard.

- End-user: This category of stakeholders involved in C&W process mostly handling soft-stripping products. They are typically low-income buyers who purchase the components at a lower price and lower performance, middle-income buyers who purchase the products with the aim of using them for replacement in existing buildings or high-income buyers who purchase components due to their aesthetic value at high prices. However, the end users of structural components are usually builders or contractors who has a higher budget and be able to purchase and handle secondary products (Coelho & De brito, 2013; Platform CB'23, 2019).

- Producers and manufacturers: They have to design and manage the deconstruction and disassembly process and be able to take their products back from buyers and clients after EoL.

- Passport (data platform) builder: For reuse of structural components such as concrete products, it is imperative to realize and develop a detailed inventory of the products including many different significant information to share with the stakeholders involved. Therefore, this actor can be linked with all the stakeholders involved, to exchange the data and information, to keep them informed about the last updated information, to ease the communication among them, and more interconnected activities. A passport builder is responsible for setting up the data format, managing this data and is also responsible for the availability and legibility of this data.

Furthermore, more responsibilities of each stakeholder and the associated factors that influence the (de)construction and waste process are explained in Appendix A.1.6.

2.9.2. The Need of Stakeholders from a Circular Construction Element (CCE) Information System

In the previous part, different stakeholders involved in the C&D sector have been discussed. According to Debacker & Manshoven (2016), building product passports developed by different platforms will suggest opportunities to regain value from recovery and reuse of materials, building products and systems applied in buildings for different stakeholders between the value chain. In principle, all the stakeholders engaged in the construction and waste industry can use and profit from a harmonized and structured information system. Because, communication, coordination and collaboration between project stakeholders and participants can increase mutual trust and reduce conflict, positively change tendencies, and also play a key role for efficient C&D waste management in various project phases (Zhao, 2021).

Different stakeholders observe the desired form and content of a passport from different interests, perspectives, phases, scale levels and, above all, different sectors and disciplines (Platform CB'23, 2019) (more information can be found in Appendix A.1.7). This research is focused on the developing of a CCE Information System for concrete building products in the end of their service life phase. Platform CB'23 (2019) illustrated in table below (table 2.8) the information that the key stakeholders in C&D chain need to provide for a passport.

Table 2.8: The interaction between Stakeholders and a building product passport (adapted from: Platform CB'23, 2019).

Stakeholders	The information that the stakeholder needs to provide for a passport
Client (Owner)	*Management of the assets: materials and the corresponding raw materials, types of connections, specific service lives and possibly measurement data. *Value of assets quantified: materials, raw materials, types of connections, surface area and quantities, technical condition of construction elements, residual service life, financial value. *Tracing the owner of leased products. *Service life extension of assets (possibly with other function): technical condition of construction elements, construction elements' load, residual service life, design principles, building physics aspects. *Reuse: changes in design principles, transportation possibilities, standard parts linked to serial numbers and/or types, and/or customization, disassembly plan. *Measuring sustainability and circularity.
Contractor	*Expanding service life of assets (possibly with another function): technical condition of construction elements, construction elements' loads, residual service life, design principles, building physics aspects. *Reuse: design principles including changes, transportation possibilities, materials, standard parts linked to serial numbers and/or types, and/or customization, disassembly plan. *Release of raw materials/materials/parts: when are which raw materials released, what is their technical state and residual service life, what loads have they been subjected to? *Leasing of structure/part/material: traceability of leased product.
Producer/ manufacturer/ supplier	*Release of raw materials/materials/parts: when are which raw materials released, what is their technical state and residual service life, what loads have they been subjected to? *Leasing of building structure/part/material: traceability of leased product.
User	*Transparency of assets: transparency in respect of user of what is being put into use. *Background information (such as a city archive or land register). *Changing structure/part: record changes.
Passport (Database) builder	*What do the users of the passport systems want? *To have data available from different systems in order to fill passport formats, to know which standardization is required and have access to these systems.

Thus, a passport builder, is the main actor in this process connecting with almost all other stakeholders, and by setting up data and managing those data is responsible to meet the requirements of other stakeholders. From the table above can also be differentiated, that the client and contractor (including demolition/deconstruction contractor) would need a harmonized passport in C&D chain due to their involvement in restarting of a structure's service life. Depends on the quality of building products at the EoL stage some manufacturers or producers (waste treatment, recycling companies) would also need and profit from a dashboard. Because, the major issue of reusing reclaimed structural components such as concrete is that there is not a real market for this type of construction components. The main issues that need to be handled for a successful reuse market are the following:

- Stock of reusable members
- Reuse management model
- Database/passport/Information System procedure
- Establishment of storage sites
- Careful deconstruction
- Performance evaluation of reusable members

- Fabrications procedures for reusable members

Thus, developing a CCE Information System for building products which will includes at least some of these issues, can contribute significantly to the optimization of reusability in C&D chain and also providing new and useful information for different stakeholders.

2.9.3. Implementing Stakeholder Financial Benefits in a CCE Information System

Although the demolition of a building system mostly causes to the mixing of different materials/elements and pollution of non-hazardous building components, but deconstruction is aimed at separating materials or building products at source. It is not often preferred to carry out a complete selective dismantling technique, mainly because of the higher costs, at least when a high purity of waste flows is not needed (JRC, 2012). Notwithstanding the financial potential, different companies in the C&D sector still experience considerable obstacles to fully taking advantage of the residual economic value embedded in resources. The major financial obstacles can be considered as; high collection costs, low end-of-life material value, and labor intensity as most of current buildings are not designed for dismantling and recycling. Also, upfront investments, fluctuations in building product volumes, and quality of them have been seen to hinder financial viability of building product reuse (Nussholz & Whalen, 2019).

Beside the environmental value, the reusability and recyclability of building product is associated with economic value by diminishing costs for input materials/components and also organizing value-adding activities. Moreover, financial evaluations of circular business practices confirm higher associated risks, consisting of uncertainty about the residual value of secondary building components after use and their price compared to primary component (Nussholz & Whalen, 2019). There are already different calculation methods such as Demolition Recovery Index (DRI) that indicates recovery potential of building products from a deconstruction project (Table 2.9).

Table 2.9: Recovery potential of component from a deconstruction project (adapted from: JRC, 2012).

Building component	Value	Potential applications
Concrete	High	1. Reuse: blockwork, structures 2. Recycling as recycled concrete aggregate (RCA) in new applications or as a sub base or as a recycled aggregate (RA) with brick stone, slate, etc. for fill operations
Nonconcrete masonry	Medium	1. Reuse: brickwork, stone, slate 2.As RA as sub base or engineering fill
Metals	High	1. Reuse: steel beams 2. Recycle aluminium and copper materials with highest value, and steel (most significant tonnage)
Wood	Medium	1. Reuse (non structural applications) 2. Chipped and use in several applications
Glass	High	1. Recycle as sand aggregate, shot blasting, filtration material for water treatment, etc.

As can be seen in the table above, concrete has a high value potential regarding reuse and recycle ability in the deconstruction process. Moreover, the calculation methods provided by European Commission (JRC, 2012) emphasize that deconstruction (selective or partly-selective) is more expensive (cost double) and also last in more days in comparison with conventional demolition. In order to move towards a more circular building products chain and maximizing reusability, therefore, increasing the rate of construction materials/products recycling (i.e. reducing demolition waste), is the fundamental driving force for applying selective or even partly-selective deconstruction.

- The Reuse Cost at EoL phase (Cost-Benefit Analysis):

As already mentioned, to implement high value information to a CCE Information System for different stakeholders involved, it is essential to provide related data regarding cost effective decision-making for reusability of building products (Tatiya et al., 2018). The benefits of reusability for stakeholders can be derived from an analysis performed in various costs associated in the deconstruction process, as deconstruction contributes highly to the increase of reuse of building products. It is also necessary to investigate the relationship between costs and stakeholders in the deconstruction process.

Many studies have already shown that deconstruction cost is higher, approximately 17-25%, than demolition cost. However, this research is aimed to estimate which stakeholder can make profit from a deconstruction process and which of make loss. Because, for example the cost of transportation from the deconstruction site to the waste company can be allocated to demolition contractor or waste treatment company. Therefore, it is essential to implement the costs of reuse for building products at the EoL phase in a dashboard for stakeholders involved.

There are different direct and indirect costs associated with the reuse of (concrete) building components. Different associated costs such as; the deconstruction cost, transportation cost, storage and reconditioning (modification or repair), tipping fees, fines on mixed substances and also cost of secondary and new materials (Liu & Wang, 2013). However, the full-cost factors of C&D waste management sectors include other costs like cost of landfill disposal, costs of recycling waste materials, and costs if reuse. To know which costs are allocated to which stakeholders it is substantial to zoom more in the costs of reuse in the C&D sector.

Liu & Wang (2013) described that reuse of waste components or martials, can perhaps be a better solution for waste products generated from deconstruction projects. The reuse process can be recognized as consisting of the following costs:

- Collection, transportation and storage of waste on-site
- Sorting into various categories of waste
- Transporting sorted waste to an either off-site or on-site location for further processing if it was required
- Processing components/materials for reuse (reapplication)

Therefore, the total reuse cost (benefit) for a (concrete) building products can be calculated as:

$$C_{RU} = C_M + C_{TRU} + C_{Process} - B_{RU} \quad (1)$$

Where;

- C_M represents the total cost of processing waste and can be calculated as:
  $$C_M = C_{C\&T} + C_{sort} + C_{store} \quad (2)$$
  in which; $C_{C\&T}$ is equal to cost of collection and on-site transport of waste component - C_{sort} is equal to the cost of sorting waste component (materials) on-site - $C_{store}$is equal to the cost of storing waste component (materials) on-site.

- C_{TRU} represents the transport cost of components to off-site or on-site processing center, and can be calculated by:
  $$C_{TRU} = Q * RUF * R_{TRC} * Dist_{RU} \quad (3)$$

in which; Q refers to quantity of component waste (tons) - RUF is equal to the reusable fraction of the total waste generation - R_{TRC} is the rate of transport cost to reuse processing facility (Euro/km/ton) - $Dist_{RU}$ is distance to the reuse processing facility (km).

- $C_{Process}$ refers to the cost of processing component (material) and can be calculated by:
  $C_{Process} = Q * RUF * R_{Process}$ (4)
  in which; Q refers to quantity of component waste (tons) - RUF is equal to the reusable fraction of the total waste generation - $R_{process}$ is the rate of process cost for reusing (Euro/ton).

- B_{RU} is finally equal to the benefit of reuse.

Therefore, by replacing the aforementioned formulas into the main reuse cost formula then the reuse cost can be calculated as follows (Liu & Wang, 2013);

$$C_{RU} = (C_{C\&T} + C_{sort} + C_{store}) + (Q * RUF * R_{TRC} * Dist_{RU}) + (Q * RUF * R_{Process}) - B_{RU} \quad (5)$$

Furthermore, the deconstruction costs, which may be considered in the cost of processing in equation (2) and can be calculated by this formula (Tatiya et al., 2018; Dantata et al., 2005):

$$C_{Dec} = C_{Pre} + C_{Disassembly} + C_{P\ and\ Risk} + C_{Storage} + C_{Trans} - V_{salvage} \quad (6)$$

Where C_{Dec} represent the net cost, C_{Pre} also representing the cost of preparation activities for removal (including disassembly costs) , $C_{P\ and\ Risk}$ is used for the risks and uncertainties in the process , V_s is equal to value added from salvage, and $C_{storage}$and C_{Trans} is taken in the equation (5). Therefore, by comparing the two equations namely; (5) and (6), it can be derived that the total cost of processing may include other costs such as deconstruction cost which also includes other costs. Because, as can be seen in Eq. (5) it takes into account the storage cost, transport cost, and added value from the reuse as well. Thus, different costs can be added in the cost of processing.

As Bleuel (2019) described, different costs associated in the reuse process would be calculated for the existing building components and thereafter should be compared with the costs for using new components. It is logical that the costs calculate before starting the entire reuse process, as the reuse process would be profitable for different stakeholders compared to using newly produced components. Therefore, the reuse cost which includes the deconstruction costs can be calculated by this updated formula:

$$C_{RU} = (C_{Pre} + C_{Disassembly} + C_{P\ and\ Risk}) + (C_{C\&T} + C_{sort} + C_{store}) \quad (7)$$
$$+(Q * RUF * R_{TRC} * Dist_{RU}) + (Q * RUF * R_{Process}) - B_{RU}$$

Thus, it is needed to zoom more in the deconstruction costs and thereafter analyzing which cost is allocated to which stakeholders involved. Therefore, the reuse costs can be categorized as:

- Preparatory Cost: is the sum of site preparation cost and planning cost. The total site preparation costs can be assumed to be 8% of the deconstruction cost. The planning cost can be varied from 10-15% depending on the size of the project.
- Disassembly Costs: Remove concrete topping - Remove Hollow Core Slabs (HCS) - Remove Façade Beams - Remove Main Beams - Remove Columns - Remove Walls.
- Profit and Risk Cost: it consists of the profit, uncertainty and the risks in the process. Because the deconstruction of structural elements is a novel process. Some unpredicted costs can happen such as delay cost which lead to higher labor and machinery costs, failure to find a buyer, etc. The profit and risk cost is assumed to be 10% for calculation purposes.
- Modification Cost: The costs incurred during the modification process of the building component for reuse are called modification costs which differ depending on the type of component i.e. floor slabs, columns, beams and etc. It also depends on the type of modification method applied. For example, for prefab HCS, the modification costs are estimated at 37 euros per element, including one cut to adjust the sides, create new openings and fill the old ones.
- Storage Cost: as explained in the work breakdown structure of deconstruction, the deconstructed components can be stored onsite by stockpiling, virtually stored on-site or they can be stored in a storage yard for a specified period of time. There is no cost associated with stockpiling at the (de)construction site. For virtual storage, it is assumed that the operational costs of an empty building are 24 euros/m2/year, however, this cost for storing in a storage yard is 12 euros/m2/year. For the calculation, it will be assumed that all types of floor components can be stored in the stack of 10 (Bleuel, 2019).
- Transportation Cost: in case of on-site reuse it will no transportation cost. It depends on the distance between the deconstruction site and destination.
- The value added from salvage: building elements have different salvage values depending on their quality, demand, price of the original product, etc. The salvage value is mostly lower than the price of the original product. The building elements with no performance information generally will be sold at 50% of the price of a new product, and that is the wholesale price of the secondary product (Bleuel, 2019).

The building elements recovered from deconstruction process have an economic value, i.e. it is the salvage value. This value is the cost-benefit ratio achieved by selling the recovered element in the market or even reusing it instead of a new component. Moreover, the higher the salvage value of the secondary (reused) product, the lower the total reuse cost. When the recovery (repair) costs are high and the salvage value of the component is low, deconstruction generally becomes uneconomical (Bradley, 2001).

Furthermore, many studies emphasized that the gross deconstruction costs are commonly higher than demolition cost. However, salvage costs can significantly diminish net deconstruction costs and make reuse profitable opportunity by generating revenue from the sale of secondary building components for different stakeholders involved. Also, different research indicated that the deconstruction costs can be approximately 30 to 50% lower than demolition if the salvage value has been taken into account. The salvage value of different components depends on their quality and condition.

- The Stakeholder-cost Relationship:

In this part of the research, the relationship between stakeholders involved and associated costs will be investigated. As, it is necessary to implement cost-related data in a CCE Information System for concrete building products that indicates which stakeholder can benefit from the reuse of components or even make a loss.

As already analyzed and discussed, there are some stakeholders who are intensively involved in the deconstruction process. The responsibility and liability of the owner/client, contractor, material dealer, transporter and the buyer implies that they can make benefits or even loss in the reusability value chain. Because, the client/owner as a main actor in the (de)construction process will decide whether or not the project deconstruct or demolish. Moreover, the generated secondary components and materials remain in the property and possession of the client/owner which has major legal and contractual consequences (Volk, 2017). The client will therefore be connected to a contractor (demolition or waste company) who would be responsible to perform the deconstruction activities.

Furthermore, depends on the deconstruction activities which have been discussed in the previous part, the costs for those activities will be allocated to the related stakeholders. Figure 2.12, shows the classical deconstruction process, commencing with building audits to plan primary decontamination and also site clearance, followed by deconstructing, crushing, sorting, reprocessing and finally recycling processes (which can indicate that the components may be reused, recycled or landfilled). In addition, the stakeholders involved in the process are assigned to each project phase (Kühlen et al., 2016).

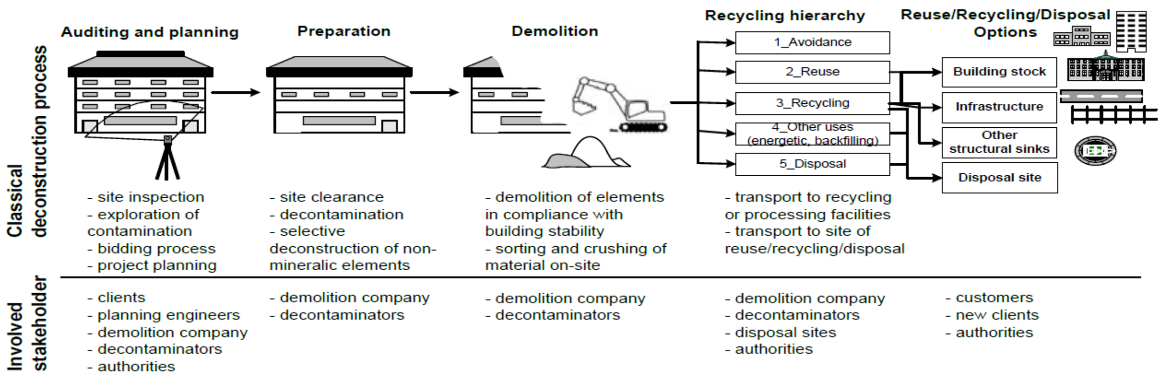


Figure 2.12: Deconstruction for reuse/recycle process, with stakeholders involved (Kühlen et al., 2016, p. 3).

As can be seen in the figure above, the costs in the preliminary phases will be allocated to these involved stakeholders; client/owner, planning engineer, and contractor (demolition or waste companies). Moreover, in the next phase namely preparation and demolition stages, the accepted company (contractor) plans the previous steps for deconstruction. Depending on the sort of structure including components/elements, and also accessible space onsite, various demolition, crushing and sorting techniques will be used to disassemble building components/elements and break the components into transportable or reusable pieces (Kühlen et al., 2016).

Therefore, the client and the contractor (demolition or waste company) can deal with many costs uncertainties, including benefits and loss. These actors may face different uncertainties that can arise due to many reasons such as the exceedance of process time, additional labor costs, and uncertainties regarding salvage value. Because if the market has insufficient capacity to offer the contractor the sales market, the risk that he will make a loss is greater than the benefits.

2.10. Conclusion

Moving towards Circular Economy strategies and sustainability goals, requires appropriate adaptation of CE strategies at the related stages of the construction process. DfD is a practice to facilitate deconstruction processes and methods through optimal planning and design, this is also a main strategy to conserve raw materials. On the other hand, deconstruction can be seen as the process of demolishing a building, while it will restore the use of the demolished materials. Deconstruction and DfD has some environmental, social, economic benefits. The application of these concepts contributes, for example, to closing the loop of materials. Therefore, the life of raw materials mines will be extended, the cost of materials will be reduced (if the supply chain is mature), and embodied energy and CO2 emissions will be significantly reduced.

Reusability is one the main aspects concerning achieving the CE strategies (10-R model) and sustainability goals. However, reuse of building components, products and elements has not yet achieved ground in Western industrialized societies such as the Netherlands. In addition, one of the main challenges in the C&D industry is to model the process of a system after EoL phase. In the other words, value recovery after EoL phase has not been taken into account as a common practice in construction. Therefore, it is necessary to zoom in more on the 'End-of-life' stage illustrated in the 'Building assessment information' model. Thereafter, compare it to the 'waste management hierarchy' that emphasized maximizing reusability, it can be concluded that various functional and technical aspects of the existing element would be analyzed.

Furthermore, analyzing the functional properties of existing elements requires to know the level of quality of those elements. Thus, the remain value, i.e. the reuse potential value, should be measured which provides insight into the qualitative and quantitative factors of an element. Functional performance characteristics of building elements depends on the properties of the material and substances used in them. In other words, the strength, fire resistance, sound insulation or other functional properties of concrete element depend on the type of aggregate, amount of cement, w/c ratio, and etc. of the substance used in it. Moreover, concrete can be damaged and degraded due to large number of different internal and external factors such as; corrosion of reinforcement - incorrect selection of constituent materials and more other factors.

To maximize the reusability of existing element it is important to carry out deconstruction instead of demolition. Deconstruction is also recognized as green (sustainable) demolition, dismantling, or reverse construction. This process is more expensive than demolition, and it consists of different activities. There are a large number of stakeholders involved in the (de)construction and waste process, all with different ambitions, interests, opinions, and benefits. Therefore, analyzing their roles, responsibilities in this sector and also their needs and benefit from a CCE Information System can optimize the reusability of any building component significantly. The main actors are; public authorities, building owner (client), contractor, Architect, material dealers, transporters, user, producer, and passport (dashboard) builder.

All the aforementioned stakeholders need to use from a central, harmonized and structured CCE Information System that helps to make a proper decision regarding reuse elements. On the other hand, one of the main issue of stakeholders involved is making the most profit from a reuse process. Thus, different associated cost in the reuse process would be analyzed and calculated to understand which party can benefit more and which of them make a loss. As, all the costs allocated to a specific stakeholder in the deconstruction for reuse process.

CHAPTER 3 | PROCESS MODELLING AND MEASURING THE REUSE POTENTIAL OF BUILDING PRODUCTS

Chapter 3 – Process Modeling and Measuring the Reuse Potential of Building Products

3.1. Assessment of the Residual Value of the Existing Concrete Building Elements

In order to be able to evaluate the reuse potential of concrete building components based on their functional performance properties, a Business Process Management Model (BPM) can play a major role in the optimization of reusability in the deconstruction process. This research is aimed to assess the reuse potential of three concrete building elements, namely concrete HSC floor, concrete beam and concrete column. In the previous chapter the systematic method to evaluate the reuse potential of concrete building elements, the process of reuse and also the related functional performances to be tested have been discussed.

A concrete building element can be reused when it meets certain performances requirements after its preliminary lifecycle. In the other words, as this research takes into consideration the functional performance characteristics of building components, therefore, these functional performances would meet the requirements for a new building system in order to be reused in the new structure. The reuse potential of a building element is considered in this research as the measure of the ability of this element to retain its functionality after EoL phase, so the level of quality of the element should be sufficient. On the other hand, the reuse of a concrete element can be implemented when it does not become too expensive in terms of economic costs for the main stakeholders involved. Thus, the reuse potential factor refers to a factor that indicates the functional feasibility and economic profitability of an existing building element.

3.2. Business Process Modeling and its Contribution to Measuring the Reuse Potential Factor

One of the most major issue in the construction and waste industry is that the point that an existing building system cannot perform its function anymore and the building may become unoccupied. It is decided by the client (owner) to demolish the building, but the transition to adopting CE strategies and also the hierarchy of waste management requires optimizing the reusability of the building components. The deconstruction process for reuse is illustrated by using Business Process Modeling approach (see Appendix A.4.7) in various steps, from the point it is intended to reuse the building elements of an existing building system to the construction of the reused elements in a new building. However, before going through all these steps of the reuse process, it is crucial to understand whether the elements are of sufficient quality for the reuse potential and also the economic feasibility for the stakeholders involved especially for the contractor.

As can be seen in the BPM, the steps of the reuse process are based on some physical process in which an inventory is carried out of the quality of the elements to subsequently remove the existing elements from the building at the EoL phase, and when it was needed to perform improvement to upgrade the quality of the component, it can then be used in a new project. Hence, before making a decision to remove the existing building components, it is substantial to map out this entire physical process earlier in the process, to determine whether reuse of the elements can be profitable for stakeholders involved. So, measuring the functional performance properties should be quantified by using indicators.

- *Tender process*:

The main aim of this process is to find a contractor (demolition company) who can deconstruct the existing building elements in the most affordable way, with the focus on optimizing reusability. In this study it was assumed that the client decided to deconstruct the existing building, as optimizing the reusability of elements required deconstruction. Firstly, it is the client's responsibility to develop an assignment for the reusability of elements in accordance with the sustainability requirements set by the government. By publishing the developed assignment/tasks different contractors will be invited to set up a plan for the process. After assessment of the entries by the client, the most appropriate plan will be chosen and the contract will be awarded.

- *Prepare to disassemble*:

This process is intended to prepare for the successful implementation of the winning tender plan by the contractor. It commences with a visual inspection by an expert to understand the level of quality of existing elements. The inspection can also take place by taking a sample (specimen). The deconstruction plan written in the tender process can be refined and improved in this step. An inventory would be performed of the reusable elements in the object. The contractor then decides how the existing elements will be dismantled. Then the definitive deconstruction plan can be derived. The last task of the contractor is to obtain a permit to start the deconstruction process.

- *Execution of disassembly*:

The purpose of this process is to execute the activities that have been planned for in order to disassemble. This phase consists of different physical activities. It has already been determined which elements would be disassembled for reuse (visual inspection). Therefore, after preparing the deconstruction site, the contractor can start to strip the elements (removing the non-essential object like paint, decorations and laminate floor). In order to remove the main elements, it is important to build the supporting systems such as scaffolding. Then the building system is ready to carry out the disassembling process of the elements, consisting of removing concrete top layers and etc. It is undoubtedly important to keep the disassembled products somewhere such as a storage yard. It is thus clear that the remaining elements have no reuse potential and can therefore be recycled or even sent to landfill (according to the 'Ladder van Lansink'), and ultimately the deconstruction site can be cleared.

- *Handling the elements*:

One of the most important processes of the deconstruction process is to handle the elements in such a sustainable and innovative way. Thus, the goal of this phase is to treat the disassembled elements in a pre-designated way for different purposes. As in previous phases, the contractor plays the main role in this process. This phase is also of great importance for the aim of this study, as by analyzing functional performances of concrete products the level of quality of elements can be estimated. Therefore, it is necessary to perform a more detailed analysis of disassembled elements to understand whether the elements can be directly reused or need to be refurbished. The refurbishment process can significantly affect the contractor's costs. In line with the aim of this research, it has been realized to support the decision making in an innovative way after registration of the data in an import sheet.

3.3. Measuring the Reuse Potential (RP) Factor of Concrete Elements

The appraisal of the reuse potential factor for a building element can be done by creating and using a Business Process Model (BPM) that takes into account the qualification performances and quantification performances of the reused concrete component incorporating the stakeholders interest. Moreover, business process modeling provides involved stakeholders including client (owner) and contractor a simple way to realize and also optimize workflows by creating data-driven visual representations of different main and key business processes.

Furthermore, the potential factor for reuse should be measured and based on this factor, thereafter, a decision can be made by the involved stakeholders about whether or not the existing concrete elements can be reused. So, high reuse potential factor certainly makes reuse of the existing concrete building elements possible for the construction of the new building. As the focus of this research lies on developing of a CCE Information System which tries to optimize the reusability of building components, therefore, adding this factors to them can improve the reuse process significantly.

Thus, to measure the reuse potential factor of the existing elements it is essential to analyze the quality of the existing components, i.e. qualification performance, as already discussed in chapter 2 (2.2.1.). Thereafter, it is important to assess the reuse of the elements. Also, it is necessary to examine whether the impacts on the economy (associated costs) are too much or not, i.e. quantitative factors.

The reuse potential factor for concrete building components is based on the deconstruction process for reuse (BPM) and can be measured by following steps:

- Inventory phase: As this research has been analyzed the functional performance characteristics of concrete building components, therefore, it is needed to describe and investigate the functional characteristics of the concrete elements (floor, beam and column), which is carried out in chapter 2 (parts 2.4. and 2.5.). Also the performance characteristics for the required concrete building components have been explained (see Appendix A.2.1). This phase can be considered as the basis activity for testing of the performance quality of the components.

- Quality performance test phase: In this stage, the condition of concrete building elements, based on the functional performance characteristics of concrete, can be estimated by experts from a demolition company (contractor). A comparison can be carried out among estimated conditions and the condition required for new concrete elements. The condition of concrete building elements will be checked on the basis of the functional performance properties, namely; strength, durability, permeability and porosity, thermal characteristics, fire resistance, and sound insulation.

By applying these two phases, it can be realized whether the concrete components meet the qualitative requirements (based on functional performance properties) for reuse. This understanding will be based on a comparison of the qualitative performances (functional) of the existing concrete building components and the required qualitative performances characteristics for the new building elements (NEN-NORMEN). Applying quality performance test will provide more insight into the level of quality of existing elements and will contribute to know whether or not the elements needs improvement process to meet the new requirements. Therefore, it is important to analyze the improvement or even modification phase which are based on the economic costs (reuse costs) and stakeholders can be involved in the improvement process due to their involvement to the costs.

- Impact of intervention phases – economic performance test phase: It is indicated which adaptations or improvement are necessary for existing elements to meet the requirements of the new construction project. As already mentioned, after performing quality performance test the level of quality of existing elements will be indicated. Experts can suggest that depending on the quality of existing component, the component may not completely meet all the requirements of the new building system. Thereafter, it can be discussed with a specialist (demolition company) and also the designer of the new-build project which adaptation or improvement activities are necessary and which should be omitted, to estimate the related costs in the process.

- Quantitative performance test phase: To measure the reuse potential (RP) factor of cocnrete elements, different economic costs would be quantified. These additional costs are actually expenditure costs that will be allocated to the stakeholders for imrpovement or adaptations of existing products in the improvement/modification phase including transport and storage costs. The total costs of improvement/adjustment including other related activities is the sum of all costs for the improvement and disassembly process of concrete building elements.

Furthermore, measuring the reuse potential of building elements is difficult to determine because it depends on many factors. These factors can be subdivided into the qualification and quantification factors. The qualification factors relate on the performance (functional) of the reused building elements from a qualitative perspective. However, the quantification factors based normally on the impact performance (e.g. economic impacts) to measure the values of the economic costs. To understand the extent of reuse potential a comparison can be made between the economic costs of the existing elements and which will be used in a new building system.

Therefore, by indicating the reuse potential (RP) factor which is already discussed in the previous chapter, different stakeholders can make a logical decision with regards to reusing building components after their EoL phase. The reuse potential (RP) factor will be indicated between 0 and 1. So, 0 indicates that the elements have no reuse potential (waste indicator), however, 1 can be considered as highest reuse potential (resource like), and showing e.g. 0.65 means that the component has a 65% reuse ability, can be said to be “65% resource-like” or “35% waste-like”. The most contribution of measuring the reuse potential factor of existing elements is indicating the profitability of existing building elements for stakeholders involved.

3.3.1. Quality Performance Test Phase

As already illustrated in Business Process Model, in two phases of deconstruction process, the quality of concrete elements would be tested to understand whether the elements will need to be improved/modified or not. Nevertheless, the focus of this research lies on the second quality performance test, in the handling the element stage (see figure 3.1). The quality of the existing concrete elements should be examined by comparing the functional performance characteristics of the existing elements with the required characteristics for an element to be reused in the new construction project. The requested information/data can be achieved through archival information/data and calculations or even visual inspection by experts.

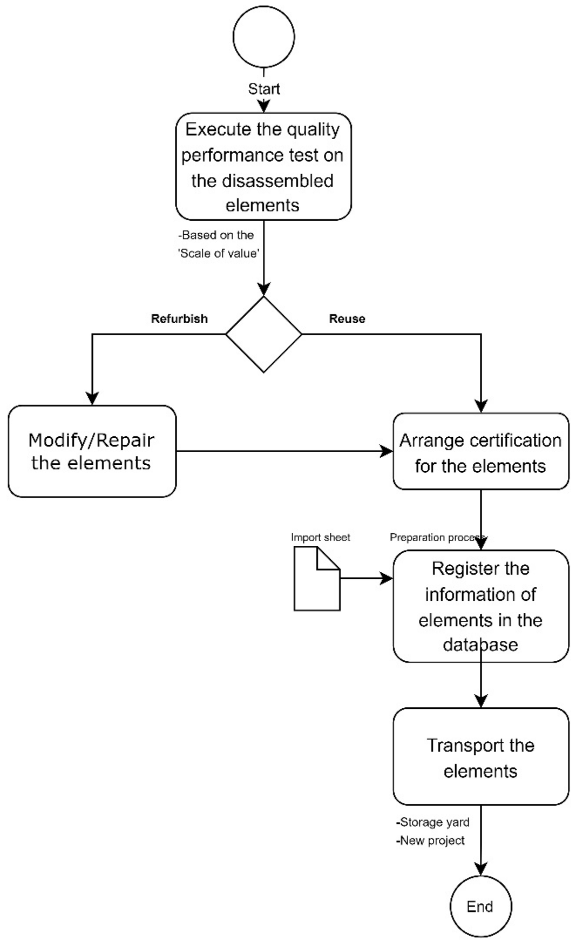


Figure 3.1: 'Handling the element phase' in the deconstruction for reuse process (own illustration).

Moreover, functional performances of existing concrete components play main role in determining whether the component can be reused in a project with the same function or even used for other purposes. In addition, lifespan and technical performance system tests (including length, height, width) cannot be so useful in the economic impact of improvement stage, as it is impossible to extend the lifespan or the length of elements. The functional performance characteristics of the existing concrete elements will be compared with the required functional performance of the new building elements (100%). All the functional properties of concrete discussed in chapter 2, such as; strength (strength class, maximum w/c ratio, maximum compressive strength), durability/lifetime, abrasion resistance, thermal characteristics (thermal conductivity, specific heat, thermal diffusivity, thermal expansion), fire resistance, and sound insulation, will be measured. Moreover, to measure the RP factor for an existing element it is needed to identify the qualification factors which affect the quantification factor and finally will affect the RP factor. For example, if the fire resistance or thermal properties of a concrete floor needs to be improved by adding an extra layer, therefore, the costs for contractor become higher. In this part, the data and information of three concrete elements namely; floor, beam and column with different strength classes (classes from existing aged elements, and the new components) will be handled and the results achieved will be applied in real cases (case studies) for the proposed dashboard.

- Strength of concrete elements:

One of the most important functional characteristics of concrete is the compressive strength of that in order to be reused in new construction project. This property can be tested with several methods, however, the most accurate one is core drilling. As already discussed, the higher the strength class of concrete, the more cement. Also, the compressive strength of concrete elements nevertheless increases after the characteristic strength is reached at 28 days. However, the concrete can be considerably weakened after many years by various forms of deterioration, as discussed earlier.

To illustrate the strength of concrete from an aged building and compare it with a new building structure, historical data has been used in this part (see Appendix A.2.1, Tables A´.2.1 - A´.2.6). As can be seen in figure 3.2, a comparison is made among B65 strength class of concrete which were applied in the 80s and 90s, and two classes (C30/37 and C53/65) which will be used in the new structures elements, concrete floor, beams and column.

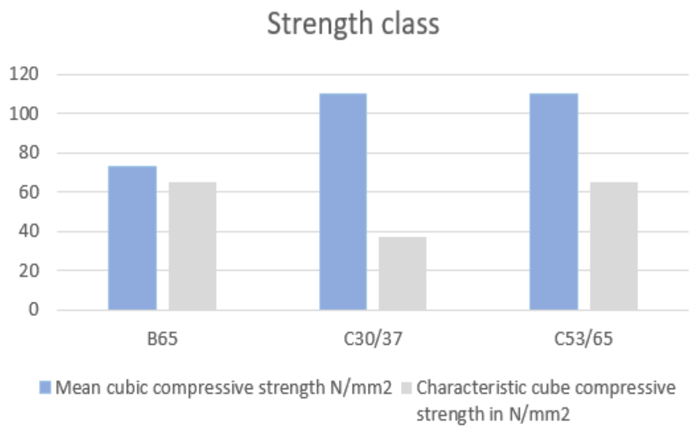


Figure 3.2: Comparison between the strength of existing concrete elements and the new strength classes for new building projects (own diagram).

According to the strength curve diagram of concrete (chapter 2, section 2.5.3.), the strength of concrete will increase after 28 days, and till 10,000 days (approx. 28 years), the strength curve increases positively, as the environmental and other internal and external conditions do not affect the strength of concrete negatively. In this case, the assumption has been made regarding no damages affected the strength of elements. Therefore, concrete with the strength class of B65 can meet the requirements for new construction project.

- Durability/lifetime:

The other functional aspects of concrete are its durability and longevity. The lifetime performance of an element can be analyzed from two perspectives, the technical lifespan performance and the functional lifespan performance. While, this research analyzes the functional performance characteristics of concrete products, therefore, it is necessary to understand that the meets the functional requirements of the new user. A building system including its components, elements and products are designed for a certain lifetime, design lifespan, related to the function of the building.

If a system and its components no longer meet the functional requirements and also the expectations of the user, it can no longer be used by the user/owner. If the client/owner decides to deconstruct the construction project, there are two options that can be applied, reuse the elements for the same function or reuse the elements for other purposes. When the elements are intended to be reused for the same function, it is essential to study the remaining functional lifespan. So, if it study indicates that the remaining lifespan of concrete elements is longer than the designed lifespan of new building components, then the components can be reused for the same function in the new building system.

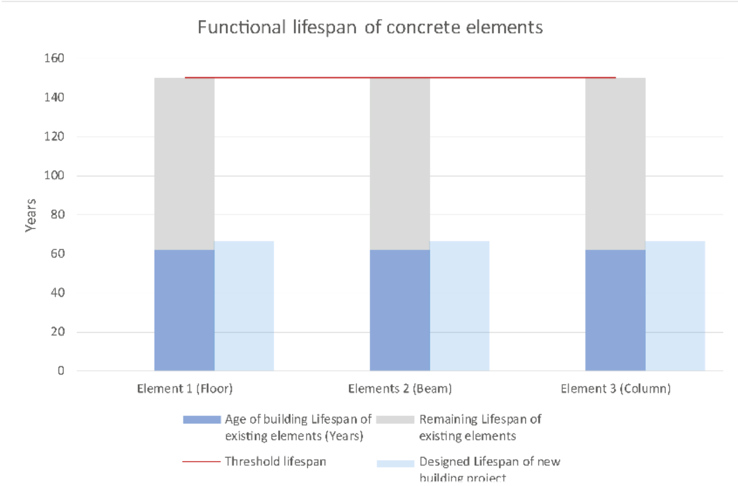


Figure 3.3: Comparison between the remaining lifespan of existing concrete elements and the designed lifespan of new building projects (own diagram).

In the figure 3.3, the remain expected lifespan that the concrete elements can have after their EoL phase, is illustrated in comparison with the designed lifespan of new building objects. Concrete can be last for a long time, the design service life for concrete structures is set at a minimum of 50 years, however concrete can last for a maximum of 200 years. There is 95% probability that the intended and designed service life will be reached. An assumption has been made that external or internal factors have no influence on the durability of elements. The threshold (upper limit) lifespan for concrete components is set at 150 years (red line), therefore, elements from an existing building from 1995 can still last about 88 years (grey color). Because, the requirement for the lifespan of new building elements is set at 65 years (light blue) and the remaining lifespan is longer than the design lifespan for the new design with the same function.

- Abrasion resistance:

Concrete elements including their materials have different functional properties. Abrasion means wearing away of the surface due to friction, rubbing, or wave action, etc. Commonly, the surface of concrete element is worn evenly, including the cement matrix and also aggregates. Abrasion/wear reduces coverage to the reinforcement, leading to corrosion. Concrete elements made of substances with a high water/cement ratio at or near the surface or even has been cured insufficiently would, of course, wear down easily (Surahyo, 2019).

So, there are some factors that affect the abrasion resistance of concrete significantly. Coarse aggregate is the main factor influencing the abrasion resistance of concrete. Thereafter, water/cementitious (w/c) ratio plays an important role in the abrasion resistance of concrete. Additionally, it has also been studied that silica fume enhances the abrasion resistance of concrete, but to a lesser extent than either the coarse aggregate or w/c affect the abrasion of concrete (Laplante et al., 1991).

A low to moderate water/cement (w/c) ratio reduces free water in concrete. This will improve the compactness of the concrete and reduces the permeability of concrete, which consequently improves the strength of concrete and thus the wear/abrasion resistance of that. The study of Adewuyi et al. (2017) showed that reducing the w/c ratio in nano-silica concrete from 0.5 to 0.33 has improved the abrasive strength of concrete by 36%, while decreasing the conductivity coefficient and porosity.

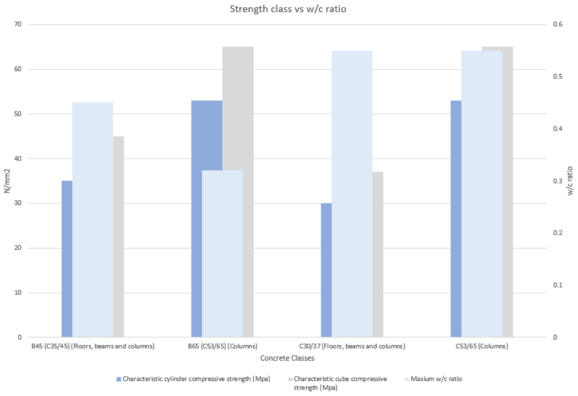


Figure 3.4: The relationship between the strength of concrete and w/c ratio for indicating the abrasive strength of concrete in existing and new building elements (own diagram).

As can be seen in the figure (3.4) above, that the existing concrete elements have had the w/c ratio requirements with maximum of 0.32 which indicates that the components had a significant abrasion resistance in comparison with new w/c ratio requirements for design of new concrete elements which is a maximum of 0.55. In this case, also an assumption has been made regarding no factors affect the strength of concrete which has a direct relationship with abrasion resistance.

- <u>Thermal characteristics</u>:

All the functional performance properties of concrete elements must meet the requirements determined by the experts of the authorities, to be applied in the construction projects. The concrete building products need also to meet the thermal characteristics for different function. Analyzing the thermal characteristics of concrete elements needed in mass concrete to which insulation is used to control the loss of heat by different phenomena like evaporation, conduction, and radiation.

As already explained in the previous chapter, paragraph 2.5.6., different thermal factors should take into consideration in the design of concrete structures, such as thermal conductivity, specific heat, thermal diffusivity, and thermal expansion. Again, different factors affect the thermal properties of concrete, such age, moisture content, type of aggregate, and w/c ratio. However, research has been emphasized that age has minimal effect on thermal conductivity after 2 days, while aggregate volume and also the moisture condition of concrete have the greatest impact on k-value. On the other hand, the thermal expansion is also a crucial parameter which influence the fire resistance of concrete elements. In addition, studies showed that the thermal conductivity and thermal diffusivity have opposite relationship with w/c ratio, i.e. thermal conductivity and diffusivity increases while the lower amount of w/c ratio has been used. However, the thermal conductivity and thermal diffusivity of concrete will be increased by increasing the compressive strength of concrete.

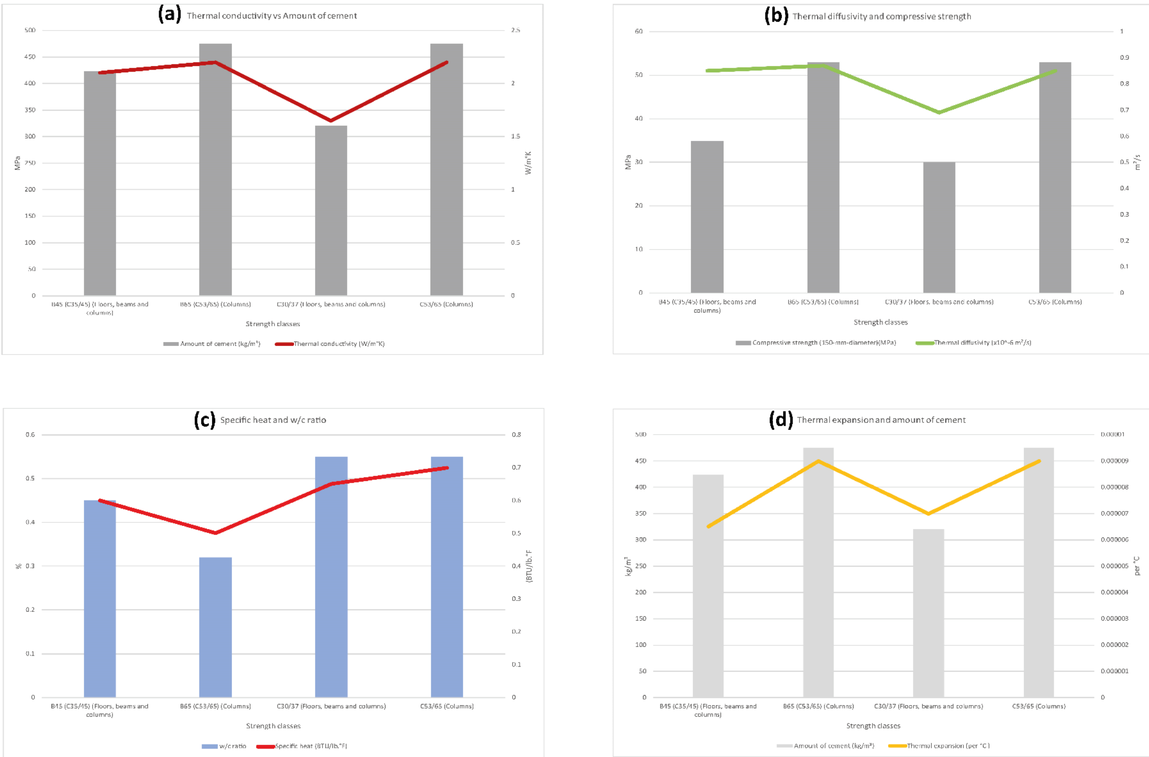


Figure 3.5: (a) Thermal conductivity and amount of cement. (b) Thermal diffusivity and compressive strength. (c) Specific heat and w/c ratio. (d) Thermal expansion and amount of cement (own diagrams).

Based on the existing data and information from literature (Talebi et al., 2020) (see Appendix A.2.1, Figure A´´.2.1, Tables A´.2.7 and A´.2.8), different thermal characteristics of four type of concrete with various strength classes has been illustrated (see figure 3.5). Thermal conductivity and thermal diffusivity of concrete classes B45, B65, C30/37, and C53/65, showed, using the relationship between compressive strength of concrete as the strength of concrete affect those thermal factors appropriately. So, the thermal conductivity and diffusivity will increase by increasing the strength of concrete.

Furthermore, Talebi et al. (2020) explained that one of the thermal characteristics of concrete, namely thermal conductivity for normal concrete has been found in the range of 1.6 to 3.2 W/m°K, in addition reported the standard range normal concrete of circa 1.4 till 3.6 W/m°K. There is also a relationship between the amount of cement used in concrete products and thermal conductivity, as the thermal conductivity value of has been increased appropriately when the amount of cement increases.

On the other hand, specific heat coefficient of concrete has direct correlation with the proportion of w/c ratio used in the concrete. The diagram (c) shows that the specific heat capacity increased remarkably as the water/cement ratio increased. Furthermore, thermal expansion of concrete largely depends on the type of aggregate used in the concrete product and also the amount of cement used. Therefore, the diagram (d) illustrates expansion due to heat of hydration of cement can be decreased through keeping the cement content as low as possible.

- <u>Fire resistance</u>:

One of the best functional performance characteristics of concrete elements is their ability to withstand fire or to provide protection against fire, and concrete can be considered as a significant substance which resist fire. As the same as other functional properties, fire resistance of concrete would also meet the determined requirements in the design and EoL phase. The fire resistance of concrete building products is rated/expressed by the number of hours of effective fire resistance, and they varying from 30 min to 120 min for different type of building with different function (Appendix A.2.1, Tables A´.2.9, A´.2.10, and A´.2.11).

Concrete has a large heat (absorbing) capacity. Prefabricated concrete floors and walls with a minimum thickness of 80 mm meet the determined fire resistance requirement of 60 minutes. With a thickness of 100 or 120 mm, the fire resistance will be increased to 90 and 120 minutes. According to the Dutch Building Decree 2012, the fire resistance requirement of the concrete floor elements is 90 minutes (for non-residential building lower than 25 meters high) (see Appendix A.2.1, Tables A´.2.10 and A´.2.11).

Table 3.1: Fire resistance requirements for concrete floor/column (adapted from: NEN 3891).

Reinforced and prestressed floors and roofs
Minimum Slab Thickness (mm)

Concrete Type	Fire-Resistance Rating (min)		
	60 (min)	90 (min)	120 (min)
Siliceous	88.9	109.22	127
Carbonate	81.28	101.6	116.84
Sand- Lightweight	68.58	83.82	96.52
Lightweight	63.5	78.74	91.44

Concrete columns
Minimum Dimension of Concrete Columns (mm)

Concrete Type	Fire-Resistance Rating (min)		
	60 (min)	90 (min)	120 (min)
Siliceous	203.2	228.6	254
Carbonate	203.2	228.6	254
Sand- Lightweight	203.2	215.9	228.6

On the other hand, there are many factors which playing essential role in fire resistance ability of concrete components, and also affect this ability. The thickness, strength of concrete, type of aggregates, concrete cover used in floor systems, and some deterioration factors. In this research, the thickness and type of concrete will be analyzed in real case study to understand the level of fire resistance of existing concrete elements, which has to meet the above requirements.

- <u>Sound insulation</u>:

To ensure that the existing concrete elements meet different requirements for new building projects, it is important to analyze also the sound resistance ability of the elements. Concrete elements can be considered as an appropriate insulator product which, because of their high density, are able to reflect up to 99% of sound energy. Moreover, the behavior of concrete as a sound conductor depends on the different types, particularly dense compositions are great sound reflectors, while light ones are sound absorbers. Thus, if concrete be denser or heavier, then the sound insulation rate that can be detected will be higher.

As this research analyze the functional performances of concrete elements (floor, beams and columns), therefore, the sound properties of HCS the most used floor systems in the Dutch buildings will be analyzed. To rank the existing concrete floor elements, it is needed to know the Noise Reduction Coefficient (NRC), which is commonly used for knowing the sound resistance ability of construction materials. NRC is measured on a scale that ranging between 0 and 1. An NRC of 0 means that the elements do not absorb sound. However, an NRC of 1 means that the building products absorb all the noise. In other words, the higher the NRC, the better the building product absorbs the sound. In addition, the NRC is directly related to density of materials (Holmes et al., 2014; Fediuk et al. 2021).

As acoustic characteristics of materials largely depend on their density, lighter ones will absorb more sound. So, the lower the density of concrete composites, the better the sound absorption (see Appendix A.2.1, Tables A´.2.14 and A´.2.15). When choosing raw substances for concrete production, it is essential to select substances with reduced density that can dampen the sound wave.

Thus, the case study part of this research will analyze the type of composites used in the existing concrete building products or the density of elements that yield the quality of sound resistance of concrete elements for new construction.

To be concluded, each functional performance analyzed in the previous part can affect the reusability of the elements. If the functional performance of the existing concrete elements; floor, beam and column does not meet the functional performance requirements for the new construction projects, some modifications or improvement must be made to the building products before they can be completely reused. Therefore, the results achieved from the quality performance test (functional performances), can contribute highly to the understanding that improvement will be needed which rise the costs significantly.

3.3.2. The Impact of the deconstruction processes – Economic Performance (Incorporating Stakeholders to the Process)

This research analyzed also the stakeholder's networks involved in the construction and waste sector. Adding the interests and benefits obtained from reuse of existing elements to a dashboard is one of the major goals of this study. Therefore, an analysis can be done regarding the stakeholders involved in this phase, which was predesignated to analyze the economic impact of improvement/modification phase. It is possible to understand which parties involved in the deconstruction process can benefit or even loss from the reuse of products. As can be seen in the Business Process Model (BPM) developed for reuse of elements in the deconstruction process, each lane represents the related stakeholders and also illustrated their activities. In other words, the two main actors, i.e. the client and the contractor (demolition company) playing a major role in the deconstruction for reuse process. However, it should be mentioned that different subcontractors such as demolition equipment cleaning company, passport (dashboard) builder, legal or financial advisor and etc. can also be incorporated to the process. But, the focus of this research lies on the two key actors, client and contractor. Moreover, these two parties may encounter the major benefit or loss of the reuse process in the market as they are the main decision maker in the process.

Furthermore, the associated and additional costs in the reuse process cannot be retrieved from the literature or other existing sources, so two interviews have been conducted to gather various data (costs) from practice. An interview protocol (see Appendix A.2.2) is set up to conduct the interview with the contractors (demolition company), who should be able to provide the most associated costs in the process. Ultimately, the data (costs) in the chapter 6 will be applied to calculate the reuse costs for the existing elements. In the case, that the contractor was not able to provide the required data (costs), the interviewees would be asked to verify the existing costs. The findings and insights from interviews will be explained and discussed in chapter 6.

Deconstruction (Disassembly) cost: Deconstruction process for reuse consists of different activities. The costs incurred during the execution, transport and storage phases are referred to as dismantling costs. In simple words, it is the sum of the costs, hired labor costs and the hired machine costs to carry out the dismantling. So, the labor and machinery will be needed to perform various tasks to disassemble the existing elements for reuse. Some tasks can be listed as follows; building the support system, removing concrete topping, removing concrete between the slabs, breaking the connections, and lifting the slabs.

Modification cost: As can be seen in the BPM, the contractor (demolition company, waste treat company) play the key role in the process. However, in the modification process, other actors like buyer (new user), or even the transporter and the trader (storage yard) involving the process directly or indirectly. The modification process will be needed after indicating the functional performance percentage in the previous part. Modifying different building products and the disassembly process also affect the economic performance. To analyze the stakeholder-cost relationship in the modification process, it is aimed to conduct interview with the main key actor in the process, namely; the contractor. To provide an overview of costs associated in the modification process including transport cost and storage cost, information and knowledge from experts can contribute significantly to the determination of reuse potential factor.

There are different types of modifications that a building product can be subjected to such as cutting (sawing) to size, filling old cutouts holes, removing fixings (connections), drilling new junction points to lift up and reconnect the component, removing nails and screws, etc. “No modification”, namely the lowest percentage achieved from the quality performance test, means that the element is good to be reused without any interactions. For example, HCS has a good reuse potential and can be reused without any modifications because these components are prefabricated and standardized, compare with cast-in-situ concrete elements. in addition, as the modification level increases, the modification costs also increase.

Repair cost: Sometimes, it can be indicated that the product needs to be just repaired in case of e.g. cracks or damages. As already showed in the diagram of deconstruction in chapter 2, the damage investigation can be perfume by visual inspection during the audit. If the damage is noticed by the experts, specific tests can be done to quantify the damage and thereby the cost required to repair it can be calculated. It is not recommended to reuse the prefabricated concrete elements with signs of localized corrosion, section loss, frost damage, etc. In addition, it would be rational to avoid using pre-stressed slabs with either corroded steel or wide cracks (Hradil et al., 2014). Mostly, damages can be occurred arising fire, water ingress resulting in material deterioration such as; spalling-off corners, honeycombs, entrapped air, scaling (by frost), delamination surface, fire damage, discoloration of concrete, craquelé (small hairline cracks), exposed reinforcement, and moisture.

Two types of repair usually can be done by responsible stakeholder; painting the surface of element to protect the exposed rebar from degradation, and also applying a coating of mortar. It can also be happened that an epoxy or polyurethane coating be applied to protect the concrete elements from wear. Repairs can be done on site or at the new project site, which is not favorable because of space constraints or at the storage yard.

Transportation cost: The transport of concrete building products after deconstruction is both challenging and crucial in the reuse process. Transport is required when the disassembled products cannot be reused in the same construction site. In that case, the elements can either be transported to a new construction site or to a storage yard where they can be stored for a period of time and thereafter transported to an end user or treatment company. The following three routes are possible for the transport of the secondary building products:

- Reuse on-site, minimum transport within 5 km
- From the deconstruction/demolition site to the new construction site
- From the deconstruction/demolition site to the storage yard and to the new-user

Storage cost: The building elements obtained from deconstruction can be stored for modification process, or to be stored after the modification process. Thus, they can be stored at the deconstruction site, transported to the new construction site and be stored there or at a designated storage yard. There are different types of storage that can be applied by contractor; virtual Storage, stockpiling, and at storage yard.

Salvage value: Building elements have different salvage values depending on their quality, demand, price of the original product, etc. The salvage value is mostly lower than the price of the original product. The existing elements recovered from deconstruction process have an economic value, i.e. it is the salvage value. This value is the cost-benefit ratio achieved by selling the improved element in the market or even reusing it instead of a new component. Moreover, the higher the salvage value of the recovered and improved product, the lower the total reuse cost.

3.3.3. Quantitative Performance Test Phase (Measuring the Reuse Potential Factor)

As already described, the quality performance test based on the functional performance properties of concrete elements provide an estimation insight into the next phases in the reuse process. If the quality performance of an elements in e.g. fire resistance ability does not meet the predetermined requirements for new construction buildings, the components must improve its fire resistance ability. This improvement process causes additional costs for the related stakeholder. Ultimately, it affects the reuse potential factor which is based on the results achieved from the quantification performances, namely economic costs.

To measure the reuse potential (RP) factor for concrete products different economic costs, as discussed in the previous part, must be calculated. Given the reuse potential factor is measured based on the results obtained from the quantification performances, i.e. the total of economic costs. Because the economic costs are affected by the quality performance of the existing building elements. The total reuse cost of the existing concrete products will be compared with the total cost of a new manufactured concrete floor, beam and column component. In addition, the reuse potential factor will indicate which of the existing building components are reusable economically.

According to the method introduced by (Park & Chertow, 2014; Androsevic et al., 2019), each indicator of the potential for reuse will be presented as a number RP factor between 0 and 1, and for 0.1 (low reuse) to 1.0 (high reuse). The reuse potential (RP) factor will be indicated between 0 and 1. So, 0 indicates that the elements have no reuse potential (waste indicator), however, 1 can be considered as highest reuse potential (resource like). Showing e.g. 0.75 means that the component has a 75% reuse ability, can be said to be “75% resource-like” or “25% waste-like”. The most contribution of measuring the reuse potential factor of existing elements is indicating the profitability of existing building elements for stakeholders involved. Therefore, reuse potential (RP) factor can be calculated by the following formula:

$$if \quad \left(\frac{\Sigma C_{Reuse}}{C_{New\ product}}\right) > 1 \qquad \mathrm{RP} = \left(\frac{\Sigma C_{Reuse}}{C_{New\ product}}/100\right) \qquad (8)$$

And;

$$if \quad \left(\frac{\Sigma C_{Reuse}}{C_{New\ product}}\right) < 1 \qquad \mathrm{RP} = 1 - \left(\frac{\Sigma C_{Reuse}}{C_{New\ product}}\right) \qquad (9)$$

Where C_{Reuse} represent the net reuse costs including the cost of deconstruction, as described in (chapter 2, section 2.9.3.1.), and $C_{New\ Product}$ representing the economic cost of new manufactured product.

Thus, the RP factor can be measured by a proportion between the cost of reusing an existing element and the production cost of a new element. However, there are two scenarios that can describe in more details how these formulas function. If the reuse cost of an existing element is higher than the cost of new product, e.g. the reuse cost is €1,000,000 and the cost of a new product is about €650,000, then this ratio will be higher than 1, namely 1.53. In other words, if this proportion yields more than 1, then the reuse potential factor approaches 0 and this is in accordance with the logic of measuring the RP factor which was based on between 0 and 1. As, a higher reuse cost results in a lower reuse potential factor.

The other scenario can be considered such that the reuse cost is lower than the cost of a new product. In this case, it is logical that the reuse potential factor approaches 1. For example, if the reuse cost is €550,000 and the manufacturing a new concrete product costs €900,000 this means that the reuse cost is 0.38% lower than the cost of a new product, i.e. this ratio is also less than 1.

The reason that the RP factor would be subtracted from 1 can be explained with examples. If the reuse cost is €550,000 and the new cost is €560,000, the reuse cost is still lower than new cost (550,000/600,000=0.91%) but the reuse potential value is not 91%, it must be subtracted from 1-0.91=9%, i.e. they have inverse relationship. If the differences increase, so the reuse cost €550,000 and the cost of new product €2,000,000 (550,000/2,000,000=0.27%) the reuse factor must be increased, and this happened by subtracting from 1 (1-0.27=0.73%). The lower the ratio between reuse and new cost the higher reuse potential factor. Therefore, the lower reuse cost would be more favorable and beneficial to the stakeholders involved in the process, especially the contractor.

3.4. The Results

The purpose of measuring the reuse potential factor of concrete building elements is to support the profitability of decision-making on the choice of existing building components for involved stakeholders. Moreover, in order to validate the measurement of the reuse potential of concrete building products in real cases, a case study approach will be applied in the chapter five, where the results achieved from the case studies are implemented in the dashboard.

The aim of performing quality performance test is to qualify different functional performances of the existing concrete products (floor, beam and column) based on the functional performances of their substance, namely concrete. For example, the fire resistance of a concrete floor depends largely on the thickness and type of aggregate used in the floor. It provides insight into the level of quality of existing elements whether those components need improvement or not, and it will also create an overview of the associated costs for stakeholder. Subsequently, in the improvement phase, the stakeholders will be incorporated in the process that indicates which of them benefits from the reuse of elements. The reuse potential factor is based on the quantity factors such as cost, therefore, it is needed to quantifying the associated costs of the existing elements. However, the RP will be based on the outcome of the comparison between the costs of existing elements and the new components.

CHAPTER 4 | DEVELOPING A ‘CIRCULAR CONSTRUCTION ELEMENT INFORMATION SYSTEM’

Chapter 4 – Developing a 'Circular Construction Element Information System'

Developing a CCE Information System for concrete building products (floor, beam and column) includes the reuse potential of concrete components based on their functional performance characteristics and economic feasibility for stakeholders. The CCE Information System will help the stakeholders to make the right decision at the EoL phase of a project, and also to understand whether reuse of the existing concrete products is possible or not. Given that the profitability of reuse of existing products plays a major role in the decision-making situation for involved stakeholders.

The CCE Information System consists of an import sheet and a dashboard, and also a between spreadsheet that shows the procedure of calculation and analyzing. The reuse potential factor which will be implemented in the dashboard is actually the result of quality performance test that is based on the functional characteristics of elements and also the results of quantitative performance test which is based on quantifying the associated economic costs in the improvement process. Thus, to measure the reuse potential factor of each concrete elements it is needed to make a comparison among the economic costs of existing and new manufactured concrete products.

4.1. A CCE Information System for Existing Concrete Building Products

The aim of this research was to develop a CCE Information System for existing building components to support the decision-making on the reuse of existing elements, which takes into consideration the functional performance features of products and also the main stakeholder issue, namely cost. Since, the lack of a central CCE Information System for existing building elements is a big challenge in the construction and waste management sector.

The proposed CCE Information System would consist of related information and data to help the main stakeholders, client and contractor, to benefit from the reuse process. Because, in order to optimize the reuse process of construction products and close the loop of finite materials it is necessary to move towards CE strategies by realizing, creating and applying innovative approaches to the C&W market. This is also in line with determined government policies which emphasized that the construction sector should be organized in such a way, with regard to the design, development, operation, management and also dismantling of different buildings, that the sustainable construction, use, reuse, preservation and dismantling of these objects is guaranteed, by 2050.

One of those innovative approaches contributing to the transition to CE strategies is the development of a CCE Information System that provides information on whether reuse of existing concrete products is possible or not. As, the deconstruction process is a complicated and dynamic process which struggles to deal with different issues and challenges. The current landscape of building product passports/data platforms includes several passport initiatives, all with their own approach and also information platform, with limited to no harmonization among building product passports. This will result in a situation where clients, contractors, or even users become cautious to implement building product databases/passports/data platforms due to of their experimental character and unproven added value.

Furthermore, as explained in chapter 2 (paragraph 2.9.2.), building product passports developed by different platforms will suggest opportunities to regain value from recovery and reuse of materials, building products and systems applied in buildings for different stakeholders between the value chain. In principle, all the stakeholders engaged in the construction and waste industry can use and profit from a harmonized Information System. Because, communication, coordination and collaboration between project stakeholders and participants can increase mutual trust and reduce conflict, positively change tendencies, and also play a key role for efficient C&D waste management in various project phases.

4.2. Information and Data Needed for the Realization of the CCE Information System

To develop and enrich an Information System based on functional properties and cost-related issues, it is important to understand which information and data must be collected to be added to the import sheet. The developed CCE Information System would take into account the quality performance test based on the functional characteristics of components. Subsequently, it would be needed to calculate the associated and additional costs in the reuse process, and finally using the results achieved from the two quality and quantitative tests, the reuse potential factor for each element will be presented in the dashboard.

The use of the BPM created for the deconstruction processes for reuse of building elements in the previous chapter helps to the realization of a structured list of system requirements for measuring the reuse potential factor. The BPM can thus be considered as a basic context that contributes to the gathering of additional information for the following processes (see figure 4.1).

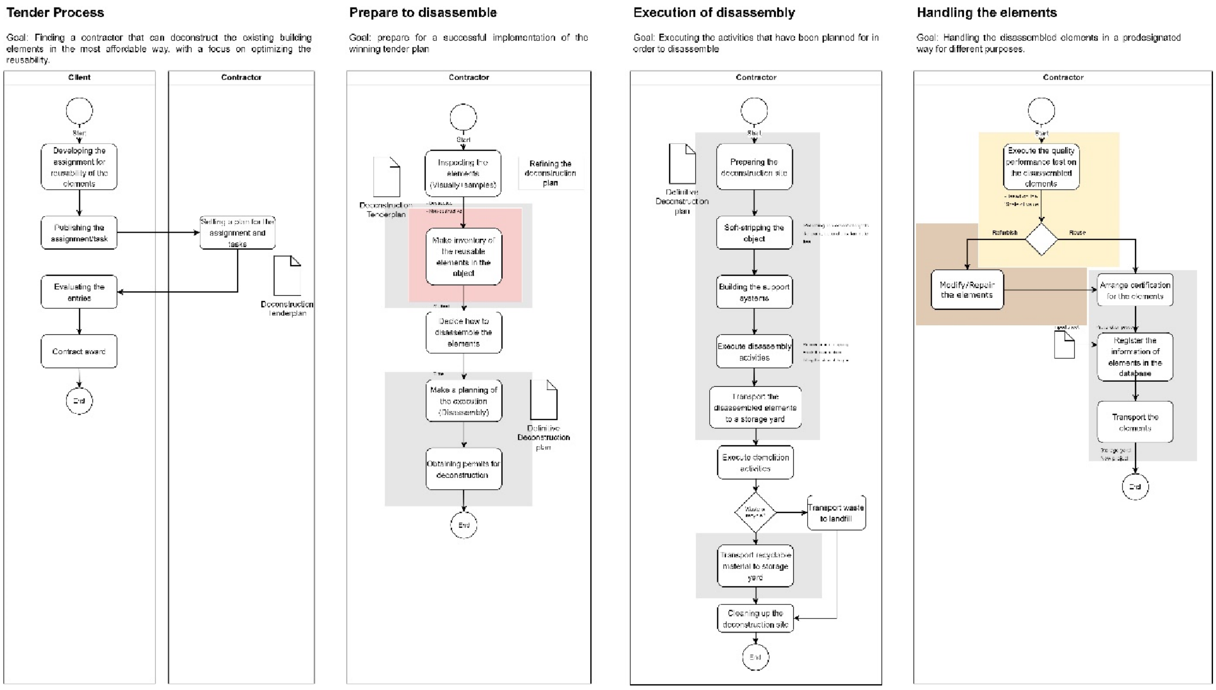


Figure 4.1: The BPM approach helps to understand which information will be needed for import sheet (own illustration).

As can be seen in the diagram above, several activities and processes have been highlighted that may be of interest for either measuring the reuse potential of existing elements or for use in the realization of CCE Information System. So, in the 'prepare to deconstruct' phase, the inventory stage has been marked in red which refers to the usefulness of this activity in measuring the reuse potential factor. Thereafter, the 'quality performance test' (yellow) in the BPM means examining the remain value of existing element to understand whether the element can be reused directly after disassembly or whether the disassembled element needs to be improved. In other words, the functional performance properties of the element would meet the new requirements.

The 'modify/repair' process in the BPM is marked in brown, this shows the relationship between the improvement process after disassembly and the impact of improvement process on the reuse cost. Decision making in the reuse process is largely dependent on different associated costs. Hence, the activities that significantly fluctuate the reuse cost, have been highlighted in grey. On the other hand, the reuse potential indicator is a quantitative metric, so it can be related to the cost.

Therefore, by identifying the relevant processes from the BPM, it is substantial to list of the system requirement steps which leads to the measurement of reuse potential factor for concrete building elements. As deconstruction for reuse process play a main role in achieving the purposes of this research, and contributes to the realization of a CCE Information System for existing construction elements. Subsequently, the information and data required for the import sheet can be derived on the basis of the illustrated flowchart below.

- A structured list of steps (work instructions) for measuring the RP factor based on BPM:

1) <u>Collecting preliminary data and information</u>: In order to measure the RP value of concrete building elements, it is necessary to start with gathering the related technical and functional data and information for both the existing and new building products. This step consists out of other sub-steps:
   1.1) Make inventory of the reusable elements
   1.2) Collecting data for the inventoried elements: This data can be generally obtained from the existing structural drawing and calculations.
   1.3) Collecting data for the newly designed project and the necessary elements: These data can be achieved from NEN-NORMS.

2) <u>Performing quality performance tests on the elements</u>: When the existing elements are disassembled all the discussed functional performance properties of concrete elements (including strength, durability, abrasion resistance, thermal characteristics, fire resistance and sound insulation), in the previous chapter, should be analyzed which can contribute to the measurement of the functional remain value of the elements. The quality performance testing phase can actually be considered as the constraints for the improvement process, that affect the ease of reusability of those components and need to be addressed significantly. Therefore, they need to be treated to meet the requirements of new construction project.

3) <u>Comparison of test results with the new requirements</u>: If the scale of value of the components indicates that the components would be improved (in terms of functionality), then the components should be upgraded and improved to meet different requirements set for new building projects. In this way, it can be determined which elements can be reused and if the functional performances of existing components approximate the predefined requirements, they can be reused directly after the disassembly process.

4) <u>Calculation of associated costs of interventions for all the elements</u>: Different intervention activities such as improvement process will undoubtedly cost extra for stakeholders involved, in the case that they have to be performed. So, it is necessary to calculate those costs to thereafter be able to calculate the reuse cost. As all the costs will be allocated to a specific stakeholder, therefore in this stage different stakeholders will be incorporated to this process.

5) Collecting data on costs for new elements: To measure the reuse potential value from an economic perspective it is needed to gather data of the newly manufactured element. This data can be achieved from different sources.

6) Determining the RP value: Ultimately, the reuse potential value can be measured from either functional or economic point of view. This can contribute considerably to the optimization of reuse process when the reuse potential indicates whether the element can be reused or not. The stakeholders can also have a better insight into the profitability of the reuse process.

4.3. Realizing the Concept of the 'CCE Information System'

Realizing the concept of CCE Information System and applying the results achieved in a dashboard is based on applying it in the real cases. As already discussed, the dashboard would be a proof of concept based on a use case or case studies which provides the opportunity to gain insight from the practice and also reveal knowledge that cannot be obtained from the literature.

4.3.1. Objective

In the construction and waste industry, it is essential to enrich the content of existing passports, databases, data platforms and etc. with new innovative knowledge and technology. The aforementioned platforms should contribute to improving sustainability, environmental quality, and socio-economic development. The main aim of this research was to develop a CCE Information System, which contains of an import sheet and a dashboard, in addition takes into consideration different functional performance characteristics of concrete building products and also associated costs allocated to stakeholders. The CCE Information System stimulates the reusability of existing products and supports stakeholders to make proper decision regarding profitability. Thus, the first part of CCE Information System (import sheet) would contain the basic data and information for measuring the quality performances of existing elements and thereafter, the additional costs allocated to stakeholders with indicating a marginal benefit achieved for the main actors. The results obtained will be demonstrated in a dashboard through different diagrams, charts and etc.

Furthermore, in order to create an innovative CCE Information System for existing elements, it has been realized a concept that includes some novel technological achievements such as QR-code. By creating and using a QR-code for existing elements, all the results gained in this research can therefore be shown in an innovative way in different devices such as mobile phone, step by step. After improving the existing products, a certificate statement should be obtained by contractor that allow the new user to reuse the elements in new construction projects, which is why this statement is included in the dashboard (more information regarding the building products certificate statement can be found in appendix A.4.1.).

4.3.2. The Structure of CCE Information System

The main aim of this research was to support decision making on reuse of existing building products by developing a CCE Information System that covers the functional performance properties of concrete elements and also the profitability of stakeholders from the reuse process in the construction and waste industry. In order to support the stakeholders involved in the reuse process in making the right decision, it is essential to present the results achieved from the research in a logical, creative and innovative way.

By following the BPM created for deconstruction process and thereafter the flowchart made for measuring the RP factor, the structure of CCE Information System can be realized. The primary factor derived from the aforementioned processes is splitting the import sheet and dashboard. The import sheet would act as the basic data content for the dashboard and therefore it should contain related data and information that can help the user understand the way to achieve the results. Moreover, the dashboard would be considered as a presentation board which gives the users an overview of the outcomes gained by demonstrating in different diagrams and charts.

In other words, the dashboard would contain related results that can assist stakeholders to choose the existing building products with high reuse potential and also provide the financial feasibility of reuse of the elements. Different functional performances would be assessed first and economic aspects of the reuse process should be analyzed to perceive whether it is possible to reuse the existing products both from functional feasibility point of view and profitability.

As already mentioned, the three most commonly used concrete building products, floor/roof, beam and column will be analyzed and handled in the reuse process after the EoL phase in the construction industry. So three separate spreadsheets/tabs in Excel need to be created for those three products.

It has been attempted to realize the structure of CCE Information System in such a way that they interpret the steps taken in this study to show the expected results. This structure is based on the BPM for deconstruction and assessment model made for measuring the reuse potential factor of existing elements (see figure 4.2).

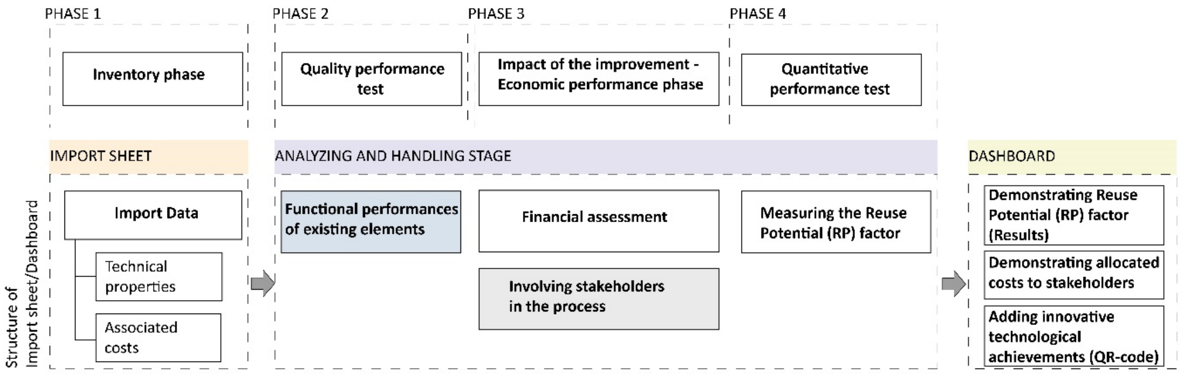


Figure 4.2: The structure of the CCE Information System for existing building products (own illustration).

Furthermore, it has been realized to take into consideration, either functional performances or different costs allocated to the stakeholders in the structure. This structure has been divided into three main parts, inspired by the process of measuring the RP value.

Primarily, the import sheet would be realized and will contains of various technical information and data about the existing concrete elements such as dimension, application, w/c ratio, amount of cement, density and etc. (i.e. in line with phase 1 of the measuring RP factor). Subsequently, the functional performances will be analyzed to estimate the remain value of existing elements, followed by calculating the associated costs in the reuse process (i.e. in accordance with phase two and three of the measuring the RP value). In this stage, the stakeholders incorporated to the process (highlighted in grey). Undoubtedly, the RP factor would be measured from either functional or economic perspective in 'analyzing and handling stage'. Finally, all the results achieved will be demonstrated in a dashboard that aimed to stimulate and optimize the reusability of existing concrete elements.

4.4. Description of the Approaches of Each Part of the CCE Information System

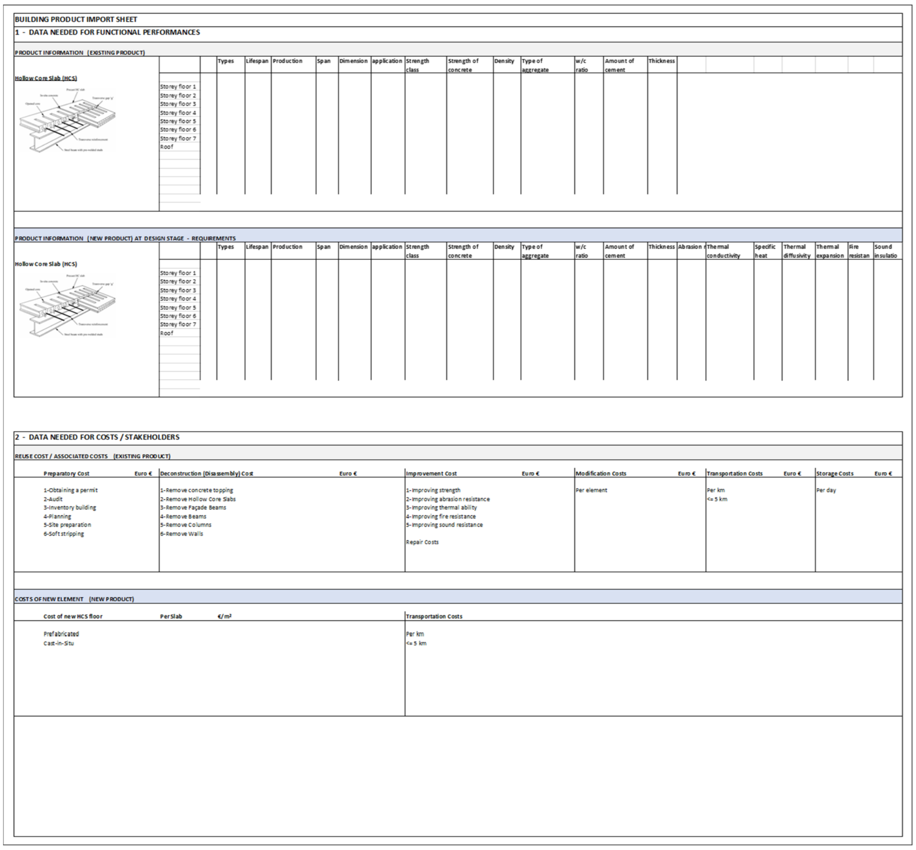
After realizing the concept of CCE Information System for existing concrete components, several phases should be described in which the data and information are implemented, calculated and ultimately have to be shown in a dashboard.

The approach describes the relationship among two main performances, i.e. quality and quantitative, which are related to functional performance characteristics and reuse costs of each element. The approach based on the structure created earlier, as gaining data and importing them in the first spreadsheet, followed by analyzing the reuse potential of functional performances of existing elements, calculating the reuse costs (including the deconstruction costs, transport costs and storage costs) in the separate tab, and finally demonstrating the outcomes as an advice in a dashboard, i.e. in the third tab of Excel-program.

4.4.1. The Import Sheet (First Step)

To understand whether the existing products have the reuse potential for new construction projects, it is important to estimate the RP factor of elements from functional and economic point of view. Moreover, the concept of the CCE Information System is based on applying it in real cases, therefore different data and information is needed from an old and new construction project. The data regarding the existing and new components can be obtained from structural or constructional drawing. However, in the case that the required data are not exist anymore and cannot be achieved from the technical drawing, assumption would be made for the aged building and NEN-NORMS will be used for the newly realized building project.

The concept of import sheet has been made in Excel program (first tab) as well as the Dashboard (figure 4.3). It is necessary to realize and create an import sheet where that data can be put in and interpreted in an innovative and novel way in different rows and columns. As already mentioned, the import sheet must be a place for putting in data achieved from the existing sources and interviews. In other words, technical data would be obtained from the structural and architectural drawings and calculations, and the associated reuse costs will be gained from interviews conducted with a demolition company (contractor). So, these two kind of data should be presented in a realized import sheet.



BUILDING PRODUCT IMPORT SHEET

1 - DATA NEEDED FOR FUNCTIONAL PERFORMANCES

PRODUCT INFORMATION (EXISTING PRODUCT)

Hollow Core Slab (HCS)		Types	Lifespan	Production	Span	Dimension	application	Strength class	Strength of concrete	Density	Type of aggregate	w/c ratio	Amount of cement	Thickness
	Storey floor 1													
	Storey floor 2													
	Storey floor 3													
	Storey floor 4													
	Storey floor 5													
	Storey floor 6													
	Storey floor 7													
	Roof													

PRODUCT INFORMATION (NEW PRODUCT) AT DESIGN STAGE - REQUIREMENTS

Hollow Core Slab (HCS)		Types	Lifespan	Production	Span	Dimension	application	Strength class	Strength of concrete	Density	Type of aggregate	w/c ratio	Amount of cement	Thickness	Abrasion r	Thermal conductivity	Specific heat	Thermal diffusivity	Thermal expansion	Fire resistan	Sound insulatio
	Storey floor 1																				
	Storey floor 2																				
	Storey floor 3																				
	Storey floor 4																				
	Storey floor 5																				
	Storey floor 6																				
	Storey floor 7																				
	Roof																				

2 - DATA NEEDED FOR COSTS / STAKEHOLDERS

REUSE COST / ASSOCIATED COSTS (EXISTING PRODUCT)

Preparatory Cost Euro €	Deconstruction (Disassembly) Cost Euro €	Improvement Cost Euro €	Modification Costs Euro €	Transportation Costs Euro €	Storage Costs Euro €
1-Obtaining a permit 2-Audit 3-Inventory building 4-Planning 5-Site preparation 6-Soft stripping	1-Remove concrete topping 2-Remove Hollow Core Slabs 3-Remove Façade Beams 4-Remove Beams 5-Remove Columns 6-Remove Walls	1-Improving strength 2-Improving abrasion resistance 3-Improving thermal ability 4-Improving fire resistance 5-Improving sound resistance Repair Costs	Per element	Per km <= 5 km	Per day

COSTS OF NEW ELEMENT (NEW PRODUCT)

Cost of new HCS floor Per Slab €/m²	Transportation Costs
Prefabricated Cast-in-Situ	Per km <= 5 km

Figure 4.3: The first realized concept for an import sheet (own illustration).

Primarily, various technical and functional data must be collected for the three chosen concrete building products, floor (HCS), beam and column. The technical data such as the lifespan of concrete element, the type of aggregate used in it, w/c ratio, the amount of cement, strength (class) of concrete and etc. The reason that those data is needed is to estimate the functional reuse potential of component based on those technical properties. Because, as the literature emphasized, there is a link between the technical and functional properties. For example, the thermal conductivity of concrete elements depends largely on the amount of cement used in it, or fire resistance of concrete elements depends on the thickness and types of concrete, and this also applies to other functional properties.

- Implementing the newly designed functional characteristics:

On the other hand, the requirements for newly designed elements would also be necessary, because to understand whether the existing components meet the new requirement or not. It is commonly determined in the design phase or afterwards which type of e.g. floor system will be applied in the project depends on the function of the building. Therefore, a case with the same function as the existing building project can be of great importance for analyzing the functional performances. However, this study also aimed to link the existing elements with other newly designed projects with different function. If, for example, the analysis of the functional properties shows that the fire resistance of the element is 60%, then the element can be linked to projects for which the fire resistance requirement is also set less than 60%. It is therefore important to conceptualize different situations in which different buildings with various functions are designed.

The second part of the import sheet contains data and information related to the associated reuse costs of the existing elements, and also the costs of new concrete elements. If it appears from the analysis of functional properties that the element would be improved in the case of e.g. fire resistance, this improvement process has consequences for the reuse costs for the contractor or the client. In addition, the BPM created for the deconstruction process has shown that it may be necessary to transport the element to a storage yard, incurring additional costs for the contractor. In order to measure the reuse potential factor of existing elements, it is undoubtedly important to compare the reuse costs with the cost of new manufactured products from an economic point of view. The data of deconstruction processes would be obtained from the interview described in the previous chapter. The costs of new manufactured product can be gained from different sources.

- Gathering all the data gained in a database:

Furthermore, all the required data and information would be gathered in a database. A database can play a major role in functioning of the tool. The next step of the tool, namely the analysis and processing stage can be programmed by e.g. Matlab or Python and this stage functions based on the data gathered in a database.

4.4.2. The Analysis and Processing Phase (Second Step)

A separate tab is designed and allocated to the analysis of functional performance characteristics and the reuse cost calculation process (in this research this tab is described in Appendix A.4.5 and A.4.6). This tab actually represents the main part of the tool which is conceptualized between the import sheet and the dashboard. Moreover, it is crucial to clearly show which steps have been taken to achieve the results to present them in the dashboard.

Furthermore, after gathering the required data and implementing them to the import sheet, different performance tests would be carried out. As can be seen in the structure of CCE Information System (figure 4.3), analyzing and handling stage consists of three phases, namely; the quality performance test (functional performance characteristics), the impact of different intervention processes such as improvement (economic performance), and the quantitative performance test (measuring the RP factor) for each element. Each step contributes to the process of measuring the reuse potential factor, from a functional and economic points of view. All the three phases will be described in more detail below.

- Estimating the reuse potential value from a functional performance perspective:

Knowing the scale of quality of each concrete building element will aid in decision making about whether the component needs to be improved, upgraded or even modified. The existing building products should meet different new functional and technical requirements after disassembling process that offers the possibility to reuse them in the new construction. However, there is a high probability that the existing products do not meet the new requirement (NEN-NORMEN), and therefore the elements need to be improved in terms of their functional performances.

For instance, if one of the functional properties of existing components such as fire resistance or sound insulation just satisfy 65% of the new required performances, then there are two opportunities to reuse it. First, the component can be reused in the new construction project which does not required a high fire resistance for its structure (<65%), or the component needs to be upgraded and improved which provide a higher probability that element can be reused for other purposes. This decision-making depends largely on the function of the new project and the requirements set for it in the design phase.

As already explained in the literature study (chapter 2, part 2.6.), concrete can degrade and deteriorate due to a wide variety of internal and external factors such as; corrosion of reinforcement, chemical attack, hot and cold weather concreting, errors in designing and detailing, exposure to fire and water, moisture, temperature, sea water effects, bacterial corrosion, physical damage and etc. These aforementioned factors can affect the functional properties of concrete significantly. Thus, in order to estimate the reuse potential of concrete elements from the functionality perspective, it is essential to consider some scenarios. In other words, it may be assumed that the element has not suffered any damage during its lifetime, or it is possible that the element has been affected by environmental factors like moisture that has largely to do with the weather in the Netherlands. However, the functional performance characteristics cannot be affected by external factors such as the element damaged through the connections break or the like, as they depend on the properties of its substance.

- Scenario 1 (Reusing in buildings with different functions): One of the most determinative factor for specifying the functional properties of construction elements is the function of the building. For example, the strength of concrete elements used in a utility building differs significantly with one used in a high-rise building.

- Scenario 2 (No environmental damages): In the case that no damages has occurred during the lifetime of element, the reuse potential factor can be estimated higher from both a functional and economic perspectives. As, the environmental factors affect the functionality of the elements followed by the additional costs included for the improvement. Therefore, in this scenario it has been assumed that the condition of the element meets the requirements set for a new construction project. Moreover, the most positive impact of this scenario is on the reuse costs for the contractor i.e. the improvement costs or additional transport costs are excluded from the total reuse costs. But the modification cost is still included depending on the requirements (dimension) of the new building system.

- Scenario 3 (Environmental damages): In this scenario, it would be considered that external factors influence the functional performance characteristics. For example, moisture can cause spalling of the concrete element and spalling can affect the e.g. strength and fire resistance of the element. Hence, in this situation the reuse potential factor can decrease in terms of both functionally and economically.

Furthermore, in order to estimate the reuse potential factor for functionality of concrete elements, it is necessary to compare the functional properties of concrete element with related properties of the substances used in it. For instance, to understand at which level the thermal conductivity of concrete element is, it is important to know the amount of cement used in it. Therefore, knowing the amount of cement used in the element and also using the information from the literature (the tests already performed in the lab to measure the e.g. thermal conductivity) for different types of concrete, then the ratio of e.g. thermal conductivity of concrete element can be estimated (see figure 4.4).

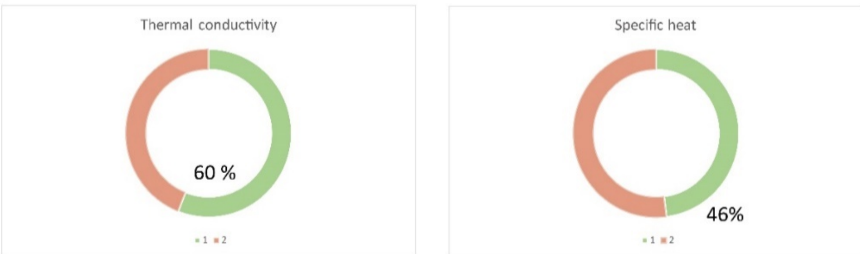


Figure 4.4: (Left) The estimated thermal conductivity of existing concrete element, based on the amount of cement used in it. (Right) The estimated specific heat of existing concrete element, based on w/c ratio used in it (own illustration).

On the other hand, the functional performance properties of new elements are already determined in the design phase. These properties can also be derived from the requirements set in the Dutch Building Decree (Bouwbesluit) for the new building element. For example, the Building Decree indicates in advance what the permitted thermal conductivity would be for the designed type of concrete HCS floor in a utility building. But to measure the reuse potential of concrete element from a functional perspective, it can be assumed that e.g. thermal conductivity of new element is 100%. So, the ratio between functional properties of existing elements and the properties of new elements can show the estimation of the reuse potential factor in terms of functional.

- Cost Analysis; Calculating the reuse costs including other associated costs:

After indicating the functional reuse potential factor of concrete element, it is obviously needed to analyze and address the impacts of this estimation process on the reuse costs. In addition, it is also possible to identify which stakeholder has an economic benefit/loss in the reuse process, as each cost is allocated to a specific stakeholder. The results achieved in this phase will also be used as input for the economic measurement of the reuse potential factor.

Depending on the scenarios adopted for estimating the functional performances, the reuse cost varies considerably. In other words, no environmental damages require no upgrade, thus no additional improvement cost, while if the element needs to be upgraded there will be additional costs involved. Moreover, depending on the technical requirement of a new building project, it may be needed to modify the elements (e.g. sawing the length of the element), and this will be an additional cost to the contractor. Consequently, after improvement process, the element need to be transferred to a storage yard, and these two activities increase the reuse cost for the contractor. It should be noted that the deconstruction costs included in the reuse cost formula are a fixed price depending on the size of the project, while the improvement/modification, transport and storage costs vary as they depend on several variables.

Therefore, when calculating the reuse costs, the following should be taken into account; (a) the functional performance quality of the element, (b) the distance between the deconstruction site and treatment company, and the distance from treatment company to the new construction site, (c) the date that the element scheduled to be reused. As already researched in the literature study, the reuse cost can be calculated from the formula (7) mentioned in (chapter 2 part 2.9.3.1.). The application of CCE Information System is based on real cases, therefore, these considerations would be adopted in a real case studies in the next chapter.

In this phase, the two main stakeholders, the client and the contractor are involved in the process. As mentioned before, the economic benefit/loss of these two actors will be indicated in the dashboard. Therefore, it has been realized to calculate the total profit (Total Profit = Total Revenue – Total Cost). So, the reuse costs can be calculated using the formula that has already been explained. The revenue that the contractor earns from the sale of the products would also be calculated (Revenue, R(x), equals the number of items sold, x, times the price, p). The two formulas that contribute to the stakeholder profit calculation are as follows;

- *Total Profit = Total Revenue – Total Cost*
- *Total Revenue(products)= Number of products sold x Price €*

Calculating the reuse costs will contribute to either measure the reuse potential factor from an economic points of view or contribute to calculate the contractor's profit. Hence, the results obtained in this section can serve as input data for the next step.

- Measuring the reuse potential factor from an economic point of view:

In chapter 3, measuring the reuse potential factor discussed in detail. In the last part of 'analyzing and handling stage', this factor will be measured from an economic perspective. Since, the profitability of reuse elements plays a major role in decision-making for stakeholders involved. The contractor as a main actor in the reuse process would have a clear insight into the associated costs and the profitability of the reuse process which can be presented as a reuse potential (RP) factor between 0 (waste) and 1 (reuse) (see figure 4.5).

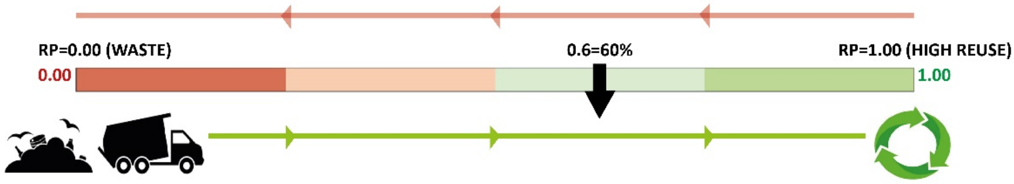


Figure 4.5: Indicating the reuse potential of an existing element from an economic point of view (own illustration).

To measure the reuse potential factor, the formulas (8) and (9) (described in chapter 3, part 3.3.3.) would be applied for two scenarios. In other words, if (a) the reuse cost is higher than the cost of new element then the formula (8) should be used, and in the case that the reuse cost is lower than the cost of new product then the formula (9) would be applied. The total reuse cost for the existing element are compared with the total cost for a new manufactured element. Since the RP factor can be measured by a proportion between the reuse cost and the cost of a new product.

Furthermore, the costs calculated in the previous step will be considered as input data for measuring the economic RP factor. As can be seen in the figure above, if the economic RP factor reads 0.6, it means that the recovered and improved element is economically 60% reusable. Indicating the economic RP factor contributes largely to the optimization of reuse process in the construction and waste market, not especially for the involved stakeholders, but it can be seen as a major challenge for the government organizations to take innovative measures and to cope with the obstacles in the reuse process.

- Making a comparison between different scenarios:

For each scenario that assumed for each phase of the reuse potential value measurement, a situation (buildings with different function/other purposes) would be realized. Thus, since the existing elements can be reused for different purposes, the reuse potential value would be measured from a functional point of view, which provide more insight into a logical decision-making process about reuse of the element for the right purpose. In addition, indicating the functional reusability of each element can contribute to the analysis of the following scenarios which assumed for calculating the reuse cost. Subsequently, the reuse potential value that was affected from an economic perspective, can be measured for different situations. Therefore, a comparison among the assumed scenarios in various situation (buildings with different function/other purposes) can be valuable for determining the profitability of reuse elements. This can also provide the relevant stakeholder insight into which strategy can be the most sustainable and affordable in terms of reusing the existing elements.

- Optimizing the cost-related issues:

The aim of developing a CCE Information System is to support the decision-making regarding the reusability of the existing elements. Therefore, the results achieved from the analysis and handling process would be optimized in the case that they do not show a profitable reuse process for both the contractor and the client. As making a profit is the main issue in the deconstruction and waste industry.

After measuring the RP factor from an economic point of view, the tool would be able to optimize the scenarios in which different cases have been examined. However, the purpose of optimizing is to combine the scenarios assumed in deconstruction for reuse process from a financial perspective.

The reuse costs, which includes deconstruction cost and more other corresponding costs, would be analyzed in more details to perceive the impact of various costs on the reusability of the existing elements. This analyzing process will be carried out in real cases to calculate different costs with the prices obtained from interviews. The optimization process will be performed by applying the What-If Analysis in Microsoft Excel using the Solver function. The aim of the optimization is to reduce the deconstruction cost followed by the total reuse cost.

Furthermore, a sensitivity analysis would be conducted which is aimed to find the best cases of the combination of scenarios. This method is usually applied in financial analysis to determine how target variables are affected based on changes in other variables known as input variables. It is a way of predicting the results of a decision based on a certain number of variables. Hence, it is needed to analyze the economic impact of different processes on the total reuse cost.

4.4.3. The Dashboard (Third Step)

Moving from a linear towards a Circular Economy in the construction industry requires more focus on systemic thinking that includes either the building life cycle or the construction value chain for stakeholders involved. The availability and redeveloping of different structured information on building product composition, various building stocks, material flow, and also different functional characteristics of building element is essential for supporting this alteration.

Realizing, creating and developing such a circular and structured Information System that includes different data and information can largely contribute to the optimization of reusability of existing elements and also close the loop of finite materials in the construction and waste management sector. In addition, developing such an Information System accelerates the realization of sustainable requirements and goals that the government has set for 2050. This research has attempted to realize the concept of a CCE Information System for the existing concrete elements, in/after the EoL phase, which provides information and data to optimize the reusability of the existing elements.

Furthermore, all the results achieved from the previous steps should be presented and summarized in an innovative way using a dashboard. Therefore, the dashboard would include the related results that can be technically and economically useful to the end user. Three main parts are realized for the concept of dashboard; (a) indicating the results gained from the quality performance test of the existing elements, (b) presenting the reuse costs including deconstruction costs and other associated cost to the stakeholders involved, and (c) providing the final advice including the certificate statement and QR-code (see figure 4.6).

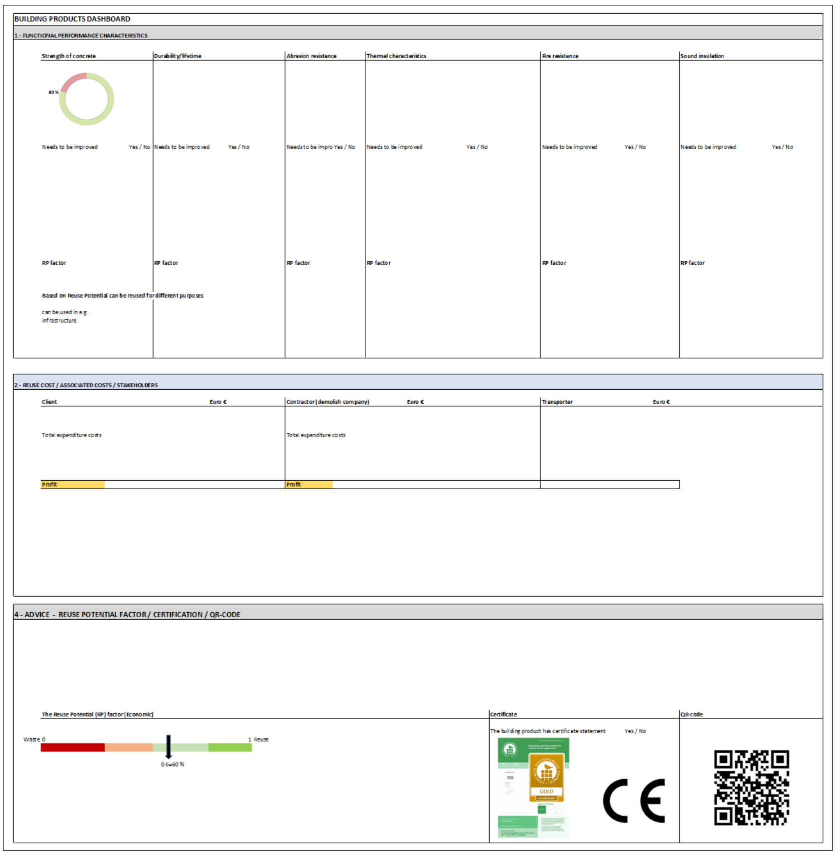


Figure 4.6: The realized concept for a dashboard (own illustration).

As can be seen in the concept of the dashboard, the first part presents the reuse potential of each element from a functional point of view through diagrams. It will be stated that the element needs to be improved in case of its functional performance properties to meet the new requirements. In this part it can also be concluded that, based on the scale of value of the element, the element can be reused in other sectors, such as infrastructure, or reused for other purposes that do not require high functional characteristics.

The second part identifies the results achieved from cost calculation procedure. The biggest challenge for stakeholders is to take advantage of a profitable reuse process. Thus, the reuse cost, the revenue, the salvage value, and the total profit would be tabulated. Ultimately, in the last part, a general advice should be given to the end user to make the most affordable decision with regard to reuse of existing elements. Also, the certificate statement will be added next to a QR-code.

4.5. Functioning of CCE Information System

As already mentioned, the CCE Information System consists of three main parts namely an import sheet, an analyzing and processing sheet and a dashboard, serving as a tool with the aim of optimizing the reusability. The functionality of CCE Information System is based on data and information gained from real cases. Therefore, it is needed to describe some practicalities for the functioning of the proposed CCE Information System as a tool.

The main goal of the developed CCE Information system is to maximize the reusability of the existing elements based on functional performance properties and cost-related issues of the stakeholders. Nevertheless, serving as a tool will require some other functionalities of each part of CCE Information

System as a tool. Thus, the general outline of the functioning of the developed tool is illustrated below (see figure 4.7).

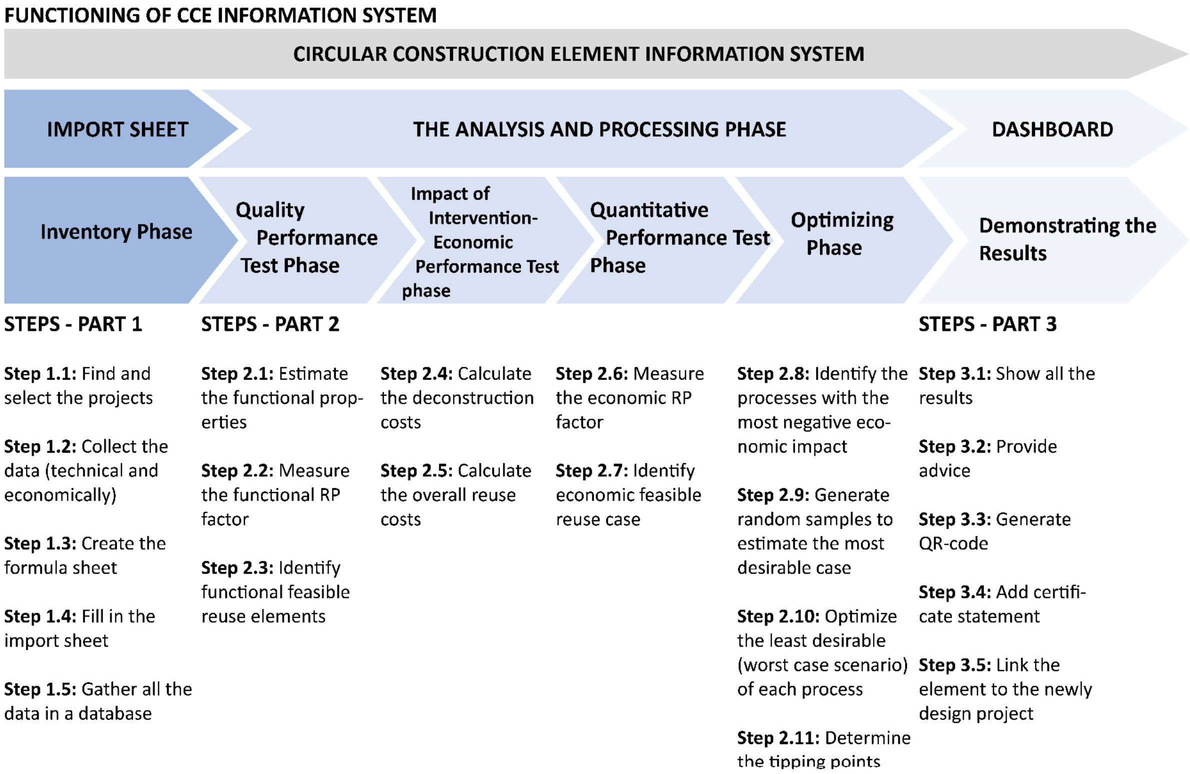


Figure 4.7: The outline of functioning of the proposed CCE Information System (own illustration).

The developed CCE information System functions actually as a tool and the functioning processes are divided into three main parts.

Steps – Part 1:

- ***<u>Step 1.1 – Find and select the projects</u>***: The functionality of CCE Information System is based on real cases. Therefore, an aged construction project at EoL phase as the main core is needed, besides different newly design projects. This procedure can be done either manually or automatically if the tool is connected to a central construction information server.
  ** In the case of unavailability of newly designed projects, different scenarios would be assumed.
- ***<u>Step 1.2 – Collect the data (technically and economically)</u>***: The main aim of the functionality of CCE Information System is maximizing the reusability based on functional performance properties and cost-related issues. Data achieved from literature will also be used. Therefore, the technical data would be needed to estimating the functional characteristics, and economically data to calculate the reuse costs. This step can also be done manually or automatically.
  ** This step is one of most important steps as measuring of RP factor from a functional and economic point of view is based on the new requirements and other data such as location.
- ***<u>Step 1.3 – Create the formula sheet</u>***: The creation of a formula sheet is considered as a basic step of tool development. It includes all the formulas needed for calculation of various quantitative factors such as deconstruction cost, reuse cost, other associated costs and also the formulas needed for measuring the RP value.

- ***Step 1.4 – Fill in the import sheet***: The import sheet contains of different technical and economic data of the existing elements for which the reuse feasibility will be determined functionally and economically. Again, this step can be fulfilled manually or automatically.
  ****** It may be necessary to manually implement the data of an obsolete construction project, as not all data of an obsolete building exists or registered in a central data server.
- ***Step 1.5 – Gather all the data in a database***: To carry out the next steps of analysis and processing stage, it is needed to gather the data in a database. This can be done in a spate sheet in Excel program. If the next steps will be programmed in e.g. Matlab or Python, then the data should be used automatically from the database.

Steps – Part 2:

- ***Step 2.1 – Estimate the functional properties***: This estimating is based on the technical data of the existing element and the data from literature. Because the functional properties would be linked to the technical data firstly, and thereafter compared with the results from literature.
- ***Step 2.2 – Measure the functional RP factor***: The next step is assigned to the measuring of RP factor from functional perspective. The tool would be able to measure the functional RP factor for different functional performance characteristics based on given formula beforehand.
- ***Step 2.3 – Identify functional feasible reuse elements***: After measuring the functional RP factor, the tool will be automatically identifying the elements which are functionally reusable. The tool, in other words, select the elements which can be reused, otherwise the tool must provide advice whether the element can be recycled or landfilled.
- ***Step 2.4 – Calculate the deconstruction cost***: Measuring the functional RP factor provides insight into whether the element can be reused or not. Then it can be decided to deconstruct the project. In this step, the deconstruction cost can be calculated by the tool.
- ***Step 2.5 – Calculate the overall reuse costs***: In order to measure the economic RP factor, it is needed to calculate the reuse costs. The tool should be able to calculate the deconstruction cost, using the data and formulas implemented in import sheet.
- ***Step 2.6 – Measure the economic RP factor***: In the next step, the tool will measure the RP factor from an economic perspective. Again, this process will be done by using formulas at the beginning of the tool.
- ***Step 2.7 – Identify economic feasible reuse cost***: The tool will be thereafter able to identify the elements which are economically profitable. If this is not the case, the tool should start with the next process, namely the optimization process.
- ***Step 2.8 – Identify the processes with the most negative economic impact***: The tool is aimed to optimize the undesirable cases. Therefore, in the first step the tool will be identified the processes which have had the most negative impacts on the reuse cost.
- ***Step 2.9 – Generate random samples to estimate the most desirable case***: The most desirable cases (scenarios) should be estimated in order to understand an approximate of upper boundary. This estimation can be done through generating random sampling in Excel.
- ***Step 2.10 – Optimize the least desirable (worst case scenario) of each process***: After identifying the least and most desirable cases, the tool will thereafter optimize the worst case scenario. This can be done through a recalculating by the tool. It is also needed to define the weightage criteria. This process will be done for all the processes that had the most negative impact on the reuse cost.
- ***Step 2.11 – Determine the tipping points***: One of the most important steps performed by the tool is determining the tipping points of each processes. In this step the actual tipping points

are determined and plotted for each case (scenario). In addition to the tipping points, the upper boundary would also be determined.

Steps – Part 3:

- ***<u>Step 3.1 – Show all the results</u>***: All the results achieved must be saved and presented to the end user and the stakeholders involved.
- ***<u>Step 3.2 – Provide advice</u>***: The tool would provide advice to the user based on the results whether the element can be economically reused or not.
- ***<u>Step 3.3 – Generate QR-code</u>***: In order to facilitate the reuse process among the stakeholders, the tool is also aimed to generate a QR-code which can be used by different devices. The QR-code will present all the results presented in dashboard in a summarized way.
- ***<u>Step 3.4 – Add certificate statement</u>***: If the developed CCE Information System be connected to a central data server, then the certificate authorities can attach a certificate statement to the dashboard. This step can also be done manually by the CCE developer.
- ***<u>Step 3.5 – Link the element to the newly design project</u>***: The main purpose of the tool is to maximize the reusability of the existing elements. Therefore, if the outcomes show that the reuse process can be profitable for the stakeholder, then the tool should link the element to the newly designed project.

4.6. Conclusion

One of the main challenges in the C&W sector is to enrich different existing data platforms for building product in such an innovative, creative, and sustainable way. This challenge can be tackled by developing a 'Circular Construction Element Information System' that contribute to the optimization of the reusability. As, the reusability of existing elements considered at the top of 'waste management hierarchy' and Ladder van Lansink.

The use of previously created BPM contributes to mapping the process for measuring the reuse potential value from a functional and economic perspective. The process of measuring the reuse potential value will thereafter help to perceive which relevant data and information would be needed for the import sheet. Hence, the reuse potential indicator can be considered as an efficient communication tool to share information (data) regarding technical quality or maximum reusability of existing element.

The realization of CCE Information System should be based on innovative approaches that includes useful data and information for different stakeholders involved in the reuse process. The CCE Information System would serve as a tool which is able to maximize the reusability by linking the existing elements to the best case scenario either functionally or economically. The developed tool should also improve sustainability, environmental quality, and socio-economic development. Therefore, it has been realized to include some novel technological achievements such as QR-code in the CCE Information System which facilitate the use of product flow in the construction industry.

The CCE Information System have been created in Excel program consisting of three various spreadsheets/tabs. The first tab is devoted to the import sheet and includes technical and functional data for both an obsolete and a new construction project. Different associated costs obtained from interviews will be the other part of the import sheet. The second tab (a separate tab in this research) is assigned to the analysis and processing phase which shows the procedure of measuring the RP value and also the calculation of reuse costs. Once the reuse potential values of all the existing elements have been calculated, decision-makers (contractor) have an information overview (dashboard) from which to prioritize reuse projects. Ultimately, all results and outcomes of previous steps are shown in a dashboard. The final results should assist the actors in the reuse process to choose the proper element functionally and economically.

The next chapter focuses on the practical implementation of the proposed CCE Information System. Thus, different case studies will be applied to test and evaluate the usability of the conceptualized tool beside conducting interviews with the related stakeholders.

CHAPTER 5 | THE EVALUATION OF 'CCE INFORMATION SYSTEM' / USING CASE STUDIES AND INTERVIEWS

Chapter 5 – The Evaluation of CCE Information System/Using Case Studies and Interviews

In this chapter, the developed CCE Information System will be evaluated using real cases to demonstrate the reuse potential value of each concrete element based on functional performance properties and the associated costs for the stakeholders involved. Applying case study approach contributes to this aim which reveals more knowledge from the construction and waste practice.

As discussed earlier, the transition to CE strategies and applying the ‘waste management hierarchy’ requires the realization of innovative solutions for a circular economy and the stimulation of the reusability of building materials/components. In addition, different sectors such as construction and waste industry, should try to maximize the reuse of the existing elements by realizing, creating and using different integrated solutions, whereby the buildings are no longer demolished but building components will be reused for a second life. Therefore, it is essential to understand whether the existing elements have the reuse potential for other new specific building projects, or even have sufficient reuse potential for other purposes.

The aim of developing a CCE Information System was to find out whether it is possible to functionally or economically reuse the existing concrete elements. The applicability of the aforementioned tool is based on the implementation of various technical and functional data from the existing building elements. However, a new realized building project in the design phase would be needed to make a comparison between different technical and functional aspects. Also, data obtained from interviews with a contractor (demolition company) would be necessary for the calculation of the reuse costs in the deconstruction process.

The literature study showed that concrete elements are the most commonly used construction product worldwide, including the Netherlands. There are a large number of buildings which have been constructed from concrete and each building component has its own functional characteristics and requirements. So, the type of each concrete elements differs in many aspects from others. In order to reuse the existing elements, the functional properties of the existing concrete elements would meet the newly determined characteristics and requirements set for the new building structure. Therefore, the aim of this phase is to gain input and data from frontrunners in the (de)construction and waste industry.

5.1. Inventory Phase for Implementing Data in the Import Sheet

In order to test and evaluate the developed CCE Information System, some cases would be needed, an obsolete building project as the main case and a new realized building system. Different technical data related to both the aged and the new building projects, is necessary to measure the reuse potential value from a functional point of view. So, it is needed to follow the structure of the CCE Information System which is already illustrated in the previous chapter.

Furthermore, two interviews have been conducted with two different contractors (demolition companies) in the Netherlands to obtain the associated cost in the deconstruction for reuse process. The interview protocol can be found in Appendix A.2.2 in which the questions are formulated based on the BPM created for the deconstruction process. The findings and insights from interviews will be discussed in the next parts. Complete transcripts of the interview 1 and 2 can also be found in Appendices A.4.3, and A.4.4.

5.1.1. Case Study: The Existing Building Project 'The City Post'

To further apply and evaluate the developed CCE Information System based on real cases with different scenarios data from the practice is needed. In the previous chapters, input from theory was taken regarding the measuring the reuse potential value from a functional perspective. Within this chapter the case study and interviews will be presented in order to achieve a clear insight into the adoption and implementation of the developed CCE Information System. Moreover, all the selection criteria, as already mentioned in (chapter 1, part 1.8.4.), have been taken into consideration when choosing the case study.

- Background of the project 'The City Post':

The former TPG-Post Expeditie Knooppunt (EKP) is located next to the station on Westerlaan in Zwolle. The object was built in the 1970s (1972) and was used as a postal sorting center until the mid-1990s (see figure 5.1). About 70 organizations have now established themselves in the current building. However, the building is very outdated. The current building consists of two building parts; high-rise and low-rise buildings. The building has a gross floor area of about 20,292 m². In addition, the function of the building can be considered as a multi-company (office) building.

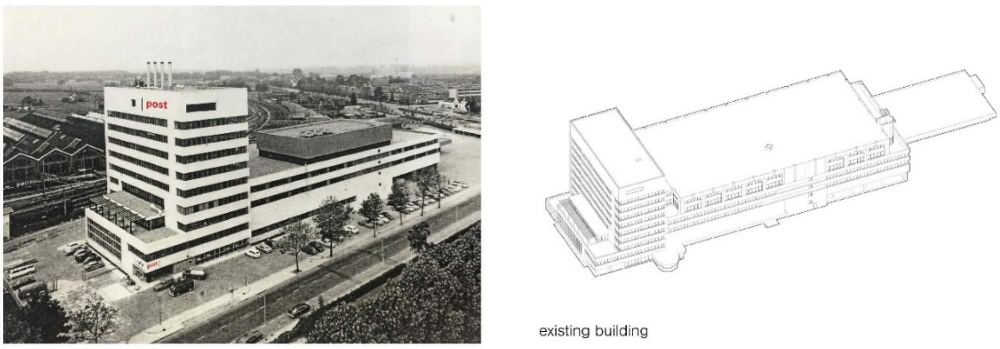


Figure 5.1: The aged building project 'The City Post' located in Zwolle, constructed in 1972 (Retrieved from: De Architekten Cie, n.d.).

The client, Westerlaan Zwolle B.V., has decided to carry out a transformation in the outdated building, since the object is obsoleted and due to the location of the project in the middle of the city of Zwolle, it is necessary to transform it into a sustainable building. The building is constructed of concrete, however the two storeys on the top of the low-rise building are constructed of steel beams.

- Deconstruction of the project:

The other stakeholder involved in the deconstruction process of The City Post in Zwolle is Weever Sloop B.V. The demolition company received the assignment to demolish the former Expeditie Knooppunt Post (EKP) to the original hull. The project is located in the heart of the Municipality of Zwolle. The impact of a major demolition project can be significant.

According to the demolition company, the characteristic of this project is the size of it in combination with the degree of difficulty, located in the center of Zwolle. The project involves the complete demolition of two storeys of the seven storeys in total, carrying out extensive asbestos remediation and completely stripping the inside and outside of the building. A very appealing demolition work in which all facets of demolition are discussed. The original building has been completely stripped. The two top storeys of the building have been demolished with heavy equipment. In other words, 30,000 m³ of the building would be demolished, and 40,000 m³ of the building capacity will be stripped (see figure 5.2). Furthermore, the two top storeys on the top of the low-rise building were added to the building in the 1980s.

Figure 5.2: The deconstruction process of the aged building 'The City Post' (Retrieved from; Tubantia, 2021).

Because the choice was made for sustainable reuse of the concrete construction, it must be 'demolished' with care and attention. Little by little, removing some of the old postal sorting center until the existing structure is fully visible. A combination of disassembly and demolition techniques ensures that parts of the building are immediately suitable for reuse.

Since the client has decided to deconstruct the project and transform it to a more sustainable building after approximately 50 years, therefore some elements can be reused after disassembly process. But this question may arise, whether the components meet the new requirements set for a new construction project, the transformation scenario, or even be reused for other purposes. The fourth and fifth floors were built around 1985 and have a separate construction. The fourth and fifth floors will be completely demolished and make way for new construction.

- Stakeholders involved:

There are different stakeholders involved in the deconstruction process of 'The City Post'. The stakeholders involved in the deconstruction phase, are as follows:

- Client: Westerlaan Zwolle B.V.
- Contractor (demolition company): Weever Sloopwerken B.V.

The stakeholders involved in the renovation (transformation) phase:

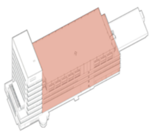
- Client: DC Vastgoed B.V.
- Contractors: Bramer – Vriezenveen - Weever Bouw
- Sub-contractor (Installer): De Groot Installatiegroep
- Sub-contractor (Façade builder): Facadis Gevelbouw
- Architects: dhr. E. van Noord - De Architekten Cie B.V.

- Technical specification (data) of the project:

The construction of the building was completely prefab in 1970 and that was a novelty at the time. The building is constructed of concrete, but the two top storeys on the top of the low-rise building which were added later, is also constructed of steel. The prefab construction of the low-rise building is the most striking architectural element. This has a grid size of 7.20 m, on which double I-beams on a fork-like column head span 18 m. In between is a system of concrete and floor slabs. The gross floor height is 7.10 m. The high-rise has a clear horizontal line of washed concrete slabs and wooden window strips. More technical information (drawing) of the project can be found in Appendix A.4.1.

Table 5.1: Technical and functional data of the concrete elements used in the project 'The City Post' in Zwolle (own table).

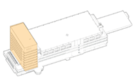
The City Post' LOW-RISE BUILDING



PRODUCTS INFORMATION

	Types	Lifes	Production	Span	Dimension (mm)	Application	Strength class	Strength of concrete	Density kg/m3	Type of aggregate	w/c ratio	Amount of cement kg/m3	Thicknes
Ground floor	HCS 150 mm	50	Cast in situ	18 m	7200x18000	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 1	HCS 150 mm	50	Prefab Conc	18 m	7200x18000	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 2	HCS 150 mm	50	Prefab Conc	18 m	7200x18000	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 3	HCS 150 mm	50	Prefab Conc	18 m	7200x18000	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 4	HCS 150 mm	50	Prefab Conc	18 m	7200x18000	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Roof	HCS 150 mm	50	Prefab Conc	18 m	7200x18000	Roof	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Column	Rectangle	50	Cast in situ		420x420	Column	B 65	C 53 / 65	2450	Coarse aggregate Crus	0.4	425	

The City Post' HIGH-RISE BUILDING



PRODUCTS INFORMATION

	Types	Lifes	Production	Span	Dimension (mm)	Application	Strength class	Strength of concrete	Density kg/m3	Type of aggregate	w/c ratio	Amount of cement kg/m3	Thicknes
Ground floor	HCS 150 mm	50	Cast in situ	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 1	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 2	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 3	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 4	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 5	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 6	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 7	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 8	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 9	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Storey floor 1(	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Floorsystem	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Roof	HCS 150 mm	50	Prefab Conc	7.2 m	7200x7200	Roof	B 52.5	C 47.5 / 52.5	2360	Coarse aggregate Crus	0.46	446	210 mm
Column	Rectangle	50	Cast in situ		420x420	Column	B 65	C 53 / 65	2450	Coarse aggregate Crus	0.4	425	

For the existing elements of the project 'The City Post', different functional performance characteristics of each element can be estimated based on the technical data achieved from the construction and structural drawings. For example, knowing the thickness of the HCS floor can contribute to the estimation of fire resistance of the existing elements.

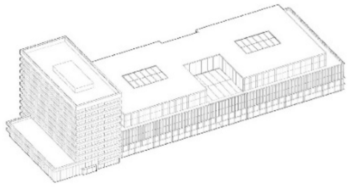
The total number of HCS prefabricated floors used in the project is 72 in the low-rise part (44 used in the storey 4^{th} and 5^{th}), so totally about 116 HCS is used (expect of ground floor) and 72 HCS floors are used in the high-rise part of the project. Because, the beams used in the project are from steel (H and I profile) therefore the focus of this analysis lies on the floor systems. On the other hand, some assumptions have been regarding the concrete columns used in the project.

5.1.2. Reuse of the Existing Element in Different Situations (Collecting Data)

One of the most important information derived from interviews was that each building has its specific functional and technical characteristics. Consequently, this affects the functional performance properties of buildings elements and components. In other words, to be able to reuse the existing elements and also to optimize the reusability of the elements of the case 'The City Post', it is essential to provide insight into the functional properties of different building systems with various function. Given that those buildings with a different function characterize elements with specific functional performance. In this way, the reuse potential value of the existing elements can be measured which is based on the proportion of existing and new elements. Therefore, the technical data or even the new requirements (NEN-NORMS) that set for the elements of new buildings with different function is needed. Thus, a scenario analysis will be conducted to zoom more in detail and compare the results achieved, particularly in the cost analysis.

1- Reuse of the existing elements for transformation/renovation (same function):

As already mentioned, the project ‘The City Post’ is under deconstruction process regarding transformation. The demolition company (contractor) is still working on the deconstruction process. Therefore, the existing structure of the building will be reused, as it meets the last requirements (NEN-EN NORMS) set for functional performances. However, the client (in the construction phase; DC Vastgoed) has decided to renovate and transforming the existing building to a more sustainable object (figure 5.3).



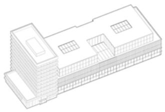
new design

Figure 5.3: The transformation design of the project ‘The City Post’ located in Zwolle (Retrieved from: De Architekten Cie, n.d.).

The supporting structure of the building consists of concrete. In the context of sustainability and reuse of material, it was decided to keep the concrete construction. The basement will be transformed into a parking garage, the concrete walls etc. will be preserved, some columns will be replaced in order to create a roadway. In addition, new concrete is poured over the existing floor to anchor the new columns.

From the ground floor, the columns continue up to the 3rd floor. Each 7.20-meter grid has a concrete column on which two large I-beam rest. The I-beams carry the floors of the 2nd floor and the ceiling of the 3rd floor. Children's beams are located between the I-beams, which are also preserved. In its current state, the 1st and 3rd floors only consist of a mezzanine, these will be demolished and new floors will be installed. The existing core at the front of the building will be demolished, the new concrete core will be built in the middle of the building. The fourth and fifth floors were built around 1985 and have a separate construction. The fourth and fifth floors will be completely demolished and make way for new construction. More information about the transformation of ‘The City Post’ can be found in Appendix A.4.2.

Table 5.2: Functional performance requirements of concrete elements for office-building according to NEN-NORMS 2012 (own table).

TRANSFORMATION OF 'The City Post'										
	**ELEMENTS**		**NEN-EN NORMS - FUNCTION (OFFICE)**							
	Application	**Type**	**Abrasion resistance**	**Thermal characteristics**				**Fire resistance**	**Sound insulation**	
				Thermal conductivity (W/m°K)	**Specific heat (kJ/kg.K)**	**Thermal diffusivity ($m^3/m^2.s$)**	**Thermal expansion (10^-6per °C)**		Minimal airborne sound insulation	maximum impact sound level
	Ground floor	Concrete	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0 - 12.0	<5m - 60 min	≥ 33 dB	≤ 65 dB
	Storey	Concrete	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0 - 12.0	5 - 13m - 90 min	≥ 33 dB	≤ 65 dB
	Roof	Concrete	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0 - 12.0	>13m - 120 min	≥ 33 dB	≤ 65 dB

In order to be able to estimate or even to measure the reuse potential value of each functional properties of concrete elements, it is needed to collect technical data from the newly designed buildings with different function. In other words, the new functional performance requirements set for e.g. fire resistance of each building depends on the (a) functionality (hospital, sport complex and etc.) of that building and (b) on the technical properties (thickness) of the elements used in the construction of the building. Therefore, based on the functionality of newly designed construction the new functional performance requirements can be gain from the Dutch Building Decree 2012.

Furthermore, in the case of fire resistance for example, the thickness of the existing element is known, so if the new functional performance requirements set in Building Decree indicate that the fire resistance of the element must be improved then it can be concluded that the thickness of the existing element would be modified by a new top-layer for instance.

2- Reuse of the existing elements in buildings with different functions:

It is undoubtedly possible to reuse the existing elements in other buildings which will be designed and function differently from the existing building. Implementing this information to the CCE Information System enhances the probability of reusability of the existing elements. Below are some functional requirements for buildings with various functions (sport, education and Healthcare institution) that have arisen from the Building Decree. However, some assumptions have been made regarding the supposed cases. The reasons for choosing these projects are; (a) to evaluate the reusability of the elements in building with different functions as they have different shape and dimensions and technical requirements, (b) to understand the effect of distance on reuse cost, and (c) assuming some other scenarios that affect the reuse cost such as direct reuse (On-site), direct reuse (off-site), indirect reuse the element (the elements would be storage).

- Sport:

An assumption has been made for the realization of a sports complex near to the city of Zwolle, a city that needs a new sustainable sports complex. The reason for choosing the locations of these projects is to be able to calculate the transportation cost in case of modification or improvement of the elements. Also to understand which distance can be seen as upper limit in case of transport cost calculation. As the existing elements have to be adjusted due to the different shape and form of new building structure.

The structure is designed to be constructed of concrete, but definitely in a different form. The sports complex has 4 storeys with swimming pool, sport halls, ice hockey field, Locker rooms, café, restaurants and more other facilities. The newly designed building structure would meet the requirements of the Building Decree in table 5.3, which affect the reusability of the existing elements and subsequently the reuse cost.

Table 5.3: Technical and functional performance requirements of concrete elements for a sports complex according to NEN-NORMS 2012 (own table).

SPORTS COMPLEX														
	ELEMENTS						NEN-EN NORMS - FUNCTION (OFFICE)							
	Application	Dimension (m)	Height (m)	Predesignated lifetime	Concrete class	Production	Abrasion resistance	Thermal characteristics				Fire resistance	Sound insulation	
								Thermal conductivity (W/m°K)	Specific heat (kJ/kg.K)	Thermal diffusivity (m³/m².s)	Thermal expansion (x10^-6per °C)		Minimal airborne sound insulation	maximum impact sound level
	Ground fl	150x220	9	50 Year	C55/67	Cast-in-situ co	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	5 - 13m - 90 m	≥ 50 dB	≤ 25 dE
	Storey 1	100x150	11	50 Year	C50/60	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 50 dB	≤ 25 dE
	Storey 2	100x150	10	50 Year	C50/60	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 50 dB	≤ 25 dE
	Roof	100x150		50 Year	C45/55	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 50 dB	≤ 25 dE

Different functional and technical requirements are tabulated in table above, gained either from Building Decree, and also based on some assumptions. Using table above will contribute to the measuring the reuse potential value of each property of each concrete element.

- Education:

The next assumption concerns the realization of an educational institution at a specific location near the city of Utrecht. The school institution has many different facilities, rooms, sport halls, lecture halls and the like. In the design phase, the structure of the school is designed to be made of concrete (figure 5.4).

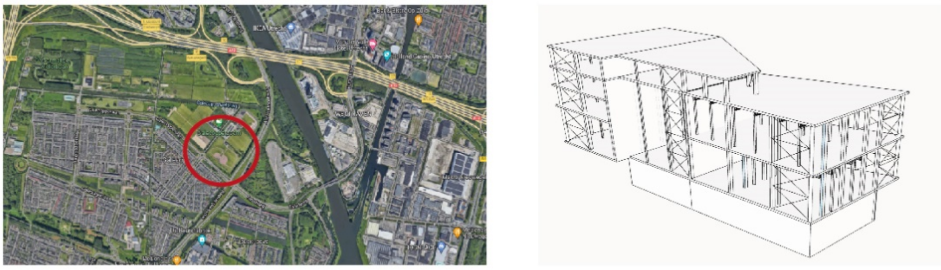


Figure 5.4: (Left) The location (Utrecht) and (Right) the structure of the educational institution from concrete (own illustration).

As can be seen in the figure above (right), the school 4 storeys including the ground floor, with a total height of 37 meters. Because the building system consists of two integrated parts, i.e. educational part and sports section, therefore the educational parts have different heights. The ground floor will be constructed from cast-in-situ concrete, while the other construction parts will be constructed from precast concrete. In order to measure the reuse potential factor of the existing elements from a functional performance perspective, the functional properties of the elements of the existing project 'The City Post' would be compared with the functional performance characteristics of the realized school. The functional performance criteria established in the Buildings Decree for an educational institution are tabulated below.

Table 5.4: Technical and functional performance requirements of concrete elements for an educational institution according to NEN-NORMS 2012 (own table).

EDUCATIONAL INSTITUTION

ELEMENTS						NEN-EN NORMS - FUNCTION (OFFICE)							
Application	Dimension (m)	Height (m)	Predesignated lifetime	Concrete class	Production	Abrasion resistance	Thermal characteristics				Fire resistance	Sound insulation	
							Thermal conductivity (W/m°K)	Specific heat (kJ/kg.K)	Thermal diffusivity (m³/m².s)	Thermal expansion (x10^-6per °C)		Minimal airborne sound insulation	maximum impact sound level
Ground fl	190x50	9	70 Year	C55/67	Cast-in-situ cc	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	5 - 13m - 90 m	≥ 43 dB	≤ 59 dE
Storey 1	190x50	11	70 Year	C50/60	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 43 dB	≤ 59 dE
Storey 2	190x50	10	70 Year	C50/60	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 43 dB	≤ 59 dE
storey 3	190x50	7	70 Year	C50/60	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 43 dB	≤ 59 dE
Roof	190x50		70 Year	C45/55	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 43 dB	≤ 59 dE

- Healthcare institutions:

As already explained, the existing concrete elements of 'The city post' can be reused for different purposes. Hence, this it can be a great challenge to provide information for the relevant user to understand whether those elements can be reused in a building system that functions as a healthcare center. Normally, a healthcare institution would be constructed strongly and also would be withstand fire and sound significantly. The healthcare institution is assumed to be located in Nijmegen.

Table 5.5: Technical and functional performance requirements of concrete elements for a healthcare institution according to NEN-NORMS 2012 (own table).

HEALTHCARE INSTITUTION

ELEMENTS						NEN-EN NORMS - FUNCTION (OFFICE)							
Application	Dimension (m)	Height (m)	Predesignated lifetime	Concrete class	Production	Abrasion resistance	Thermal characteristics				Fire resistance	Sound insulation	
							Thermal conductivity (W/m°K)	Specific heat (kJ/kg.K)	Thermal diffusivity (m^3/m^2.s)	Thermal expansion (x10^-6per °C)		Minimal airborne sound insulation	maximum impact sound level
Ground fl	350x90	6	70 Year	C70/85	Cast-in-situ co	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	5 - 13m - 90 m	≥ 48 dB	≤ 52 dE
Storey 1	350x90	3.5	70 Year	C60/75	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 48 dB	≤ 52 dE
Storey 2	200x50	3.5	70 Year	C60/75	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 48 dB	≤ 52 dE
storey 15	200x50	3.5	70 Year	C60/75	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 48 dB	≤ 52 dE
Roof	200x50		70 Year	C60/75	Prefab Concre	w/c ratio of 0.32 - 0.55	1.60 - 3.2	0.8 - 1.4	20 x 10^-6	7.0-12.0	>13m - 120 mi	≥ 48 dB	≤ 52 dE

The table above, shows different functional and technical requirements determined in Building Decree for the realization of a healthcare center. There are many advantages to use concrete as the main structure elements in a healthcare center. Applying concrete can largely contribute to the sound attenuation, sustainability, safety, high durability and minimum maintenance. The project is realized to have 15 storeys.

3- <u>Reuse of the existing elements in infrastructure (Pavement, bridge, tunnel):</u>

In order to maximize the reusability of the existing building elements, it is essential to find out which project the element can be linked to. It is therefore not always the intention to reuse the obtained element in construction industry. They can also be reused for infrastructural purposes such as reuse in bridges, tunnels, roads, and railways, as the infrastructural concrete elements do not require high strength, while they last longer compared to concrete used in building industry.

Concrete used in the infrastructure will be designed to last for a period of 50 to 100 years, in some cases this can be longer. The existing concrete elements from the project 'The City Post' can be reused for road or dam pavements (figure 5.5). This procedure, i.e. concrete pavement consists of concrete slabs placed over a fixed base and subsoil. Concrete pavements are broadly applied to support heavy loads and also provide long-lasting and durable solutions in airports, highways (roads), and bridge decks. In comparison with asphalt pavement, concrete pavement process may require less maintenance (Torgal et al., 2018).

Figure 5.5: Applying concrete in infrastructure projects in the Netherlands (Diemel & Fennis, 2018).

On the other hands, the functional performance requirements needed for a construction building is not required for pavement purposes. Concrete used in road pavements has usually been made of a mix of Portland cement, coarse aggregate, sand, and water, and in addition the concrete is mostly unreinforced. As already discussed, there are many different types of concrete strength classes, but the most typical used concrete compressive strength classes for highway (road) pavements are among 20 N/mm² and 40 N/mm². In some cases, it can a higher strength be used but this can lead to higher shrinkage and also higher costs.

It is assumed that the existing concrete elements from 'The City Post' are reused in an infrastructure project in the city of Delft. The project concerns the improvement of the bike path from TU Delft to the Central Station. It is estimated that the paving elements will last approximately 40 years.

5.1.3. Costs-related Findings from the Interviews

After measuring the reuse potential value from a functional point of view, it is needed to analyze and address the impacts of this estimation process on the reuse costs. Additionally, it is also possible to identify which stakeholder has an economic benefit/loss in the reuse process, as each cost is allocated to a specific stakeholder.

Furthermore, in order to gain insight into the costs of different activities in the deconstruction process, an interview would be held with the main actor in the deconstruction process, i.e. the contractor (demolition company). Therefore, two interviews have been conducted with two different demolition companies, to extract the necessary data and information from the practice (Complete transcripts of the interviews can also be found in Appendix A.4.3 and A.4.4). Given that the deconstruction process consists of a large number of activities, therefore it is needed to calculate those associated cost to understand whether the existing element has an economic reuse potential value. The obtained deconstruction and its associated costs from interviews is based namely on the procedures made in BPM. Both interviewees assessed and validated the BPM created for the deconstruction process. The procedure of deconstruction can sometimes be considered as the inversed procedure of the construction process. Deconstruction process for reuse consists of different activities. The costs incurred during the execution, transport and storage phases are referred to as dismantling costs.

Important remark from the interviews: There is definitely no fixed prices in the (de)construction and waste industry. All the costs are estimates and the reason is that for each project and element, costs vary significantly.

- ‘Prepare to disassemble’ phase:

Inspecting the elements/Inventory/Audit: This phase consists of different activities allocated to contractor (demolition company). The preparation for the deconstruction process is generally not very difficult. In this stage, the demolition company starts with inspecting the elements (visually/samples). By performing this activity, it is possible to understand which elements have the potential value for reuse from an expert perspective. This statement is exactly in accordance with the intention of interviewees, that the investigation (inspection) must be done first. Furthermore, according to the interviewee, the cost of performing an inventory or audit varies significantly, i.e. from €1,000 to €5,000, and it depends largely on many factors such as the number of the storey of the building. Nevertheless, it can be stated that an inventory of a building with 12-storey, can cost the contractor €250 per storey.

Planning: Making the deconstruction plan is the responsibility of the party carrying out the disassembling and is included in the budget of the total deconstruction cost.

Obtaining a permit: Moreover, the cost of obtaining a permit could be derived from the interviews. According to the contractors, obtaining a permit is not a difficult activity and can be requested from the municipality where in the building is registered. In order to deconstruct a building, it is necessary to request it as a demolish report (Sloopmelding in Dutch), and this can be obtained within four weeks.

The cost of obtaining a permit also varies and depends on several factors e.g. depends on the height of the building and where the building is located e.g. in a metropolitan. Still, it can be stated that it costs between €1,000 and €10,000.

- 'Execution of disassembly' phase:

Preparing the deconstruction site: At this stage, the contractor as the main actor is responsible for carrying out most of the activities including site preparation for deconstruction, soft-stripping, and etc. All these activities would be performed attentively which requires more labor and therefore extra cost for the contractor. According to the interviewees, site preparation is always included in the budget for construction or demolition, and the cost of demolition (deconstruction) is approximately 1 to 2% of the total share price. However, this percentage undoubtedly depends on the size of the deconstruction work. In other words, deconstruction of a high-rise building is more expensive than a small building.

Stripping: Furthermore, the stripping of the objects which are on top of the concrete layer is the next procedure when deconstructing a building. This process also has estimated costs and is calculated based on the working hour of the labor. In other words, it is labor-intensive work and the cost of stripping is about 45 €/m². On the other hand, the stripping of those objects will usually be done when the client decides to renovate the building. But in the case of reuse of the elements, it costs 1.5 more. (45 x 1.5=67.5 Euro).

Execution of the disassembly processes: In the next stage, the demolition company will start removing the concrete top layer, which will cost approximately 10 €/m². Although these costs, like other costs, vary largely and it could be 15 €/m² if more were to be removed. According to the contractors, estimating the costs for the removal of Hollow Core Slabs (HCS) is very difficult, but costs about 30 €/m. Removing the HCS floors is not a tough job and there is no need to cut those elements. Furthermore, the cost of removing other elements such as façade beams, beams, columns, walls is difficult to determine and it is very specific and depends on various factors. But it can be estimated close to these costs: - Remove façade beams: estimated between 15 to 40 €/m² - Remove beams: estimated between 20 to 35 €/m² - Remove columns: estimated between 20 to 35 €/m² - Remove walls: estimated between 20 to 40 €/m².

Transport the element: This process is necessary when the client cannot find a new buyer, or even decides to store the elements in a storage yard. So, one contractor explained that this process is not the responsibility of a demolition company and that the client is responsible for transporting the elements. One the other hand, the other contractor mentioned that their company transfer also the elements, but this process is expensive. Furthermore, one of the interviewee described that the cost of transport depends on the distances between e.g. point A and B. Hence, the cost of transporting an element from point A (which can be a deconstruction site) to point B (storage yard) is about 95 €/hour.

- 'Handling the elements' phase:

Repair/Improvement process: This phase also consists of various processes, but the most important process in this research is the execution of the quality performance test. After performing this process, it can be understood whether the element has the reuse potential value in terms of its functionality. So, this process indicates whether the elements need to be improved or not. According to both contractors, the improvement of existing elements will be done by a treatment company. However, one of the contractor verified the cost of improvement already gleaned from the other sources. According to the interviewee, the cost of improving the existing elements can be approximately 90 €/hour. Both contractors pointed out that this process is neither the favorable process for a demolition company nor for other parties.

Modification cost: The use of the existing elements in other buildings with different function, requires their modification and adjustment. This process thus depends on the function of newly designed building project. The contractors mentioned that the modification cost is very project specific and depends on many factors. The demolition companies usually calculate the modification cost as; e.g. a beam that costs €9,000 and is 3-meter-long, then the modification cost can be about €3,000 per linear meter. Although, the costs verified by both contractors are as follows: modification of beam is about 179 €/element, column 135 €/element, wall 311 €/element, and HCS 236 €/element.

Storage of the elements: In the case that the contractor, or the new buyer decides to store the elements (before or after improvement), then this will be at a cost to each of the parties. The contractor pointed out that the storage cost depends on the period of time required to store the elements and also on the amount of space that will be needed. However, the storage cost can be about 25 €/m²/year. In other words, renting 1,000 m² of storage space for a year costs 25,000 €/year. According to both interviewees, the storage of the elements is not an economically desirable activity, if the elements can be reused directly after disassembling. Although, this depends largely on finding a new buyer.

Salvage value: The building elements recovered from deconstruction process have an economic value, and according to the interviewee this value will be twice as expensive as new. However, the salvage value depends highly on the quality of the elements, i.e. before or after improvement.

5.1.4. Functioning (Instruction) of the Steps Needed for Import Sheet in the CCE Information System Based on the Case

As explained in the previous chapter, part 4.5., there are some steps need to be fulfilled in order to satisfy the functionality of import sheet realized for the CCE Information System. The developed CCE Information System consists of three main part namely an import sheet, an analyzing and processing sheet and a dashboard, serving as a tool with the aim of optimizing the reusability. The functionality of each part of CCE Information System is based on data and information gained from real cases.

In this study, 'The City Post' project is used as an aged project which was at the EoL phase in order to be renovated. The step 1.1 concerns the selection of an outdated project and also some newly designed construction projects with different functions. However, newly projects have been assumed in this research. Step 1.2 is about collecting different technical and functional data for both an aged and new designed element. In addition, the cost-related data gained from interviews need to be implemented in other part of the import sheet. In the developed import sheet in Excel program, there are different orange fields realized to be filled in.

It has been attempted to develop a tool which can be function either manually by an operator (CCE Information System developer) or automatically if all the information of the projects, aged and newly designed, are connected to a central data server. All the functioning and instruction steps (steps 1.1 to 1.3) regarding the functionality of the import sheet have been described in more details in Appendix A.4.8.

5.2. Analysis and Processing Phase (Functional Performances and Costs)

To measure the reuse potential factor of each element in terms of functionality, the discussed functional performances of concrete elements (strength, thermal characteristics, fire resistance and etc.) of both the element of the existing building and the new design building would be estimated. However, the functional performance requirements for newly designed elements could be achieved from the Building Decree, which lays down the requirements for new buildings with different functions. (see tables 5.2 to 5.5). Therefore, in this step, it is just required to estimate the functional performance properties of the existing project 'The City Post' to further measure the reuse potential value.

5.2.1. Estimating of the Functional Performance Characteristics of the Existing Elements

Based on the technical data and information achieved from the constructive and structural drawings of the project 'The City Post' in Zwolle, the discussed functional performances of concrete elements will be estimated (see also chapter 3, part 3.3.1). Investigating whether the reuse potential value of the existing elements is of sufficient quality to be reused for other purposes can play a major role in measuring of the reuse potential factor in different situations. Consequently, the reuse costs can be calculated which include different associated costs such as improvement or transport cost that affect the decision-making regarding the existing elements.

- Strength of the existing elements:

The strength of concrete depends on many factors, but one of the most factors that appropriately influence the strength of concrete is the w/c ratio. There is an inverse relationship between the strength of concrete and the w/c ratio. Moreover, the strength of concrete will increase by diminishing the water/cement ratio and conversely, the strength decreases by increasing the water/cement ratio. Hence, decrease the W/C ratio, the higher the strength of concrete.

Furthermore, the compressive strength class of the existing concrete elements, can indicates either the mean cubic compressive strength (cylinder) or characteristics cube compressive strength in N/mm². It was also explained in the literature that the strength of concrete will increase over time, as it is a nonlinear curve.

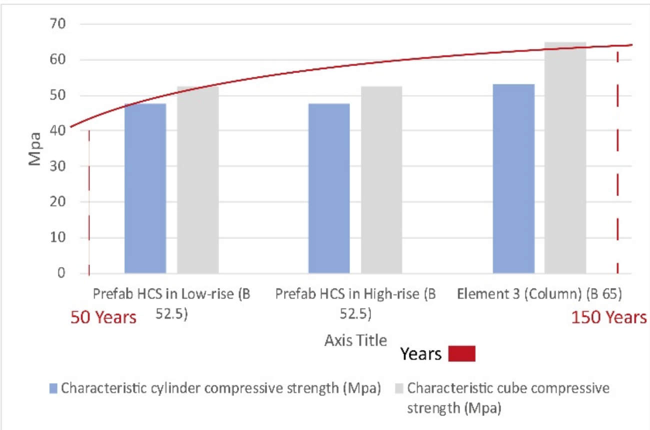


Figure 5.6: Estimating the strength potential of the existing elements of 'The City Post' (own diagram).

Figure 5.6 above shows that the strength of concrete elements (floor, column) extracted from project 'The City Post' can remain its strength if no environmental damages affects the strength of the element and its substances negatively. It can also be seen that strength increases over time with a moderate gradient.

- Durability/lifetime:

The City Post in Zwolle is constructed in 1972, and is about 50 years from the lifetime of concrete elements used in the building. Concrete can be last for a long time, i.e. concrete can last for a maximum of 200 years. Therefore, by assuming the lifetime threshold for concrete elements at 150 years, then it can be concluded that the existing elements have a ˜ 0.67 % durability potential.

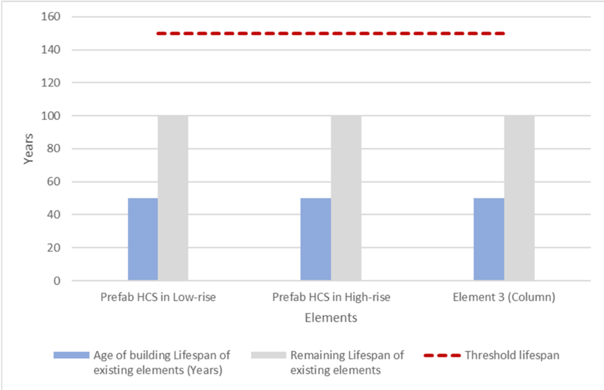


Figure 5.7: Estimating the lifespan potential of the existing elements of 'The City Post' (own diagram).

If the design lifetime of the new building project (in any cases; transformation, building with different functions and also infrastructure) pass the threshold, then it is impossible to reuse the element. Thus, the remaining of functional lifetime of the existing elements of the project 'The City Post' is approximately 100 years, and the predesignated functional lifespan of the new structure must be between this domain.

- Abrasion resistance:

Abrasion resistance of concrete is one of the functional performance properties that has a direct relationship to the water/cement ratio used in the element. Concrete elements made of substances with a high water/cement ratio at or near the surface or even has been cured insufficiently would, of course, wear down easily.

Figure 5.8: Estimating the abrasion resistance potential of the existing elements of 'The City Post' based on the w/c ratio (own diagram).

Furthermore, a low to moderate water/cement (w/c) ratio reduces free water in concrete. This will improve the compactness of the concrete and reduces the permeability of concrete, which consequently improves the strength of concrete and thus the wear/abrasion resistance of that. Thus, if the w/c ratio of existing elements from The City Post lies between the lower and upper bound of 0.32 and 0.55, then it can be concluded that the element has an appropriate abrasion resistance.

So, the columns with a w/c ratio of 0.40 can be considered to have an appropriate abrasion in compare with the floors, as this ratio is near to 0.32, and less w/c ratio results a better abrasion resistance. Nevertheless, the abrasion resistance of the concrete elements can be considered significant as the w/c ratio lies between lower and upper bound.

- Thermal characteristics:

In order to reuse the existing concrete elements in buildings with different functions, it is required to estimate the thermal properties of them. Since the thermal characteristics requirements are established in Building Decree and therefore the existing elements need to meet those requirements. As the same as other functional performances of concrete, there are a direct relationship between different thermal features of the element and different properties of the substance (concrete) used in it. Thermal conductivity and thermal expansion can be measured by knowing the amount of cement used in element. On the other hand, thermal diffusivity and specific heat can be estimated by knowing the compressive strength and w/c ratio, respectively.

Furthermore, the aforementioned thermal characteristics have been tested for different concrete samples in the laboratory and the results achieved is noticed in the research of Talebi et al., 2020. Thus, using the technical data from the structural drawing and implementing them in the test carried out in literature for different types of concrete can estimate different thermal properties. In addition, the estimated thermal characteristics must be between the lower and upper bound of those properties in the diagrams.

Table 5.6: (Above) Thermal conductivity and the amount of cement. (Below) Thermal diffusivity and compressive strength (own table).

Strength class	Thermal conductivity (W/m°K)	Amount of cement (kg/m³)	Lower bound	Upper bound
Prefab HCS in Low-rise	2.35 (W/m°K)	446 (kg/m³)	1.6 (W/m°K)	3.2 (W/m°K)
Prefab HCS in High-rise	2.35 (W/m°K)	446 (kg/m³)	1.6 (W/m°K)	3.2 (W/m°K)
Element 3 (Column)	1.95 (W/m°K)	425 (kg/m³)	1.6 (W/m°K)	3.2 (W/m°K)

Strength class	Thermal conductivity (W/m°K)	Compressive strength (150-mm-diameter)(MPa)	Upper bound	Thermal diffusivity (x10^-6 m²/s)
Prefab HCS in Low-rise	2.35 (W/m°K)	52.5 (MPa)	20.0 x10^-6 m²/s)	1.1 (x10^-6 m²/s)
Prefab HCS in High-rise	2.35 (W/m°K)	52.5 (MPa)	20.0 x10^-6 m²/s)	1.1 (x10^-6 m²/s)
Element 3 (Column)	1.95 (W/m°K)	65 (MPa)	20.0 x10^-6 m²/s)	1.19 (x10^-6 m²/s)

Tables above shows the result of estimating different thermal properties of the existing elements in the project 'The City Post'. Thermal conductivity of the existing elements has been estimated by using and comparing to design value (Figure A´´.2.1 and Table A´.2.7 in Appendix A.2.1). Subsequently, based on the estimated thermal conductivity, the thermal diffusivity could be substantiated.

Table 5.7: (Above) Specific heat and w/c ratio. (Below) Thermal expansion and the amount of cement (own table).

Strength class	Specific heat (kJ/kg.K)	w/c ratio	Lower bound (kJ/kg.K)	Upper bound (kJ/kg.K)
Prefab HCS in Low-rise	1.01 (kJ/kg.K)	0.46	0.8 (kJ/kg.K)	1.4 (kJ/kg.K)
Prefab HCS in High-rise	1.01 (kJ/kg.K)	0.46	0.8 (kJ/kg.K)	1.4 (kJ/kg.K)
Element 3 (Column)	0.96 (kJ/kg.K)	0.4	0.8 (kJ/kg.K)	1.4 (kJ/kg.K)

Strength class	Thermal expansion ×10^−6/◦C	Amount of cement (kg/m³)	Lower bound ×10^−6/◦C	Upper bound ×10^−6/◦C
Prefab HCS in Low-rise	8.4 ×10^−6/◦C	446 (kg/m³)	7.0 ×10^−6/◦C	12.0 ×10^−6/◦C
Prefab HCS in High-rise	8.4 ×10^−6/◦C	446 (kg/m³)	7.0 ×10^−6/◦C	12.0 ×10^−6/◦C
Element 3 (Column)	8.6 ×10^−6/◦C	425 (kg/m³)	7.0 ×10^−6/◦C	12.0 ×10^−6/◦C

Specific heat capacity of the existing elements has been estimated by comparing to the design value in the literature, as this capacity depends largely on the w/c ratio of the material used in the element.

Ultimately, the thermal expansion is estimated in comparison with the amount of cement used in the concrete elements.

- Fire resistance:

One of the most important functional performance characteristics of concrete elements is their ability to resist fire. The fire resistance of concrete building products is rated/expressed by the number of hours of effective fire resistance, and they varying from 30 min to 120 min for different type of building with different function. By knowing the thickness of the existing elements the fire resistance of them can be estimated. Prefabricated concrete floors and walls with a minimum thickness of 80 mm meet the determined fire resistance requirement of 60 minutes. With a thickness of 100 or 120 mm, the fire resistance will be increased to 90 and 120 minutes. According to the Dutch Building Decree 2012, the fire resistance requirement of the concrete floor elements is 90 minutes (for non-residential building lower than 25 meters high).

Table 5.8: Estimating the fire resistance potential of the existing elements of 'The City Post' based on the thickness of the elements (own table).

Strength class	Thickness (mm)	Fire resistance rating (min)
Prefab HCS in Low-rise	210 mm	>120 min (240 min)
Prefab HCS in High-rise	210 mm	>120 min (240 min)
Element 3 (Column)	420 mm	>120 min (240 min)

- Sound insulation:

Sound insulation was the other functional performance properties that in this research was analyzed. Concrete elements can be considered as an appropriate insulator product which, because of their high density, are able to reflect up to 99% of sound energy. The sound insulation of concrete elements largely depends on the density of its materials used in it. Concrete is commonly considered as a preferred building product for blocking sound transmitted into a space because of its excellent and great performance as sound-reflecting substances. However, this element extremely limited in terms of its sound absorbing ability.

Table 5.9: Estimating the sound insulation ability of the existing elements of 'The City Post' based on the density of the elements (own table).

Strength class	Density	Sound insulation (dB)
Prefab HCS in Low-rise	2360 kg/m3	30-55 dB
Prefab HCS in High-rise	2360 kg/m3	30-55 dB

As can be seen in the table above, the existing floor and column elements in the project have 2360 and 2450 kg/m³ density respectively, however, how denser the concrete how better the sound reflection. Thus, if concrete be denser or heavier, then the sound insulation rate that can be detected will be higher.

As the functional performance properties of new designed structures is tabulated before (obtained from NEN-NORMS and assumptions), then the reuse potential factor can be measured from a functional points of view.

5.2.2. Measuring the Reuse Potential Value from a Functional Perspective for Each Situation

To measure the reuse potential factor of each element in terms of functionality, the estimated functional performances of the existing concrete elements (strength, thermal characteristics, fire resistance and etc.) will compare to the functional performances of new design building structures. In other words, the measurement of the RP factor is based on the ratio of existing and new functional properties. Therefore, it is substantial to measure the remain value of functionality of each element in the assumed situations.

- <u>Method</u>:

To find reuse potential value of each functional performance characteristics of the existing elements in different situations, it is used from the finding the percentage of a number within an interval method. In other words, for example, to find the reuse potential value (factor) of thermal conductivity of HSC floor in the existing building for transformation situation it would the lower and upper bound derived from NEN-NORM be subtracted, then the estimated reuse value found for the existing element would be subtracted from the lower bound and then the result would be divided to the results of the range of lower and upper bound.

$$range = max - min \qquad so; \quad range = upper\ bound - lower\ bound$$

$$corrected\ Start\ Value = input - min \qquad so; = Estimated\ RP\ value - lower\ bound$$

$$percentage = (corrected\ Start\ Value * 100)\ /\ range$$

- (1) Reuse potential factor of functional performances in transformation situation:

The functional performance properties of both the existing project and the new transformation structure has been analyzed. The elements of the transformation project need to meet the new requirements provided in the Building Decree. Therefore, the reuse potential value of each functional performance would be indicated in this (transformation) situation.

Table 5.10: The reuse potential value of the existing elements that are reused in a transformation situation (own table).

Transformation									
	Strength of concrete	**Durability/lifetime**	**Abrasion resistance**	**Thermal characteristics**				**Fire resistance**	**Sound insulation**
				Thermal conductivity	**Specific heat**	**Thermal diffusivity**	**Thermal expansion**		
Prefab HCS in Low-rise	100%	67%	60%	47%	35%	55%	28%	100%	76%
Prefab HCS in High-rise	100%	67%	60%	47%	35%	55%	28%	100%	76%
Element 3 (Column)	100%	67%	34%	22%	27%	59%	32%	100%	

All the reuse potential value for each functional performance properties in transformation situation is tabulated above. As an example, measuring the reuse potential factor of thermal conductivity of existing element in transformation situation is as follows;

$$range = 3.2 - 1.6 = 1.6$$

$$corrected\ Start\ Value = input - min = 2.35 - 1.6 = 0.75$$

$$percentage = (corrected\ Start\ Value * 100)\ /\ range = 0.75 * 100/1.6 = 46.87\%$$

Furthermore, this means that the existing elements extracted from the project 'The City Post, have a reuse remain value of 47% in terms of thermal conductivity, and this factor can contribute to the following steps to understand whether the elements is also profitable from an economic point of view.

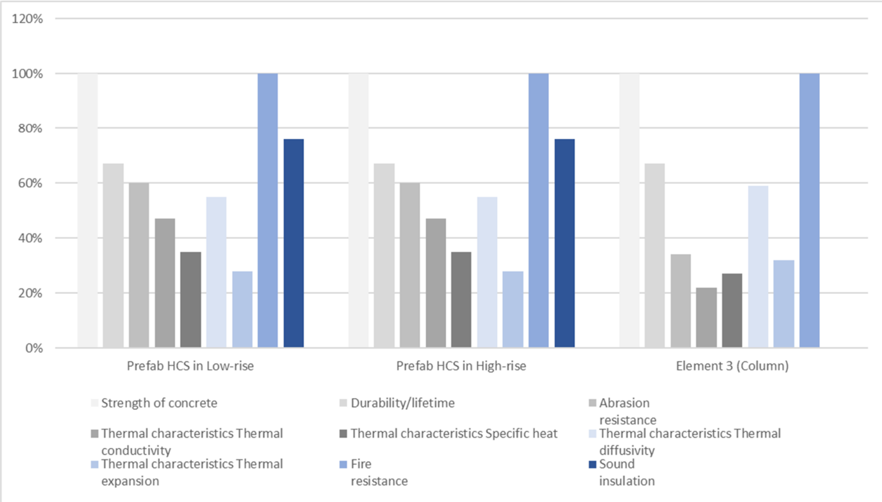


Figure 5.9: Reuse potential factor of different functional performance properties of the existing elements reused in transformation situation (own diagram).

- (2) Reuse potential factor of functional performances in buildings with different functions:

In order to understand to what extent the existing elements have sufficient reuse potential value from a functional perspective, the functional remain value would be measured in different building with various functions. This approach can significantly increase the likelihood of reusability by providing the opportunity to reuse the existing elements for different purposes.

- Sport/Educational institution/Healthcare institution:

As already explained, the existing project is considered as a utility building, therefore its components may also be suitable for these building systems. Sports complexes often consist of large components with large dimensions. This can maximize the reuse chance as the modification process will not be needed. The estimated reuse potential value of the existing elements would be compared to the requirements of an assumed sport complex.

Table 5.11: The reuse potential value of the existing elements that are reused in a sport building (own table).

SPORT									
	Strength of concrete	**Durability/lifetime**	**Abrasion resistance**	**Thermal characteristics**				**Fire resistance**	**Sound insulation**
				Thermal conductivity	**Specific heat**	**Thermal diffusivity**	**Thermal expansion**		
Prefab HCS in Low-rise	87%	67%	60%	47%	35%	55%	28%	100%	100%
Prefab HCS in High-rise	87%	67%	60%	47%	35%	55%	28%	100%	100%
Element 3 (Column)	97%	67%	34%	22%	27%	59%	32%	100%	

Moreover, the remain ruse potential of existing elements is measured for the sport scenario based on the estimated reuse potential value that was estimated before and also by application of the aforementioned calculation method. The above approach has also been applied for the other two scenarios (situations), namely educational and healthcare institutions which have different functional performance requirements according to NEN-NORMS (Dutch Building Decree). Below, the reuse potential factor for each discussed functional performance characteristics of HCS floor and concrete columns used in the project 'The City Post'.

Table 5.12: The reuse potential value of the existing elements that are reused in (Above) an educational institution and (Below) in a healthcare institution (own tables).

EDUCATIONAL INSTITUTION									
	Strength of concrete	Durability/lifetime	Abrasion resistance	Thermal characteristics				Fire resistance	Sound insulation
				Thermal conductivity	Specific heat	Thermal diffusivity	Thermal expansion		
Prefab HCS in Low-rise	87%	67%	60%	47%	35%	55%	28%	100%	76%
Prefab HCS in High-rise	87%	67%	60%	47%	35%	55%	28%	100%	76%
Element 3 (Column)	97%	67%	34%	22%	27%	59%	32%	100%	

HEALTHCARE INSTITUTION									
	Strength of concrete	Durability/lifetime	Abrasion resistance	Thermal characteristics				Fire resistance	Sound insulation
				Thermal conductivity	Specific heat	Thermal diffusivity	Thermal expansion		
Prefab HCS in Low-rise	70%	67%	60%	47%	35%	55%	28%	100%	76%
Prefab HCS in High-rise	70%	67%	60%	47%	35%	55%	28%	100%	76%
Element 3 (Column)	86%	67%	34%	22%	27%	59%	32%	100%	

Furthermore, to demonstrate the measured reuse potential values of different functional performances, (i.e. strength, durability, abrasion resistance, thermal ability, fire resistance and also sound insulation) of the existing concrete elements, it has been tried to show them by diagrams (see figure 5.10).

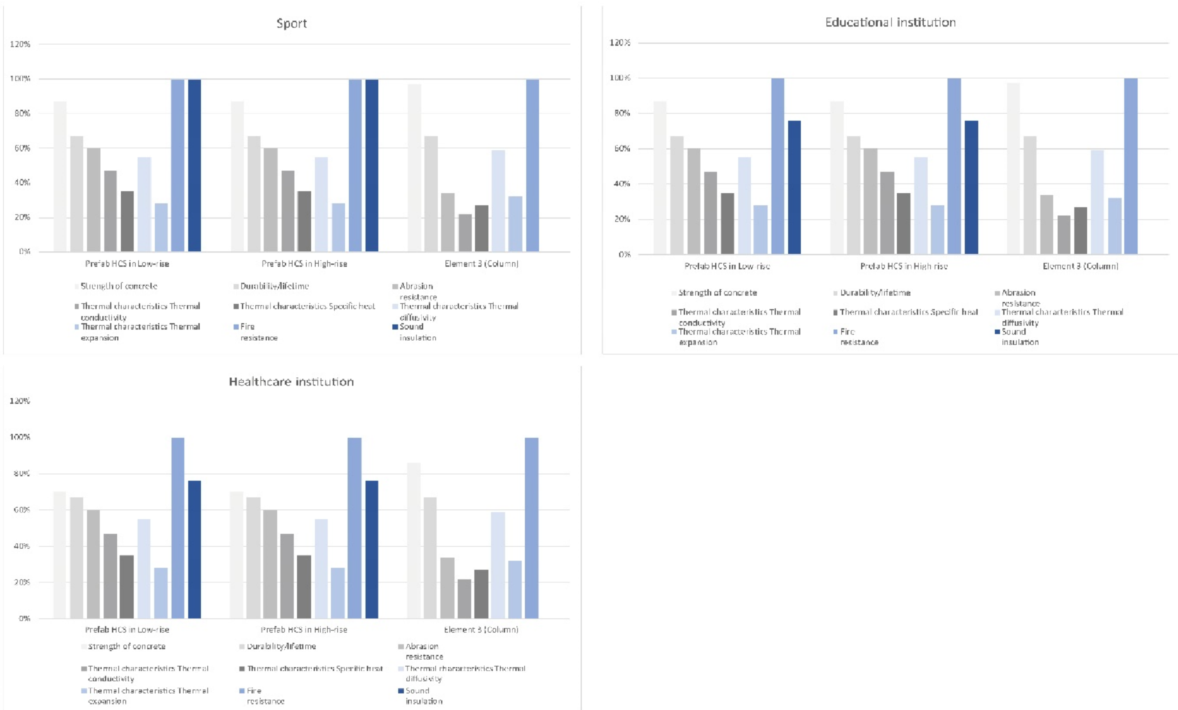


Figure 5.10: Reuse potential factor of different functional performance properties of the existing elements reused in (Left above) a sport situation, (Right above) an educational institution, (Left below) in a healthcare building (own diagrams).

- (3) Reuse potential factor of functional performances in infrastructure:

One of the most suitable situation that can maximize the reusability of the existing elements extracted from the project is the realization of reuse in an infrastructure project. As mentioned earlier, the elements can be easily reused for the pavement of a bike path or even in highways (roads) that do not require sound insulation, thermal capacity or other functional requirements set for the building industry. High quality, durable, attractive hard standings can be some advantages of using block paving or in-situ concrete in infrastructure projects.

The only two functional performances analyzed in this research, namely strength and abrasion resistance of concrete, play major role in determination of the reusability of existing elements in infrastructure. Generally, concrete with a compressive strength class between 20 and 40 N/mm² will be used for road pavements, however, it is also possible to use with a higher strength class. Concrete for road pavement last about 40 to 50 years. The w/c ratio used in the most used concrete for road pavement is about 0.40 to 0.52.

Table 5.13: The reuse potential value of the existing elements that can be reused in an infrastructure project (own table).

INFRASTRUCTURE			
	Strength of concrete	**Durability/lifetime**	**Abrasion resistance**
Prefab HCS in Low-rise	100%	67%	56%
Prefab HCS in High-rise	100%	67%	56%

Some functional performance properties of the existing elements are important for designing a new building structure, while those features are less important in other cases. Therefore, knowing the level of quality of each characteristic for the right purposes can optimize the reusability of that element due to the relationship between the functional properties and the function of the system.

5.2.3. Cost Analysis, Calculating the Reuse Costs and Associated Costs affected by different Scenarios

One of the reasons why deconstruction and thus reuse of structural concrete elements are not common solutions to this day, is the uncertainty about the extra level of costs. In addition, this research also focused on the cost-related issues of stakeholders in the process of deconstruction for reuse. Therefore, it is substantial to analyze the reuse and other associated costs in the deconstruction process. It is already being discussed which costs are included in the process. Moreover, the quality performance test phase has been carried out for the existing elements of the project, namely 'The City Post' in Zwolle.

Furthermore, it is necessary to calculate the reuse costs, according to the steps of BPM and the approaches realized for the developed CCE Information System. In this way, the contractor (demolition company) as a key stakeholder in the deconstruction process sees whether the reuse process can be profitable or not in different situations. Despite most of the associated costs in the deconstruction process have been obtained from interviews, some estimations have been made as the calculation of the deconstruction costs is not a known procedure.

In order to calculate the reuse cost, the realized circumstances and situations in which the existing elements can be reused would also be applied. Because assuming those situations also create other scenarios which significantly affect the reuse cost. In the transformation situation, for example, there is no need for storage or transport, which can be more beneficial for the client. On the other hand, the sports complex which has been realized to be constructed in the city of Leiden, takes the transport cost into account. Therefore, all three situations will be treated with different scenarios to understand which of them can be the most profitable for the contractor. Table 5.14 shows some general information about the existing building and its elements needed for the reuse cost calculation.

Remark: The reuse cost calculations can be found in Appendix A.4.5.

Table 5.14: General and additional information of the project 'The City Post' (own table).

Additional information of the existing building	
Project	The City Post
Location	Zwolle
Storey	Low-rise (5), High-rise (11)-Total: 16
Gross floor area	Low-rise (each storey has area of 1,555 m² x5=7,776 m²) High-rise (each storey has area of 777 m² x11=8,554 m²)
HCS dimension	Low-rise (7.2x7.2), High-rise (7.2x18)
Total number of HCS	Low-rise (72), High-rise (116)-Total: 188
Total number of Columns	Low-rise (each storey has 24x11)=Total: 264 High-rise (each storey has 36x5)=Total: 180

- (1) Transformation (Renovation):

In this situation, the existing elements do not need to be modified, transported or stored in a storage yard and this has an appropriate impact on the reuse costs. So, the large expenditure costs will be allocated to the deconstruction costs. However, the elements would be improved in terms of their thermal properties which have been substantiated from the quality performance test. But this can undoubtedly be done on-site, since the transformation process does not require disassembly of the elements. Therefore, different activates that would be performed in the renovation process of the existing project can be summarized as;

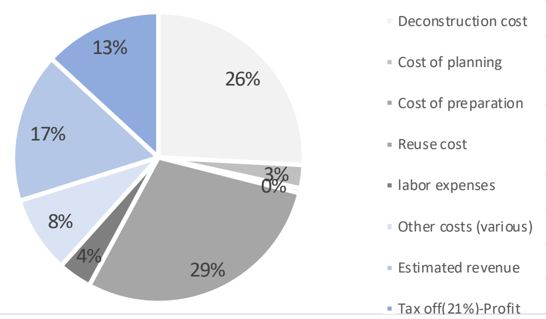
- The contractor (demolition company) would carry out the inspection, inventory and audit of the existing building elements.
- The deconstruction would be performed according to a beforehand predesignated planning.
- The contractor needs to obtain a permit for deconstructing the project.
- It is also required to prepare the deconstruction site
- Stripping of the objects is the next activity.
- In the execution of disassembly phase, it is just needed to remove the concrete topping, remove the façade beams, and remove walls.
- Thereafter, the elements would be improved in terms of their thermal properties (on-site).

There have been some assumptions made in the transformation scenario;

i) It is assumed that a labor works 8 hours a day. A Construction Worker in the Netherlands earns an average of € 2,375 gross per month.
ii) Improvement process is assumed to be done within 4 months.
iii) Deconstruction process is assumed to be performed within 1 year.

Table 5.15: Different calculated costs used in the first scenario 'transformation' (own table and diagram).

Transformation	Costs (Euro)
Deconstruction cost	1,965,185
Cost of planning	196,518
Cost of preparation	39,903
Reuse cost	2,201,606
labor expenses	285,000
Other costs (various)	650,000
Estimated revenue	€ 1,266,606
Tax off(21%)-Profit	1,000,618



In this situation, the transport and modification processes did not affect the reuse cost, as the elements will still be reused. Since the project is still under the deconstruction process, therefore, some assumptions have been made regarding the labor cost and the duration of the process. This scenario can be seen as the most favorable and affordable situation for the contractor.

Remark: In this situation (renovation), the reuse costs for each element cannot be calculated as the elements are reused on-site and no new elements are used.

- (2) Sport/Educational/Healthcare:

In order to measure the RP factor from an economic perspective, it is needed to calculate the reuse cost for a specific element of an existing building, namely a HCS of the project 'The City Post'. The cost of a new product will also be required. This can contribute to the measurement of the RP factor in the other assumed situations (sports complex, education, healthcare and infrastructure).

- *Sports complex*:

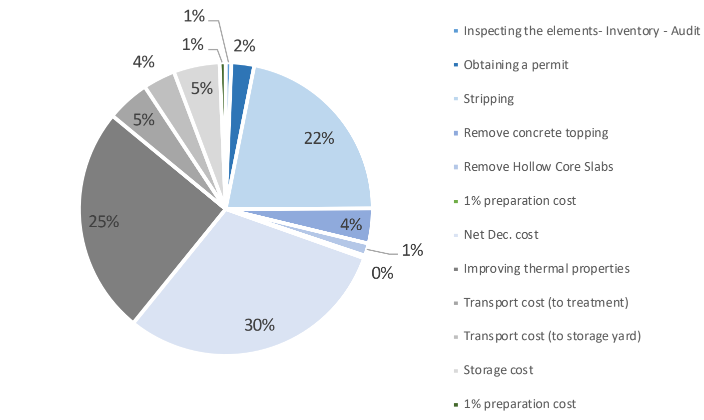
The sports complex is located near to the city of Zwolle, which has a distance of 15 km from the deconstruction site. It would be mentioned that the HCS floor elements will be analyzed and measured in this research. As mentioned in the previous paragraph, first the reuse cot for just an HCS element is calculated to measure the reuse potential factor. In order to calculate the reuse cost for an element in sports complex situation, it would some assumptions be done;

i) Assumption: Reuse cost of one HCS floor from the low-rise part (7,200x18,000mm).
ii) Assumption: The distances between Zwolle (Dec. site) to other destinations (the new construction sites) are substantiated from Google maps.
iii) Assumption: For all scenarios, it is assumed that the treatment company is 10 km away from the deconstruction site. Also, a distance of 10 km between the treatment company and the new construction site is assumed.
iv) Assumption: The storage yard is assumed to be 15 km far from the treatment company (for all the scenarios). It is also assumed that the elements would be stored 2 months after deconstruction/improvement/modification process, for 1,000 m². (It costs less than 1 euro/m²/day).
v) Assumption: Improvement process is assumed to be completed within 2 weeks for only one HCS element.

There are two main reasons why the treatment company and the storage yard close to the demolition site were chosen, (a) the demolition company which performs the disassembling process is located in Zwolle, and (b) the transport cost is relatively expensive. Therefore, this can affect the reuse value negatively.

Table 5.16: Calculating the Dec. and reuse cost of an HCS element in an assumed scenario (sports complex) (own table and diagram).

Reuse cost of one HCS element	Costs (Euro)
Inspecting the elements- Inventory - Audit	250
Obtaining a permit	1,000
Stripping	8,748
Remove concrete topping	1,555
Remove Hollow Core Slabs	540
1% preparation cost	120
Net Dec. cost	€ 12,210
Improving thermal properties	10,080
Transport cost (to treatment)	1,900
Transport cost (to storage yard)	1,425
Storage cost	2,040
1% preparation cost	265
Net Reuse cost	26,803



In addition, to calculate the reuse cost of an HCS element, the deconstruction costs must first be calculated. Most of the costs used in the calculation process was gained from the interviews. But in order to measure the reuse cost, the element must be in a real or assumed situation. Therefore, the deconstruction cost resulted approximately €12,210 followed by the reuse cost of €26,803.

It can be seen that the highest percentage in the reuse process is allocated to the improvement of the element and thereafter to the stripping process. These two processes can therefore be regarded as the most important limitations in the reuse process as yet.

Measuring the reuse potential value for each situation requires the cost of an HCS element of the same dimension, as the reuse potential factor will be measured by a proportion of reuse cost and new costs. Therefore, a logical assumption has been made for estimating a Hollow Core Slab floor of 210 mm thickness. The cost for a new HCS floor can be estimated as approx. 70 €/m². So cost of a newly manufactured element can be approx. 9,100 Euro.

Consequently, the reuse cost for all the HCS element of the 'City Post' project can be calculated, since the total number of HCS floor is 188. The reuse costs can be estimated as 7,482,850 Euro.

By taking into account the 50% and 100% of the salvage value (the cost of a recovered element is twice more expensive than the new one=38,880 Euro), then reuse cost come out as; 3,654,720 and 7,309,440 Euro respectively.

- *Educational institution*:

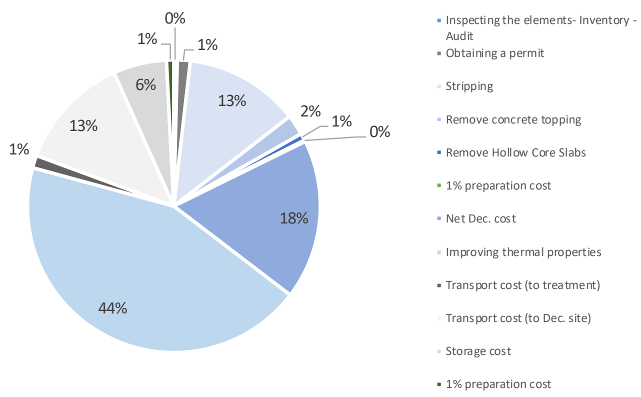
The educational institution is located in the city of Utrecht with a distance of 92 km from the project site, Zwolle. The same assumptions have been considered for this situation. The only differences are;

i) The elements will be stored for 2 months.
ii) The element would be improved from three functional performance properties.
iii) The distance between the Dec. point and new site point increase largely.

The quality performance test of the existing element which can be reused in a building systems like an educational institution showed that the elements would be improved in terms of their thermal expansion, conductivity and specific heat. It is optionally to improve the sound insulation as the element can still fulfill its sound insulation functions. One of the advantages of reusing an HCS floor element in utilities building like educational and healthcare institutions is that those building systems need elements with large dimensions.

Table 5.17: Calculating the Dec. and reuse cost of an HCS element in an assumed scenario (Educational institution) (own table and diagram).

Reuse cost of one HCS element	Costs (Euro)
Inspecting the elements- Inventory - Audit	250
Obtaining a permit	1,000
Stripping	8,748
Remove concrete topping	1,555
Remove Hollow Core Slabs	540
1% preparation cost	120
Net Dec. cost	€ 12,210
Improving thermal properties	30,240
Transport cost (to treatment)	950
Transport cost (to Dec. site)	8,740
Storage cost	4,080
1% preparation cost	551
Net Reuse cost	55,654



In this scenario, the Dec. cost is also calculated and the reuse cost has been increased with a very high percentage. However, the highest percentage of expenditure cost is allocated to the improvement process, i.e. 44%. It can be seen that the reuse cost for just an HCS element come out approximately, 55,654 Euro. This cost will increase for all the floor components to 13,613,546 Euro, without taking into account the salvage value.

- <u>*Healthcare institution*</u>:

The healthcare institution is located in the city of Nijmegen with a distance of approximately 89 km from Zwolle. In this scenario, the Dec. and reuse cost is also calculated with the same approach and assumptions as the previous scenarios. However, the only changed factor in comparison with educational situation is the distance between the Dec. site and new project site, and also in terms of functional performance properties improvement. The reuse cost for just an HCS element in this situation is estimated as 46,144 Euro and the reuse cost for all the HCS element without taking into account the salvage value is about 11,611,120 Euro. The reuse cost will be optimized by taking the 50% or 100% of salvage value into consideration, but the contractor still make loss in the reuse process.

- (3) Infrastructure (bike path pavement):

The bike path pavement project would be carried out in the city of Delft. Delft has a distance of 155 km from the city of Zwolle. The only factor that affect the reuse cost significantly is the transport cost as the distance between the deconstruction project (Zwolle) and delft is too much. The reuse cost by taking into consideration of 155 km distance between two points come out as; 26,935 Euro. On the other hand, ignoring the transport cost reduces the reuse cost remarkably; 12,210 Euro.

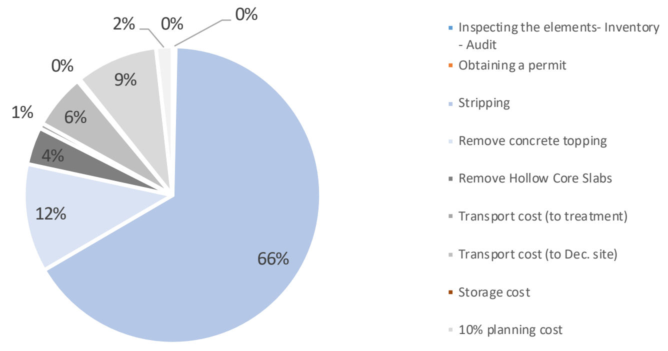
This cost is calculated without taking into account the

This scenario can be considered as the favorable situation for the contractor, as it is not needed to improve or repair the element. The transport cost and maybe the storage cost can affect the reuse cost for the contractor. While, by subtracting the salvage value from the total reuse cost the contractor can benefit from the reuse process. By assuming that;

i) The elements need to be stored 4 months after disassembly process in a space of 1,000m².
ii) It would 10 trucks be needed to transport all the elements to the new construction site.

Table 5.18: Calculating the reuse cost of HCS elements in an assumed scenario (Bike path pavement) (own table and diagram).

Reuse cost of HCS element in Infra	Costs (Euro)
Inspecting the elements- Inventory - Audit	4,000
Obtaining a permit	5,000
Stripping	1,644,570
Remove concrete topping	292,368
Remove Hollow Core Slabs	101,520
Transport cost (to treatment)	14,250
Transport cost (to Dec. site)	147,250
Storage cost	8,160
10% planning cost	221,711
2% preparation cost	44,342
Net Reuse cost	2,483,171



Then the reuse cost for all the 188 HCS elements, by taking into account the 10% planning cost and 2% the preparation cost, about 2,483,171 Euro. If the contractor sells the elements after 4 months' storage with a 20% higher value (14,652 Euro), then the contractor can make profit of 271,405 Euro.

5.2.4. Measuring the Reuse Potential Value from an Economic Point of View

After the calculation of the reuse cost in different situation with different scenarios, it is essential to measure the reuse potential value (factor) in those aforementioned situations. The reuse potential value will indicate whether the existing element has an economic reuse potential value or not. This factor can be measured by the formulas (8) and (9) that already described in chapter 3 part 3.3.3.

The reuse potential value would be a factor between 0 and 1, which indicates that near to 0 has almost no reuse potential and the factor near to 1 expresses the high reuse value. In each assumed situations, different scenarios applied which could either affect the reuse potential value positively or negatively. Therefore, by measuring the reuse value in each situation it can be understood which element in which situation (with different scenarios) have sufficient reuse potential value, despite the high cost of transport, improvement or modification.

Furthermore, the RP factor will first be measured based on the deconstruction cost (€12,210) in a neutral situation (no assumptions regarding transport, repair, modification and etc.). This means that the contractor disassembles the HCS elements of 'The City Post' project and wants to sell it. The cost of a new manufactured HCS element (with the same dimensions and almost with the same materials) is estimated about 9,100 Euro. Therefore, the RP factor can be as;

$$\left(\frac{\sum C_{Reuse}}{C_{New\ product}}\right) = \frac{12{,}210}{9{,}100} = 1.34 > 1 \quad therefore, RP = \frac{1.34}{100} = 0.014\%$$

- Transformation (renovation):

In the transformation (renovation) situation, the reuse cost of each element could not be calculated as all the HCS elements will be reused in the project. this scenario can be affordable and profitable for the contactor, since the contractor make profit from the reuse process.

- Sports complex/Educational and healthcare institutions:

Since this research also analyzed the functional performance characteristics of concrete elements, therefore it was needed to select cases with the same and different functions to evaluate the level of functionality of the existing elements. In these three different situations several scenarios have been applied to assess the reuse cost logically.

In all three situations some functional performances of the existing elements would be improved. On the other hand, the distances between the deconstruction site and new projects affect the reuse cost negatively. However, the net deconstruction cost of an HCS element, without taking into consideration the improvement/repair, modification or transport cost is higher than a new element. Therefore, the reuse potential (RP) factor comes out near to 0 when the reuse cost be higher than a newly manufactured element.

- Infrastructure (bike road pavement):

This situation can also be affordable for the contractor, because the contractor (demolition company) can make profit with a salvage value of 20%. In other words, the deconstruction cost is about 12,210 Euro, and if the contractor can sell all the element with a price of 14,625 Euro, then they can have a revenue (salvage value) of 2,754,576 million Euro and make a profit of 271,405 Euro. Consequently, the reuse potential value can be as;

$$\left(\frac{\sum C_{Reuse}}{C_{New\ product}}\right) = \frac{2{,}483{,}171}{2{,}754{,}576} = 0.90 \qquad so; \qquad RP = 1 - 0.90 = 10\%$$

This RP factor is not too high because the profit of the contractor is just about 271,405 Euro. Nevertheless, reuse of the existing elements in infrastructure projects can be an appropriate option to maximize the reusability of them.

The aim of measuring the RP factor from an economic perspective is to facilitate and ease the reuse process for different stakeholders involved. In the other words, demonstrating the RP factor in a dashboard skips the calculation and handling process and will undoubtedly contribute to faster communication in the reuse industry. Since the CCE Information System provides the buyer with sufficient information and data regarding the existing elements.

5.3. The Analysis of results Achieved from the Functional Properties of Each Scenario

The developed CCE Information System has been applied in a real case project 'The City Post' located in Zwolle in the Netherlands. In this way, the tool could be evaluated and different results could be achieved by adopting the tool in practice. In addition, various data and information has been derived from interviews with the contractors from the (de)construction and waste industry.

This study was aimed to support different stakeholders involved in the deconstruction process to make an appropriate decision regarding reusability of the existing elements by realizing and developing a tool. Thereafter, the developed tool would take into consideration relevant data and information to address the functional features of the existing elements, which is in line with the main stakeholder issues, namely cost. Given that the deconstruction process is an expensive process compare to the demolition, therefore the stakeholders should be informed when they can make a profit or even loss.

The results gained from the functional performance analysis of the existing project and different scenarios (situations), and also the results obtained from the reuse cost calculation, would be handled, compared and eventually optimized.

5.3.1. Result of analysis of functional properties of the existing project 'The City Post'

Concrete as the most used building element/material in the construction industry has different functional performance properties which can be determined based on the functional properties of its substances. Additionally, the functionality of building systems affects those performance characteristics of elements remarkably. To optimize the reusability of the existing elements it is required to link the existing elements with the same predesignated functional requirements products as much as possible.

Furthermore, following the processes of deconstruction for reuse in BMP, requires to test the quality performance of the existing elements, which contributes largely to the applicability of those elements in the newly designed building systems. The results achieved would be analyzed and compared to each other in different scenarios (situations), to understand to what extent the functional performance properties of elements affect the reusability of them.

This project is constructed in 1972 from concrete and contains of two parts, a 5-storey low-rise building and 12-storey high-rise. According to construction, structural and architectural drawings, the concrete floor used in the building is a prefabricated HCS element with the strength class of B52.2 which means that the elements have a characteristic cylinder compressive strength of 47.5 N/mm^2 and a characteristic cube compressive strength of 52.5 N/mm^2. So, it can be mentioned that the strength of the elements can still fulfil their strength ability, if no environmental damages affected this ability of the element.

The concrete elements passed one third of their lifetime, i.e. 67% durability potential, as the upper limit of the lifespan of concrete to be set 150 years. The next functional properties of the existing element, namely the abrasion resistance, can be estimated appropriate as the w/c ratio of the concrete used in the element (0.46) lies between 0.32 and 0.55. In terms of thermal features, the thermal conductivity of the HCS floor elements have a 2.35 W/mK, estimated based on the amount of cement (446 kg/m^3) used in it. The thermal diffusivity of the elements estimated approximately 1.1x10^-6 m^2/s, followed by a specific heat of 1.01 kJ/kg.K, and a thermal expansion of 8.4×10^−6/◦C.

The fire resistance of concrete elements has been estimated based on the thickness of the element, since the fire resistance related highly to the thickness of the element. The HCS elements have a thickness of 210 mm and the columns have a thickness of 420 mm. Therefore, the elements can have a fire resistance of up to 120 min, i.e. 240 min. The other functional feature of concrete elements is their sound insulation capability which can be estimated based on analyzing the density of the materials used in them. The precast HCS floors in The City Post project have a density of 2360 kg/m^3 which can reflect the sounds of maximum 55 dB.

However, to measure the reuse potential factor of the existing elements from afunctional performance perspective, it is required to compare the functional characteristics of existing elements with the specific requirements set for newly designed buildings.

- The comparison of strength/durability/abrasion resistance of the elements compared in all scenarios (situations):

The measured RP factor of the strength of the existing elements for various scenarios is illustrated in diagram below. The diagram shows in which situation the elements have the highest reuse potential in terms of their strength ability.

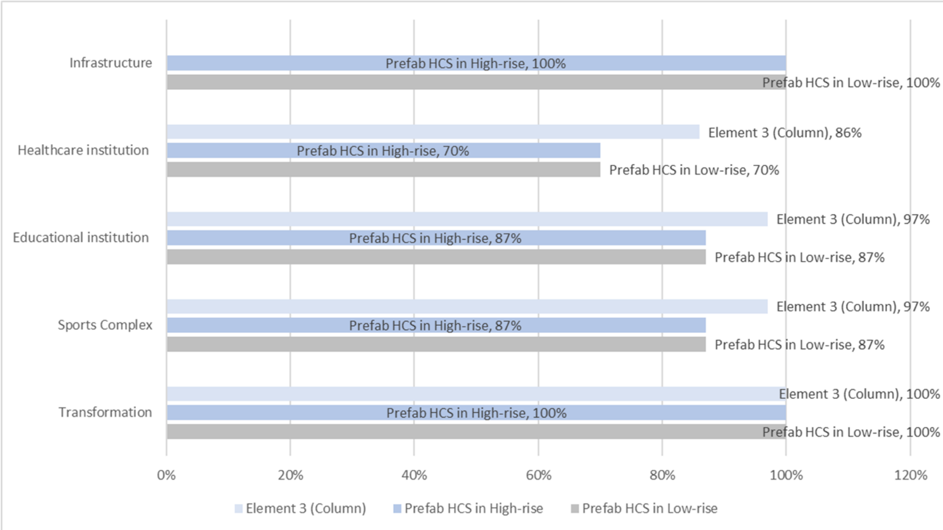


Figure 5.11: The impact of functionality of the building on the strength's element ability (own diagrams).

As can be seen in the diagram above, the functionality of new building systems affect the new requirements set in NEN-NORMS and thereafter will influence the reuse potential factor in terms of e.g. strength of the element. Reusing the elements in infrastructure can highly be suggested to the contractor in terms of strength ability. On the other hand, constructing a healthcare institution requires a higher strength concrete classes as the result of safety in e.g. earthquake circumstances.

The durability of the existing elements in all of the situations has been estimated as 67% and this functional ability cannot be changed and it can be considered as a fixed quantitative factor.

In different assumed scenarios (situations) the abrasion resistance capability of the existing elements did not affected significantly by the functional requirements set for new projects. This functional ability depends on w/c ratio used in concrete and according to the requirements of new elements would be between 0.32 and 0.55. Therefore, the existing elements can still perform their abrasion resistance. It may be necessary to recoat the concrete in the sports complex and healthcare scenario where the element may be more worn due to the equipment used on the element.

- The comparison of thermal properties of the elements in all scenarios (situations):

One of the most important functional requirements that the concrete elements would to meet is the thermal properties set for new building systems. In order to move towards CE strategies, it is essential to realize energy efficient buildings and this requires using elements with high thermal abilities.

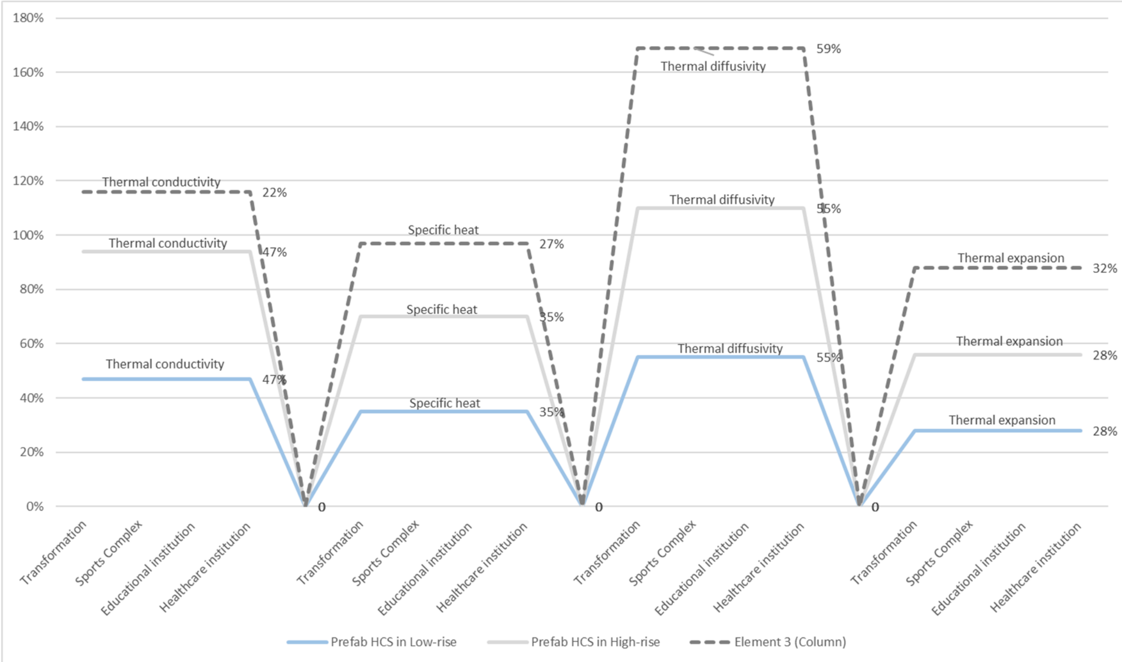


Figure 5.12: The impact of functionality of the building on thermal properties of the element (own diagrams).

Diagram above shows the influence of the thermal functionality of new buildings on the reuse potential factor. It is obvious that an HCS floor element from 50 years ago does not meet the new determined thermal NEN-NORMS. This can particularly be seen in thermal expansion property of the existing elements in different situations (RP factor of 28%, 28% and 32%). The next thermal property that can be improved in all situations is specific heat with also a low percentage of RP factor (27%, 35% and 35%). Improving of thermal properties will affect the reuse cost remarkably as the improvement process is an expensive procedure.

Furthermore, RP factor of thermal conductivity can still be accepted in some constructions but the RO factor of column in terms of conductivity is not high enough and this can cause thermal bridge (koudebrug) phenomenon. Ultimately, thermal diffusivity of the elements in various situations is sufficient to fulfill this property.

- The comparison of fire resistance/sound insulation of the elements in all scenarios (situations):

As already discussed, the fire resistance of elements depends on the thickness of that, and this functional ability of concrete can be estimated based on the thickness of it. The HCS floor components of 'The City Post' have a thickness of 210 mm, the fire resistance can therefore be stressed in more than 120 min, namely 240 min. This quantity meets the fire resistance requirements of new building structures in all situations. The sound insulation of the elements has also an appropriate RP factor in different scenarios, a range between 76% to 100%. Since the estimated sound insulation of existing elements meets the new requirements set in Building Decree, or predetermined in design criteria of new buildings.

To be concluded, the main functional performance property that affected the RP factor in different situations is thermal properties which measured lower than other functional characteristics. However, the functionality of a newly designed building/construction play a major role in the measurement of reuse potential factor of the existing elements. Consequently, the RP factor from functional perspective will impact the RP factor from economic point of view, either positively or negatively.

5.3.2. Analysis of the Results Obtained from the Reuse Cost Calculation of Different Scenarios

After analyzing different functional performance properties of the existing elements from 'The City Post' project, it was appeared that some of them would be improved. Therefore, in the next step all the costs including deconstruction, transport, and storage cost are calculated to measure the RP factor from an economic perspective. The reuse process would be profitable for all stakeholders involved, otherwise no companies are keen to deconstruct a building system whiteout making profit.

Furthermore, there were some scenarios (situations) assumed, expect of transformation, because the renovation would be happened next year when the deconstruction process is finished. So, it is important to analyze the impact of each process on the reuse cost in each scenario, as some costs in the reuse process affected it negatively and make it uneconomic. In addition, some costs in the reuse process are fixed and some of them such as transport or storage cost can be seen as variables. Additionally, the aforementioned costs have a great impact on the total reuse cost. The developed CCE Information System has been applied in real cases which is the approach to evaluate the reliability of the results based on the data and information achieved from the practice and interview. The following assertions are examined to validate the reliability of the tool.

- The impact of improvement/repair process on the reuse cost:

It is known that the project 'The City Post' is currently under the transformation process. Functional performance quality test has shown that the existing element meets the new functional requirements in case of transformation (expect of thermal properties which have to be improved). To assess the measured RP factor from a functional perspective in more detail, some other scenarios (cases) has been assumed with different functions and location.

Moreover, the existing elements would also be improved in terms of different functional properties in the other situations. The repair/improvement process is a costly process and can increase the reuse cost for the contractor and also for the client (who has to decide to deconstruct or demolish) significantly.

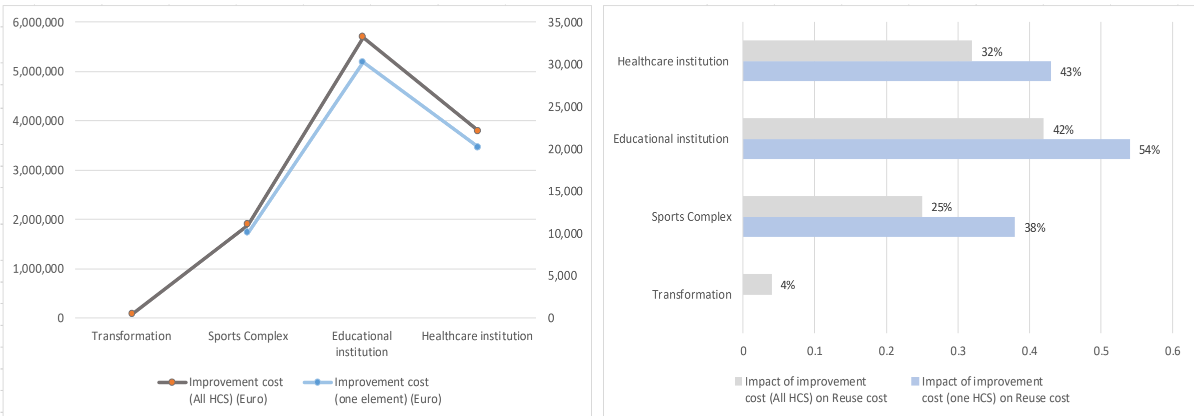


Figure 5.13: (Left) The calculated improvement costs in different scenarios. (Right) The impact of the improvement cost of (one or whole) element(s) on the total reuse cost (own diagrams).

The above diagram (left) shows the calculated improvement costs for different situations with various assumed scenarios. According to the performance quality test (RP factor from functional point of view), the sports complex required the improvement of elements in terms of thermal characteristics, followed by the improvement of the elements in educational and healthcare situations. The improvement process will be calculated in practice by €/hour, and according to the interviews it costs about 90 €/hour. In other words, if the level of quality of each element indicates that the element should be repaired, this has undoubtedly negative impact on the reuse cost.

The highest improvement cost is allocated to the educational scenario which recognized higher functional requirements for its elements, and this was also resulted from measured RP factor from a functional perspective. The impact of improvement cost on the total reuse cost in educational situations is about 52% for one HCS element and about 42% for whole of HCS elements, and this correspondent a high negative impact on the salvage value. Consequently, this makes the economic feasibility of the reuse elements inconceivable, i.e. the reuse process uneconomical.

Therefore, it can be expressed that a favorable and affordable situation for both the client and the contractor is a scenario which requires less functional improvement. The tool would thus take into consideration when optimizing the reuse cost to find a scenario which requires less improvement, however, this depends on the budget of the client or new buyer, and the functional requirements of the newly designed building.

- The impact of transport process on the reuse cost:

The existing project 'The City Post' is located in the city of Zwolle. After deconstruction process, the disassembled elements would be transported to (a) a new construction site if the quality performance of the element was sufficient, or (b) to a storage yard to keep the element for a period of time, or (c) will be transported to a treatment company to improve/modify the element. All these scenarios depend on the agreement between the client and contractor, the remain value of the element, and the function of the newly design construction/project. Nevertheless, the transport cost is also a costly process as well as improvement. The cost of transport derived from interviews is approximately 95 €/hour.

Transport cost				
	Sports Complex <50 km	**Educational institution 50km-100km**	**Healthcare institution 50km-100km**	**Infrastructure >100 km**
The distance *(km)*	15	92	89	155
Transport cost *(Euro)*	3,325	9,690	10,355	147,250
Impact of transport cost on the Reuse cost	12%	17%	22%	6%

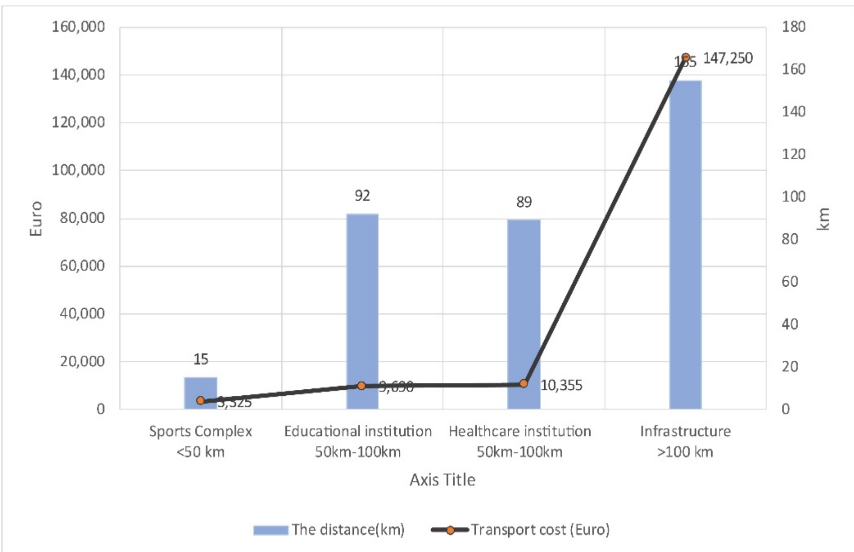


Figure 5.14: (Above) The calculated transport costs in different scenarios. (Below) The relationship between the cost and the distance of deconstruction site and the destination (own table and diagram).

Obviously, if the distance between two points, e.g. deconstruction site and storage area, increases, so will transport costs. The higher transportation costs enhance the total reuse cost for either the client or the contractor. The favorable scenario for the stakeholders is to find a new project which is close to the deconstruction site.

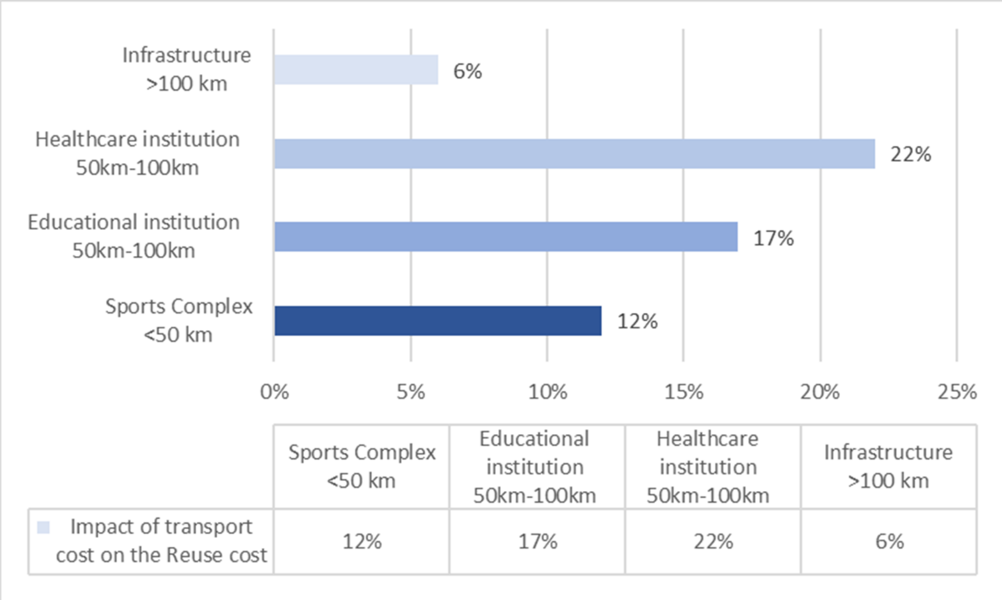


Figure 5.15: The impact of the transport cost of on the total reuse cost (own diagram).

A conscious choice was made for various projects with (a) less than 50 km away from the deconstruction site, (b) between 50 and 100 km and (c) more than 100 km. One of the main conclusions from the analysis of this result is that it cannot always be concluded that the transport cost will negatively affect the reuse cost. Because the greater distance leads to higher transport costs, but the proportion of transport cost of the total reuse cost is not too much, as the reuse cost includes also other associated costs and this can be seen in the table and diagrams above.

For example, the transportation cost in the case of an infrastructure project is just 6% of the total reuse cost, while the distance between deconstruction site and infrastructure project is greater than the distance between healthcare project and deconstruction site. In other words, there are other costs that were more influential than transportation costs in infrastructure projects, like stripping cost.

- The impact of storage process on the reuse cost:

The disassembled elements of the project need to be stored and thereafter transported to a treatment company or new construction site. However, the storage of the elements is not an expensive procedure, although it is not a desirable activity for the both the contractor and the client (new buyer). Insight from interviews showed that 1,000 m² of area on a storage yard will cost the contractor or the new buyer approx. 25,000 €/year. This cost will increase if the required surface area and storage time also increase. This cost can also be considered as a variable in the reuse cost process and can be optimized by finding a new buyer or a project before deconstruction begins.

- The impact of salvage value on the reuse cost:

The contractor (demolition company) or the new buyer can make profit from the reuse process when they can sell the extracted, recovered or modified products at an affordable price. If this is not the case, then the reuse process is undoubtedly uneconomical. The price of a recovered element is two times more expensive than a new one. Therefore, a higher salvage value would be desirable if the contractor or new buyer wants to have an appropriate revenue.

5.3.3. Economic Feasibility by Combining and Optimizing the Scenarios

In order to make the reuse process possible from an economic point of view (profitability) for both the contractor or for the client (new buyer), it is necessary to optimize the reuse process which included different fixed and variable costs. The fixed costs are like obtaining a permit, inspection and the cost that allocated to activities that have a fixed price. On the other hand, variable costs were affected by different qualitative factors either from functional performance properties or qualitative factors in the deconstruction process such as improvement. These qualitative factors provided insight into the possibility of reusing the existing elements, i.e. by measuring the RP factor. Therefore, the sensitivity of those factors could be derived from the measurement of RP factor and could be concluded which of them had the most impact on the reuse possibility of existing elements in terms of economically.

The sensitivity analysis referred to the process of recalculating the results achieved under the other alternative assumptions to specify the impact of different variables under sensitivity analysis can be beneficial for a range of objectives. Also, this process contributes to understand which combination of assumed scenarios results the best cost effective reuse process for the contractor or for the client.

The cost analysis has shown that some calculated costs have the greatest impact on the total reuse cost including deconstruction cost. The cost of stripping had 71% impact on the deconstruction cost in all the scenario (situations), which had thereafter impact on the total reuse cost. On the other hand, the improvement process as a consequence of functional performance quality test influenced the total reuse costs remarkably, followed by the transportation cost in all the assumed scenarios. In other words, these costs can be considered as the underlying variables in the sensitivity analysis. Thus, in order to understand which costs can be reduced to make the reuse economically possible, it is important to carry out a sensitivity analysis which provides insight into this aim.

Remark: All the recalculations regarding the 'Sensitivity analysis' can be found in Appendix A.4.6.

- Estimating the desirable and undesirable scenarios of the stripping process and optimizing the worst scenario:

The impact of this process on the deconstruction cost is estimated of about 71%. The estimated stripping cost from the interviews that used in the calculation of deconstruction cost was 67.5 €/m². In order to conduct a sensitivity analysis, the upper limit (best case) would be estimated based on the calculations performed for the deconstruction cost. On the other hand, the cost of a newly manufactured HCS element is about 9,100 Euro, which means that the upper limit of the stripping cost per m² would be less than 67.5 €/m² such that the deconstruction cost will be reduced to the under limit of new cost. In this way, the reuse will be feasible from an economic perspective, at least to deconstruct the existing element, not to demolish it.

Therefore, to understand which cost per m² can be considered as least desirable factor for the stripping process, 'What If' analysis has been carried out in Excel which generate random samples. The samples provide insight into which combination of scenarios can reduce the costs of stripping.

Table 5.19: Performing a sensitivity analysis through generating random sample variables for stripping cost (own table).

Euro	HCS element (m²)					
8707.5	129	2580	6450	12900	19350	24510
€ 35	€ 4515	€ 90300	€ 225750	€ 451500	€ 677250	€ 857850
€ 40	€ 5160	€ 103200	€ 258000	€ 516000	€ 774000	€ 980400
€ 50	€ 6450	€ 129000	€ 322500	€ 645000	€ 967500	€ 1225500
€ 60	€ 7740	€ 154800	€ 387000	€ 774000	€ 1161000	€ 1470600
€ 68	€ 8707.5	€ 174150	€ 435375	€ 870750	€ 1306125	€ 1654425
€ 70	€ 9030	€ 180600	€ 451500	€ 903000	€ 1354500	€ 1715700
€ 75	€ 9675	€ 193500	€ 483750	€ 967500	€ 1451250	€ 1838250

As can be seen in the table above, it has been tried to find the most desirable combination of scenarios of which the impact of stripping cost on deconstruction and thereafter on the reuse cost can be reduced. In the horizontal row the dimension of an HCS element (7.2 x 18=129m²) is noted as the cost of the stripping would be calculated by €/m². This dimension cannot be changed and it can be seen as a fixed variable. However, if the number of the HCS element increases then the stripping cost will also increase. In the vertical columns the cost of stripping of one HCS element with the real price, achieved from interview 67.5 €/m², has been set at the least-desirable which makes the reuse process non-feasible economically. A range of other costs is realized to predict the most desirable stripping cost in the sports complex situation.

Furthermore, to find an approximate of the most desirable variable (best case scenario) for the cost of stripping, the deconstruction cost would be recalculated using the range of between 40 € and 50 € of the random samples which are less than 67.5 €. In this way, the cost of stripping process for an HCS element in all the scenarios (sport, education and etc.) can be estimated. The weighted criteria for assessing the random samples is set to an upper limit of 0.71.

Table 5.20: Optimizing the least desirable (worst case scenario) stripping constraint to the desirable (best case) scenario (own table).

Reuse cost of one HCS elemen	weightage	
Inspecting the elements- Inventory - Audit	0.01	
Obtaining a permit	0.02	
Stripping	0.22	0.71
Remove concrete topping	0.04	
Remove Hollow Core Slabs	0.01	
1% preparation cost	0	
Net Dec. cost	0.3	100%
Improving thermal properties	0.25	
Transport cost (to treatment)	0.05	
Transport cost (to storage yard)	0.04	
Storage cost	0.05	
1% preparation cost	0.01	
Net Reuse cost		

Reuse cost of one HCS elemen	weightage	
Inspecting the elements- Inventory - Audit	0.01	
Obtaining a permit	0.02	
Stripping	0.45	0.25
Remove concrete topping	0.04	
Remove Hollow Core Slabs	0.01	
1% preparation cost	0	
Net Dec. cost	0.3	73%
Improving thermal properties	0.25	
Transport cost (to treatment)	0.05	
Transport cost (to storage yard)	0.04	
Storage cost	0.05	
1% preparation cost	0.01	
Net Reuse cost		

As can be seen in the table above, the share of stripping cost in deconstruction cost was about 0.71 followed by a share of 0.22 in the total of reuse cost. By generating the random samples, the undesirable stripping cost is optimized by 25% of the deconstruction cost. Nevertheless, this optimizing is not sufficient to reduce the total reuse cost as this cost also affected by other associated costs. But, the deconstruction cost will be optimized which also plays a major role in maximizing the reusability of the existing elements. Additionally, the optimization of the undesirable stripping cost applied not only for the sport complex situation, but it can also apply for other scenarios by a similar way.

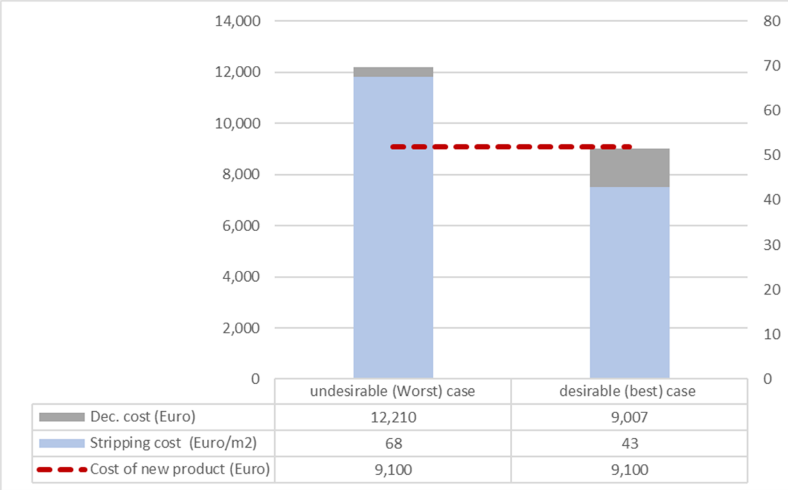


Figure 5.16: Estimating the most desirable (best) case and undesirable (worst) case scenario for the stripping process (own diagram).

The figure above shows that in desirable (best) case scenario the stripping cost can be reduced to 43 €/m², which will lead to an economic feasible reuse process. Because, in this scenario the deconstruction cost descend to about 9,007 Euro and this price is less than the price of a new manufactured element. However, this cost calculation was just for deconstruction cost, but the reuse cost includes also deconstruction cost, therefore the reuse cost will reduce subsequently.

On the other hand, in the undesirable (worst) case scenario, the stripping cost was calculated based on the data achieved from interview, namely 67.5 €/m². In this scenario the deconstruction for reuse will be uneconomic, as the calculated cost passes the upper limit i.e. the cost of a new product

- Estimating the desirable and undesirable scenarios of the improvement/transportation process and optimizing the worst scenarios:

There are two other processes (variables) that affected the reuse cost remarkably by their costly procedures. As the results showed, the impact of the improvement process on the reuse cost was about 25% in sport situation, 44% in educational situation, 21% in healthcare and 0% in infrastructure project. In addition, the effect of the transportation process on the reuse cost was approx. 9% in sport situation, 14% in educational situation, 22% in healthcare and 7% in infrastructure project. All these weightages can be seen as worst-case scenarios, since the reuse cost becomes uneconomic due to their costly impact. The purpose to optimize the worst case is to recognize under which least desirable factors, the reuse case is still economic for the contractor.

The both transport and improvement cost is calculated by the price obtained from interview, namely 95 €/km and 90 €/hour. This means that calculating the reuse cost by these two prices resulted an uneconomic reuse process for the stakeholders, thus they are undesirable costs (worst-case). To estimate and find the desirable (best-case) cost, it would random samples be generated to be able to recalculate the reuse cost. As the same as the previous random sampling for stripping cost, the same method will be applied for just sport situation to find the least desirable random sample.

These two processes have great impact on the reuse cost, thus not on the deconstruction cost, because the improvement and transportation would be done after disassembling of the elements. Therefore, it is needed to find the random samples which leads to a profit for either the contractor or the client.

The other issue regarding optimizing of these two factors is the existing of more than one continuous constraints, i.e. cost and distance, cost and hour. Thus, it has to find desirable samples for cost variable in sports complex situation.

Table 5.21: Performing a sensitivity analysis through generating random sample variables for improvement cost (own table).

hour	Euro							
€10,080	€90	€80	€70	€60	€50	€40	€30	€20
hour80	7200	6400	5600	4800	4000	3200	2400	1600
hour 90	8100	7200	6300	5400	4500	3600	2700	1800
hour100	9000	8000	7000	6000	5000	4000	3000	2000
hour112	10080	8960	7840	6720	5600	4480	3360	2240
hour125	11250	10000	8750	7500	6250	5000	3750	2500
hour135	12150	10800	9450	8100	6750	5400	4050	2700
hour145	13050	11600	10150	8700	7250	5800	4350	2900

Calculating the improvement cost by the price obtained from the interviews is considered as the worst case scenario. Finding the samples for the desirable constraint will result also to find the best case for the labor works hour. In other words, in the worst scenario the labor would works 112 hours to improve an HCS element, while estimating the desirable cost value for the improvement process results to figure out how many hours would be also being sufficient to repair the element with a profit. The red highlighted samples would be examined in the reuse cost formula to figure out the best-case scenario for the improvement process.

Table 5.22: Performing a sensitivity analysis through generating random sample variables for transportation cost (own table).

km	Euro							
€3,325	€95	€90	€80	€70	€60	€50	€40	€ 30
km15	1425	1350	1200	1050	900	750	600	450
km25	2375	2250	2000	1750	1500	1250	1000	750
km35	3325	3150	2800	2450	2100	1750	1400	1,050
km45	4275	4050	3600	3150	2700	2250	1800	1350
km55	5225	4950	4400	3850	3300	2750	2200	1650
km65	6175	5850	5200	4550	3900	3250	2600	1950
km75	7125	6750	6000	5250	4500	3750	3000	2250
km85	8075	7650	6800	5950	5100	4250	3400	2550

As already mentioned, the impact of transport and improvement/modification processes is just on the reuse cost. This optimization thus contributes to the profitability of the reuse process, when the reuse costs decrease, the effect of the salvage value is regarded as a revenue, then a profit for the contractor can be guaranteed. The cost of transportation is the target variable, because the location of the project can be seen as a fixed variable and cannot be changed or optimized. Some range of samples would be implemented in the reuse formula to recalculate the transport cost. The red line indicates the desirable values which reduces the reuse cost appropriately. (see Appendix A.4.6 for calculation process).

The essence and applicability of sensitivity analysis to find the best combination of scenarios that leads to a profitable outcome. Therefore, the recalculation of reuse cost applying the random samples between 20 and 40 Euro for improvement and among 30 and 40 Euro for the transportation process. Due to time constraints in this research, the recalculating is just done for one scenario, namely sports complex. However, the impact of improvement or transport costs on the reuse cost is almost the same as in other scenarios. The weighted criteria for evaluating the random samples is set to an upper limit of 0.25 and 0.09 for improvement and transport process respectively.

Table 5.23: Optimizing the least desirable (worst case scenario) of improvement and transport constraint to the desirable (best case) scenario (own table).

Reuse cost of one HCS elemen	weightage
Inspecting the elements- Inventory - Audit	0.01
Obtaining a permit	0.02
Stripping	0.22
Remove concrete topping	0.04
Remove Hollow Core Slabs	0.01
1% preparation cost	0
Net Dec. cost	0.3
Improving thermal properties	0.25
Transport cost (to treatment)	0.05
Transport cost (to storage yard)	0.04
Storage cost	0.05
1% preparation cost	0.01
Net Reuse cost	Negative impact on Reuse cost

Reuse cost of one HCS elemen	weightage	
Inspecting the elements- Inventory - Audit	0.01	
Obtaining a permit	0.02	
Stripping	0.45	
Remove concrete topping	0.04	
Remove Hollow Core Slabs	0.01	
1% preparation cost	0	
Net Dec. cost	0.3	+
Improving thermal properties	0.20	80%
Transport cost (to treatment)	0.03	60%
Transport cost (to storage yard)	0.02	50%
Storage cost	0.05	
1% preparation cost	0.01	
Net Reuse cost	Reuse cost is optimized	

Optimizing with two variables has also some advantages, i.e. by finding the desirable value for one variable leads to the estimation of the desirable value for the other one. For example, finding the range of samples between 20 to 40 Euro in improvement process indicates also the optimal hours that one labor should work to improve the existing element, less than 112 hours. The tables above demonstrate that the undesirable improvement and transportation costs can be optimized by 0.8, 0.6 and 0.5.

- Desirable and undesirable scenarios in the improvement/transport process:

The other variables that had great impact on the reuse cost was the improvement and transportation cost in all the assumed scenarios (sport, educational and healthcare institutions). The calculation of reuse cost was based on the costs achieved from interview for both improvement and transport, namely 90 €/hour for improvement process and 95 €/km for transport cost.

These two estimated costs resulted in an undesirable (worst-case) scenario for reuse process, as the contractor could not make a profit from the salvage value obtained from selling the products. Thus, to understand the lower limit (best-case) scenario for the reuse process, the reuse cost has been recalculated based on reducing both the improvement and transportation costs to 34 €/hour and 35 €/km, which could provide a revenue (salvage value) for the contractor that the contractor could make a profit. In other words, the reuse cost for just an HCS element will reduce to 18,166 Euro which is less than the cost of a recovered element (2x9100=18,200 Euro). So, the contractor can make a profit of about 6,000 Euro by selling the recovered products with the price of 18,200 Euro.

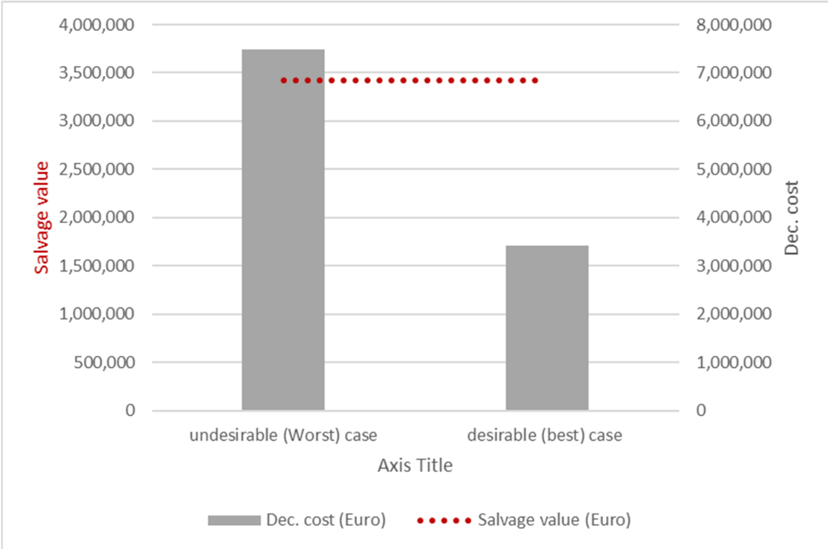


Figure 5.17: Estimating the most desirable (best) case and undesirable (worst) case scenario for improvement/transport process (own diagram).

It has been assumed that the improvement cost decreases simultaneously with the transport cost in the sports complex situation. Moreover, this recalculation can be carried out in the same way for the education and healthcare situations. By reducing these two costs the reuse cost will decrease significantly, such that the contractor can even make a profit and the reuse process becomes economical and profitable. In the case of the most desirable condition where there is no improvement cost associated and it is at the discretion of the contractor or the client (new buyer), it is expected that the cost saved should increase the revenue by selling the recovered products and thereby improve the profit of contractor.

- Upper limit and finding the tipping points of the analyzed processes in the sports complex scenario:

After optimizing the cost of stripping, improvement, and transportation processes, the tipping points or the upper limit of desirable cost would be calculated. Finding the tipping point of the processes can make the deconstruction or reuse costs profitable for the contractor regardless of optimizing other corresponding fixed costs. In other words, the element can be stripped with the same optimized cost but for another value of km, square meter or etc. However, the impact of those associated costs may be fluctuate the tipping points.

- Estimating of cost tipping point for the stripping process:

Tipping points are referred to the highest value of a variable cost element, as above which deconstruction or reuse of that given element becomes uneconomical or not profitable. In other words, it is the maximum budget that can be determined for a variable cost while the total reuse cost remains less than the cost of a new manufactured element. This tipping point for the discussed processes has been estimated by recalculating the best and worst case scenarios. Tipping point would be determined for the continuous (changeable) variables such as cost, time and distance (km).

After estimating the cost of stripping process on the deconstruction cost by generating random sampling, the tipping point of this process should be calculated. However, the observed tipping points for stripping, improvement and transport cost is just being done for the sports complex scenario, as the rest of situations can be experienced and examined in the same way as well. This can be done through a goal attainment (break-event) analysis which indicates the maximum value, i.e. tipping point for each scenario. In this break event analysis, the calculated revenue is assumed as a negative revenue that has to become 0.

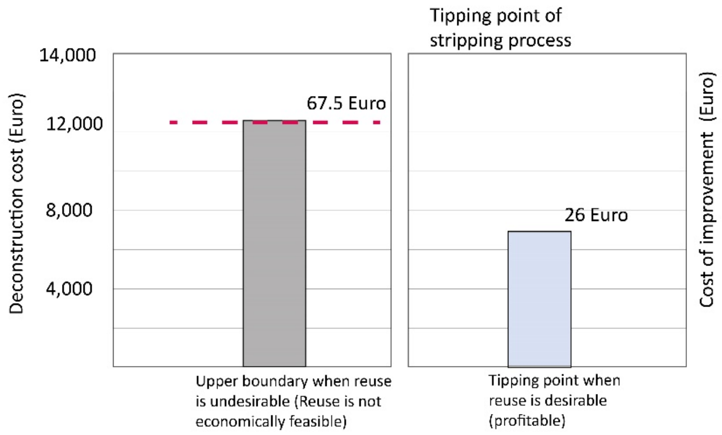


Figure 5.18: Estimating the cost tipping point for the stripping process in sport situation (own diagram).

Hence, it is important to know in the best estimated scenario for stripping process how much the price can be optimized, given that the deconstruction cost is still affordable. This can be considered as the tipping point of cost of stripping beyond which the deconstruction cost becomes higher than the manufacturing costs of a new element, i.e. the deconstruction is not economically feasible.

The stripping cost obtained from the interviews, namely 67.5 €/m² is an undesirable cost and is considered as an upper limit for the stripping of an element. By reducing this cost and still make the deconstruction process profitable for the contractor the tipping point of cost can be indicated about 26 Euro. Thus, the stripping process can be performed while the other associated costs are still taken into account by their undesirable prices. In other words, in the estimating of the tipping point of the stripping process other corresponding costs are not taken into consideration. Therefore, the impact of those associated costs would be measured on the tipping point in the next phase. Additionally, the calculation of the deconstruction cost can be carried out in exactly the same manner as for other scenarios.

- <u>Tipping point of the improvement process:</u>

The improvement cost has also tipping points when the reuse cost is desirable (profitable) or undesirable (not profitable) for the contractor, as this cost affects the reuse cost. In the calculation of the improvement process the element will be transported to the treatment company two times and also one trip to the storage yard, thus a total distance of 35 km. Also, the element will be stripped and removed. Nevertheless, the improvement cost would be done after disassembling of the element and this process is included in the reuse cost. A more detailed and explained break-event analysis is to be found appendix A.4.6.

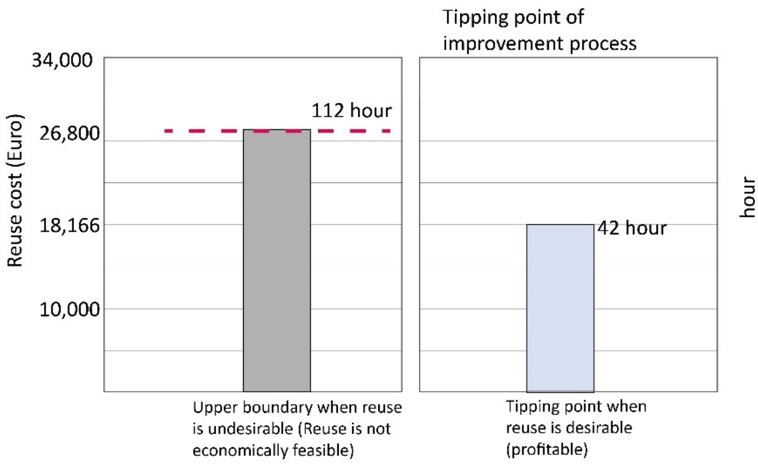


Figure 5.19: Estimating the tipping point for the improvement process in sport situation (own diagram).

It was assumed to perform the improvement process within 112 hours, by a cost of improvement about 90 €/hour. On the other hand, the best case scenario regarding the cost of improvement was recalculated to 34 € for an hour. In order to estimate the tipping point of the hours a worker can fulfill the improvement process, the 112 hours that resulted a non-profitable reuse cost, is considered as upper limit. Therefore, in the recalculation of the reuse cost, 3,808 Euro was calculated for the improvement cost in 112 hours. Therefore, by using this cost in the reuse formula as a revenue, then this cost must be 0. In other words, the hours would reduce from 112 as this time was also an upper limit for the reuse cost.

The result shows that the improvement tipping point has been estimated about 42 hours in a desirable scenario, i.e. calculating by taking into account 90 €/hour. Therefore, the reuse of the existing element can be profitable for the contractor by reducing the reuse cost. Hence, this means that the existing element extracted from the project 'The City Post' in Zwolle can be transported to treatment company, also to the storage yard for a maximum distance of 35 km and being stripped. Exactly the same approach can be applied for the other scenarios (situation educational and healthcare).

- Tipping point of the transport process:

To find the tipping point of the transport process in the sport complex scenario, it has been tried to estimate the tipping point based on approach used for finding the tipping point of improvement process. The transport process is also considered as a continuous constraint in the reuse cost calculation, as the distance between deconstruction site and treatment company, storage yard and to the new construction site is a variable that can be optimized. On the other hand, the cost of transportation derived from interview is a costly process.

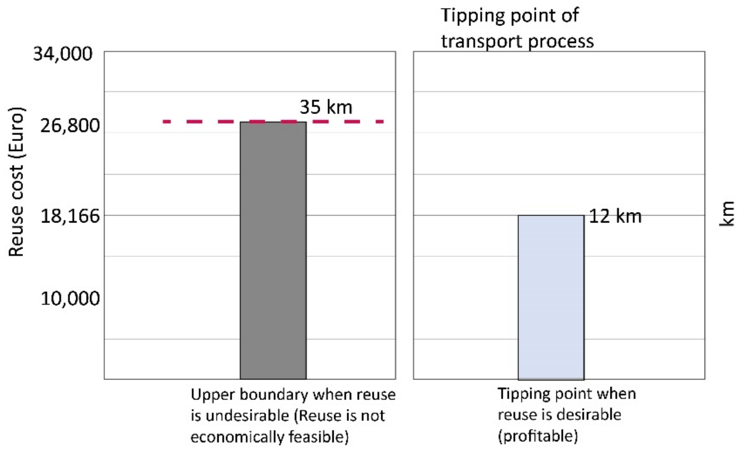


Figure 5.20: Estimating the tipping point for the transport process in sport situation (own diagram).

The transport cost is calculated in all the scenarios with the price of 95 €/km. Additionally, the distance between the project 'The City Post' and sports complex is assumed to be 15 km. Although, the element would be transported to the treatment company to be improved and transporting to a storage yard. Therefore, a total distance of 35 km is assumed, and this distance resulted a high expenditure cost for the contractor and makes the reuse process not-profitable. Figure 5.20 shows that 35 km is weighed as an upper limit which would be beyond of a tipping point.

As the same as previous method, by using a goal attainment approach the tipping point for the transport process is calculated. This tipping point must undoubtedly be lower than upper limit to make a profit after selling the products. 12 km is the outcome of the calculation above which the reuse cost becomes more than the salvage value. Given that the reuse cost includes different corresponding costs, the recalculation thus would be done by replacing the tipping points achieved.

Remark: The proposed CCE Information System including an import sheet and a dashboard can be found in Appendix A.4.9 in which the results of the case study analysis have been demonstrated.

5.3.4. Functioning (Instruction) of the Steps Needed for 'Analysis and handling stage' in the CCE Information System Based on the Case

The second part of functioning of the CCE Information System handles the steps regarding the analysis and processing stage of the tool (chapter 4, part 4.5). These steps have been taken based on the real case study 'The City Post' located in the city of Zwolle. All the functioning and instruction steps (steps 2.1 to 2.11), which are describing the functionality of the analysis and processing stage of CCE Information System, have been explained in more details in Appendix A.4.8.

As already mentioned, to measure the RP factor from both a functional and economic perspective, it is needed to use different newly designed construction projects beside an aged project. However, the new construction projects with various functions have been assumed in this study. In the explanation of functionality of analysis and handling stage, it has been attempted to describe the steps by using spots complex scenario, while the same approaches can be applied for other scenarios. The aforementioned steps have been clarified in such a way that they can be translated in different programming software such as Matlab and Python.

5.3.5. Results

After finding the tipping point values for different processes of a scenario like the sports complex, different reuse costs have been recalculated to estimate the reuse cost. As explained before, the RP factor for different scenarios was not sufficient form an economic point of view. The reuse potential factor has been recalculated and the result is as follows;

$$\left(\frac{\sum C_{Reuse}}{C_{New\ product}}\right) = \frac{Reuse\ Costs}{Salvage\ Value} = \frac{3{,}393{,}964}{3{,}421{,}600} = 0.99 \qquad so; \qquad RP = 1 - 0.99 = 1\%$$

The measured Reuse Potential factor is still not too high, as the contractor's profit is not too high either (a profit of about 27,636 Euro). Optimizing a totally uneconomically reuse process into a profitable reuse process, even if the profit of the concerned stakeholder is not too high, can be a huge step towards circular economy strategies. It can despite be concluded that there is a probability that the project can be deconstructed and disassembled for reuse. This would be of great importance for achieving the sustainable goals in the construction and waste sector. Furthermore, the reuse process is very complex and dynamic with a large number of uncertainties. The companies, stakeholders and other involved actors dealing with many obstacles, constraints and regulations which must be tackled, improved, and reviewed to maximize the reusability as much as possible.

The improvement process has been improved about 38% and the transport process experienced an improving of about 35%. It can be concluded that the CCE Information System, would act as a tool that analyzes different scenarios of target projects and after analyzing and combing the best cases, the most profitable project would be linked to the existing element. For instance, if the existing elements cannot be linked to the sports complex project due to large distance or high improvement/modification costs, a new alternative project should be available that is economically feasible for the contractor, such as reuse in an infrastructure project. A project for example which is located less than 12 km from the deconstruction site or it requires less improvement or other costly interventions.

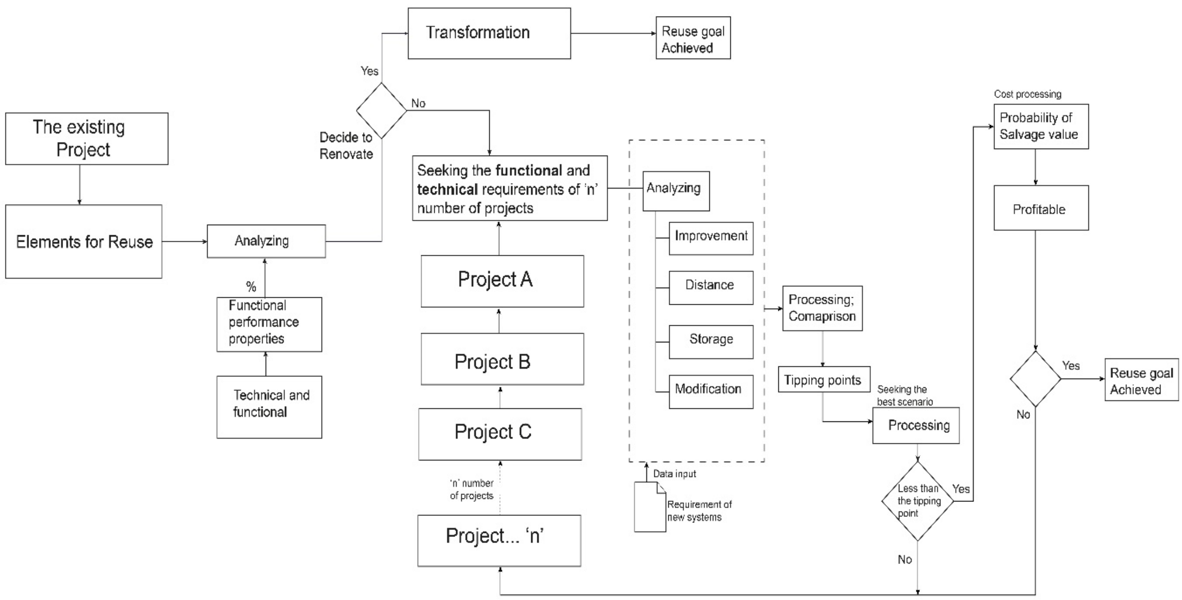


Figure 5.21: The method for maximizing the reusability of the existing building elements (own diagram).

After analyzing and measuring the results achieved, it has been attempted to illustrate the results of this research through proposing an optimization method (see figure 5.21). This method can contribute significantly to close the loop of using the existing building elements. The aim of this research was to develop a CCE Information System consisting of an import sheet, dashboard and a process and handling stage sheet, which can function as a tool. Therefore, the tool must maximize the reusability of existing elements by keeping them in a closed loop. All the building products have the remain reuse value depends on functional and technical requirements for the newly designed systems.

Therefore, in the first step the reuse potential value of the existing elements would be measured from a functional and economic perspective. It should mention that deciding to renovate the existing project means that the reusability of the elements is reached despite some improvement would be needed. The above method is developed based on the analysis carried out for the real case study ‘The City Post’ in Zwolle. The project is still under deconstruction process for renovation. The analysis showed that this option can be seen as a beneficial option either for contractor or for the client because the transformation closed the use of finite materials and is profitable for the contractor.

On the other hand, to maximize the reusability, it is needed to reuse the elements as much as possible by facilitating the reuse process for the stakeholders involved. The proposed method therefore focuses on this aim, to find and select the best case scenario from both the functional and economic perspective. The method emphasizes that different technical and functional data of newly designed projects (‘n’ project) would be implemented as an input data to the tool. However, the data and information of the existing project considered as the main inputs data to the tool. Analyzing and comparing the data shows the tipping points of different processes and requirements beyond which the reuse is not possible either functionally or economically. In the case that the tool indicates that the examined processes meet the functional and economic requirements, and if this is not the case, then the tool will seek other alternative projects which can act as the best case scenario. Then the salvage value probability should be calculated which play a major role in making decision regarding profitability. By keeping the existing elements in this proposed method which aims to maximize the reusability, the loop of finite materials can be closed. However, this aim depends largely on the level of quality of the existing elements.

CHAPTER 6 | CONCLUSION, DISCUSSION, AND RECOMMENDATIONS

Chapter 6 – Conclusion, Discussion and Recommendations

In this chapter the conclusions will be presented with highlighting of the findings achieved in this research, thereafter the conclusions will be discussed. The conclusions provide answers to the main and sub research questions as formulated earlier in chapter 1. Some recommendations will be given for future studies and also for the practice based on the conclusions of this research.

6.1. Conclusion

The main research question in this study was, '*How can analyzing the functional performance characteristics of existing elements and stakeholder challenges, improve the insight into the reusability of building products for decision-making in construction circularity issues*?' There were also sub research questions realized and formulated which provided a path to find the answer to the main research question.

What are the challenges and obstacles in extending the life cycle of existing building elements in the EoL phase?

Moving towards Circular Economy strategies and sustainability goals, requires appropriate adaptation of CE strategies at the related stages of the construction process. The strategies R3 to R7 (from 10-R framework) emphasizes that the reusability would be maximized as much as possible in the 'extend lifespan of product and its parts' stage of the framework as reusability is one the principal aspects concerning achieving the CE strategies and sustainability objectives. On the other hand, to maximize the reusability of the existing elements it is essential to apply deconstruction process at the EoL phase. Deconstruction can be seen as the process of demolishing a construction project, while it will restore the use of the demolished materials and elements. Deconstruction and DfD has some environmental, social, economic benefits. The application of these concepts contributes, for example, to closing the loop of finite materials. Therefore, the life of raw materials mines will be extended, the cost of materials will be reduced (if the supply chain is mature), and embodied energy and CO2 emissions will be significantly reduced. However, deconstruction and DfD have not yet gained enough success in the construction sector because of its impracticality imposed by standards, codes, and also professional practices.

Thus, to maximize the reusability of the elements it is required to model the process of a system after EoL phase, and to zoom more in on the EoL stage illustrated in the 'Building assessment information' model and compare it to the 'waste management hierarchy' that emphasized maximizing reusability. While, the obstacles which hindering reuse of building products include cost, inconsistent quality and quantity, understanding and also trust between the stakeholder involved, also reuse has been considered labor-intensive. One of the main challenges in the C&D industry is to model the process of a system after EoL phase. In other words, value recovery after EoL phase has not been taken into account as a common practice in construction. So, it is important to measure the reuse potential value of the existing elements by quality performance test that indicates the level of quality of building components of which can be reused, repaired, refurbished, remanufactured, or even recycled. On the other hand, the reuse value can also be measured from a quantitative point of view such as cost, as some intervention activities in the deconstruction process can affect the reuse value. Therefore, it is a great challenge in the (de)construction and waste industry to fulfill different performance tests to estimate thereafter functional and economic feasibility of the existing elements.

What are the functional performance characteristics of concrete building elements? and which external and internal factors affect those functional performances?

Analyzing the functional performance characteristics of existing concrete elements in this research requires to know the level of quality of them. Thus, the remain value, i.e. the reuse potential value of a concrete element such as HCS floors and columns, should be measured which provides insight into the qualitative and quantitative factors of those elements. Each construction project consists of a large number of elements and products with various functional properties. This study aims to analyze and handle the aforementioned characteristics of the existing concrete elements.

The functional features of concrete elements are strength and stability, durability, abrasion resistance, fire resistance, and resistance to passage heat (thermal) and sound. Concrete elements like floor, roof, column and etc. can be used either prefabricated or cast-in-situ. The most commonly used concrete floor in the Netherlands is Hollow Core Slab (HCS) in different forms and with reinforcement materials. Moreover, the concrete elements have been made of different substances such as cement (normally Portland cement), sand, crushed stone or gravel (aggregate), chemical additives and water. The research has showed that the functional performance features of concrete elements depends on the functional properties of the substances used in it. For example, strength, fire resistance and sound insulation of concrete elements depend on the type of aggregate, amount of cement, w/c ratio, density and etc. Therefore, to carry out the functional performance test in order to understand the remain potential value of concrete elements it is necessary to analyze the functional features of substances such as concrete used in the existing elements. For example, the fire resistance of concrete floors depends on thickness and type of aggregate used in it, and this applies for other functional characteristics.

Furthermore, Concrete structures become obsolete and deteriorate with time and these phenomena will affect the performance of the structures significantly. Concrete can be damaged and degraded due to large number of different internal and external factors such as; corrosion of reinforcement - incorrect selection of constituent materials - poor construction methods - chemical attack - hot and cold weather concreting - errors in designing and detailing and etc. Therefore, when the concrete being damaged its two most important functional properties namely; strength and durability affected remarkably and hence the service life of the concrete will decrease.

Which parties involved in the (de)construction and waste industry would benefit from better insight into the Circular Construction Elements?

The (de)construction and waste projects involve a large number of stakeholders including public authorities, private organizations, building owner (client), demolition companies (contractor), dealers, transporters and etc. of various characteristics that may have different opinions, ambitions, interests and benefits on CCE Information System. Nevertheless, the client and the contractor (demolition company) considered as the two main parties in this process. The client should decide whether the construction system would be deconstructed or even demolished. The contractor is the main responsible actor for carrying out the demolition or deconstruction of a building and handling of the released EoL products.

In principle, all the stakeholders involved in the deconstruction and waste industry can use and profit from a harmonized and structured information system developed for the existing elements. However, the client and the contractor would more benefit from better insight into a CCE Information System. As, these two actors play major roles in decision-making regarding the reusability, and they make the most profit or even loss in the deconstruction process. The client and contractor would collaborate with other parties involved in the deconstruction process as much as possible. Therefore, a CCE

Information System can provide them relevant information, facilitate the reuse of the existing elements, and also improve the communication and collaboration between different stakeholders.

Which costs are included in the process of deconstruction for reuse?

All the stakeholders involved in the deconstruction process have their own financial ambitions, and they have to make a profit from this process. Notwithstanding the financial potential, different companies in the C&D sector still experience considerable obstacles to fully taking advantage of the residual economic value embedded in resources. The major economic obstacles can be considered as; high collection costs, low end-of-life material value, and labor intensity as most of current buildings are not designed for dismantling and recycling. It is required to carry out deconstruction to optimize the reusability, however, the deconstruction is a costly process compare to the demolition. So, it is important to calculate the reuse costs which includes deconstruction cost and different associated costs such as the cost of improvement or transport. Analyzing the reuse costs should contribute to understand which costs are allocated to which actors. This makes possible to observe whether the contractor or the client has made a profit or even a loss. Analyzing the reuse cost has also this advantage to perceive which processes in the deconstruction process are costly and have major impacts on the total reuse cost. Therefore, to facilitate the reuse process, maximize the reusability, increase the collaboration among various stakeholders, and support the decision-making in the reuse of existing elements, it is required to realize and develop a centralized, harmonized and structured Information System.

How is it possible to measure the Reuse Potential (RP) factor of a concrete element, and how this measurement contributes to optimizing its reusability?

One of the most important issue in the construction and waste industry is that when one existing building system cannot perform its function anymore and the building may become unoccupied. The elements of this construction system would be disassembled in order to be reused. Creating a Business Process Model (BPM) for the deconstruction process contributes to zoom more in details of each separate processes. Given that the deconstruction process includes different activities that affect the reusability and thereafter the reuse cost. Moreover, the developed BPM for deconstruction provides more insight into the measurement process of the reuse potential factor.

To measure the reuse potential factor of the existing elements it is needed to perform quality performance test that reveals the functional remain value of the elements. The reuse potential value of different functional properties of concrete elements such as strength, fire resistance and etc. would be estimated based on their technical information. This indicates whether the components have sufficient functional ability for reuse. In the next step, the impact of different processes such as improvement and transport on the reuse cost should be analyzed in a real case, which ultimately contributes to measure the reuse potential value of the existing elements from an economic point of view.

What are the critical elements (functional requirements) to develop a CCE Information System for existing building elements such that maximizing the reusability, waste efficiency, and the end circularity of building elements, and also meet the needs of stakeholders involved?

The aim of this research was to conceptualize and develop a CCE Information System in a simple manner in Excel, which consists of an import sheet, a dashboard, and a between tab (analyzing and handling stage). The CCE Information System includes the measured functional properties of existing building elements and covers the cost-related issues of the stakeholders. The structure of CCE Information System was based on the BPM created for deconstruction. It has been attempted to develop such a CCE Information System that includes these two main aspects in an innovative way. Therefore, it has been realized to include some novel technological achievements such as QR-code in the dashboard which facilitates the reuse of product flow in the (de)construction industry.

The import sheet contains technical and functional data for both an obsolete (existing) and a new construction project. Different associated costs obtained from interviews will be the other part of the import sheet. A separate tab is assigned to the analysis and processing phase which shows the procedure of measuring the RP value and also the calculation of reuse costs. The functional properties would be measured using the technical information of the existing project and the results achieved from the laboratory tests in the literature. The costs calculations will lead to understand the economic impact of deconstruction processes and intervention activities such as improvement on the reuse cost and ultimately the profit or loss of the stakeholders.

Once the reuse potential values of all the existing elements have been calculated, decision-makers (contractor or the client) have an Information system, i.e. dashboard, from which to prioritize reuse projects. In other words, all the results and outcomes of previous steps are shown in a dashboard. The dashboard should assist the actors in the reuse process to choose the proper element functionally and economically. However, the CCE Information System would act as a tool, therefore, this tool is able to optimize the reuse process, economically. Therefore, the information and data of other newly designed projects would be needed to be implemented in the import sheet which makes the tool able to combine and find the best case scenario for the existing elements.

Which cost issues and stakeholder challenges exist in the Dutch (de)construction industry?

There are many challenges, constraints and issues in the (de)construction sector that different stakeholders dealing with them generally. One of the approaches applied in this study was conducting interviews with relevant stakeholders to obtain data and information regarding deconstruction cost issues. This data can also be implemented in the import sheet which will be used in the calculation of the reuse costs. Given that the deconstruction process consists of a large number of activities, therefore it is needed to calculate those associated cost to understand whether the existing element has an economic reuse potential value.

One of the most important information achieved from the practice of the deconstruction industry is that fixed prices cannot be derived in this sector. All the costs are estimates and the reason is that for each project and element, costs vary significantly. Some of the deconstruction activities such as inspecting the elements/Inventory/Audit are not very difficult and their costs depend on various factors such as the height of the building. On the other hand, some procedures like stripping, improvement/modification, can be costly to the contractor due to high prices of manpower, equipment and the execution time. It can be concluded that this processes can affect the reuse cost remarkably as the reuse cost can be influenced by different factors.

How can information on functional performance characteristics of the building elements contribute to the improvement of building circularity?

The applicability of the developed CCE Information System is based on its usability in real cases. Hence, an aged building project has chosen which is still under deconstruction process to be renovated. Estimating the RP factor of the existing elements requires the technical data collected from structural drawing. All the functional performance properties of the existing project 'The City Post' have been estimated based on the technical data achieved from the drawing and the data from literature. For example, the fire resistance depends on the thickness of the element, the thickness of the HCS floor used in the project is 210 mm, therefore, it can be substantiated that the fire resistance rating is more than >120 min (240 min).

Furthermore, it is needed to assume some other scenarios beside the transformation scenario to be able to measure the RP factor from a functional perspective. The RP factor of some functional performance features can be measured by a proportion of the estimated functional properties of existing elements and the requirements set for newly designed projects (which can be assumed as 100%). On the other hand, the RP factor of other functional properties like thermal conductivity can be measured by using the method of finding a percentage between two intervals (upper bound and lower bound). The HCS elements had various RP factor in different scenarios. For instance, the RP factor of the element in terms of its strength was 100% for reusing in transformation or bike path pavement project, while this factor reduced to 87% and 70% in sport and healthcare situations. Thus, it can be concluded that the functional performance properties of the elements differ per functionality of target building system and it depends also on the requirements set for newly designed project.

The structure of CCE Information System is realized in such a way that the construction circularity will be optimized. This requires the implementation of analyzed functional performance characteristics of existing elements in the developed CCE Information System. In other words, to maximize the reusability of the existing elements according to the concept of CCE Information System it is firstly needed to estimate the functional properties. Therefore, the functional remain value indicates whether the components can be reused or even improved in terms of different functional features.

How can information on cost-related issues of the stakeholders contribute to maximizing the reusability?

The developed CCE Information System takes also into account the cost-related issue of the stakeholders beside functional performance properties. It is of great importance that the stakeholders involved be able to choose the existing elements with the insight into profitability. To calculate the reuse costs including deconstruction cost, some scenarios have been assumed. This procedure contributes to understand which interventions affect the reuse and deconstruction cost as well, in addition it contributes to measure the RP factor from an economically perspective.

The analysis has shown that the stripping process influenced the deconstruction cost negatively. On the other hand, the improvement and transportation process is considered to be the most expensive processes in the reuse cycle. These two processes affected the reuse cost approximately between 20% to 40%. Consequently, the RP factor was measured, and it appeared that in no situation the elements can economically be reused expect of reusing in transformation and infrastructure. However, the contractor's profit from the reuse process in the infrastructure project depends on the salvage value (revenue) that is achieved through the sale of the elements. It can also be concluded that the impact of different intervention depends on various factors. For example, the functional remain value determines the level of impact of improvement process on the reuse cost, and the distance between the deconstruction site and storage yard/new construction site/treatment company determines the level of impact of transport process on the reuse cost.

Therefore, it can be mentioned that the client or the contractor (demolition company) can deal with many costs uncertainties, including benefits and loss. These parties may face different uncertainties that can arise due to many reasons such as the exceedance of process time, additional labor costs, and uncertainties regarding salvage value. Because if the market has insufficient capacity to offer the contractor the sales market, the risk that he will make a loss is greater than the benefits.

How could a CCE Information System maximize the reusability of the existing elements?

One of the main aims of this research was to maximize the reusability of the existing elements by optimizing the shortcomings in the reuse process. Moreover, one of those shortcomings is related to the economic issues of key stakeholders. They must make a profit from the reuse process otherwise the reuse process has meaningless to them. In order to make an economically feasible reuse process, i.e. profitable for both the contractor or for the client (new buyer), it is necessary to optimize the reuse process which included different fixed and variable costs.

The CCE Information System would also serve as a tool which be able to opt the elements from various cases, analyze them, combine the scenarios, and find the best case scenario to the contractor. All these procedures can be fulfilled by different methods, such as random sampling, goal attainment that can be done in Excel or in Matlab. Firstly, it is needed to estimate the desirable and undesirable scenarios of the intervention processes such as stripping and then optimizing the worst scenario. This approach contributes to find the desirable (best) case scenario of each intervention. By analyzing the impact of different processes on both the deconstruction and reuse cost it can be concluded that which price can be considered as an upper limit, which helps thereafter to find the tipping point of each scenario. Finding the tipping points refers to the highest value of a variable cost element, as above which deconstruction or reuse of that given element becomes uneconomical or not profitable. The results showed that e.g. the improvement intervention can be done within 42 hours and still have a profitable reuse process and this applies for the other interventions. Therefore, an optimization method has been ultimately presented which aims to illustrate and describe all the ideas behind the concept of CCE Information System. The proposed method tries to close the loop of the existing elements as much as possible by linking the elements to a suitable project. The purpose of the method is exactly in accordance with the 'waste management hierarchy' that emphasizes maximizing reusability.

The main research question; '*How can analyzing the functional performance characteristics of existing elements and stakeholder challenges, improve the insight into the reusability of building products for decision-making in construction circularity issues*?'

Moving towards Circular Economy strategies and sustainability goals, requires appropriate adaptation of CE strategies at the related stages of the (de)construction process. There are different aspects such as functional performance characteristics and cost-related issues of the stakeholder need to be analyzed, handled and improved in the reuse process. The research showed that these two aspects are strongly related to each other in order to maximize the reusability. Thus, developing a 'Circular Construction Element Information System' that takes into consideration the aforementioned aspects can contribute largely to the optimization of reusability.

The analysis of functional performance properties resulted to insight into the functional remain value of the existing elements and subsequently the economic impact of different intervention processes on the reuse cost. On the other hand, the stakeholders involved in the reuse process need to make a profit, therefore, analyzing the reuse cost provides them a better insight into the decision-making regarding profitability. So, it has been attempted to base the concept and structure of the developed CCE Information System on these two reuse aspects which are related to each other and also cover the main aim of this research.

6.1.1. Limitations

However, the proposed CCE Information System has proven to meet the goals of this study, although there are some limitations of the tool that would be noted. The developed CCE Information System is a simplification of the reality, and it means that some factors that may affect the course of the deconstruction and reuse process have not been included.

- The deconstruction for reuse process faces a large number of uncertainties that affect the reuse process and subsequently the reuse cost. The proposed CCE Information System did not take into consideration those uncertainties such as exceedance of process time, additional labor costs.
- Determining the costs of different activities in the deconstruction process is chaotic and irregular with a lot of estimates. The cost calculations therefore can be varied remarkably.
- The RP factors and tipping points are measured and calculated just for HCS elements. The essence of the tool is to function also for other components as well, but it is not examined in the proposed tool.
- The CCE Information System functions in the availability of data, but it is sometimes difficult to collect the required data due to the lack of transparency in the (de)construction industry.
- The proposed CCE Information System did not take into account the Environmental Costs Indicator (ECI) (in Dutch; Milieu Kosten Indicator - MKI) and is not calculated within the CCE Information System environment. The tool therefore does not provide insight into the reuse costs that take into account the calculated MKI value.
- The lifetime performance of the HCS floor element is related to the lifespan of the HCS element and also the degradation mechanisms that can affect the lifetime of the element. Based on the information about the lifetime of the construction project itself, the lifespan of the element can be determined. The degradation mechanisms (such as environmental factors; moisture) can affect the life of the floor element when the element exposed to the environment, e.g. an element used in parking garage. These degradation mechanisms (external factors) must be demonstrated and also investigated whether they have affected the lifespan. This investigation can be performed by an expert. Nevertheless, it was not possible to calculate the residual lifespan of an element by taking into account the degradation mechanisms in the proposed CCE Information System by conducting either a visual inspection or a calculation. Because, there are many complex factors involved in the reuse process, a specialist or expert would always be needed to estimate and determine the remaining lifetime.
- The technical data and information are necessary to estimate the functional performance properties of existing element, and thereafter to measure the functional reuse potential factor. These specification data and information can be gained from existing technical drawings and construction calculations. However, if there are fewer technical drawings or the drawings do not contain the needed data, or are not legible, then the element should visually be inspected. This takes a lot of time and is a costly process. Therefore, the use of assumptions may reduce the reliability of the calculations.
- There are some other factors that can affect the disassembly process and subsequently the deconstruction cost such as type of connection between the elements. However, the disassembly process can also be affected by more other factors, such as the removal of the concrete topping, the size of the construction project to be dismantled, the available devices and equipment, and etc. The developed CCE Information System did not take into consideration these factors because of inadequate information about the effects of these factors.

6.2. Discussion

In this part of the research, some topics will be discussed which play an important role in the evaluation of the developed CCE Information System from various point of view. In the first part of the discussion the tool will be discussed, followed by the second part which covers the role of the tool in achieving the circularity goals. Therefore, to explore my proposed solution, topics like the working of the tool, the evaluation of the aim of the tool and etc. would be addressed. In this way the reliability, validity and also usability of this study and the developed CCE Information System can be investigated.

The aim of this research was to develop a Circular Construction Element Information System which functions as a tool and tries to optimize the reusability of the existing construction element by taking into consideration the functional performance characteristics and cost-related issues of the stakeholders. The tool must still be assessed and applied in different situations and scenarios to understand whether the tool functions appropriately and also to achieve the circularity goals.

The functionality of the tool: One of the main assessment aspects to consider is to investigate whether the proposed CCE Information System functions properly, applied in different scenarios and cases. The developed tool should support different stakeholders in decision-making on the reusability of the existing elements from a functional and economic point of view. This aim is also in accordance with the CE strategies and the waste management hierarchy. Thus, the functionality of the CCE Information System to transmit the insight obtained in this research is of crucial importance.

The CCE Information System has been developed in Excel program in a simple manner. Additionally, in order to facilitate the use of the tool for the end-user the analysis and processing stage needs to be programmed in different software such as Matlab, Python or even in Excel. So, the proposed tool tries to provide the needed guidance and steps to different users, an expert with significant experience in reuse process, a programmer and an end user like a contractor who want to be informed about the profitability of his activities. In the explanation of functioning of the concept of the tool it has been tried to use short-cuts for the users as the tool consists of different steps. This will also provide a clear insight into the arrangement of steps, the information and data needed for each step and the required formulas for calculation of cost-related issues. This may ensure that the results and outcomes of the CCE Information System is not be misinterpreted. The functionality of the tool is based on the two main subjects of this research, namely the functional performance properties of the existing elements and the cost-related issues of the stakeholders in the reuse process. The essence of each sheets developed for the tool is based on these factors. On the other hand, the concept of the tool is designed in such a way to keep the existing elements in a closed loop by linking them to an appropriate project, functionally and economically. The presented results in dashboard of the tool, provide the user different insights into the reuse process and this means that the tool functions significantly. Also, the functioning of the tool emphasizes that the reuse process can be optimized from various point of views.

However, it is possible that some diagrams, the results shown in percentages or other demonstrated technical aspects are not comprehensible and perceivable for, for example, the contractor. The functionality of the analysis and processing stage which consists of different calculation and programming subjects has been conceptualized for an expert with the coding and programming ability. Because this stage is realized to carry out the analysis and processing steps that will lead to the optimization of the reuse process. On the other hand, the tool is a proof of concept based on the use cases, therefore it is necessary to explore more other issues and topics related to the process of deconstruction for reuse.

Optimization points: The tool tries to take into consideration the factors that did not already handles by other software and tools. The functionality of the proposed tool will contribute to the challenge of the wider context, reducing the waste from construction industry by maximizing the reusability. However, the functionality of the proposed CCE Information System has undoubtedly some issues e.g. some diagrams and results may be not comprehensible or understandable for some users or due to the lack of data assumptions would be used, or the lack of the connection of the tool to a central data server. But, these issues can be resolved and improved when the tool will be applied by various users from the practice in the reuse process.

Therefore, some functioning part of the tool such as presenting of the outcomes or using from simpler diagrams can be discussed. The RP factor measured for lifetime of a HCS floor element is presented in percentage, while perhaps comprehensibility of this percentage is difficult for a non-expert user. The availability of the structural drawings is substantial for the tool which need be implemented in the import sheet and thereafter gathered in a database, this can interrupt the functionality of the tool. But, there is no other alternative options to use the data and information of the existing construction elements from the past when there was no possibility to archive the data, expect using of the drawings. It has been attempted to implement the technical data from which the functional performance properties can be estimated. However, those functional performance features are widely dependent on many other technical aspects of elements. Thus, it is possible to use other technical data and information to measure the RP factor.

Advantage of using the tool: This question may be arising who can benefit from the developed CCE Information System. The tool has been conceptualized with the aim of maximizing the reusability of the existing elements. Different stakeholders are involved in the reuse process as already discussed in previous chapters. There are two main actors who can largely apply the developed tool in their reuse systems. The client or owner of the project and the contractor (demolition companies) playing major roles in deconstruction for reuse process. These two actors are involved in a large number of intervention activities and decision-making. Thus, the aforementioned parties can have the most benefits from using of this tool. The tool provides them clear information regarding the reuse process from a functional and economic perspective. Additionally, the tool facilitates the complex, chaotic, dynamic and careless market of deconstruction for reuse by connecting all actors together and stimulating the collaboration between them, as this market still faces the lack of a centralized and harmonized tool for reuse of the elements. Nevertheless, the tool can be useful and beneficial for all actors involved in the deconstruction process, but it just depends on their needs and requirements of the tool.

The role of the tool in achieving the circularity goals: This study showed that (de)construction and waste industry is still encounter different issues regarding the optimization of reusability. This industry should be circular and also moves towards using CE strategies before 2050. The amount of the existing elements being reused is not sufficient and therefore, the deconstruction sector must take more innovative and sustainable measures in order to stimulate the reusability.

To optimize the reuse of the existing construction elements it is essential to analyze and address different aspects of sustainability and circularity. A large amount of waste elements in the construction sector being recycled after EoL phase, but this is not in accordance with the 'Waste Management Hierarchy' that emphasizes to maximize the reusability of the existing elements. Hence, it has been attempted in this research to handle the important factors of the existing elements at the EoL stage which can contribute to the optimization of reusability. Each existing element needs to satisfy the required functional performances set in the design phase or NEN-NORMS for the newly designed projects, thus the functional performance characteristics of those elements would be examined with high attention. On the other hand, there are different stakeholders involved in the deconstruction process, all with various benefits, ambitions and economic visions. In other words, to stimulate the reusability of the elements it is undoubtedly important to make a profitable reuse process for those actors, otherwise they do not have any motivation to engage into the reuse process. If just a small percentage of the existing elements being reused by applying the CCE Information System, then it can be concluded that the tool had a significant footprint regarding the circularity issues. The construction and waste sector can apply this tool to prepare for the CE around the reuse of building elements. Given that the CCE Information System tries to stimulate the circularity and sustainability by optimizing the reusability addressed in waste management hierarchy model.

The impact of reuse process on the environment: The reuse process which consists of many activities can also have an environmental impact. By using Life Cycle Assessment, the environmental contribution in different life cycle stages such as EoL phase, can be identified. This research was focused on the End-of-Life stage from 'Building assessment information model', namely C1-4 including deconstruction, transport, waste processing, and disposal (described in chapter 2, part 2.1.2). All these intervention activities like transport can impact environment remarkably. This envormental impact can be assessed in various impact categories such as (Global warming, Human toxicity, Eutrophication, Freshwater aquatic eco-toxicity, Acidification Potential of land and water, and etc.). The Life Cycle Assessment can thus contribute to more insight into the environmentally right selection of building materials/elements by make a comparison among the environmental scores with each other. Calculating a building's Life Cycle Assessment helps to make knowledgeable decisions and gain true sustainability. In order to classify the aforesaid environmental impact categories in one-unit indicator, the Environmental Cost Indicator (ECI) (in Dutch: Milieu Kosten Indicator-MKI) has been applied in the Netherlands. MKI makes it possible that different environmental impact categories are weighed up against each other and thereafter translated into a number which reflects the social costs for these impacts in Euros. The MKI are also related to the terms shadow price or in other words prevention costs. Different environmental impacts will be weighted on the basis of the shadow price method. The shadow price is the highest acceptable cost level determined by the governments per unit of emission control (prevention costs). so, the total environmental costs (total MKI) can be determined by adding up all the calculated environmental costs of each environmental impacts on the basis of all life cycle stages (like EoL phase).

This research has focused on measuring the reuse potential factor from a functional and economic point of view, and the developed tool did not take into account the environmental impact costs, namely MKI. As already mentioned, different interventions activities such as transport or improvement can affect the environment negatively by e.g. more CO_2 emissions or global warming. Transporting the exiting element from the city of Zwolle to the treatment company or even to the new construction site requires using fuel for the trucks. By calculating the economic RP factor of each element, the MKI can also be added up to the calculation, or a separate RP factor can be measured for just the environmental impact (MKI) of the reuse elements and compare it to the environmental impact of a newly manufactured elements in the factory. In this way, the tool will provide one more step towards the achieving of the sustainability goals, beside the obtained circularity aims provided by the CCE Information System.

6.3. Recommendation

In this part recommendations for future studies and for the practice will be presented based on the findings and conclusions of this research.

- *Recommendations for future studies*:

Taking uncertainties into consideration: The deconstruction process consists of large number uncertainties, as already explained. The execution time can be exceeded, the labor cost may increase and more other uncertainties. This question may arise how can these uncertainties affect the deconstruction processes, and consequently affect the reuse cost, as these uncertainties will take into consideration.

Applicability of the tool in other fields: The use of finite materials would be minimized and this aim is not applied just for construction industry. For example, the automobile industry tries also to manufacture cars from the waste extracted from the oceans. The future research can analyze and apply the concept of the developed CCE Information System in different fields to perceive to what extent the results and contributions of this tool can help to maximize the reusability of waste elements in the relevant fields.

Legal and Finance: One of the main barrier in the reuse process is the high costs of activities and processes. Governments should therefore take economic-related measures, such as abolishing or deducting taxes in some processes to make reuse more profitable. This can be a challenging subject for the future studies to analyze which regulations would be needed in the reuse process and in addition to what extend will deducting or abolishing taxes affect the profitability of reuse process.

More references projects: The essence of functioning of the proposed CCE Information System is based on real cases, thus it is substantial to gain more data from more reference projects. Because through the variation of parameters and data from different reference projects, more general and reliable results can be achieved. A future research can be fulfilled by using for example a few more of case studies all with different functions.

Socio-economic: Moving towards sustainability aims, more research will be needed on different sustainable topics. The developed CCE Information System can still be enriched from different sustainable perspectives. The effect of noise pollution, damage to ecosystem or employment through deconstruction can still be studied and the results can be implemented in a more enriched Information System.

Labor productivity: According to the literatures, the two main measures of labor productivity are as follows: the effectiveness and efficiency with which labor is deployed in the (de)construction process; and the relative efficiency of labor doing job is needed at a specific time and place. The labor productivity can be an interesting subject to be analyzed and eventually added to an enriched Information System.

- *Recommendations for the practice*:

Governments and legislators: In order to make the reusability of the existing elements profitable, it is highly necessary to take different policy measures. For example, some environmental policy such as the landfill ban in building waste industry, Provincial Environmental Regulations and adjustment or improvement of the Building Materials Decree appear to have a positive effect on the adoption of reuse.

Moreover, increasing taxes on raw building materials and substances, taxes on gravel would be applied across Europe which can also maximize profitability in the reuse process. To make the reuse of existing components more effective, a competitive market would be arisen for secondary elements which makes a balance between the new and secondary elements. This aim can be obtained by substantiating landfill taxes in such a way that higher taxes are set for reusable elements when wasting them. Once the products that need policy support are identified, these taxes can be regulated. On the other hand, it can be suggested that some technical and financial support (subsidy), such as tax deductions for salvaged components, and land acquisition loans to demolition and treatment companies, will boost the reuse market and create more job opportunities.

It is very difficult to optimize the reusability if left merely to the private market forces, therefore it needs active government legislation aid. On the policy fronts, element and building codes would be adapted and alternative solution ways for existing elements should be provided. In order to diminish the risk, the government would set up a system of certifications and guarantees. Furthermore, the government authorities should increase their support for local economic development policies such as granting subsidies and low-interest loans, in this way secondary market can be established, more job opportunities will be created, and the reuse of elements will be stimulated.

Architects and designers: In order to maximize the reusability of existing elements it is required to adopt DfD in the design phase of each project. Architects and designers involved in the design process need to have sufficient information about the existing elements and procure these elements by incorporating them into their design. Therefore, it is highly recommended to apply a developed CCE Information System which provides them insight into different technical and functional aspects of the existing elements like dimension that they can use e.g. a similar structural grids and etc. in the design phase and reuse the elements with the highest value recovery.

The client (project owner): The other key actor in the deconstruction process is the client who should decide whether the project can be demolished or deconstructed. By involving the contractor in earlier stages of deconstruction process and allowing the demolition companies to collect and sell the existing elements to a third party (new buyer), allowing more time to deconstruct the project, the probability that the client will be motivated to deconstruct the project will enhance remarkably.

Demolition contractors: One the main actor in the deconstruction process is the contractor (demolition company) who is responsible for performing of different processes. On the other hand, one of major issues in the deconstruction sector is the lack of cooperation and communication between the parties. Demolition companies would try to expand their communication and networks in order to tackle inconsistency in demand. They have to abolish the monopoly of their developed data products and also share their information through a centralized, harmonized and structured data platform. Thus, improving the communication and collaboration among demolition companies will undoubtedly facilitate and accelerate the reuse process.

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