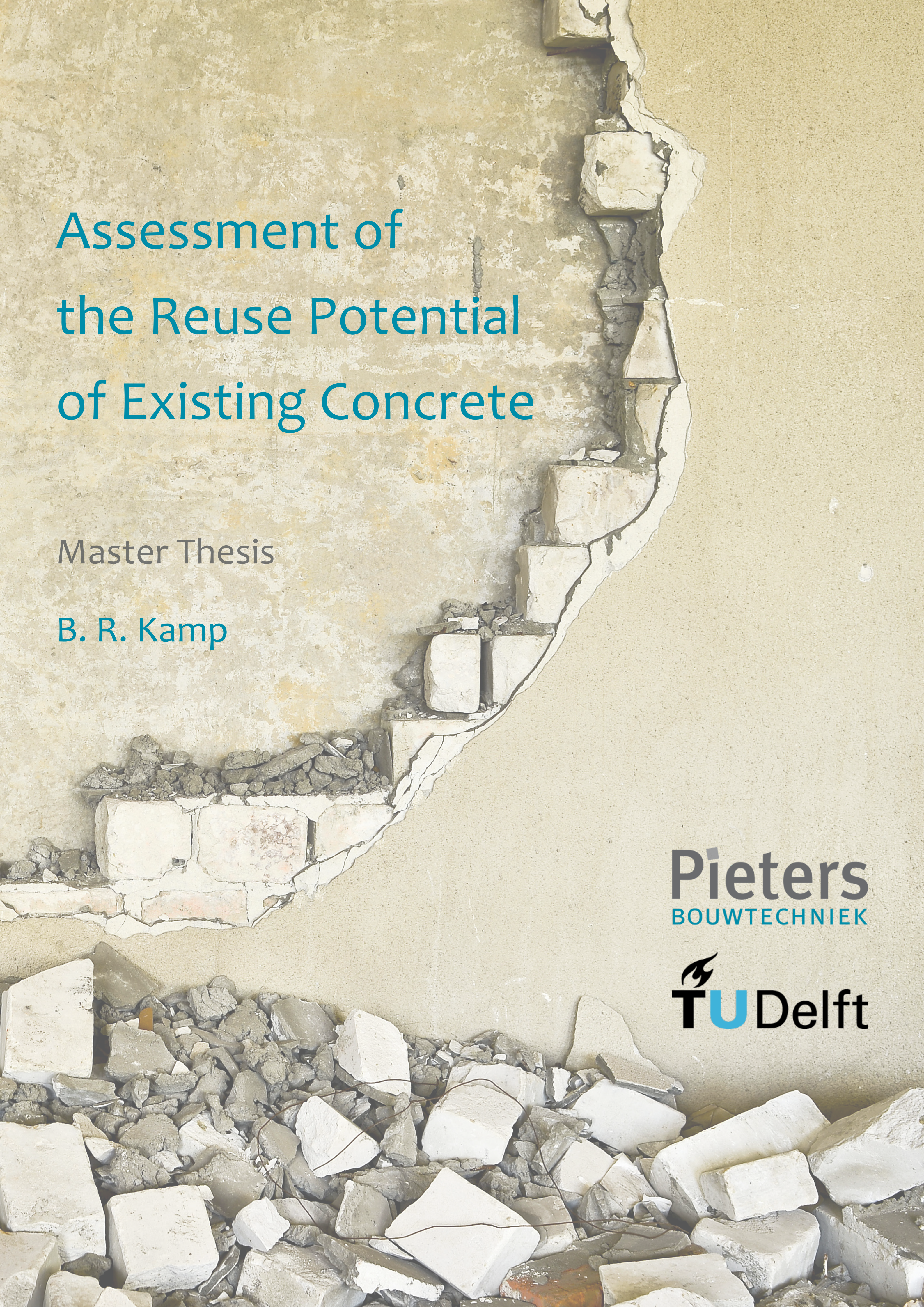

Assessment of the Reuse Potential of Existing Concrete

Master Thesis

B. R. Kamp

Pieters
BOUWTECHNIEK

TU Delft

A new type of thinking is essential if mankind is to survive and move toward higher levels.
- Albert Einstein (1946)

Front page: Partially destroyed wall inside an industrial building under demolition by Ostariyanov (Stockphoto-ID: 748511770)

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Assessment of the Reuse Potential of Existing Concrete

Enhancing circularity in the Dutch building sector by harvesting structural elements from demolition projects

by

B. (Bente) R. Kamp

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During my childhood, I was already fascinated by buildings that define the world in which we live, now and in the future. An obvious choice was to study Architecture at Delft University of Technology. This Bachelor integrates design, engineering and theory into the built environment. As I gained more interest in structural and technical challenges of buildings I decided to follow a Master at the faculty of Civil Engineering. During my Master Track Building Engineering (BE) I have specialized on Structural Design, a field of study which enthusiasts me greatly. In front of you lies my thesis which marks the end of my master's program.

During my studies, I became aware of the impact the construction sector has on the environment and that the planet pays the price for what we are building. In order to keep our planet habitable in the coming years, the construction sector is currently facing the transition towards a Circular Economy (CE) that eliminates residual waste and requires a fundamentally different way of dealing with raw materials. In the Netherlands, a circular way of building is aimed for in 2050. However, proposed actions and interventions are limited. For this reason, I have chosen to combine my structural knowledge and sustainable interests in my master's thesis topic and to make the theoretical research operational. This thesis is developed to become one of the first steps towards the reuse of concrete elements, and to spread my belief to achieve a circular way of building.

This thesis has been performed in collaboration with Pieters Bouwtechniek, where I was supervised by Paul Rijpstra and Cecilia Braendstrup. First, I would like to thank Paul for overseeing the bigger picture of my thesis, without losing the details out of sight. You pointed me in the right direction and shared your network, which brought me to colleagues and external parties at the right time. Cecilia, I would like to thank you for enthusiastically following my research developments and asking me the right questions, that forced me to critically review my research. Even more, your drive regarding sustainability was inspiring to experience. In addition, I would like to express my gratitude towards all other people at Pieters Bouwtechniek Amsterdam for the inspiring and enjoyable working environment. You have given me valuable insights into sustainable engineering and helped me to develop the Decision Support Tool. I appreciate all the input, cooperation and enthusiasm of the interviewees and executors of the test-case which was essential for the research process. Especially, the discussions about the implementation of the Decision Support Tool in practice motivated me even more. Furthermore, I am grateful for the opportunity to follow the disassembling of De Nederlandsche Bank (DNB), where I gained practical insights for reuse that I could not have imagined in advance.

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For now, I have only one comment left to the readers of this thesis: **enjoy**!

Bente Kamp

Delft, July 2021

Executive Summary

The increased concentration of greenhouse gasses (GHG) in the atmosphere, such as carbon dioxide (CO_2), is a critical environmental issue. One of the largest contributors to the total global CO_2 emissions are structural materials, of which cement causes 8% (2016). Cement is widely used in the concrete elements of the superstructure of buildings. This means structural engineers can be pioneers when it comes to reducing the carbon footprint of building materials. Other critical environmental issues are the disposal of waste and the resource depletion of the *take-make-waste* model. In order to address today's challenges, this linear economy can be converted to a Circular Economy (CE) by keeping products in use and by designing out waste. In the construction industry, one way of reducing the use of raw materials is by transforming waste residuals from demolition projects into resources to be reused. By implementing these resources in new buildings, the supply of harvested (structural) elements and the demand of resources in new buildings can be matched.

Due to the high amount of embodied carbon in superstructures, this research focuses on the reuse potential of harvested concrete (structural) elements in the design of new buildings. The demolition and construction of buildings is analysed from the point of view of structural engineers with an extensive literature study, interviews and a case-study. This analysis considers the principles of the Circular Economy (CE) and results in the definition of the process of Deconstruct & Reuse, as illustrated by Figure 1. This process considers three phases: the first Phase (Pre-Disassembling) and second Phase (Disassembling & Post-Disassembling) both analyse existing concrete which is available in demolition projects and the potential to reuse a harvested (structural) element. The third Phase (Re-Assembling) analyses the possibility to implement a second-hand element in the design of a new building during the initial phase. Here, the input of structural engineers to initiate circularity has the greatest potential to affect the design of a new building.

The three phases of the process of *Deconstruct & Reuse* are subdivided into indicators which are of interest for structural engineers. Next, the indicators which affect the reuse potential of harvested concrete (structural) elements in the design of new buildings are arranged in seven Stages. An overview of the assessment of the reuse potential in Phases, Stages and Indicators is shown in Figure 1. The assessment is made operational in the Decision Support Tool, which makes this research the first of its kind. In order to assess the reuse potential, all indicators of the process of *Deconstruct & Reuse* have been written into assessment questions. The needed information to answer these questions is analysed in combination with how this information can be retrieved. Next, the retrieved information per assessment question is translated into answer options. All answer options are graded and a range of uncertainty is applied according to the Fuzzy calculation, which indicates the unfavourable or favourable value regarding the reuse potential of an element with any number between 0 and 1. Based on the filled-in answers in the Decision Support Tool, the reuse potential with related risks and advice can be generated at the end of each Phase, as shown in orange in Figure 1. The output can be generated in the form of a PDF file and used as a subject for discussion with the client or other parties.

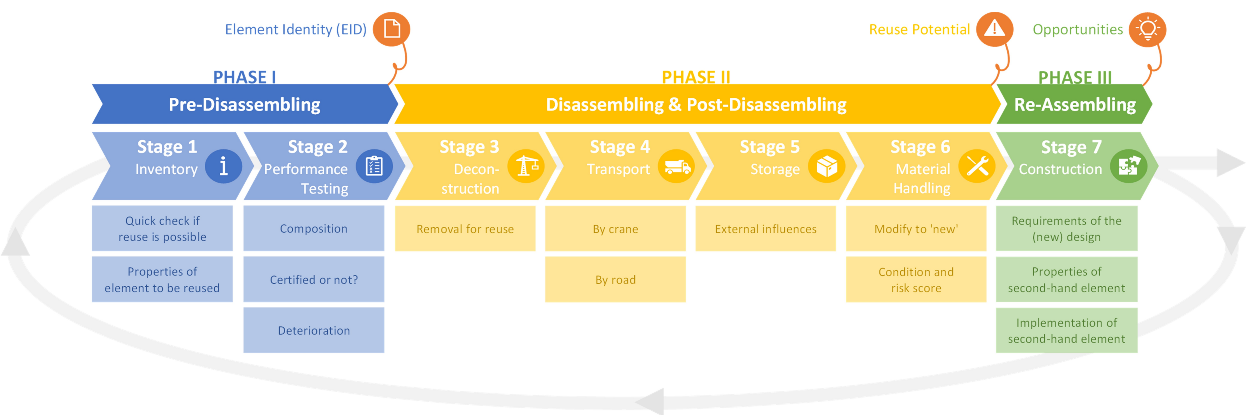

Figure 1: Assessment of reuse potential of existing concrete in Phases, Stages and Indicators (own figure).

The three phases of the process of *Deconstruct & Reuse* assess the reuse potential as follows: (Figure 1)

- *Phase I: Pre-Disassembling*
  The Pre-Disassembling Phase is divided into two stages, indicated in blue. In Stage 1 (Inventory), existing information of a concrete element is reviewed by drawings and desk research. With a quick check, it can be determined if reuse is possible according to the following so-called deal-breakers: condition, residual lifespan, accessibility of the connection and transportation. If reuse is possible, the properties of the element are investigated. In Stage 2 (Performance Testing), information on site is researched. First, it is determined if the filled-in properties of Stage 1 can be certified by testing, followed by examining the presence of toxic materials in the composition. Last, internal and external deterioration are investigated. The output of Phase I is the Element Identity (EID) of the harvested (structural) element.
- *Phase II: Disassembling & Post-Disassembling*
  The Disassembling Phase and Post-Disassembling Phase are divided into four stages, indicated in yellow. In Stage 3 (Deconstruction), the removal for reuse is investigated considering the (applied) equipment to disconnect. In Stage 4 (Transport), transport by road and by crane are considered. If the element is already deconstructed, the susceptibility to external influences is analysed in Stage 5 (Storage). In Stage 6 (Material Handling), modifications of the element are investigated considering a (new) precast element. In addition, the fire resistance and the condition and risk score are examined in Stage 6. The output of Phase II is the reuse potential per Stage carried out in Phase I and II. With this information, the possibility to implement the harvested (structural) element in a new building can be asessed.
- *Phase III: Re-Assembling*
  The Re-Assembling Phase considers one stage, indicated in green. In Stage 7 (Construction), the design requirements of the new building are investigated based on the properties of the assessed element. In addition, the implementation of the second-hand element is considering the equipment required to reconnect. In each option, the relative merits, general procedure and adaptation of the element are investigated. The output of Phase III indicates the opportunities of the second-hand (structural) element in the design of a new building.

The Decision Support Tool is validated and verified with a test-case executed by the researcher and by experts, resulting in four aspects for use in practice. Firstly, by guiding the executors of the Decision Support Tool through the process of *Deconstruct & Reuse*, awareness is created about the reuse potential. Thereby, the executors concluded that the assessment includes all information needed to assess a harvested concrete (structural) element on its reuse potential and its possibility to be implemented in the design of a new building. Secondly, the Graphical User Interface (GUI) of the Decision Support Tool can be executed in a relatively quick manner by structural engineers leading to unambiguous and comparable results. The output in the form of a PDF is easy to understand and discuss with other parties, which lead to more reuse of concrete (structural) elements. Thirdly, the assessment depends on the judgement of the executor which means the output of the Decision Support Tool can only be interpreted as advice. Nonetheless, during the initial phase structural engineers can advise the client about the use of second-hand elements instead of new elements. Fourthly, unfamiliarity, sensitivity and lacking information to answer assessment questions in the Decision Support Tool can generate skewed results. The fixed and 'unknown' answer options, explanations and range of uncertainty deal with this.

For further research, it is recommended to investigate the legal liabilities of the process of *Deconstruct & Reuse*, because the needed information to assess the reuse potential can depend on other parties. Additionally, reuse can be enhanced even more by stating its environmental impact, economic value, or by combining the supply and demand of harvested elements with a database. The next step is to extend the assessment for buildings as a whole, for multiple connections, for other (concrete) elements and materials. Additionally, the assessment can be automated by integrating standards or linking 3D models (BIM) of existing and new buildings to be able to assess the reuse potential during its service life.

In conclusion, the Decision Support Tool has a high practical value as it stimulates the reuse of concrete elements through an operational method. The output provides valuable insights with which a structural engineer can decide if a harvested (structural) element can be reused and implemented in a new building. Hence, the assessment of the reuse potential is considered to be a step towards circularity in the construction industry.

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Acronyms

Notation	Description	Page List
ASR	Alkali-Silica Reaction	38, 45, 120, 132, 133, 136
BCI	Building Circularity Indicator	25
BIM	Building Information Modelling	86, 90, 94, 99, 113
BOM	Bill of Materials	22, 114
C&DW	Construction and Demolition Waste	1, 3, 11
CDC	Circular Design Collective	113
CE	Circular Economy	4, 5, 12, 15, 95
DNB	De Nederlandsche Bank	x, 3, 10, 20, 46, 58, 65, 69, 155, 156, 161–163
EID	Element Identity	28, 43, 44, 46, 84, 114
EoL	End of Life	25, 39, 115
GHG	Greenhouse Gasses	1, 3
GUI	Graphic User Interface	11, 31, 89, 91, 93
HCS	Hollow Core Slab	147, 148
LCA	Life Cycle Analysis	15
NDT	Non-Destructive Testing	22, 44, 116, 134
RS	Reuse Scenario	23
RSL	Reference Service Life	5, 6, 17, 39, 60
SDG	Sustainable Development Goals	4, 12, 95
UMC	Urban Mining Collective	113

Glossary

Notation	Description	Page List
Circular Economy	design process which eliminates residual waste and requires a fundamentally different way of dealing with raw materials.	iv, 4, 5, 10, 12
Decision Support Tool	executable method to assess the reuse potential of harvested elements of existing concrete structures. The aim of the Decision Support Tool is to allow structural engineers to make use of harvested (structural) elements in the design of new buildings.	iv, 11, 30, 67, 89, 93, 95
deconstruct	operation by which it is technically feasible and viable to recover the residual value of harvested elements of existing (to-be-demolished) structures.	iv, 15, 92
Fuzzy calculation	any number between 0 and 1 is assigned to a indicator where 1 stands for the most favourable value regarding the reuse potential of an element ('true') and 0 for the least favourable value ('false').	iv, 31, 32, 89, 91, 93
reuse	operation by which a product its components or materials can be used again for the same purpose/function for which they were conceived. The waste is prepared by checking cleaning or repairing recovery activities to be reused without the need for any modifications reprocessing or treatment.	iv, 19, 92
reuse potential	possibility to reuse a harvested concrete (structural) element in the design of a new building considering the process of 'Deconstruct & Reuse'.	iv, 26, 33, 92
substructure	portion of a building that is constructed below ground level (i.e. foundation and plinth)	2, 98
superstructure	part of the structure that is constructed above ground level (i.e. beams/columns/slabs/all finishes and frames)	iv, 2, 3, 9, 11, 15, 42, 123

1 | Introduction

This Chapter describes the motive of this research concerning the need for circularity in the building sector in Section 1.1. Following that, the state of the art is presented in Section 1.2. This Chapter finishes with the problem definition (Section 1.3) upon which the research approach is elaborated in the subsequent Chapter.

1.1 Motive

Awareness about our planet is more important than ever before. Every day, journals write about crossing the borders of the planet in terms of climate change, biodiversity, the Nitrogen and Phosphorus cycle and water. Ultimately, the limits of resource depletion and scarcity will be crossed if nothing changes [Stolk, 2018]. In order to reverse this situation, appropriate measures must be taken to protect the environment. Critical environmental issues are the disposal of waste, resource depletion and the increased concentration of greenhouse gasses (GHG).

During the early days of industrialization (almost 250 years ago), a linear model of resources consumption was established, known as the 'take-make-waste' principle [Ellen MacArthur Foundation, 2013]. This means that the materials and energy which are used to make a product are thrown away when they no longer serve their purpose. This consumer-focused model, or 'linear model', thus leads to additional waste disturbing ecosystem services. Considering the Netherlands, Construction and Demolition Waste (C&DW) is accountable for 47% of the annual incinerated waste and landfill in 2010. 40% of this C&DW originates from concrete, 26% of asphalt and 25% of masonry. Next to the disposal of waste, the building sector is accountable for the depletion of more than three billion tonnes of raw materials worldwide [Bijleveld et al., 2015; Bijleveld and Beeftink, 2020; Glias, 2013; Stofberg and Duijvestein, 2008, p. 10]. Since the earth population grows significantly, more incinerated waste and landfill can be expected in the forthcoming years. Additionally, the availability of resources is challenged like never before. This accelerates the current exceedances leading to the scarcity of raw materials [Stolk, 2018, p. 33]. The depletion of raw materials can be stopped by reducing the use of raw materials which can be achieved by minimizing the damage caused by the extraction, by using different types of materials or by considering waste residuals and resource use [Glias, 2013].

By minimizing resource use another critical environmental issue reduces too, namely the concentration of greenhouse gasses (GHG). Especially, the increased concentration of carbon dioxide (CO_2) in the atmosphere forms a problem. Considering the total global greenhouse gas emissions, the building sector is responsible for 38% of which structural materials form one of the largest contributors [Rodgers and Chatham House, 2018; Glias, 2013]. The most applied structural materials (concrete, steel and aluminium) account for 22% of the total global CO_2 emissions (2016), of which cement forms 8% due to the need for large amounts of energy, quarrying and high levels of CO_2. Since 1990, the production of cement has increased almost fourfold resulting in 2,2 billion tonnes of CO_2 emissions in 2016 [Kent et al., 2019; Watson, 2020].

Concrete is one of the most applied structural materials, while concrete is also one of the largest contributors to the carbon footprint of buildings. In order to reduce the embodied carbon in concrete buildings, different applications of concrete can be considered. The environmental impact of the production of a cubic meter of new, recycled and reused concrete is compared in the research of Salama [2017]. The findings show that the production of reused concrete results in a considerably lower environmental impact compared to the other applications of concrete (Figure 1.1).

Additionally, the embodied carbon in concrete buildings can be reduced by analysing the highest CO_2 emission per type of structure and components. The research of Brand [1994] refers to the type of structure as the 'structural layer' which forms 55% of carbon footprint of a typical building. The structural layer can be distinguished in the superstructure and substructure, where the first mentioned implies all beams, columns, walls and slabs and the latter implies the foundation. The research of Kent et al. [2019] and Watson [2020] compares the structural system of residential, educational and commercial buildings. As can be seen in Figure 1.2, the highest proportion of embodied carbon is in slabs (40-47%), which is followed by walls (16-25%). In total, the superstructure accounts for approximately 80% of the of the embodied carbon of the structural layer, whereas the substructure forms around 20%.

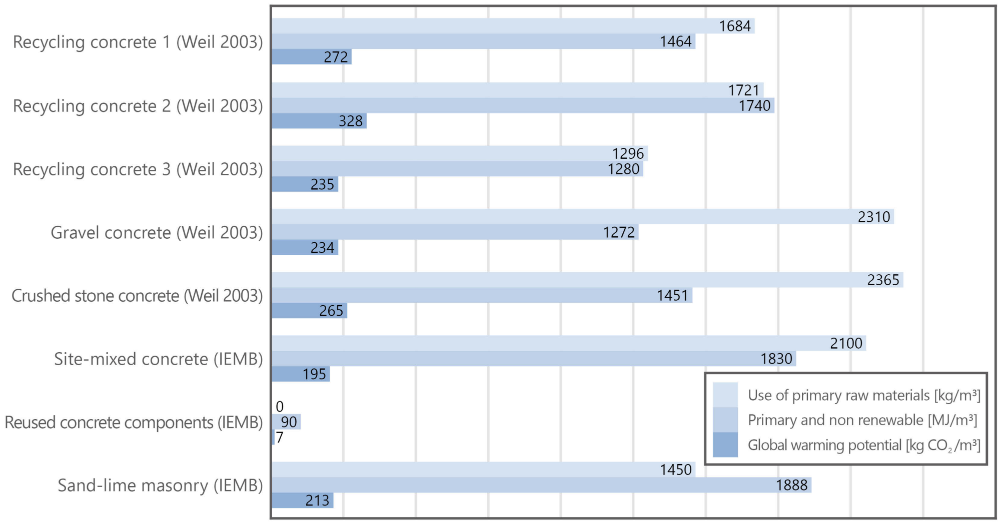


Figure 1.1: Environmental impact comparison of the production of a cubic meter of new, recycled and reused concrete as building material. Adapted from Glias [2013]; Salama [2017].

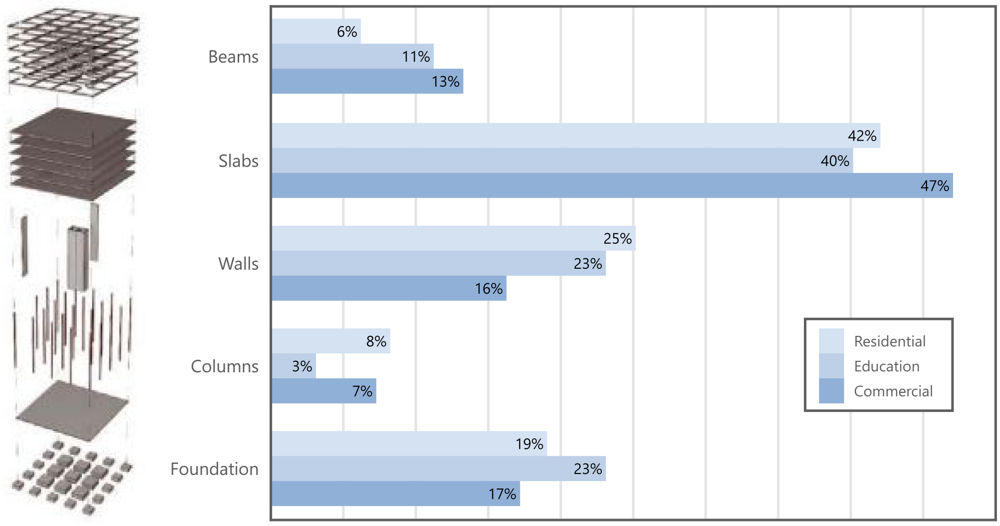


Figure 1.2: Distribution of embodied carbon within structures. Adapted from Kent et al. [2019]; Watson [2020].

In conclusion, critical environmental issues which can be construed to the building sector are the disposal of waste, resource depletion and the increased concentration of greenhouse gasses (GHG). In order to protect the environment, this research focuses on the application of concrete as a structural material, because concrete is one of the most applied structural materials, concrete forms 40% of the Construction and Demolition Waste (C&DW) in the Netherlands and cement is one of the largest contributors to the carbon footprint of buildings. The amount of waste and CO_2 emissions relating to concrete can be reduced by applying reused concrete and by considering the design of the superstructure. This means structural engineers can be pioneers when it comes to protecting the environment [Kent et al., 2019; Watson, 2020].

1.1.1 Sustainability chart of Pieters Bouwtechniek

This research is carried out on behalf of Delft University of Technology and Pieters Bouwtechniek. This engineering firm consists of several expertises, of which one focuses on the concept of sustainability. This expertise of Pieters Bouwtechniek developed a sustainability chart which is shown in Figure 1.3 (in Dutch).

According to the chart, a sustainable design can take into account a long service life *(ontwerp voor lange gebouwlevensduur)* or the possibility for multi-life *(ontwerp voor meerdere levenscycli)*, which is respectively defined in the upper-left and upper-right. A sustainable design can also be achieved by making use of sustainable materials *(duurzaam materiaalgebruik)*, as defined in the lower-right. The lower-left definition considers the conservation and exploitation of existing structural elements by redevelopment *(herbestemming)*.

As described, this research focuses on the application of reused concrete and the design of the superstructure. The definitions which relate to the scope of this research are highlighted in Figure 1.3. These definitions are taken into account throughout the research and are discussed in Chapter 12: Recommendations. Additionally, these definitions are in line with the case-study of this research which is a project of Pieters Bouwtechniek. In this project (De Nederlandsche Bank: DNB), the harvested elements of the concrete structure are reused in the design of a new building at another location in Amsterdam. More information about the case-study can be found in subsection 3.3.1.

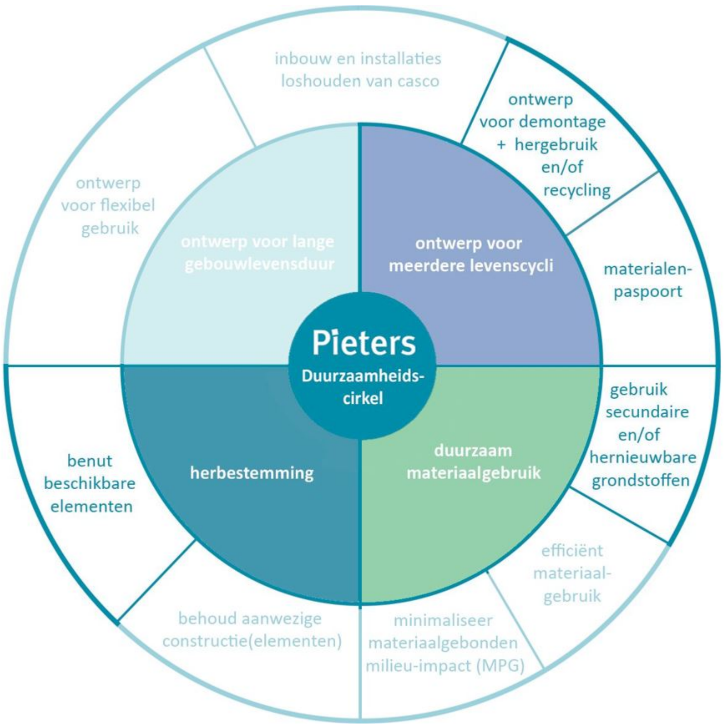


Figure 1.3: Sustainability chart of Pieters Bouwtechniek (in Dutch), where the scope of this research is highlighted. Adapted from Pieters Bouwtechniek [2020].

1.2 State of the art

Considering the critical environmental issues, the linear model (or 'take-make-waste' principle) needs to be converted to a circular model which is referred to as the Circular Economy (CE). The transition from a linear to a Circular Economy focuses on the design process of a product which eliminates residual waste. This means the transition changes the perspective on waste and requires a fundamentally different way of dealing with raw materials. The different design processes of the linear and Circular Economy are shown in Figure 1.4.

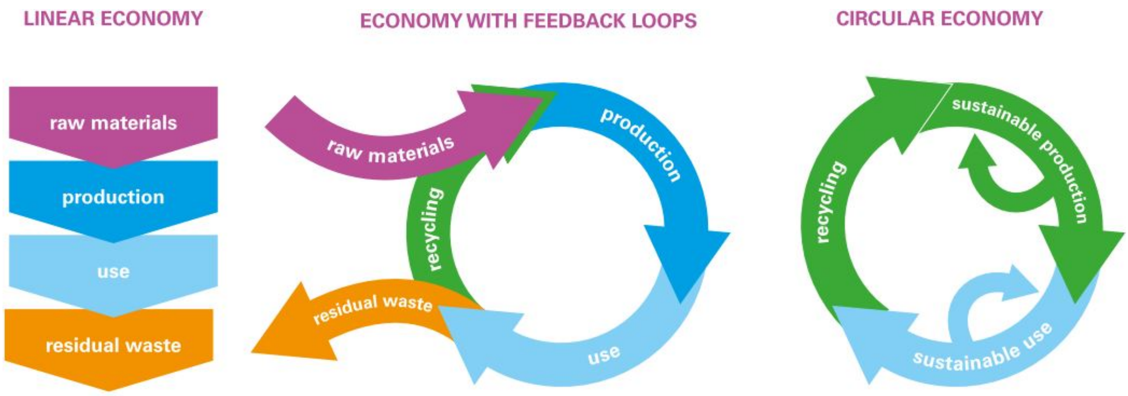


Figure 1.4: Design processes of the linear economy, the economy with feedback loops and the Circular Economy (CE) which eliminates residual waste and requires a fundamentally different way of dealing with raw materials [Council for the Environment and Infrastructure, 2015].

The Circular Economy (CE) aims to meet the needs of future generations as well as the current ones which is in line with the most widely used definition of sustainable development by the Brundtland Commission [WCED, 1987]. Additionally, the Circular Economy conforms the Sustainable Development Goals (SDG), specifically the fifth target of SDG 12 which ensures sustainable consumption and production patterns by reducing waste generations through prevention, reduction, recycling and reuse [United Nations, 2018].

In 2015, the *Paris Agreement* was established at the Climate Change Conference yearly held by the United Nations. Based on this agreement, Dutch ministries announced the program 'Nederland Circulair in 2050' applying to five industries, including the building sector. Since then experts, governments and scientists investigate which CE-principles can be applied and how this can be translated into the building sector [Backx, 2020; Kanters, 2020]. In the Netherlands, this led to the *'Transitieagenda Circulaire Bouweconomie'* in 2018 which aims to accelerate the transition of the building sector towards a Circular Economy (CE) in 2050. This so-called *'Transition Agenda'* distinguishes three stages: [Stolk, 2018, p. 2]

1. 2018 - 2023: in which a fully equipped base is developed;
2. 2021 - 2030: in which 50% of the final objective needs to be achieved;
3. 2030 - 2050: in which the final objective (100% circular) is achieved.

Within the building sector, developments around sustainability are getting more and more common. However, the stages of the *'Transition Agenda'* demonstrate that significant changes are needed in the upcoming years before the final objective is achieved. In the Netherlands, Platform CB23 [2020b] focuses on the first Stage of the *'Transition Agenda'* and thus on the period till 2023. Additionally, the Ellen MacArthur Foundation [2017] investigates the Circular Economy (CE) and describes the following principles:

- Keep products and materials in use (by e.g., reuse);
- Design out waste and pollution (instead of using finite resources);
- Regenerate natural systems.

By considering the design process of the Circular Economy (Figure 1.4), this research focuses on the following two principles of the Ellen MacArthur Foundation: to keep products in use & to design out waste. However, 90% of the buildings which are nearing the end of their design service life are currently demolished [Van Berlo, 2019]. The design service life of a building consists of a technical, functional and economic service life which all indicate a different amount of years: [Vissering et al., 2011; Verberne, 2016]

- The technical service life is the period in which a building fulfils the technical requirements;
- The functional service life is the period in which the building fulfils the users' functional requirements;
- The economic service life is the period in which it is economically unfeasible to use the building;

The research of Vissering et al. [2011] presented the average technical service lives of construction products based on experts' estimates. For structural elements, experts are confident that the average life in standard situations is more than 100 years. Therefore, a reference service life (RSL) of 100+ years can be assumed for structural elements made of concrete. Nevertheless, the functional service life of buildings is often shorter which results in demolition (Figure 1.5). However, demolishing buildings creates a significant pile of waste with debris and non-reusable concrete elements. This in combination with the environmental impact of the building sector gives a need to keep elements in use and/or to design out waste, which is in line with the principles of the Circular Economy.

Available solutions for buildings which are nearing the end of their functional service life are to preserve, renovate or transform these to buildings for which there is a demand. Preservation, renovation or transformation all have their strengths and weaknesses. Criteria to preserve, renovate or transform can be on a constructional or technical base or related to parameters around place attachment, identity, or image [Najah, 2012, p. 35-73]. Environmental, financial or social parameters can also be a reason to preserve, renovate or transform existing buildings, just like implementation, urban or market parameters [Tijssens, 2011]. This makes it hard to examine which of the available solutions is the most suitable for any project and specific time [Rijksdienst Voor Ondernemend Nederland, 2014; NRP Gulden Feniks, 2020; Durmisevic, 2006; Madaster services, 2020].

However, it can be the case that preservation, renovation or transformation are no solution resulting in demolition of a building. Available solutions for the pile of waste are crushing and separating the elements after which the smaller pieces can be transported to a concrete recycling plant [Glias, 2013, p. 68]. On the one hand, processing and recycling the pile of waste demands a lot of energy. On the other hand, the production of new elements leads to the depletion of raw materials and increases global warming.

Since the demand for (raw) materials to construct new buildings remains, solutions need to be found to further reduce the energy of recycling and to minimize the environmental impacts of producing materials [Glias, 2013; Geraedts and Van der Voordt, 2007]. This can be realized by reusing the (structural) elements of a building to be demolished. As shown in Figure 1.5, elements of buildings which are nearing the end of their functional service life have a residual lifespan due to the longer technical service life. With the principles of the Circular Economy (CE) in mind, the demand for (raw) materials can be fulfilled by keeping these elements in use and by designing out waste. In case a building is carefully demolished, waste residuals can be transformed into resources to construct new buildings. This can be referred to as deconstructing and reusing.

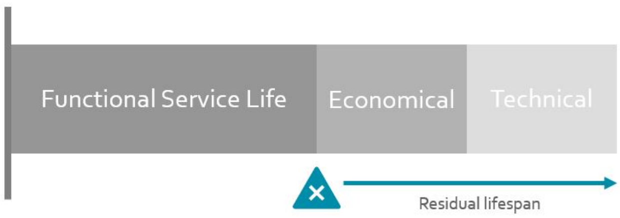


Figure 1.5: Bar with the functional, economical and technical service life. Buildings nearing the end of their functional service life are often demolished, while they have a residual lifespan due to the longer technical service life (own figure).

1.3 Problem definition

Structural elements made of concrete have a reference service life (RSL) of 100+ years. This means the elements of buildings which are nearing the end of their functional service life have a residual lifespan due to the longer technical service life (Figure 1.5). Instead of demolishing these buildings, elements with a residual lifespan and performance can be transformed into resources to construct new buildings. However, in the current building sector mostly new elements are used in the construction instead of elements with a residual lifespan and performance. This obstructs the realization of the *'Transition Agenda'* of which the first stage needs to be finished in 2023. With the approaching goals of 2030 and 2050 to achieve 100% circularity in the building sector, more research is needed to keep elements in use and to design out waste.

As described, the *'Transition Agenda'* is based on several factors which led to a series of proposed actions and interventions. However, since not all actors support circularity yet, proposed actions and interventions are hard to implement in the building sector [Stolk, 2018, p. 2]. The barriers and drivers of the transition towards a Circular Economy are studied by Kanters [2020]. For the reuse of harvested (structural) elements in the design of new buildings, the findings describes the conservativeness of the building sector, the lack of political priority and the dependency throughout the building sector. This results in a lack of confidence of all actors. Especially because no building standards exists to assess the potential to reuse harvested (structural) elements, actors do not want to commit to reuse due to uncertainties about the residual performance and properties [Glias, 2013]. Existing methods to assess the reuse potential are investigated in Appendix C.1. In conclusion, none of the existing methods takes into account the process of 'Deconstruct & Reuse'. Additionally, analysed gaps of the existing methods state that a practical guideline to assess the reuse potential of harvested concrete (structural) elements in the design of new buildings is currently missing [Van Berlo, 2019]. Besides, lots of existing buildings have not been constructed with circular principles in mind. The lack of appropriate skills, no approved standard procedure and time constraints often make deconstruction an unsafe procedure and more expensive compared to the traditional way [Stolk, 2018, p. 30]. Lastly, most of the current studies about reuse are qualitative instead of quantitative and do not provide insights on the economic, environmental and social value of reuse [Van Berlo, 2019]. This results in the fact that the building sector is currently unaware of the potential to reuse elements with a residual lifespan and performance.

In order to overcome the described barriers, a method needs to be developed which assesses the reuse potential of harvested (structural) elements from existing concrete structures. Such method provides more insight in the residual performance and properties of a second-hand element which decreases the uncertainties and lack of confidence to reuse harvested (structural) elements in the design of new buildings. A method which assesses the reuse potential also reduces the extra effort and research currently required for reuse. This enables the building sector to use second-hand elements in the construction instead of new elements. Additionally, more reuse decreases the lack of confidence and creates awareness among all actors to keep products in use and to design out waste. This enhances the transition towards a Circular Economy.

In conclusion, this research aims to contribute to three aspects (Figure 1.6). Firstly, the research should support the transition towards a Circular Economy by providing valuable information about the potential to reuse harvested (structural) elements in the design of new buildings. Secondly, this research should focus on the pioneering role of structural engineers since this research focuses on the application of concrete as a structural material. Especially during the initial phase, the design of a new building can alter due to the input of structural engineers to use second-hand elements instead of new elements in the construction. Thirdly, this research should develop a practical guideline to assess the residual performance of buildings nearing the end of their service life. This will ease the design process to keep products in use and to design out waste, which are in line with the principles of the Circular Economy. However, all actors of the building sector have to adjust for the transition towards a Circular Economy. Since a supportive client with a well-defined assignment can be considered as a main driver [Kanters, 2020], this research should also help Pieters Bouwtechniek in informing their clients about the potential to reuse.

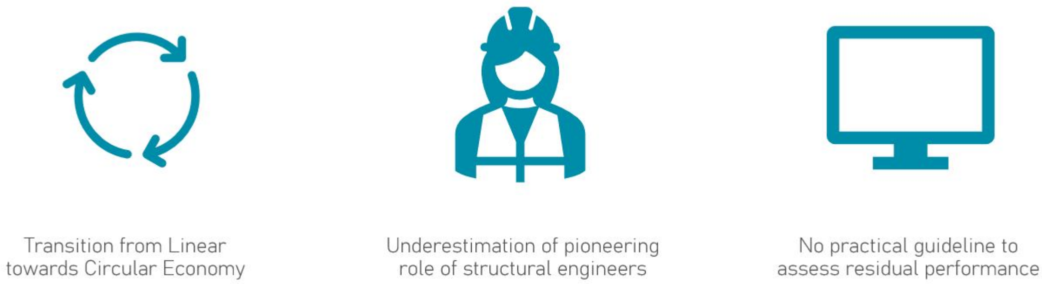


Figure 1.6: Three aspects of the problem definition this research aims to contribute to (own figure).

2 | Research Approach

This Chapter describes the research objectives and research questions respectively in Section 2.1 and Section 2.2. Next, the design of the research is described with the Decision Support Tool (Section 2.3). Section 2.4 provides the specifications of the Decision Support Tool and system boundaries of the research. In addition, the relevance of the research is analysed in Section 2.5. This Chapter finishes with the research outline in Section 2.6. After, the framework, methods and results of the research are elaborated in subsequent Chapters.

2.1 Research objectives

This section describes objectives that contribute to solving the problem statement (Section 1.3). First, a meta goal is formulated followed by a more specific research objective. The meta goal is an overarching goal and formulated as follows:

> *To allow structural engineers to make use of the existing concrete building stock by means of deconstructing and reusing the harvested (structural) elements in the design of new buildings.*

Since the overarching meta goal cannot be achieved by only this Master's thesis, a more specific research objective is formulated which contributes to parts of the meta goal. The research questions and phases are based on this objective and described in the subsequent sections.

> *To qualitatively and quantitatively assess the reuse potential per harvested (structural) element of existing concrete structures.*

2.2 Research questions

In order to reach the main research objective (set out in Section 2.1) the subsequent section formulates the research questions.

2.2.1 Main research question

The main research question of this Master's thesis is derived from the main research objective and formulated as follows:

> *How can the reuse potential of harvested (structural) elements of the existing concrete building stock be assessed to allow structural engineers to make use of these elements in the design of new buildings?*

2.2.2 Sub−research questions

In order to answer the main research question, a total of three subquestions are formulated keeping the scope of this research in mind. Gradually, these sub−questions lead to solving the problem definition (Section 1.3). Additionally, these subquestions provide a structure on which the parts of this research are based, which is elaborated in Section 2.6.

1. *Which phases and indicators of the process of Deconstruct & Reuse influence the reuse potential of harvested concrete (structural) elements in the design of new buildings?*
   - What is the definition of Deconstruct & Reuse from the point of view of structural engineers?
   - Which phases are part of the process of Deconstruct & Reuse?
   - How can these phases be subdivided into indicators focusing on existing concrete structures?
   - What is the definition of the reuse potential regarding the phases and indicators of the process of Deconstruct & Reuse?

2. *How to assess the reuse potential of harvested concrete (structural) elements in the design of new buildings based on the indicators of the process of Deconstruct & Reuse?*
   - What information is needed to qualitatively and quantitatively assess the indicators?
   - How can this information be retrieved during the process of Deconstruct & Reuse?
   - Which grading can be assigned to the retrieved information to assess the reuse potential of harvested concrete (structural) elements in the design of new buildings?
   - Which indicators are dependent to other indicators?

3. *How can the Decision Support Tool add value in practice?*
   - What is the Decision Support Tool?
   - How can the assessment of the reuse potential of harvested concrete (structural) elements in the design of new buildings be implemented in the Decision Support Tool?
   - What is the validity of the Decision Support Tool?

2.3 Research design

The main research objective of this research is to assess the reuse potential of a harvested concrete (structural) element. In order to achieve this objective, a research design is set up based on the research questions in the previous section. This is shown in Figure 2.1.

This research starts by analysing concrete elements of the superstructure of existing buildings to be demolished. This is done by harvesting the (structural) elements for reuse in the design of new buildings. The first sub-question dives into the process of 'Deconstruct & Reuse' which is subdivided in Phases and Indicators of interest for structural engineers. Next, the indicators which affect the reuse potential of harvested concrete (structural) elements in the design of new buildings are arranged in Stages. Thereby, the process of 'Deconstruct & Reuse' can be seen as a decision tree. In here, a definition for the reuse potential is analysed.

The second sub-question analyses the needed information to assess the process of 'Deconstruct & Reuse'. Therefore, the indicators which affect the reuse potential of harvested concrete (structural) elements in the design of new buildings are translated into assessment questions. The needed information to answer these questions is analysed in combination with how this information can be retrieved. Next, the retrieved information per assessment question is translated into answer options. A grading is assigned to the answer options to make the assessment of the reuse potential rational. Additionally, the dependences between the indicators are analysed in the decision tree of the process of 'Deconstruct & Reuse'.

The third sub-question implements the assessment of the reuse potential in the Decision Support Tool which makes the framework operational. How the Decision Support Tool operates is described in the next subsection.

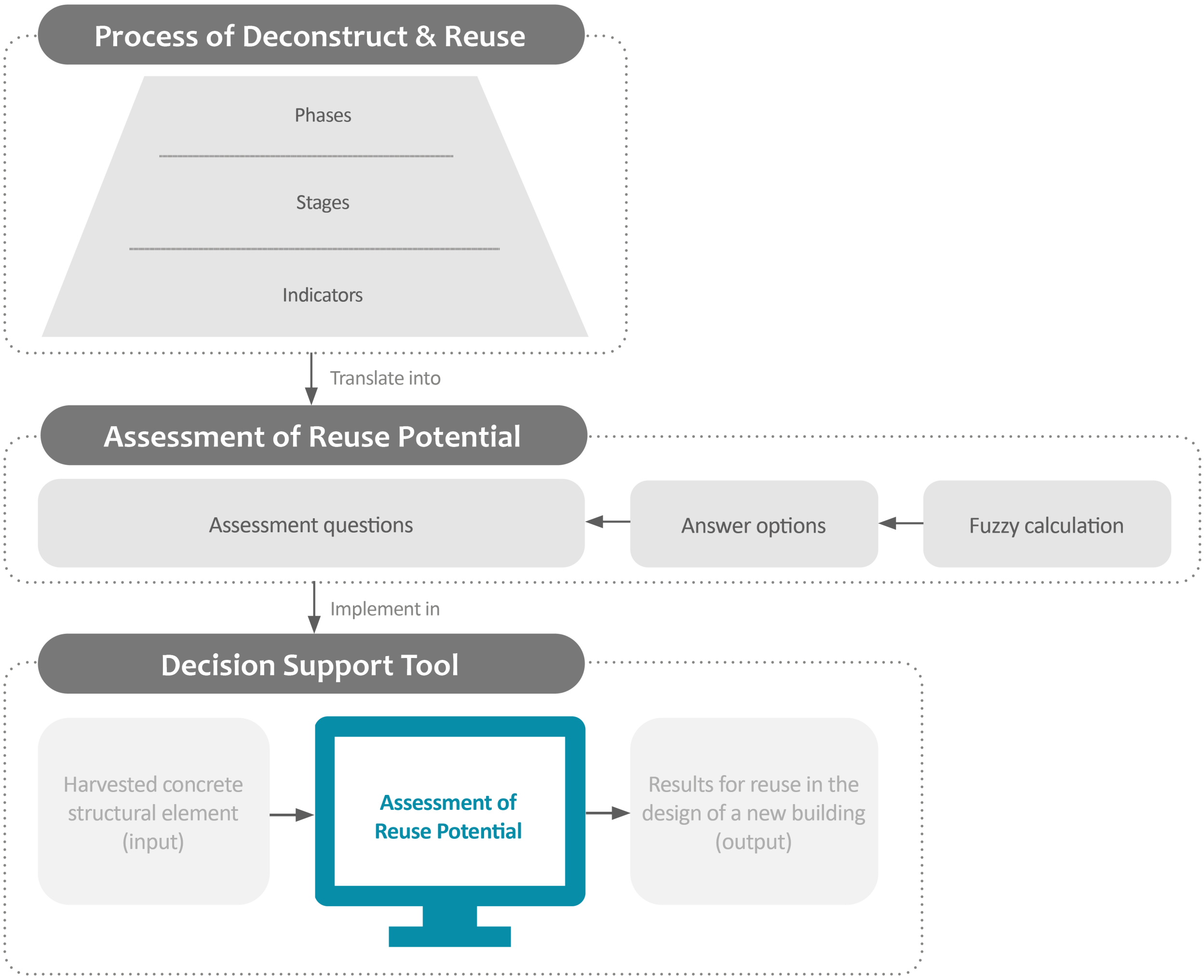


Figure 2.1: Research design with the assessment of reuse potential (own figure).

2.3.1 Decision Support Tool

As described, the assessment of the reuse potential is made operational in the Decision Support Tool. The Decision Support Tool assesses if a harvested concrete (structural) element can be reused in the design of a new building. At the start of the research, specifications are set for the Decision Support Tool which help with the development of the assessment of the reuse potential. An overview of the specifications of the Decision Support Tool is shown in Table 2.1. For use in practice, the validity of the final version of the Decision Support Tool is tested. Verification is tested with structural engineers in conformance with the specifications, while validation is tested with a case-study of Pieters Bouwtechniek: De Nederlandsche Bank (DNB). The aim of the Decision Support Tool is to provide confidence and to create awareness to keep products in use and to design out waste. This is in line with the principles of the Circular Economy.

Table 2.1: Specifications of the Decision Support Tool

Subject	Description
Practical guideline	The assessment of the reuse potential is made operational in the Decision Support Tool. Thereby, the Decision Support Tool gives a first indication if reuse of a harvested (structural) element made of concrete is possible. Additionally, the Decision Support Tool advises on the implementation of a second-hand element in a new design.
End-user	The Decision Support Tool is set up from the pioneering role of structural engineers. The end-user of the Decision Support Tool is considered to have basics structural knowledge.
Execution	The Decision Support Tool can be executed in a relatively quick manner. This makes it possible to quickly assesses the reuse potential of an element.
Software design	The Decision Support Tool is set up in Excel with a Graphical User Interface (GUI). This makes the assessment relatively easy to execute and understand. Additionally, Excel makes the assessment alterable for further developments.
Results	The Decision Support Tool can be uniformly executed generating comparable results in the form of a final score for the reuse potential. Therefore, it is necessary that the Decision Support Tool gives unambiguous results.

Table 2.2: System boundaries of the research

Subject	Description
Building type	This research considers the existing concrete building stock in the Netherlands, especially buildings nearing the end of their functional service life of which the elements still have a residual lifespan and performance.
Elements	This research considers elements of the superstructure of an existing concrete building for reuse, due to the high amount of embodied carbon of the structural layer.
Deconstruct & Reuse	This research considers the harvested (structural) elements of buildings to be demolished which can be directly or indirectly implemented in the design of new buildings. This means elements with a residual lifespan and performance are transformed into resources to construct new buildings, which is referred to as the process of 'Deconstruct & Reuse'. Therefore, only the potential for reuse is researched and not for other strategies (e.g., recycling of concrete by crushing the aggregates). Additionally, circular design strategies of the new building are out of the scope of this research.
Material	This research considers reinforced concrete for reuse as a structural material, because concrete is one of the most applied structural materials, concrete forms 47% of the Construction and Demolition Waste (C&DW) and cement is one of the largest contributors to the carbon footprint of buildings (Section 1.1). As analysed in Appendix B, this research only considers in-situ and pre-cast concrete.
Aspects	This research focuses on the technical and material aspects of (structural) concrete elements, less attention is paid to economic aspects.
End product	This research develops a Decision Support Tool based on the process of 'Deconstruct & Reuse', specifications of the Decision Support Tool are listed in Table 2.1.
Practice	This research is carried out on behalf of Delft University of Technology and Pieters Bouwtechniek. Therefore, the research makes use of current regulations and practices and is thus applicable to the current situation of the building sector.

2.4 Research scope

Since it is impossible for this research to solve all related problems, this section describes system boundaries which help to solve the research objectives and research questions respectively in Section 2.1 and Section 2.2. The system boundaries of this research are based on the introduction (Chapter 1) and shown in Table 2.2. With all system boundaries and specifications set, this research tries to make a significant contribution and provide valuable insights into the field of circularity.

2.5 Research relevance

Multiple aspects relate to the societal and scientific relevance of the research. Firstly, this research focuses on the Circular Economy (CE) which conforms the CE-principles of Ellen MacArthur Foundation [2017] by keeping products in use and by designing out waste. Secondly, this research contributes to the *'Transition Agenda'* in the Netherlands and the Sustainable Development Goals (SDG) of the United Nations. Thirdly, this research assesses the reuse potential of a harvested (structural) element according to the process of Deconstruct & Reuse. By making the assessment operational in a Decision Support Tool, this research is the first of its kind. Lastly, this research helps Pieters Bouwtechniek in informing their clients about the potential to reuse.

2.6 Research outline

This research is structured in three research parts:

- Part I: Research Framework
- Part II: Research Methods
- Part III: Results and Final Remarks

Each part represents a set of chapters which answer the sub−questions in Section 2.2. The scheme in Figure 2.2 indicates the research parts with chapters, where sub-question 1 is answered in Part I, sub-question 2 in Part II and sub-question 3 in Part III.

In Part I, the research investigates the process of 'Deconstruct & Reuse' which forms the basis for the assessment of the reuse potential. In Part II, the Decision Support Tool is set up based on the findings of Part I. As a result of an iterative process, the input distinguishes three phases indicated by different colours. The preliminary versions of the Decision Support Tool are researched with literature study, case-study and interviews resulting in the final version of the Decision Support Tool, which is presented in Part III. The Decision Support Tool is validated and verified by the researcher and experienced structural engineers. The validity of the Decision Support Tool results in insights for the conclusion, discussion and recommendations.

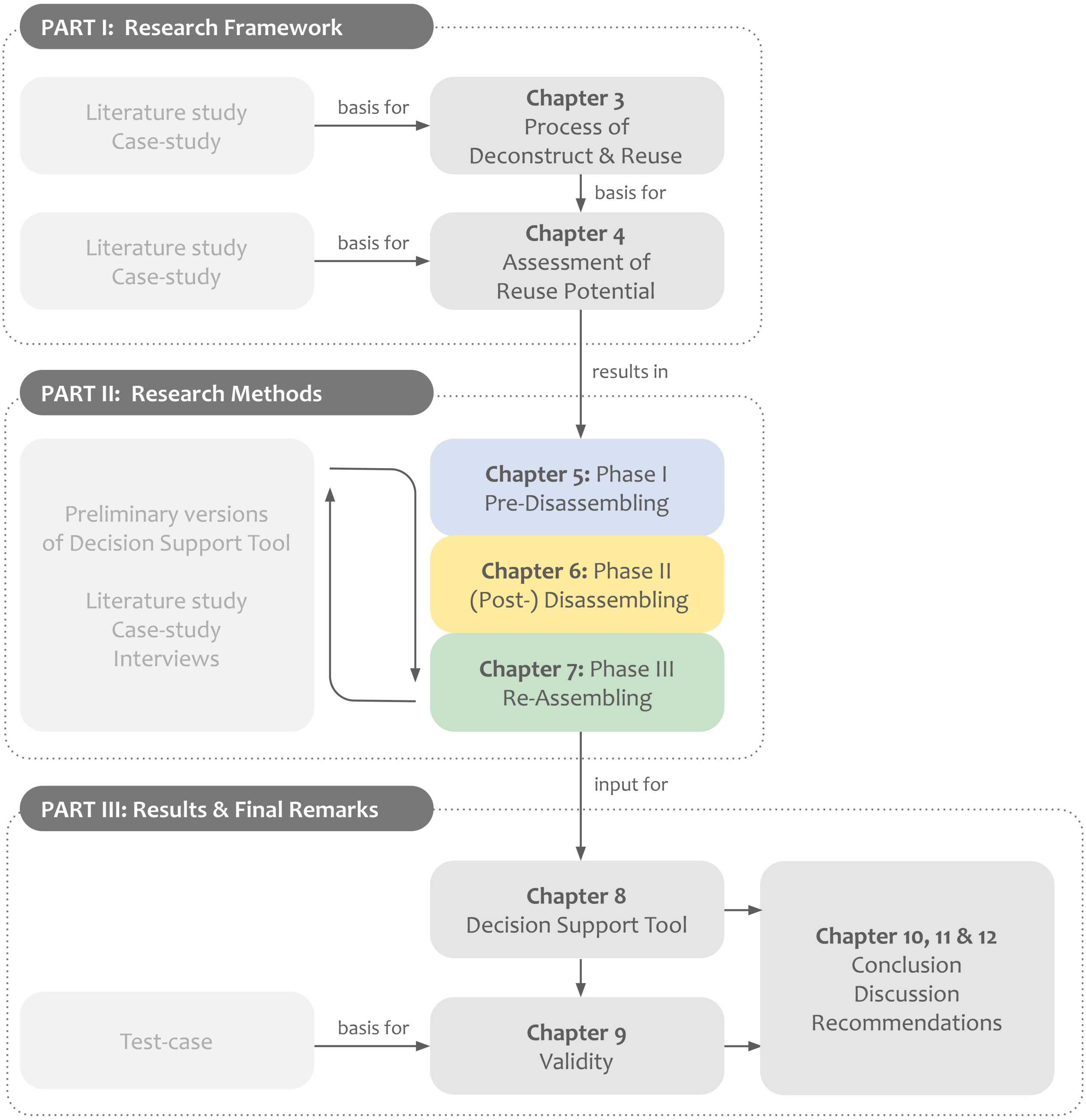


Figure 2.2: Research parts with chapters (own figure).

Part I
Research Framework

The first part of this research describes the research approach. The second and third part respectively describe the research methods and results.

3 | Deconstruct & Reuse

In this Chapter, the definitions of Deconstruct & Reuse are analysed respectively in Section 3.1 and Section 3.2. Next, information about the process of Deconstruct & Reuse is gathered with an extensive literature study and case-study (Section 3.3). This Chapter finishes with an overview of all information after which the assessment of the reuse potential is further explored in the subsequent chapter.

3.1 Deconstruct

As described, the transition from a Linear to a Circular Economy (CE) requires a fundamentally different way of dealing with raw materials. Therefore, the properties and varieties of existing concrete structures are analysed in Appendix B. Pre-cast construction is considered as a 'dry' system whereas in-situ construction is a 'wet' system, because prefabricated elements only have to be assembled on site. In terms of disassembling, a 'dry' system is known as an easier way to deconstruct [Suzyo, 1996, p. 34-35]. This section investigates the definition of Deconstruct. Therefore, the layers of Brand [1994] and their corresponding interactions [Schmidt III et al., 2010] are taken into account.

3.1.1 Definition of Deconstruct

In order to reuse harvested (structural) elements from demolition projects in the design of new buildings, the building process requires specific measures and initiatives tailored to the related phase. In the Life Cycle Analysis (LCA), the stages of the building process are subdivided into the product and construction stage (module A), the use stage (module B) and the end-of-life stage (module C). The last module (D) indicates the benefits and loads beyond the system's boundaries in which the reuse-, recycle- and recover potential of the Building Life Cycle are investigated, expressed as the 'circularity index' [Stolk, 2018, p. 30].

Structural engineers can assess cost-effective and whole-life solutions when it comes to reducing the carbon footprint of building materials, especially when it comes to the superstructure (Figure 1.2). By reusing harvested (structural) materials, structural engineers can decide where an element can be used to its maximum residual value (in order to reduce downcycling). However, if the residual value of elements is not maximized during deconstruction due to e.g., unforeseen damage, structural engineers of new building designs will not reuse these elements in their buildings due to uncertainties and lower quality. Examples of decisions are shown in Figure 3.1, where the left side of the figure indicates the residual value of existing buildings and the right side indicates the design of new buildings [MacNamara, 2020; Mayor of London, 2019, p. 11]. This research focuses on existing buildings on site of which it is not technically feasible nor viable to retain the building in whole or in parts. In order to prevent demolition and aim for 'Deconstruct & Reuse', it should be technically feasible and viable to recover the residual value of elements/materials. This is blue coloured in Figure 3.1.

> *Deconstruct is an operation by which an existing building is carefully disassembled because it is technically feasible and viable to recover the residual value of harvested elements for reuse.*
>
> [MacNamara, 2020; Mayor of London, 2019; Iacovidou and Purnell, 2016]

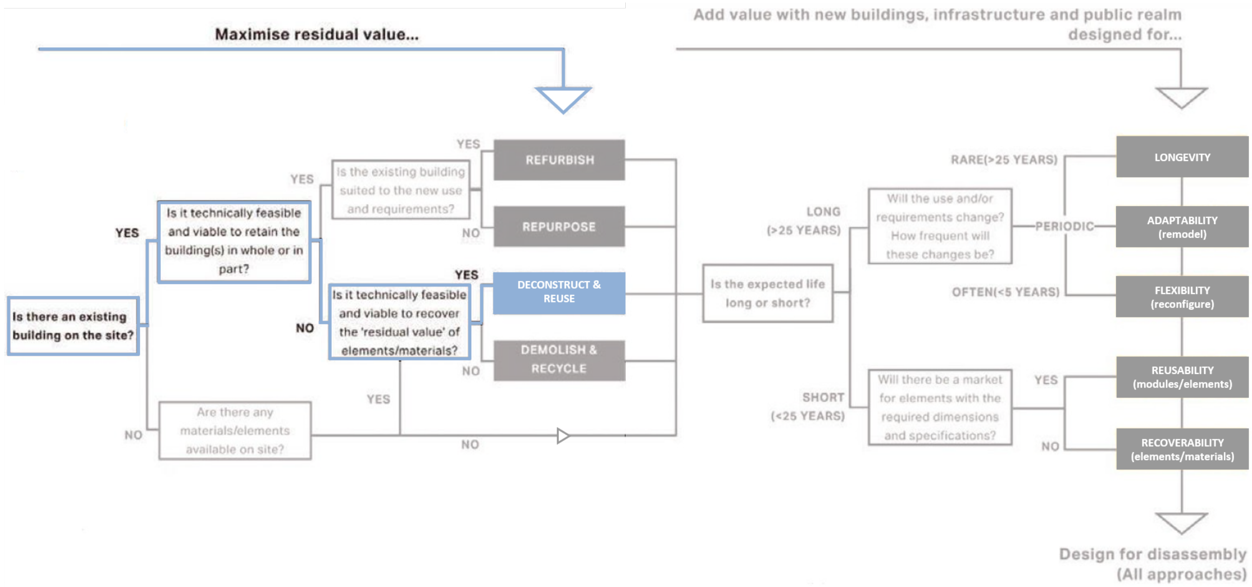


Figure 3.1: Examples of decisions of structural engineers, where the scope of this research is coloured in blue. Left arrow at the top indicates the residual value of existing buildings, right arrow indicates the design of new buildings. Adapted from MacNamara [2020]; Mayor of London [2019, p. 11].

3.1.2 Building layers and interdependencies

On the long term, buildings are constantly adapting due to the different environmental conditions, changing user demands and technology. One of the main theories of building adaptability is that buildings consist of layers, which means that the interdependencies between the layers enable adaptation [Heidrich et al., 2017; Schmidt III et al., 2010]. Firstly, the research of Duffy [1990] has identified four building layers which only include 'hard' aspects of building adaptability (*shell, services, scenery and set*). The research of Brand [1994] has extended this categorization by two extra building layers (*site and skin*). Since each layer changes at a different range, all building layers have a different corresponding expected lifetime in years. The following list shows the six building layers according to the research of Brand [1994] where the four original definitions of Duffy [1990] are oblique within brackets:

- Site — geographical setting, urban location, and legally defined lot (eternal);
- Structure *(shell)* — foundation and load-bearing elements (30-300 years);
- Skin — exterior surfaces (20 years);
- Services *(services)* — installations like heating, plumbing, etc (7-15 years);
- Space plan *(scenery)* — interior layout like walls, ceilings, floors and doors (3-30 years);
- Stuff *(set)* — furniture like chairs, desks, phones, pictures, lamps (< 1 year).

Later, the research of Schmidt III and Austin [2016] added three 'soft' layers (social, space and surroundings) linking to external influences, neighbourhood, infrastructure, natural elements, and users of the building who define the function of it. Figure 3.2 displays the interactions between these 'hard' and 'soft' building layers. Since this research assesses harvested (structural) elements, the structural layer and its interdependencies are considered. As can be seen, the structural layer has a strong link with the space plan (interior) and skin (exterior). This can be explained by the foundation and load-bearing elements of the structural layer which are 'the building' and thus perilous and expensive to change. Therefore, the expected lifetime of the structure is longer than the space plan and skin which changes approximately every 20 years, to keep up with technology, fashion or wholesale repair. For this and other reasons, buildings are demolished at an early age forming a mismatch with the residual lifetime of structural materials, of which this research assumes the reference service life (RSL) to be 100+ years [Vissering et al., 2011]. Therefore, this research focuses on the reuse of the structural layer which links to the space plan and skin. In addition, the sequence of disassembling in general and for the case-study are analysed n Appendix F.

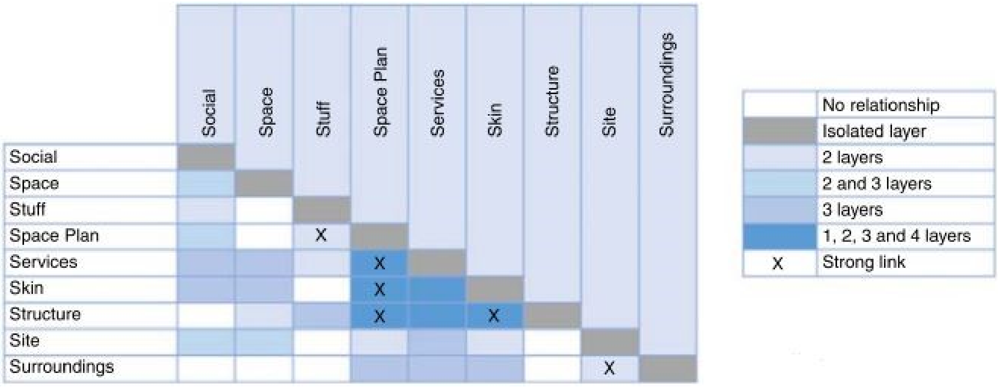


Figure 3.2: Interaction between building layers [Schmidt III and Austin, 2016, p. 57].

The parts of which building layers consist can be seen as a hierarchy of materials and their relations, which represent the way parts are arranged in a building. For this research, it is assumed that each building layer consists of several materials. The combination of these materials makes an element or component, and multiple elements form a building construction product. In conclusion, this hierarchy of material distinguishes four material levels consisting of: [Durmisevic and Brouwer, 2002, p. 7]

- Building level; Composition of systems which are the main carriers of the building functions (e.g., load-bearing, enclosure, partitioning, servicing);
- System level; Composition of components which are the carriers of the system functions (e.g., bearing, finishing, insulation, reflecting, distributing);
- Component level; Component functions are layered through the elements and materials (e.g., lowest level of building assembly);
- Parts; Materials of which building layers consist.

As described, on the long term buildings are constantly adapting which makes it hard to predict forthcoming requests. Therefore, a design strategy should be developed where it is possible to disassemble parts back into components and to reassemble them in new combinations. This would extend the lifetime of building components significantly because disassembling, reusing and recycling would give building components the possibility for multi-life. As observed by the research of Schmidt III and Austin [2016], building components of the structural layer have a high chance to disassemble and reassemble. This concept of disassembly is in line with the principles of the Circular Economy and can be characterized by three types of transformation [Durmisevic and Brouwer, 2002, p. 3]:

- Spatial transformation;
- Structural transformation;
- Material/element transformation.

At first, spatial transformation (or adaptability) progresses the service life of space. Secondly, the service life of a building and its components is ensured by structural transformation through replaceability, reuse and recovery of building components. This can be referred to as disassembly of the building structure. Thirdly, the service life of materials is ensured by material/element transformation through recycling or reuse of building materials [Durmisevic and Brouwer, 2002, p. 3].

These three types of transformation show similarities with the earlier described hierarchy of materials, as shown in Figure 3.3. Here the building level can be referred to as spatial transformation, the system level as structural transformation and the component level as material/element transformation. At any level, the higher level dominates the lower level on technical, functional and economical composition, as indicated by the arrows in Figure 3.3 [Durmisevic and Brouwer, 2002, p. 7]. Additionally, different types of connections can be applied between the levels, due to the way building materials are applied by each transformation resulting in minimal environmental impact. Since this research focuses on harvested (structural) elements, the component level and corresponding element transformation are considered for reuse (blue coloured in Figure 3.3).

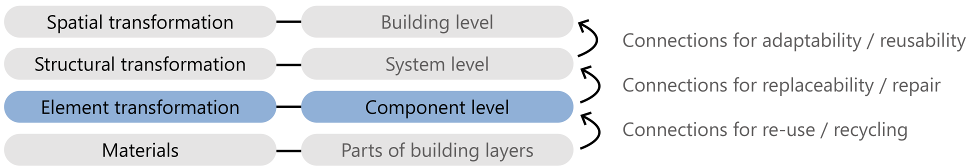


Figure 3.3: Hierarchy of material levels. Adapted from Durmisevic and Brouwer [2002, p. 3-7].

3.2 Reuse

This section analyses the definition of reuse considering harvested (structural) elements made of in-situ and pre-cast concrete (Appendix B). Pre-cast construction is considered as a 'dry' system whereas in-situ construction is a 'wet' system, resulting in non-standardized elements which must meet the requirements for the entire project. Currently, this makes in-situ construction more difficult to assess for reuse which leads to demolition [Suzyo, 1996, p. 34-35].

Structural engineers can take a pioneering role during the deconstruction of existing buildings to reuse the harvested (structural) elements in the design of new buildings. Additionally, structural engineers of new building designs can decide which elements are suitable to implement in their design. Actions that structural engineers should take at each stage of the building process to maximise the circular potential of their design are discussed in the research of MacNamara [2020]. This author suggests appointing structural engineers as earliest as possible in the design phase, also called the initial phase, where big decisions can be made [Treacy, 2020]. Therefore, the initial phase provides the greatest potential to affect and add value to a building project [Khasreen et al., 2009]. Here, the design of a new building can alter due to the input of structural engineers to use second-hand elements instead of new elements in the construction (Section 1.3).

Currently, many different interpretations about circularity and sustainability exist. An overview of the concepts of the four most important circularity strategies (the *Ladder of Lansink*, the *Delft Ladder*, the *R-list*, and the *Butterfly Model*) is shown in Figure 3.4. The definitions of the concepts can be found in Appendix A, which are based on the lexicon of Platform CB23 [2020a]. On the right of Figure 3.4, the concepts are split into three main categories [Potting et al., 2017]. Based on these categories, the principles can be distinguished in different phases of the process [Cramer, 2015]. For the *R-list*, the design phase is represented by step R0 - R2, the use phase by R3 - R7 and the discard phase by step R8 - R9. In order to implement (structural) elements that arise from demolition projects in the design phase of a new building, the concepts of the use and discard phase should be linked to the design phase of a new project to close the resource loop [Ellen MacArthur Foundation, 2017]. By doing so, product, component and material waste are restored into the market at the highest possible quality for as long as possible. The arrows on the right in Figure 3.4 point out that the concepts at the top of the figure indicate a higher priority compared to the lower concepts. It can be seen that the highest priority is given to the design phase of a new project.

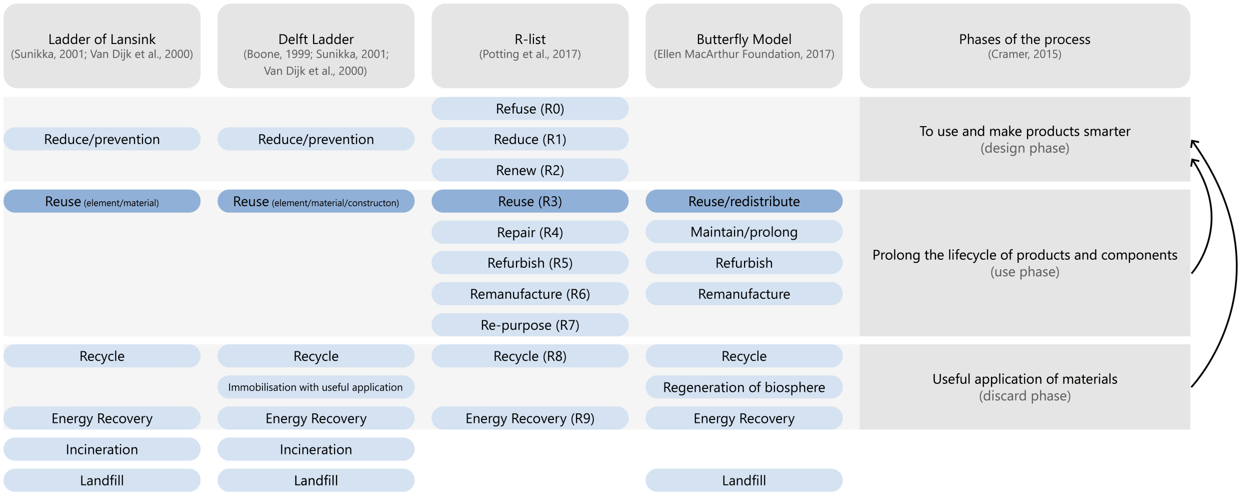


Figure 3.4: Overview of four circularity strategies, where the scope of this research is indicated by the blue coloured concept of reuse. Definitions of all concepts can be found in Appendix A (own figure).

3.2.1 Definition of Reuse

In terms of environmental issues, the most favourable solutions in the building sector are reduce (R1), reuse (R3), and recycle (R8). Due to the high priority of the design phase, this research only considers the concepts of the use and discard phase which link to the design phase. Thereby, the concepts of reuse and recycle are compared. Reuse indicates a process in which elements are used again for the same function without demolition, whereas recycling indicates a process in which materials are reproduced into raw materials for new products. The research of Akanbi et al. [2018] provides an overview of the factors influencing the reusability and recyclability of materials (Table 3.1).

Although recycling of building materials is a common practice, reuse is a more value-driven use due to two important factors. Firstly, recycling requires large amounts of energy due to transportation, recycling, processing, manufacturing, and distributing [Akanbi et al., 2018; Iacovidou and Purnell, 2016]. Secondly, recycling can degradate the material quality, even when the technical lifecycle is not completed. Degradation leads to the need for any modifications, reprocessing or treatment which requires more embodied carbon than reuse [Glias, 2013]. Therefore, this research considers reuse as the purest form of deconstruction.

Table 3.1: Factors influencing reusability and recyclability of materials [Akanbi et al., 2018, p. 279].

No.	Factors	Reference	Material reusability	Material recyclability
1.	Specification of reusable materials during design	(Webster and Costello, 2005; Guy et al., 2006)	★	□
2.	Specification of recyclable materials during design	(Webster and Costello, 2005; Guy et al., 2006)	□	★
3.	Use of nut/bolt joints instead of nails and gluing	(Crowther, 2005; Webster and Costello, 2005; Guy et al., 2006)	★	□
4.	Use of prefabricated assemblies	(Crowther, 2005; Guy and Ciarimboli, 2008)	★	□
5.	Minimisation of types of building components	(Chini and Balachandran, 2002; Guy et al., 2006)	★	□
6.	Avoidance of toxic and hazardous materials	(Crowther, 2005; Guy et al., 2006)	□	★
7.	Layering of building element according to anticipated life span	Brand (1994)	★	★
8.	Avoidance of secondary finishes	(Crowther, 2005; Guy et al., 2006; Tingley, 2012)	★	□

★ – key factors that must be considered. □ – factors that may be considered.

Reuse means an operation by which a product, its components or materials can be used again for the same purpose/function for which they were conceived. The waste is prepared by checking, cleaning, or repairing recovery activities to be reused without the need for any modifications, reprocessing or treatment.

[Platform CB23, 2020a]

3.3 Process of 'Deconstruct & Reuse'

With the definitions of Deconstruct & Reuse, the process of 'Deconstruct & Reuse' can be analysed. This section describes the process with an extensive literature study and case-study and arranges the process of 'Deconstruct & Reuse' in phases, stages and indicators. The overview of the process of 'Deconstruct & Reuse' (Figure 4.1) forms the guideline for the Decision Support Tool and upcoming sections.

3.3.1 Case-study

Next to the extensive literature study, the process of 'Deconstruct & Reuse' is based on a case-study of Pieters Bouwtechniek. De Nederlandsche Bank (DNB, Dutch National Bank) is established in 1968 at the Frederiksplein in Amsterdam and designed by the architect M.F. Duintjer. His (original) design consists of a rectangular office tower of 66 meters high surrounded by a low-rise building of 120 meters wide and 100 meters deep. The building stands on a cellar of two floors and three safes which are used for storing e.g., banknotes and gold [Architectuur Centrum Amsterdam, 2019]. From 1988 to 1991, De Nederlandsche Bank (DNB) was expanded with a round cylindrical tower designed by Abma+Dirks+Partners. This tower of fourteen stories (56 meters high) is called the 'Satellietgebouw'. Impressions of the office building from 1988 and 2020 are shown in Figure 3.5.

As with any fifty-two-year-old office building, DNB has outdated installations and is no longer sustainable considering the CO_2-emissions and energy consumption. Through a European Tender, *Mecanoo* was selected to realize the renovation of the DNB to a sustainable, future-proof and more open building [Mecanoo, 2018]. The renovation will be finished at the end of 2023 and from 2024 employees, stakeholders and all interested citizens can make use of the renovated building [De Nederlandsche Bank, 2019]. Artist impressions of the new design of De Nederlandsche Bank (DNB) are shown in Figure 3.6, where it is clearly visible the round cylindrical office tower (Satellietgebouw) disappeared [Architectuur Centrum Amsterdam, 2019]. The Satellietgebouw is disassembled with the purpose of reuse. The tower consist of a post-tensioned concrete structure (1st floor), concrete prefab elements (2nd-14th floor) and a steel topping (15th floor). The structure, skin and service layers are reused in a new design at another location in Amsterdam, where 3 turrets of each 4 floors or one tower of 14 floors will be realized (with a new foundation). The disassembling of the Satellietgebouw started in the fourth quarter of 2020. For this research, the disassembling of the Satellietgebouw construes to the process of 'Deconstruct & Reuse'. Additionally, this research assesses the reuse potential of the harvested (structural) elements. The case-study is elaborated in more detail in Appendix E.

(a) Impression from 1988
[Pieters Bouwtechniek Internal Document, 2021d]

(b) Photo from 2020
[NU, 2020]

Figure 3.5: De Nederlandsche Bank (DNB) from Stadhouderskade.

(a) Entrance from Stadhouderskade

(b) Facade from Frederiksplein

Figure 3.6: Artist impressions of the new design of De Nederlandsche Bank (DNB) to be finished in 2024 [Mecanoo, 2018].

3.3.2 Extensive literature study

In Appendix C.1.1, indicators which affect the reuse potential are researched with an extensive literature study. An overview can be found in Figure C.2. In combination with the case-study, this research analyses what structural engineers want to know before applying a harvested element for reuse in a new project. Therefore, the preliminary versions are discussed with structural engineers throughout the research, as described in Appendix H.1. This resulted in a selection of indicators of interest for structural engineers: (from left to right in Figure 3.7)

- Quick check — Is reuse possible? Is information available?
- Properties — What properties can be assigned to the element to be reused?
- Composition — Does the element to be reused contain toxic materials?
- Certification — Are the properties of the element to be reused certified?
- Deterioration — Is the element to be reused internally or externally deteriorated?
- Removal for reuse — How can the element be disconnected, limiting the amount of damage?
- Method of hoisting — What kind of system is needed to hoist the element?
- Transport — Does transportation of the element require any particularities?
- External influences — Is the element at a storage yard? If yes, was it susceptible to external influences?
- Modifications — What is needed to modify the element as new/prefab?
- Condition / risk — What is the condition of the element? What are the risks for reuse?
- Requirements of new design — What are the design requirements of the new design?
- Properties of element — Does the element fulfill the requirements of the new design?
- Implementation of element — How can the element be reconnected, considering the general procedure and needed adaptation of the element?

3.3.3 Overview of process of 'Deconstruct & Reuse'

According to the extensive literature study in Appendix C.1.1, the research of Glias [2013, p.42-80] analyses the whole reuse process in order to identify the technical obstacles of reusing structural elements. The following basic actions are found with an extensive literature study, interviews and a case-study: Inventory, Quality Check, Deconstruction, Transportation, Storage, Modification and Construction. In addition, the research of Jabeen [2020, p. 37-50] analyses the process of component reuse. Thereby, she distinguishes the Deconstruction, Material Handling and Consumption.

For this research, the selected indicators of the previous section are arranged in the stages of Glias [2013]. resulting in the process of 'Deconstruct & Reuse'. The preliminary actions before deconstruction of a (partial) building can start (such as obtaining the permit, doing the site audit and a planning) are not taken into account. The process for the reuse of harvested (structural) elements in the design of new buildings is shown in Figure 3.7, with descriptions of the stages below. In the next Chapter (4), the process of 'Deconstruct & Reuse' is translated in the assessment of the reuse potential of existing concrete.

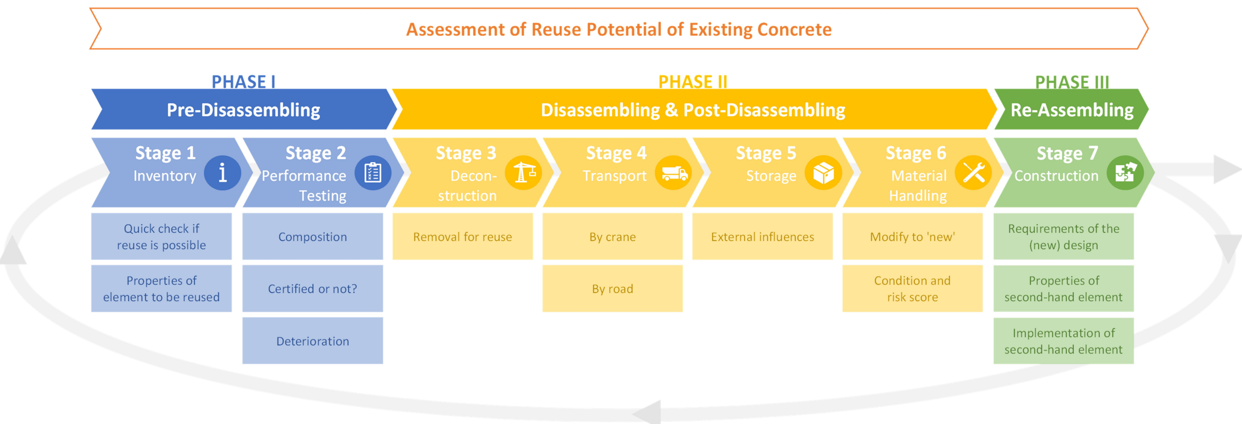


Figure 3.7: Assessment of reuse potential of existing concrete in Phases, Stages and Indicators (own figure).

- Stage 1: Inventory
  Existing information by drawings and desk research is reviewed in order to determine if an existing building is suitable for deconstruction. If a building is suitable for reuse, information has to be recorded for the inventory which can be referred to as the Bill of Materials (BOM). Next, the building needs to be reduced to only main load-bearing elements by recovering the elements from temporary layers of the building. After stripping, Stage 1 consists of a quick check to determine if reuse of a (structural) concrete element is possible according to deal-breakers. If reuse is possible, the properties of the (structural) element are investigated in the next indicator. If reuse is not possible, the problem needs to be assessed to see if it is feasible to try again.

- Stage 2: Performance Testing
  After the quick check if reuse is possible and the stripping of the building, performance testing of the elements can be carried out by visual inspection, Non-Destructive Testing (NDT) and Destructive Testing. The level of testing depends on the available documents and the requirements of the user since no protocol exist for performance testing. During Stage 2, information on site is researched to check the existing information or, in case desk research was unavailable or insufficient, to obtain lacking information. First, the presence of toxic materials in the composition of the (structural) element is investigated. Second, it is important to determine if the filled-in properties of Stage 1 are certified by performance testing. Last, internal and external deterioration of the element are investigated.

- Stage 3: Deconstruction
  In order to safely deconstruct existing buildings, the sequence of disassembling is important to avoid unexpected collapse (Appendix F). During Stage 3, the disconnecting of the connections is considered. Therefore, the removal for reuse is investigated by considering the (applied) equipment to disconnect.

- Stage 4: Transportation
  After the element is disconnected, the element needs to be hoisted and transported to either the deconstruction site, the new construction site or a storage yard. This means the element is transported from the deconstruction site to either the end-user, the new construction site or a storage yard. During Stage 4, any particularities of the transport by road and by crane are investigated. In order to limit costs and environmental impacts, it is suggested to keep transportation distances as small as possible.

- Stage 5: Storage
  Storage of an element is needed when the new project is unknown or when elements cannot be brought directly to the construction site. If an element is stored, it is important to determine how long an element has been at the storage site since this can cause (external) deterioration. Therefore, Stage 5 considers the susceptibility to external influences. In addition, it is suggested to only deconstruct a building when the new project is known.

- Stage 6: Material handling
  After deconstruction, elements are modified in order to be able to reuse them in a new project. During Stage 6, modifications of the element are investigated considering a 'new' prefab concrete element. In addition, the condition and related risks of the (structural) element are investigated.

- Stage 7: Construction
  If the new design is known, elements can be modified to the requirements of the design. During Stage 7, the requirements of the new design are investigated considering the properties of the second-hand element, as assessed in the previous stages. In addition, the implementation of the second-hand element is analysed regarding the equipment to reconnect. Per option, the relative merits, general procedure and adaptation of the element are investigated.

However, the reuse of harvested (structural) elements in new designs depends on the supply of elements which come from demolition projects or storage sites. Therefore, this research takes both the harvested (structural) elements from demolition projects as storage sites into account resulting in different Reuse Scenarios (RS). An overview of how the stages correspond to each other is shown in Figure 3.8.

- RS I: Element in building, design of new building is known
- RS II: Element at storage, design of new building is known
- RS III: Element in building, design of new building is unknown (database)
- RS IV: Element at storage, design of new building is unknown (database)

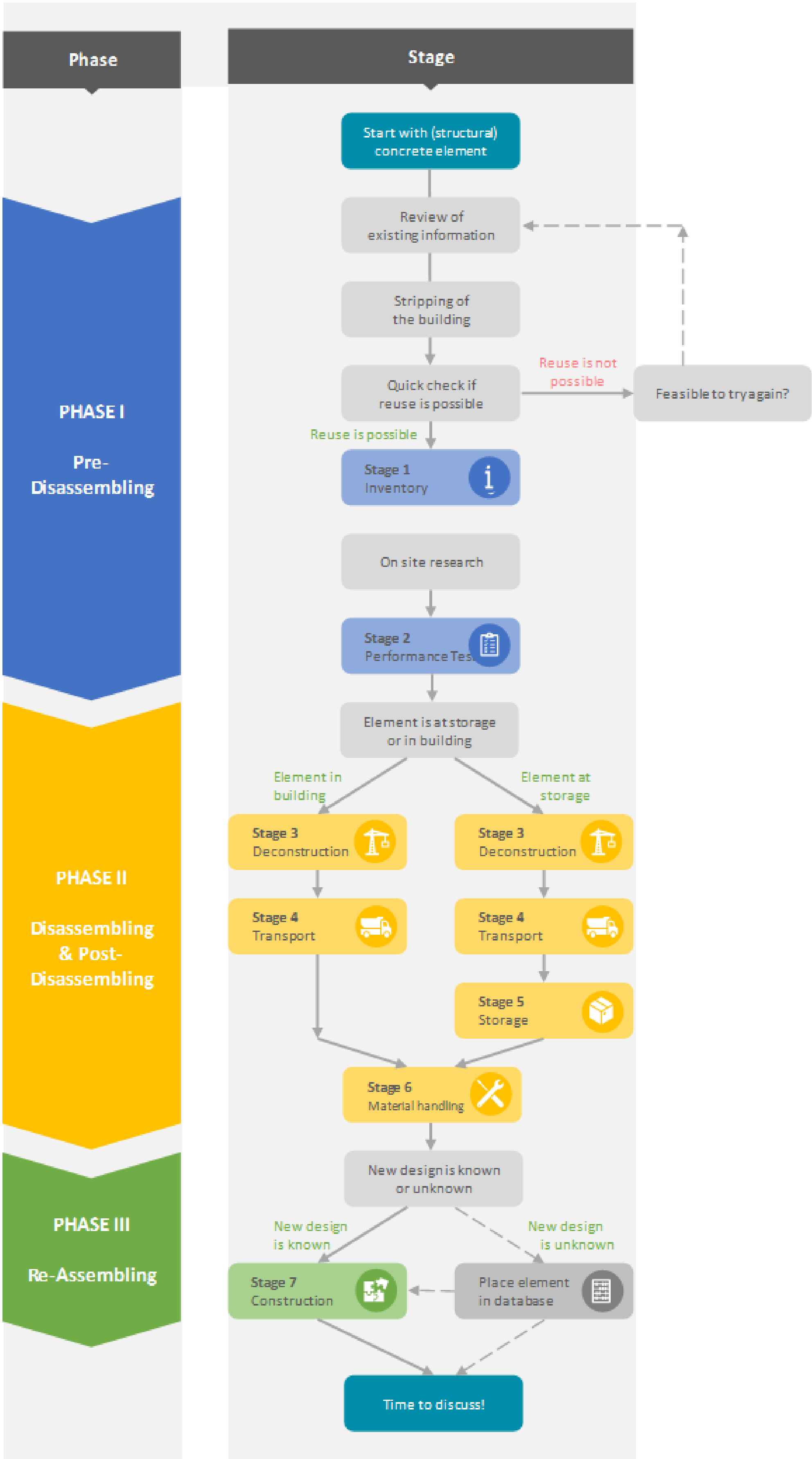


Figure 3.8: Flowchart with how the Stages of the process of 'Deconstruct & Reuse' correspond to each other if the element is located in building or at storage and if the design of the new building is known or unknown (own figure, extended in Figure 4.3).

4 Reuse Potential

This Chapter analyses the definition of Reuse Potential (Section 4.1). In Section 4.2, the process of 'Deconstruct & Reuse' is translated in the assessment of the reuse potential. Additionally, the results per phase are analysed resulting in a flowchart which is made operational in the Decision Support Tool. This Chapter finalizes with an introduction of the Decision Support Tool.

4.1 Definition of reuse potential

Durable concrete means that concrete can last and be used for a long time without being damaged (Cambridge Dictionary, 2020). Other properties and varieties of existing concrete structures can be found in Appendix B. However, concrete, like any element, depreciates due to wear, tear and obsolescence. During deterioration defects occur as identifiable, unwanted conditions that were not part of the original intent of the design. This means that the residual performance of elements with a residual lifespan needs to be tested before transforming these elements into resources to construct new buildings (Figure 1.5). The salvage value of an element can be determined at the end of life (EoL) as the estimated or expected market value of the element that is saved from being depreciated. Therefore, if an element is sold as scrap at its end of life (EoL), the element still possesses a salvage value [Akanbi et al., 2018]

Moreover, the value of elements does not necessarily have to be estimated at the end of life. This can be referred to as the residual value, which implies the expected value of materials after it has been used for a particular period (Cambridge Dictionary, 2020). The significance of the residual value is that it allows to calculate the value of depreciation of elements over time, indicating its residual performance. A calculation of the residual value can be based on the number of years the material remains to exist where a distinction is made between the technical, functional and economic service life of an element (as described in Section 1.2). However, such calculation can be misleading, because the value can easily be under- or overestimated where a lower value implies more depreciation and thus lower profits for the owner.

Based on the technical, functional and economic service life, the research of Ellen MacArthur Foundation [2013], Verberne [2016] and Disseldorp [2018] analyses Building Circularity Indicators (BCI's) which asses the residual value and corresponding residual performance. The BCI's are arranged in technical, functional and economic indicators. The technical indicators relate to the technical characteristics of all materials such as input, usage, and output. The functional indicators relate to the characteristics of a building's 'attractiveness for usage' [Ellen MacArthur Foundation, 2013; Verberne, 2016; Disseldorp, 2018]. The economic indicators relate to the institutional, organizational, juridical, and behavioural area to embrace circularity in business' standards [Cramer, 2015]. However, the economic service life is not a material-dependent factor and thus time depending. Therefore, this research only considers the technical and functional service life of an element.

Besides the service life and corresponding Building Circularity Indicators (BCI's), the research of Iacovidou and Purnell [2016] considers two other factors to assess the residual value of an element:

- Embodied carbon reuse efficiency;
- Reuse potential.

First, the embodied carbon reuse efficiency is a factor that stimulates reuse by providing knowledge of how much carbon can be saved by reusing an element. However, the embodied carbon is hard to depict due to dependence on the mass, characteristics, function, material handling, transport and construction. Secondly, the reuse potential is a measure of the ability of a construction component to retain its functionality after the end of its primary life. With a literature study, the research of Iacovidou and Purnell [2016] has depicted the reuse potential rates of a range of (structural) elements. However, the rates are estimations due to dependence on cultural, historical and organisational aspects. Additionally, the reuse potential of concrete is difficult to generalise due to numerous uses, variable composition and strength, purity and form. In addition, the research of Hradil et al. [2014] states that the concrete has the lowest reuse potential compared to steel and timber. Since this research only considers technical and functional indicators, the reuse potential of concrete can be assessed with the residual value and corresponding residual performance.

Reuse potential means the possibility to reuse a harvested concrete (structural) element in the design of a new building considering the process of 'Deconstruct & Reuse'.

(interpretation of the researcher)

4.2 Assessment of reuse potential

As shown in Figure 3.7, the process of 'Deconstruct & Reuse' is arranged in phases, stages and indicators based on an extensive literature study and a case-study. Next, the needed information per indicator is analysed based on what structural engineers want to know before applying a released element for reuse in a new project. The needed information is based on interviews with structural engineers throughout the research, as described in Appendix H. An overview of the phases, stages, indicators and needed information for the process of 'Deconstruct & Reuse' is shown in Figure 4.1. This overview forms the guideline of the Decision Support Tool and the upcoming sections, where the indicators per stage are further analysed.

In order to assess the reuse potential, information about the process of 'Deconstruct & Reuse' needs to be retrieved. NEN 8700 is a standard for the assessment of the safety and usability of existing structures which describes the following steps to retrieve information: [Van Berlo, 2019]

- Collect information about the use of the structure (e.g., geometry, material properties, loads and current condition like cracks, deflections, discolouration);
- Execute technical investigation to reduce uncertainties;
- Perform calculation based on requirements, load combinations and the desired residual lifespan.

Therefore, Stage 1 (Inventory) gathers and reviews existing information with desk research, while and Stage 2 (Performance Testing) researches on site. However, in order to assess the reuse potential from a structural perspective, information from several parties is needed. Sources to retrieve this information can be codes, inspections, and results of measurements. However, contract specifications, calculations and drawings provide information that must be handled carefully, because properties from the actual construction can be out of date or differ from what is indicated in the original construction (e.g., dimensions of elements, position of reinforcement, applied materials, etc). Additionally, accidents (e.g., damages or deterioration) can occur during the service life of an element which can obstruct reuse. The research of Volkov [2019] refers to this by saying that every structure is somehow 'unique'. In order to tackle these uncertainties and to make sure elements from a demolition project can be reused without risk, this research considers the sources to gather information as drawings and desk research, visual inspection, inspection report and the project team.

Phases	Stages	Indicators	Needed information
Phase I Pre-Disassembling	Stage 1: Inventory	Quick check if reuse is possible	1. General information about the (structural) element
			2. General information about the (origin) building
			3. Deal-breaker questions
		Properties of the (structural) element to be reused	1. Properties of concrete
			2. Concrete cover
			3. Function
			4. Design load(s)
	Stage 2: Performance Testing	Composition	1. Toxic materials
		Certified or not?	1. Properties of concrete
		Deterioration	1. Internal deterioration
			2. External deterioration
Phase II Disassembling and Post-Disassembling	Stage 3: Deconstruction	Removal for reuse	1. Type of connection
			2. Accessibility
			3. Equipment to disconnect
	Stage 4: Transport	By crane	1. Method of hoisting
		By road	1. Geometry
	Stage 5: Storage	External influences	1. Amount of years at storage
			2. Susceptibility
	Stage 6: Material Handling	Modify to 'new'	1. Modifications
			2. Fire resistance
		Condition and risk score	1. Condition score
			2. Risk score
Phase III Re-Assembling	Stage 7: Construction	Requirements of the (new) design	1. Project name and location
			2. Construction year
			3. Design service life
		Properties of second-hand element	1. Properties
			2. Concrete cover
			3. Function
			4. Design load(s)
			5. Holes for services
		Implementation of second-hand element	1. Change of function
			2. Type of reconnection
			3. Equipment to reconnect
			4. General procedure
			5. Adaptation

Figure 4.1: Overview of the process of 'Deconstruct & Reuse' with Phases, Stages, Indicators and needed information based on extensive literature study, case-study and interviews (own figure).

4.2.1 Results per Phase

At the end of each Phase, results can be obtained which outline the assessment of the reuse potential so far. This section analyses the output of Phase I, Phase II and Phase III. The flowchart in the next subsection provides the overview of the process of 'Deconstruct & Reuse' that forms the guideline of the Decision Support Tool in the next section.

The indicators and needed information of an element which are relevant to assess the reuse potential are analysed in Figure 4.1. Data regarding the mentioned properties could be stored in a so-called material passport. For new buildings, a material passport can easily be implemented. However, for a lot of existing buildings, information is not stored properly and thus unknown. The research of Van Berlo [2019] states that if the information is stored properly, the retrieval eases the process of deconstruction and gives more value to the harvested (structural) elements. Therefore, the assessment should aim to store retrieved information in the form of a material passport per element. This makes it possible to build a database which can predict when and where elements can be harvested. Thereby, the database brings together the supply and demand of harvested (structural) elements which means a long-term construction planning can be created based on harvested elements. The database is out of the scope of this research, but prone to further development (Chapter 11).

For Phase I (Pre-Disassembling), the research of Glias [2013, p. 54-63] recommends to perform a quality check for reuse. This check can be satisfied with the use of the Element Identity (EID) which contains details about the properties of the element and can be used as a certificate that proves if an element is suitable for reuse. With the gathered and reviewed information of Stage 1 (Inventory), a preliminary Element Identity (EID) can be signed by the responsible engineer. After Stage 2 (Performance Testing), the final Element Identity (EID) is signed (Figure 4.3).

For Phase II (Disassembling and Post-Disassembling), the reuse potential of the harvested (structural) element is considered per stage carried out in Phase I and II. An example is shown in Figure 4.7.

For Phase III (Re-Assembling), the opportunities of the second-hand element in the design of a (new) building is considered. Since the circular and sustainable strategies of the design of new buildings are out of the scope of this research, the output provides valuable insights with which a structural engineer can determine if the assessed element is applicable in the design of a new building or whether modifications are needed.

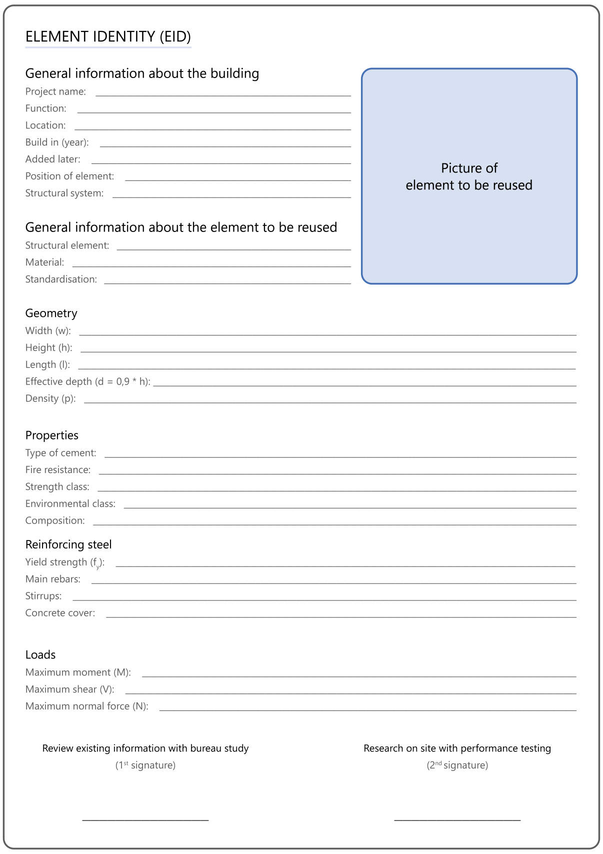


Figure 4.2: Element Identity (EID) with first and second signature. Adapted from Glias [2013, p. 54-63]

4.2.1.1 *Flowchart*

The flowchart in Figure 3.8 showed how the stages of the process of 'Deconstruct & Reuse' correspond to each other. Additionally, the flowchart indicates what happens if reuse is not possible (coloured in red) with dotted lines. As a follow-up, Figure 4.3 provides the flowchart including the results per phase (coloured in orange).

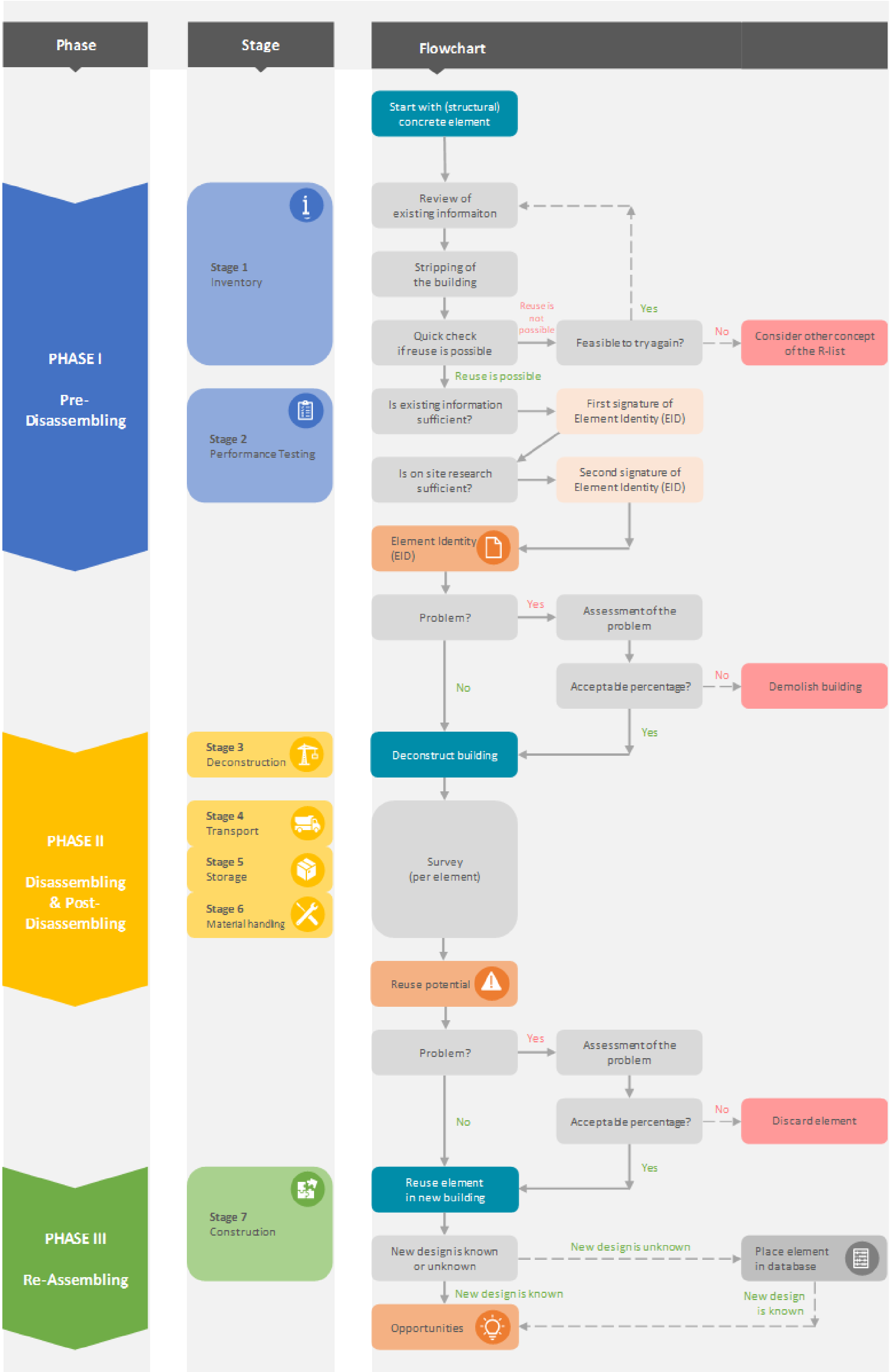


Figure 4.3: Flowchart with Phases and Stages of the process of 'Deconstruct & Reuse' which declare if reuse is possible with the Element Identity (EID) at the end of Phase I, reuse potential at the end of Phase II and opportunities at the end of Phase III (own figure).

4.3 Decision Support Tool

As described, the process of 'Deconstruct & Reuse' is translated in the assessment of the reuse potential. Next, the indicators are rewritten in assessment questions and answer options which are implemented in the Decision Support Tool (subsection 2.3.1). The overview in Figure 4.4 follows the flowchart in Figure 4.3. As analysed in Appendix C.1, existing methods lack a practical guideline. Therefore, the assessment of the reuse potential is made operational in the Decision Support Tool. The Decision Support Tool is further explained in Chapter 8, where the validity of the preliminary versions and final version of the Decision Support Tool is tested with a case-study.

> *Decision Support Tool is an executable method to assess the reuse potential of harvested elements of existing concrete structures in such a way to allow structural engineers to make use of these elements in the design of new buildings.*
>
> (interpretation of the researcher)

The Decision Support Tool distinguishes three phases which are set up based on the information provided during the Pre-Disassembling, Disassembling & Post-Disassembling and Re-Assembling. The three phases each categorize several stages and at the end of each phase, results can be obtained which outline the assessment of the reuse potential so far. An overview of the Decision Support Tool is shown in Figure 4.4, where all phases and stages are indicated with the corresponding colours.

The Decision Support Tool can be used by structural engineers who want to test the reuse potential of a (structural) concrete element and reuse this element in the design of a (new) building. Moreover, the second-hand (structural) element to be tested and reused can originate from a storage site, a demolition project or a building to be demolished. However, basic knowledge about (structural) concrete is expected for the input that makes the Decision Support Tool particularly useful for structural engineers.

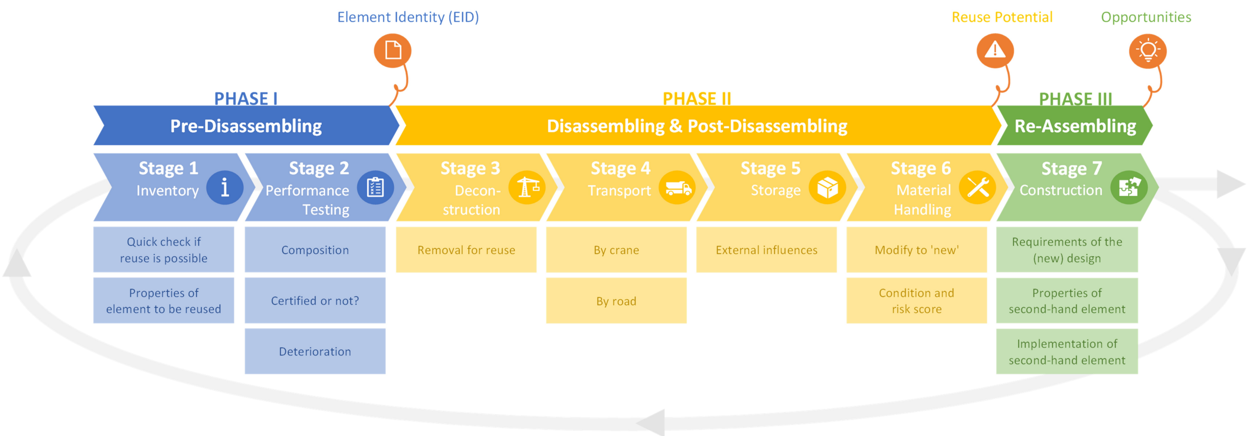


Figure 4.4: Assessment of reuse potential of existing concrete with Phases, Stages and Indicators (own figure).

The Decision Support Tool is set up in Excel, consisting of worksheets for Input, Formulae and Output. Firstly, the input of the Decision Support Tool consists of a harvested concrete (structural) element to be tested for reuse. Secondly, the formulae of the Decision Support Tool is the assessment of the reuse potential. As described in the Chapter 3, this is determined with an extensive literature study and a case-study. Additionally, interviews with structural engineers have been conducted throughout the research. Thirdly, the output of the Decision Support Tool indicates the results for reuse of the assessed element in the design of a new building. As described in subsection 4.2.1, results can be obtained at the end of each phase. Thereby, the output indicates if reuse is possible and how harvested (structural) elements can be implemented in the design of a new building.

An overview of the Input, Formulae and Output of the Decision Support Tool is shown in Figure 4.5. The input and output are referred to as the front-end of the Decision Support Tool, whereas the formulae is referred to as the back-end. The front-end and back-end are described in the next subsections.

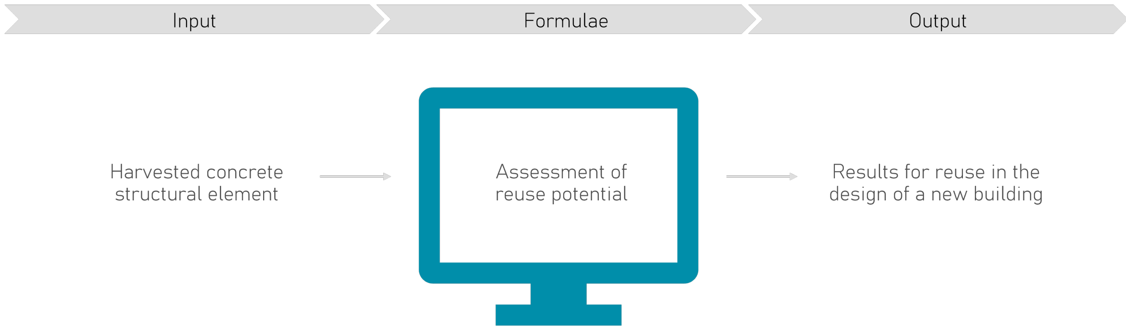


Figure 4.5: Decision Support Tool with worksheets for Input, Formulae and Output (own figure).

4.3.1 Front-end of Decision Support Tool

The input of the Decision Support Tool follows the flowchart in Figure 4.3. Additionally, the process of 'Deconstruct & Reuse' is translated into assessment questions and answer options. The assessment questions are linked to a Graphic User Interface (GUI) which makes the assessment easy to execute. The GUI is a form to be filled in by a structural engineer who wants to test the reuse potential of a harvested (structural) element. Additionally, the answer options of Phase I, II and III are explored respectively in Chapter 5, Chapter 6 and Chapter 7.

As described in subsection 4.2.1, results can be obtained at the end of each phase which outline the assessment of the reuse potential so far. The output per Phase is generated in in the form of a PDF file that can be saved locally. The reuse potential (or output) is easy to understand for construction parties, which makes it a subject for discussion in the initial phase of a (new) building. This can accelerate the Circular Economy (CE) in the building sector. The goal of the Decision Support Tool is to advise structural engineers who want to test or reuse a harvested (structural) element in the design of a new building. Especially when the design is still in the initial phase, the results of the Decision Support Tool can influence the implementation of a harvested (structural) element in a (new) building.

4.3.2 Back-end of Decision Support Tool

The worksheet with the Formulae assesses the reuse potential, which is referred to as the back-end of the Decision Support Tool. The final goal of the Decision Support Tool is to represent all indicators that have an impact on the reuse potential, through a single number. However, some indicators contain vague data and lack certainty. In order to handle this, a fuzzy calculation can be performed. A Fuzzy calculation is defined as indicators that contain any number between 0 and 1, where 1 stands for the most favourable value regarding the reuse potential of an element ('true') and 0 for the least favourable value ('false'). An example of fuzzy logic is a moving car with the fuzzy rule "if the speed is high, then reduce gas". This rule does not specify when the speed is high or the amount by which the speed is reduced. Yet, the speed of the car can be controlled by assigning low, medium, fast and very fast values (so without precise meanings), referred to as approximate reasoning. An example of four fuzzy logics in trapezoidal shape is shown in Figure 4.6. up to 80 km/h, where values overlap.

The example in Figure 4.6 shows values up to 80 km/h, where values overlap. A number between 0 and 1 can be associated with these values, e.g., 30 km/h can be associated with the value 1 as medium speed. This degree of association implies that when the medium speed differs from 30 km/h in any direction, the fuzzy value decreases to a value lower than 1 [Durmisevic, 2006, p. 209-219]. Typically, a Fuzzy calculation can be specified by:

If a = A *(e.g., 'true / 1'),*

Then b = B *(e.g., 'false / 0')*

For this research, the Fuzzy calculation is implemented in grading and a range of uncertainty. With the grading and range of uncertainty, calculations can be made to generate the results per Phase. For simplicity, the worksheet with the Formulae is not visible for the executor of the Decision Support Tool.

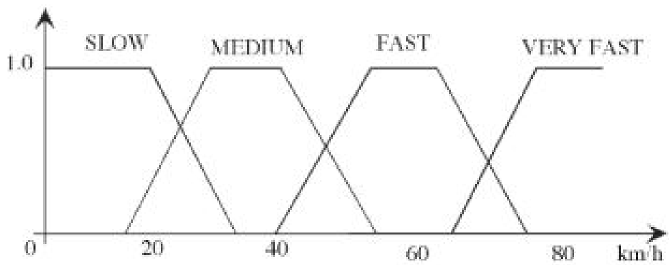


Figure 4.6: Four examples of fuzzy logics with low, medium, fast and very fast values of the car speed [Durmisevic, 2006, p. 220].

4.3.2.1 *Grading of indicators*

By grading the indicators, values regarding the reuse potential can be obtained. The arrangement of the grading is as follows: [Durmisevic, 2006, p. 209-219]

- Values between 0 and 0,3 result in (total) demolition of an element;
- Values between 0,3 and 0,6 result in partial demolition of an element;
- Values between 0,6 and 0,9 result in no demolition of an element and in the possibility to reuse an element;
- Values between 0,9 and 1,0 result in the possibility to reuse an element.

4.3.2.2 *Range of uncertainty*

If an answer can not be filled in due to insufficient or absent information, the person who executes the Decision Support Tool can follow the further instructions or select 'unknown'. In that case, a conservative lower limit is taken for the answer option. However, the answer option can alter with sufficient information, resulting in a higher or lower grade. Therefore, a range of uncertainty is applied to calculate the reuse potential if all answers can be filled in. The **(+) uncertainty** assumes that all answers which could not be filled in get a grade of 1,0. The **(-) uncertainty** assumes that all answers which could not be filled in get a grade of 0. The range of uncertainty provides insight into how the reuse potential looks like if all uncertainties are discharged, as shown in Figure 4.7. The calculation of the range of uncertainty makes use of the following relation:

$$\text{Reuse potential} = \frac{\text{Scored grade}}{\text{Highest possible grade}} \cdot 100\% \tag{4.1}$$

where

Reuse potential	can contain any number between 0 and 1, where 1 stands for the most favourable value and 0 for the least favourable value ('false'),
Scored grade	depends on the filled-in answers (and range of uncertainty),
Highest possible grade	is the case where all filled-in answers grade a score of 1.

After grading all indicators, a box plot can be obtained which assesses the reuse potential of an element. The green line of the box plot in Figure 4.7 indicates a high reuse potential (value of '1', see fuzzy calculation). If an indicator is poorly graded, this becomes visible in the box plot with a line close to '0'. Individual box plots make a comparison between harvested (structural) elements possible.

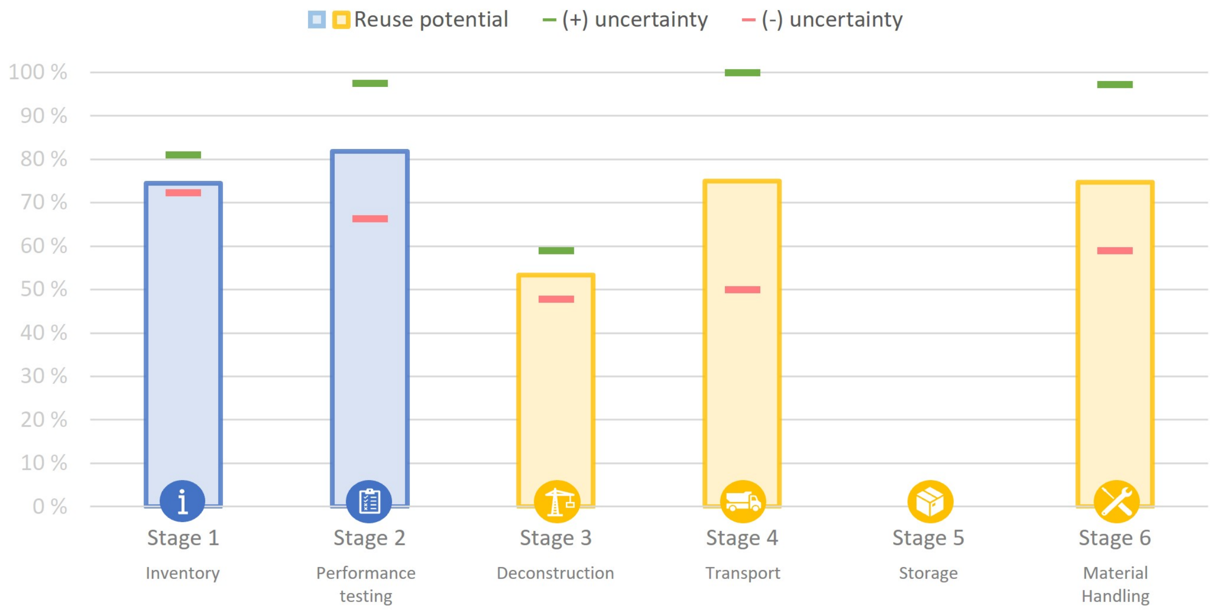


Figure 4.7: Example of reuse potential with range of uncertainty at the end of Phase II (own figure).

Part II
Research Methods

The second part of this research describes the research methods, which follows the research framework of the first part. The third part describes results and final remarks of this research.

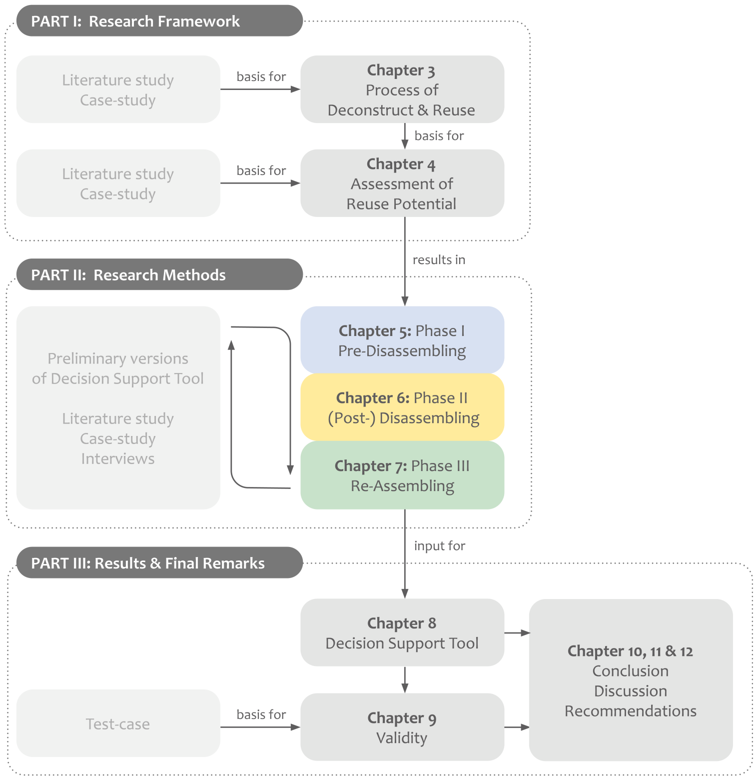


Figure 4.8: Research parts with chapters (own figure).

5 | Phase I: Pre-Disassembling

The first Phase of the process of 'Deconstruct & Reuse' distinguishes two stages, namely Stage 1: Inventory and Stage 2: Performance Testing, as highlighted in Figure 5.1. Stage 1 and Stage 2 are analysed respectively in Section 5.1 and Section 5.2. An overview of the input and grading of all three Phases can be found in Appendix G.

5.1 Stage 1: Inventory

Stage 1 (Inventory) considers if reuse of a harvested (structural) element is possible. Therefore, a preliminary assessment of the technical properties and condition of each element needs to be done. A quick check is performed to determine if reuse is possible. The subsequent section explains how this check is implemented in the Decision Support Tool. More information about Stage 1 can be found in Appendix D.1.

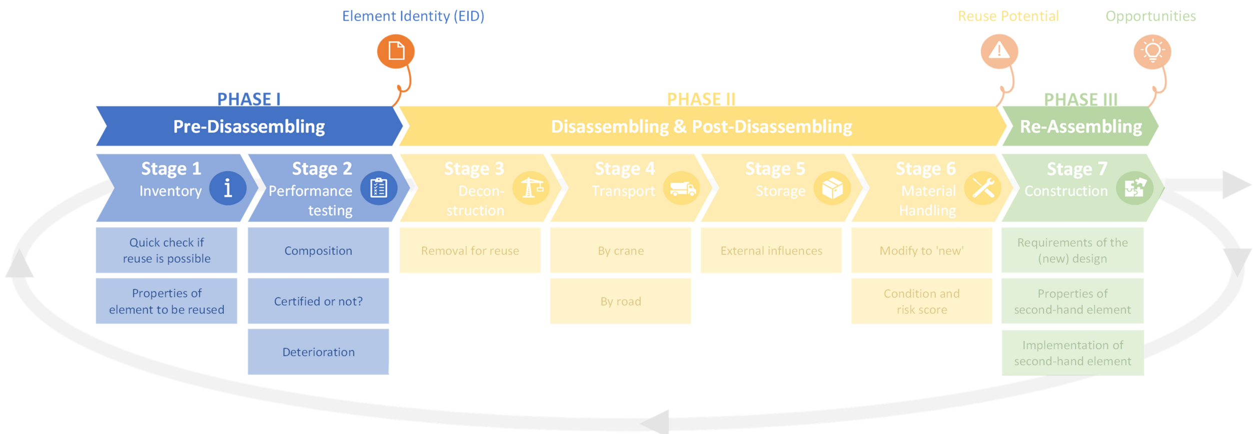


Figure 5.1: Assessment of reuse potential of existing concrete with Phase I highlighted in blue (own figure).

5.1.1 Quick check if reuse is possible

In order to determine if reuse of a harvested (structural) element in a new design is possible, a quick check is implemented at the start of the Decision Support Tool. The quick check firstly gathers general information about the (structural) element and (origin) building. With this information, deal-breaker questions are formulated which quickly check if reuse is possible.

5.1.1.1 *General information about the (structural) element to be reused*

In this section, general information about the (structural) element is gathered based on the following:

- Element to be reused;
- Standardisation of the element;
- Density of the concrete mixture;
- Dimensions of the element.

Element to be reused
In the Decision Support Tool, the following structural elements are considered: concrete beam, concrete column, concrete slab and concrete wall. Additionally, an image of the element to be reused can be added in the Decision Support Tool.

Standardisation
Standardisation refers to the deployment of a harvested (structural) element. In-situ concrete is usually project specific, heavy and difficult to handle and analyse if information about the reinforcement is lacking. Additionally, in-situ concrete has no joints between elements, making it harder to dismantle from the rest of the structure without damage. Pre-cast concrete can be recovered and reused as such in new construction due to more commonly applied dimensions. Therefore, information about the standardisation and the dimensions of an element are relevant. However, some elements may require small modifications to enable their (original) connections [Van Dijk et al., 2000; Iacovidou and Purnell, 2016; Hradil et al., 2014].

Additionally, standardisation indicates the impact on disassembly [Durmisevic and Brouwer, 2002]. Since this research only considers in-situ and pre-cast concrete, this impact can be distinguished from best to worst as 1) Fully standardised pre-made geometry (e.g., pre-cast concrete); 2) Half standardised geometry and 3) Geometry made on construction site (e.g., in-situ concrete). On the one hand, half standardised geometry can be pre-cast concrete where the dimensions are based on a design perspective and for a specific project. But on the other hand, half standardised geometry can be pre-cast concrete with standard dimensions where the reinforcement is designed for a specific (structural) situation [Van Berlo, 2019]. In order to distinguish these two concepts, the Decision Support Tool considers the standardisation as shown in Table 5.1, where the reuse potential of pre-cast and in-situ concrete is translated in grading [Durmisevic, 2006; Van Berlo, 2019].

Table 5.1: Standardisation with answer options and grading. Adapted from Durmisevic and Brouwer [2002]; Van Berlo [2019]

Option	Explanation	Grading
1	Non-load bearing pre-cast concrete	1,0
2	Load bearing pre-cast concrete	0,5
3	In-situ concrete	0,1

The concepts are ordered from the best to worst impact on disassembly. This means disassembling of non-load bearing elements has a higher reuse potential than load-bearing elements because reuse of the latter requires re-calculation(s). Additionally, in-situ concrete is more difficult to reuse due to its specific shape and connections [Van Berlo, 2019]. If an element is pre-cast or cast in-situ can be found in drawings or during visual inspections. More information about pre-cast and in-situ concrete can be found in Appendix B.2.

Density
Information about the density of the concrete mixture can be found on drawings. If unknown, 2400 kg/m^3 can be assumed for normal concrete and 2500 kg/m^3 for reinforced concrete. The density is used to calculate the weight of the element and to determine if transportation is possible (Stage 5).

Dimensions
Information about the dimensions of the structural element can be found on drawings. The dimensions are used to determine if transportation is possible (Stage 5).

5.1.1.2 *General information about the (origin) building*

In this section, general information about the (origin) building is gathered based on the following:
- Project name and location;
- Construction year and deconstruction year.

Project name and location
The (origin) building is analysed with the project name and location. For this research, only locations in the Netherlands are considered.

Construction and deconstruction year
The construction year indicates in which year the (origin) building was constructed. Additionally, the Decision Support Tool analyses if the element is added later. If so, the construction year is taken as the year in which the element was constructed and added to the building.

The deconstruction year indicates in which year the (origin) building was deconstructed or will be deconstructed. The deconstruction year can thus be in the past or future. By comparing the deconstruction year and current year, the Decision Support Tool indicates if the element is located in the building or already deconstructed. This check ensures correct information is stored in the Decision Support Tool, because as an executor you already know if the element is located in the building or already deconstructed. Moreover, the age of the element is calculated by subtracting the deconstruction year and construction year. The age is used to determine the residual lifespan of the element, which is described in the next section.

5.1.1.3 *Deal-breaker questions*

After gathering general information about the (structural) element and (origin) building, deal-breaker questions are formulated which quickly check if reuse of a harvested (structural) element in a new design is possible. In the Decision Support Tool, the answers to the deal-breaker questions directly indicate the positive or negative effect on the reuse potential by highlighting respectively in green or red. The questions are compiled considering the negative effects among all stages, together with the interpretation of experts and the researcher. Therefore, the questions are a combination of desk research and research on site. The following deal-breakers are considered (in between brackets indicates the corresponding stage):
- Technical condition of the element; (Stage 2: Performance Testing)
- Residual lifespan; (Stage 2: Performance Testing)
- Accessibility of the connection(s) of the element; (Stage 3: Deconstruction)
- Transport by road; (Stage 5: Transport)

Technical condition
The condition of a concrete harvested (structural) element can be expressed by the condition assessment (NEN 2767) which ensures objective and uniform measurements of the physical quality of construction and installation parts of buildings and/or infrastructure. The condition assessment is a method that objectively determines and unambiguously records the technical condition of buildings, infrastructure, and other management objects [NEN 2767, 2013]. In order to assess the physical quality or technical condition of objects, it is relevant to know the performance quality of the objects [Geldermans, 2016]. Therefore, defects are inspected whether they have an undesirable effect on certain performance requirements during the service life of objects. Next, the severity, size and intensity of the observed defects are determined. Based on these results, the condition is expressed in a score of 1 to 6 (Table 5.2) which indicates the technical condition in an objective value.

For this research, a first indication of the condition score is determined by technical questions, which can be found in Figure 5.2. The questions are compiled considering defects to existing concrete (NEN 8700, p. 16; NEN 8702, p. 8). Each technical question that can be answered with "no" has a positive effect on the reuse potential, which is indicated by "1" according to the fuzzy grading. However, each technical question that can be answered with "yes" has a negative effect on the reuse potential, which is indicated by "0". If an answer is "unknown", an average grade is assumed as "0,5". An example of how the condition score (C_I) is determined with the answers to the technical questions is shown in Figure 5.2, where C_I is (6 - 3,5 =) 2,5. This score is translated to the options Table 5.2 to 2 for the (+) uncertainty and 3 for the (-) uncertainty.

Table 5.2: Condition score with answer options and grading. Adapted from NEN 2767 [2013]; Van Berlo [2019].

Option	Explanation	Grading
1	No effect (incidental minor failures)	1,0
2	Slight effect (incidental beginning of deterioration)	0,75
3	Mild effect (partially visible deterioration, no danger of performance failure)	0,5
4	Moderate effect (visible deterioration, danger of performance failure)	0,25
5	Strong effect (deterioration is irreversible)	0
6	Very severe effect (technically ready for demolition)	0

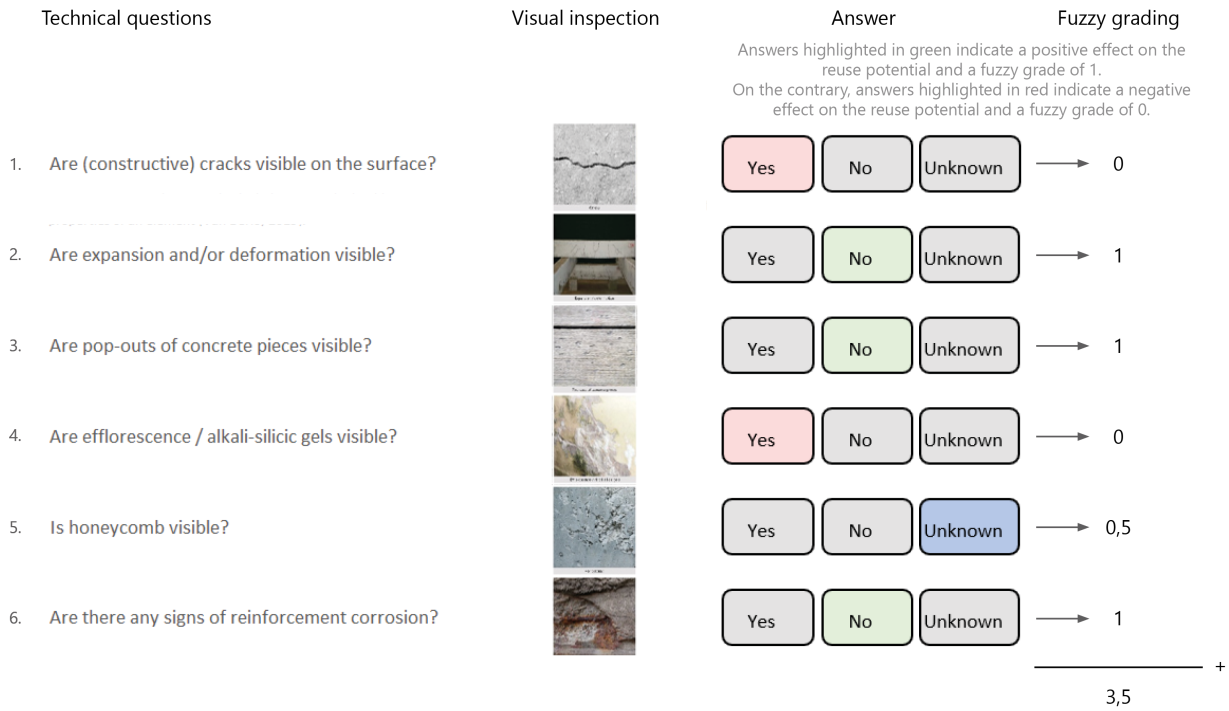
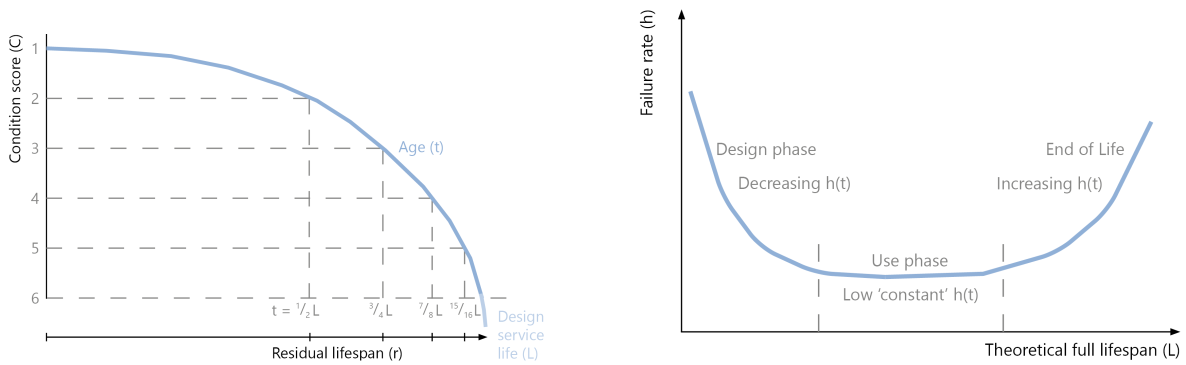


Figure 5.2: Example of determination of condition score (own figure).

Information to answer the technical questions can be found by inspection reports or visual inspections, as shown in Figure D.3. The technical questions which have a negative effect on the reuse potential are further analysed in Stage 2 (Performance Testing). For example, the first question indicates the presence of (constructive) cracks which decrease the load-bearing properties of an element. Cracking can also relate to the expansion and/or deformation of an element (second question). Another example is Alkali-Silica Reaction (ASR), which can be signalled by (micro) cracks, expansion/deformation, pop-outs of concrete pieces and efflorescence/alkali-silicic gels. These signals respectively correspond to the first, second, third and fourth question. The fifth and sixth question respectively indicate the presence of honeycomb and reinforcement corrosion [Van Berlo, 2019]. Cracking, ASR and corrosion are further analysed in Appendix D.2.2.

Residual lifespan

The residual life of an element can be expressed by the difference between the minimum acceptable performance and the present performance. The most used model to describe the reliability behaviour of elements over their lifespan is the Weibull distribution function or 'bathtub model', where the reliability is indicated by the failure rate [Jiang, 2020]. At the beginning of a life cycle, the failure rate is high due to design and manufacturing errors. During the use phase, the failure rate decreases towards a constant level. As an element approaches its end of life (EoL) the failure rate sharply increases, which means the performance of an element decreases making them less suitable for reuse [Akanbi et al., 2018]. These three phases are shown in Figure 5.3b. For the simplicity of this research, only elements approaching their 'second life' are considered.



(a) Structural performance versus time with residual lifespan. Adapted from Somerville et al. [1995]; Vissering et al. [2011].

(b) Hypothetical failure rate versus time in bathtub or Weibull model. Adapted from Jiang [2020]; Akanbi et al. [2018].

Figure 5.3: Two models of the residual lifespan and failure rate.

The residual lifespan (expressed in years) can be determined in three ways. Firstly, the design service life of the element can be considered. As described, a reference service life (RSL) of 100+ years can be assumed for structural elements made of concrete [Vissering et al., 2011]. By subtracting the service life and age of an element, the residual lifespan based on the design service life can be determined.

Secondly, the residual lifespan can be determined based on NEN 2767 or NEN 8700. The latter is a very extensive calculation, which makes NEN 2767 more suitable for a quick check [Van Berlo, 2019]. NEN 2767 roughly calculates the age (t) based on the condition score in Table 5.2 using the following relation in $years$:

$$t = L - \frac{1}{2} \cdot L \cdot (C - 1) \tag{5.1}$$

where

t is the age,

L is the design service life [Vissering et al., 2011],

C is the condition score (Table 5.2).

With this equation, the residual lifespan (r) can be calculated in $years$. This is shown in Figure 5.3a. Besides the condition of the element, the residual lifespan can be determined based on chloride or carbonatation penetration. This is further analysed in Stage 2: Performance Testing (Appendix D.2.2). The grading of the residual lifespan corresponds to Table 5.3. On the one hand, the residual lifespan gives a proper indication, but on the other hand, a lot of uncertainties can be present in its calculations. In order to deal with this inaccuracy, the research of Van Berlo [2019] recommends inspecting at all times. Additionally, he argues it might be better to just look at the condition of the element because the residual lifespan highly depends on this. In Stage 6: Material Handling (Section 6.4), it is analysed if the condition score (and corresponding residual lifespan) can be extended by material handling.

Table 5.3: Residual lifespan with answer options and grading. Adapted from Van Berlo [2019]

Option	Explanation	Grading
1	> 50 years	1,0
2	> 40 years	0,8
3	> 30 years	0,6
4	> 20 years	0,4
5	> 10 years	0,2
6	≤ 10 years	0

Accessibility

The accessibility of an element refers to the level of access without causing damage to the element or other surrounding elements. Damage during removal has a negative effect on the reuse potential, this indicator can thus be seen as a deal-breaker. Desk research and research on site can indicate the accessibility with e.g., construction drawings, inspection reports or visual inspections [Van Berlo, 2019]. The accessibility is shown in Table 5.4 with written examples and grading. Additional operations are specified as operations for which extra equipment to disconnect the element from the structure is needed. The answers are linearly graded from most accessible (1) to less accessible (0) based on the scores from Durmisevic [2006].

Table 5.4: Accessibility with answer options and grading. Adapted from Durmisevic [2006, p. 212].

Option	Explanation	Grading
	Not applicable, element is already at storage site	-
1	Accessible without additional operation	1,0
2	Accessible with additional operation which causes no damage to the element	0,75
3	Accessible with additional operation which causes repairable damage to the element	0,5
4	Accessible with additional operation which causes partly repairable damage	0,25
5	Not accessible without causing total damage to the element	0

Transport

The dimensions and weight of a harvested (structural) element play an important role in transport. For this research, only transport by road in the Netherlands is considered which means transport by air, rail or water are out of scope. Regarding the maximum dimensions and weight allowed for transport by road, normal and exceptional transport can be distinguished. "Normal" transport indicates indivisible cargo within the legally permitted dimensions and weight, specified by the Wegenverkeerswet (Road Traffic Act). "Exceptional" transport of larger indivisible cargo is only permitted with an exemption. Many regulations are attached, which increases the difficulty and transportation costs [Minister van Verkeer en Waterstaat, 2021]. For both "normal" and "exceptional" transport, checkups along the route are recommended with maps and visual inspections. To illustrate, passage widths and permitted weights play a role, because a truck may not be able to pass e.g., a bridge. Another example is the road type because different regulations apply for provincial and national roads in the Netherlands. In addition, regulations for transport during or outside of rush hour differ [Van Berlo, 2019, p. 25-26].

For the simplicity of this research, only "normal" transport by road is considered regarding the following requirements: [Minister van Verkeer en Waterstaat, 2021]

- Length (L) $\leq$ 22,0 m;
- Width (w) $\leq$ 3,0 m;
- Height (h) $\leq$ 4,0 m;
- Weight (G) $\leq$ 50.000 kg.

In the Decision Support Tool, the weight of an element is calculated with the dimensions and density. As specified by the Wegenverkeerswet (Road Traffic Act), the legally permitted weight for "normal" transport in the Netherlands is a maximum of 50.000 kg to pass. Since a truck weighs approximately 15.000 kg, an element can have a maximum weight of 35.000 kg to be transportable by "normal" transport (e.g., a truck). This is further analysed in Stage 4: Transport (Section 6.2).

Conclusion of deal-breaker questions

In conclusion, reuse is possible if the technical condition scores lower than 5 or 6, the residual lifespan is more than 10 years, the accessibility scores lower than 5 and the element can be transported by road. This is explained in the subsequent sections.

5.1.2 Properties of the (structural) element

This section describes the properties of the (structural) element which follows up the general information and deal-breaker questions of the previous sections. Firstly, general properties of the element to be reused are analysed such as type of cement, fire resistance, strength class, environmental class and yield strength of the reinforcing steel. The properties are graded according to Table 5.5. Next, the concrete cover is checked. Lastly, the function of the (origin) building and the design loads on the element are analysed.

As described earlier, this research considers existing information to be sufficient for the input of the Decision Support Tool. Since it is hard to estimate the exact strength of concrete on site without testing [Braam et al., 2011], this research follows what is known by drawings and calculations. In addition, the properties of Stage 1 can be certified in Stage 2: Performance Testing.

5.1.2.1 *General properties*

In this section, general properties of the (structural) element are gathered based on the following:

- Type of cement;
- Fire resistance;
- Strength class;
- Environmental class;
- Yield strength.

Table 5.5: General properties of the harvested (structural) element with grading.

Option	Explanation	Grading
1	Property of element is known	1,0
2	Property of element is unknown	0,5

Type of cement

As described in Appendix D.1.1, this research considers CEM I, CEM II/A, CEM II/B, CEM III/A, CEM III/B and CEM III/C which are implemented in the Decision Support Tool as respectively CEM I, CEM II and CEM III. If the type of cement is unknown, CEM I (Portland cement) is assumed as a conservative lower limit which can be certified in Stage 2 (Performance Testing).

Fire resistance
As described in Appendix D.1.2, this research considers the fire resistance of new and existing buildings which are implemented in the Decision Support Tool as respectively 30 min, 60 min, 90 min and 120 min. If the fire resistance is unknown, 30 min is assumed as a conservative lower limit which can be certified in Stage 2 (Performance Testing).

Strength class
As described in Appendix D.1.3, this research considers "normal" concrete which is implemented in the Decision Support Tool as C20/25, C25/30, C30/37, C35/45, C40/50, C45/55, and C50/60. If the strength class of the structural element does not refer to NEN-EN 1992-1-1, the corresponding strength class of older codes can be found in Table D.4. If the strength class is unknown, the following (minimum) assumptions can be made:

- For in-situ concrete, the most common strength classes are currently C20/25, C25/30, and C30/37. These mixtures can be easily processed on the construction site without much special attention and are well suited to a large part of the daily applications of concrete constructions;
- For prefab concrete, the most applied strength classes are C45/55 and C50/60, with a bare minimum of C35/45.

Environmental class
As described in Appendix D.1.4, this research considers the environmental classes according to NEN-EN 206-1 where the classification is based on the chance of damage to the reinforcement (corrosion) and the concrete (degradation). Environmental classes which apply to the superstructure are implemented in the Decision Support Tool (X0, XC1, XC3, XC4, XD1, XS1 and XF1) relating to the maximum water cement factor (wcf) and minimum binder content. These are not considered for this research. If the environmental class is unknown, the environmental class with the highest chance of damage to the reinforcement and concrete is considered (XD1). This can be certified in Stage 2 (Performance Testing). If the environmental class of the structural element does not refer to NEN-EN 206-1, the corresponding environmental class of older codes can be found in Table D.6.

Yield strength
As described in Appendix D.1.6, this research considers yield strengths of the reinforcing steel of 220, 400 and 500 N/mm^2 corresponding to NEN-EN 1992-1-1. If the grade of the reinforcing steel does not refer to NEN-EN 1992-1-1, the corresponding grade of older codes can be found in Table D.10.

If the reinforcing steel is unknown, the following can be assumed. FeB 220 (smooth rebar) is widely used in concrete structures built before 1960. FeB 400 (ribbed rebar) was used in structures built between circa 1960 and 1990. Since 1990, only FeB 500 has been used in the Netherlands which corresponds to B500 in NEN-EN 1992-1-1 [Braam et al., 2011, p. 76].

5.1.2.2 *Concrete cover*

If the thickness of the concrete cover is unknown, the minimum concrete cover ($c_{min,dur}$) can be determined by the environmental class and the strength class of the origin design with the assumed construction class S4 [Eurocode 2, 2013]. If the environmental class or strength class is unknown, conservative lower limits have been indicated in the previous sections. By adding the design allowance for deviation ($\Delta\ c_{dev}$) of 5 mm to $c_{min,dur}$, an assumption can be determined for the final concrete cover (c_{nom}) in equation D.2. Additionally, for slabs and walls the c_{nom} can be smaller than for other (structural) elements, such as beams and columns [Braam et al., 2011]. More information about the concrete cover can be found in Appendix D.1.5.

In the case of reuse, it should be determined whether the concrete cover withstands the durability requirements of the new design according to Eurocode 2 [2013], being the environmental class and construction class with relating service life, strength class, geometry and quality control [Braam et al., 2011; Van Berlo, 2019]. The implementation in the new design is further explored in Stage 7 (Section 7.1).

5.1.2.3 *Function*

The function of the (origin) building is linked to the categories and loads in NEN-EN 1992:

- Residential areas (category A);
- Office areas (category B);
- Congregation areas (category C);
- Shopping areas (category D);
- Storage areas (category E).

5.1.2.4 *Design loads*

The geometry of the reinforcing steel plays an important role. For reuse, it can be assumed that a second-hand element originates from a building that is built according to a standard. Therefore, the element complies with (origin) design guidelines. However, for reuse the geometry and strength of the reinforcing steel should be checked. If reinforcement drawings are available, the dimensions of the reinforcing steel can be determined. Based on the calculations needed for re-connecting (Appendix D.4) and the interviews with experts (Appendix H.1.1), the needed information of the geometry is investigated for the design loads at midspan and at the support. The rebars are distinguished in tension ($_t$), compression ($_c$), flank ($_f$) and stirrups ($_s$). Next, the amount (n), diameter (d) and distance to the concrete surface (a) are analysed. In the case of multiple rows of rebars (in tension, compression or flank) or a reinforcing mesh, the total amount of bars and the average diameter should be filled in. In addition, the average diameter and governing spacing (s_s) should be filled in for stirrups.

The diameters of the rebars and distances to the concrete surface are shown in Figure 5.4. However, the information about the rebars in tension ($_t$), compression ($_c$), flank ($_f$) and stirrups ($_s$) can only be filled-in if the reinforcement drawings are available. Additionally, due to time constraints this research assumes a general theory since different geometries are used in structural elements (e.g., beams, columns, walls and slabs). The general theory is based on the interpretation of experts and the researcher, as described in Appendix H.1.1. For beams and slabs, the Decision Support Tool only considers the main rebars (in tension) because in many calculations rebars in compression are not taken into account. Often, slabs have an additional compression layer to enlarge the capacity. Another difference between the reinforcing steel in beams and slabs is the presence of flank rebars due to the height of beams. Therefore, the flank rebars are implemented in the Decision Support Tool, but not included in the calculations. Lastly, for columns and walls, the Decision Support Tool considers the rebars in tension and compression.

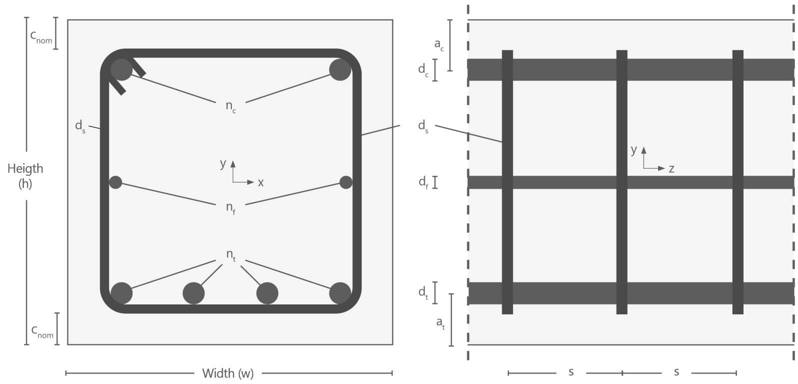


Figure 5.4: Diameters and distances of rebars in tension ($_t$), compression ($_c$), flank ($_f$) and stirrups ($_s$) (own figure).

5.1.3 First signature of Element Identity

If the filled-in answers of Stage 1 are correct and researched by drawings and desk research, the executor of the Decision Support Tool can set a first signature below the Element Identity (EID), which is the output of Phase I (page 75).

5.2 Stage 2: Performance Testing

After the inventory has taken place (Stage 1), but before deconstruction (Stage 3) of a building can start, performance testing of the elements needs to occur. As mentioned, Stage 1 (Inventory) and Stage 2 (Performance Testing) consider if reuse of harvested (structural) elements is possible before an element is deconstructed (Figure 4.3). After performing a quick check to determine if reuse is possible (subsection 5.1.1), the desk research of Stage 1 is followed up by research on site which is indicated by Stage 2: Performance Testing.

This stage determines what an element has endured and what its residual value for reuse is by visual inspection and/or testing. After the survey is completed, a report is set up with all results. It can be assumed the building is constructed according to the existing information if the existing information matches the results of the survey. In this case, the survey on site is followed by signing the EID (for the second time). If no problems or problems with an acceptable percentage occur, elements can be deconstructed (Stage 3). However, if existing information does not match the results of the survey, the problem needs to be assessed with extra visual inspections and/or more specific testing. After, more detailed calculations and drawings need to be made of e.g., the location of the structural elements, the position of the reinforcement and concrete properties. The results of this new survey indicate if the elements are suitable to be deconstructed. More information about Stage 2 can be found in Appendix D.2. The subsequent sections each analyse an indicator of Stage 2:

- Composition;
- Certified or not?
- Internal and external deterioration.

5.2.1 Composition

The composition of concrete and the presence of toxic materials are analysed in Appendix D.2.1. Since all fibres, admixtures and slags form a different risk for circularity, only iron fibres, composite fibres, asbestos and chlorides need to be assessed for reuse of an element [Van Berlo, 2019]. For some elements information about the applied toxic materials is stored. If this is not the case, lab research is necessary to find out the exact composition, which is out of the scope of this research. The presence of toxic materials in the composition is graded as shown in Table 5.6.

Table 5.6: Composition of the harvested (structural) element with grading.

Option	Explanation	Grading
1	Toxic materials are not present	1,0
2	Toxic materials are present	0
3	Presence of toxic materials is unknown	0,5

5.2.2 Certified or not?

During Stage 2, research on site is performed to check if the existing structure (still) meets the type of cement, fire resistance, strength class, environmental class and yield strength (properties are addressed in subsection 5.1.2). This includes visual inspection and testing. Visual inspection is often carried out by an expert who locates degradation and potential damages and examines the condition of the structural elements. However, the credibility of this professional judgement can be questioned, because no protocol exists for performance testing of reusable elements [Glias, 2013, p. 60]. Therefore, only visual inspection is acceptable if the following three conditions are met: the existing information is sufficient, the owner does not demand further testing and the building is not older than 50 years. However, if degradation is identified during visual inspection, Destructive or Non-Destructive Testing by a second- or third-party is needed [Jabeen, 2020]. Non-Destructive Testing (NDT) obtains information from concrete elements without damaging (or minimal damage). When NDT does not correspond with the existing information or more accurate information is needed, destructive testing is necessary. This requires sampling and laboratory research, which is out of the scope of this research.

Examples of the laboratory testing of concrete properties (such as the compressive strength, elasticity modulus, bending strength and tensile strength) can be by drill samples. Other less accurate methods are the rebound hammer, probe penetration, pull-out test, or Ultrasonic Pulse Velocity (USPV) [Glias, 2013, p. 58-59]. The concrete cover can be measured with an electromagnetic field generated by e.g., a Profometer or Ferroscan. However, it is not possible to obtain a reliable measurement when iron fibres are present inside the concrete. The reinforcing steel can be tested with electromagnetic fields and high-frequency sound with a Ferroscan or ground-penetrating radar. However, measurements of the diameter are a conservative assumption. For a more accurate measurement, destructive testing is necessary (e.g., opening the reinforcement). Additionally, measurements can be carried out to determine the possible presence and degree of reinforcement corrosion in a structural part. In the Decision Support Tool, testing of the yield strength is implemented, which is only needed if the building is constructed before 1975 [Glias, 2013, p. 58-59]. Especially for older constructions, data about the position, diameter, cover, spacing and number of reinforcing bars are no longer available.

The extent of testing depends on the requirements of the buyer of the element and on the specific project. Unfortunately, large dimensions (i.e., slabs) make testing complicated. Additionally, performance testing takes place when an element is still in the building, so experiments are not always possible and thus an expensive solution [Van Berlo, 2019; Täljsten et al., 2019; Jabeen, 2020]. Additionally, an assessment per element requires time and investments, since advanced equipment and knowledge are needed. If the assessment can be done on multiple elements with similar properties, performance testing becomes much more cost-effective. Due to the individual assessment, this research considers existing information to be sufficient for the input of the Decision Support Tool. The certification of the properties of the element is graded as shown in Table 5.7.

Table 5.7: Certification of properties of the (harvested (structural) element with grading.

Option	Explanation	Grading
1	Property of element is certified	1,0
2	Property of element is not certified	0,5
3	Property of element is not certified and unknown	0

5.2.3 Deterioration

Over time, concrete deteriorates due to internal or external sources. In Appendix D.2.2, possible internal and external deterioration which make reuse in a new project inapplicable are analysed. The risk of the deterioration is graded as shown in Table 5.8. Since the internal and external sources form a different degree of deterioration, only the following need to be assessed for reuse of an element: [Van Berlo, 2019]

- Internal sulphate attack;
- Alkali-Silica Reaction (ASR);
- Corrosion;
- Cracks;
- External sulphate attack;
- Penetration of chlorides;
- Penetration of carbonation.

Table 5.8: Deterioration of the harvested (structural) element with grading.

Option	Explanation	Grading
1	Deterioration of element forms no risk	1,0
2	Deterioration of element forms partial risk	0,5
3	Deterioration of element forms risk	0

5.2.4 Second signature of Element Identity

If the filled-in answers of Stage 2 are correct and researched on site with performance testing, the executor of the Decision Support Tool can set a second signature below the Element Identity (EID), which is the output of Phase I (page 75).

5.3 Overview of Phase I

The relations between the stages and indicators of Phase I are made visible in a decision tree (Figure 5.5). Each indicator represents a node which includes the grading of the needed information. From right to left, the decision tree distinguishes the needed information in the input and formulae, the indicators and the two stages of Phase I. The grading of the needed information (colored in grey) results in the output of Phase I: the Element Identity (EID). The EID summarizes the gathered and reviewed information of Stage 1 and Stage 2, as shown on page 75. After generating the output of Phase I, the executor of the Decision Support Tool can continue to Phase II (Disassembling and Post-Disassembling). The total overview of the relations between Phase I, II and III can be found in the decision tree on page 82.

The preliminary versions of the Decision Support Tool are validated and verified with the case-study of De Nederlandsche Bank (DNB) and with the feedback of experts throughout the research. The validity of Phase I can be found in Appendix H.1.1. Additionally, Chapter 8 provides an overview of the processed improvements of Phase I, II and III which make the Decision Support Tool useful in practice.

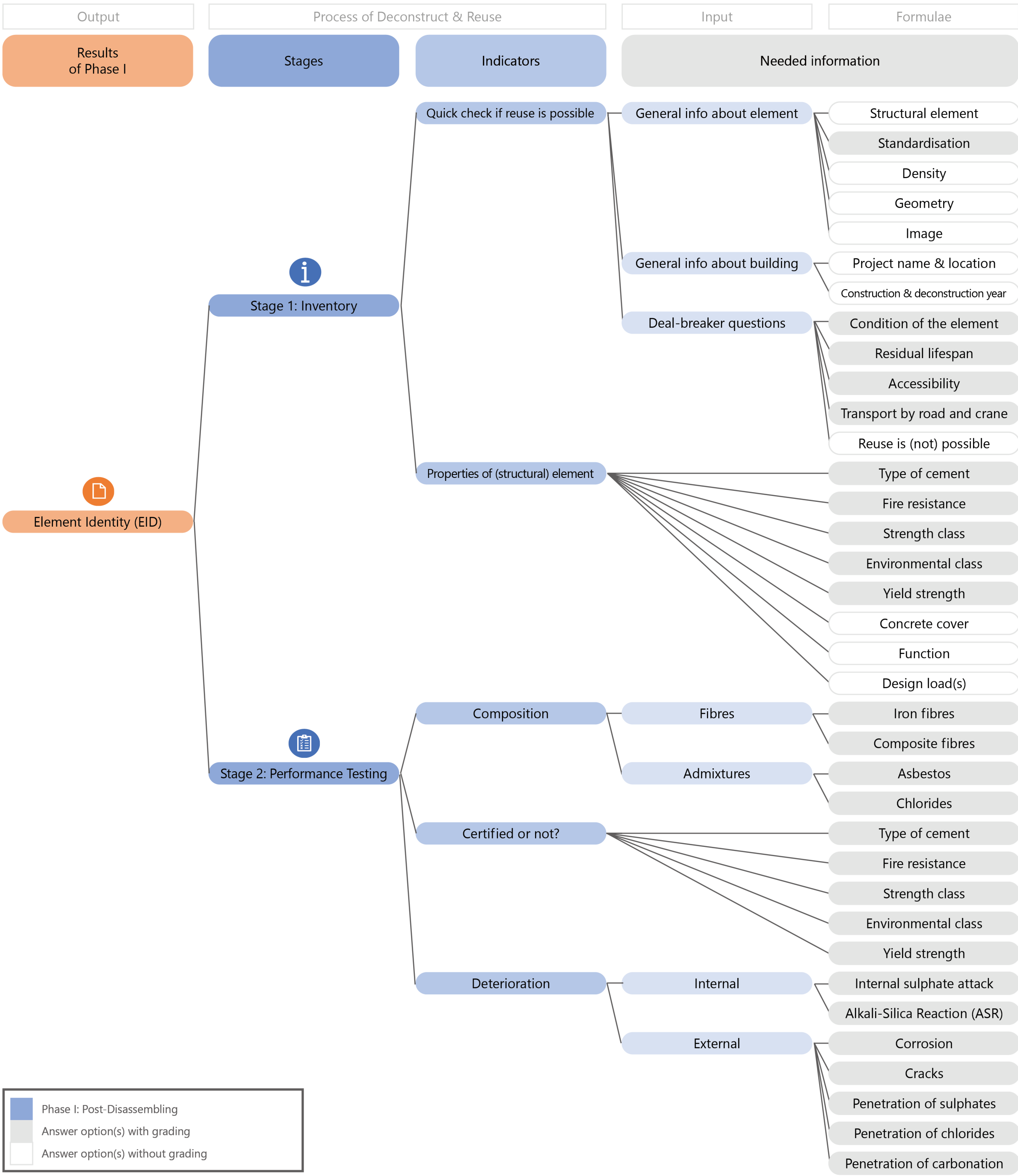


Figure 5.5: Decision tree of Phase I with the graded indicators relating to the assessment of the reuse potential (own figure).

6 | Phase II: Disassembling & Post-Disassembling

The second Phase of the process of 'Deconstruct & Reuse' distinguishes four stages, as highlighted in Figure 6.1. Stage 3, Stage 4, Stage 5 and Stage 6 are analysed respectively in Section 6.1, Section 6.2, Section 6.3 and Section 6.4. An overview of the input and grading of all three phases can be found in Appendix G.

6.1 Stage 3: Deconstruction

After performance testing, the site needs to be prepared to deconstruct the structural elements to be reused. Deconstruction considers the removal for reuse and hoisting of harvested (structural) elements. Demolition should be done with care in order not to damage the (structural) elements to be reused [Volkov, 2019]. Additional testing and lab research are required after deconstruction to determine the reuse potential of the harvested (structural) elements. The subsequent sections each analyse an indicator of Stage 3, followed by Stage 4: Transport. More information about Stage 3 can be found in Appendix D.3.

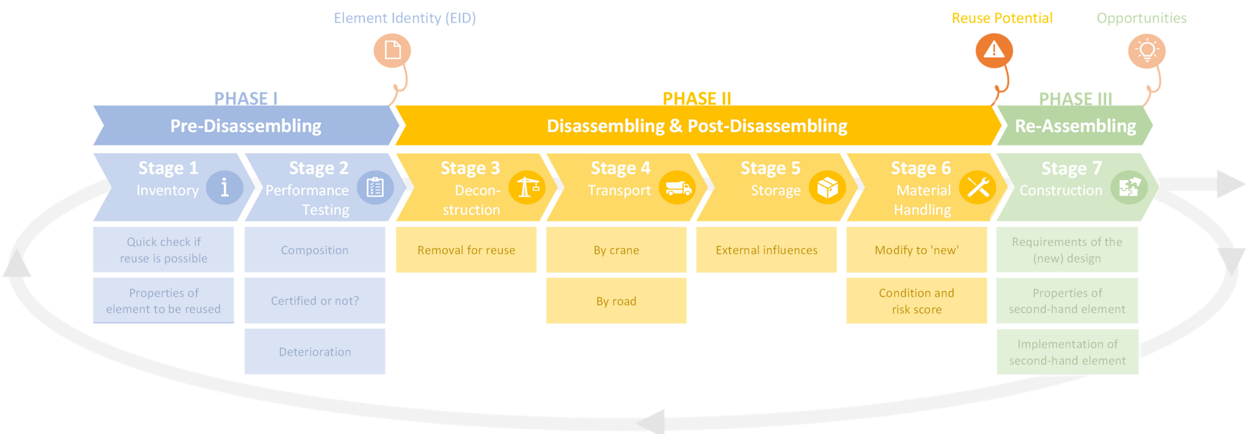


Figure 6.1: Assessment of reuse potential of existing concrete with Phase II highlighted in yellow (own figure).

6.1.1 Removal for reuse

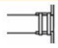
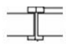
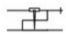
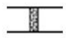
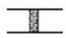
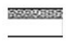
During deconstruction, the disconnecting of elements is affected by the type of connection and the accessibility. This is referred to as the *removal for reuse*. As shown in Figure 3.8, two scenarios are possible for Phase II: the element is located in the building or at the storage site.

In order to deconstruct an element, a disconnection point should be considered. For this point, factors that should be considered are the internal forces, internal moment and rebar location. Additionally, the available room for deconstruction and the safety of the structure after deconstruction should be considered [Volkov, 2019, p. 12]. For this research, only statically determinate structures are considered which means no bending moments occur at the supports. Therefore, supports are considered as disconnection points.

6.1.1.1 *Type of connection*

The type of connection implies the level of difficulty to disconnect the element. Desk research and research on site can indicate the type of connection with e.g., construction drawings, inspection reports or visual inspections [Van Berlo, 2019]. Different types of connections are shown in Table 6.1 with written examples and sketches. The answers are ordered from 'easily to remove' (flexible) to 'hard to remove' (fixed). The grading is linearly distributed over the possible answers, based on the scores of Durmisevic [2006]. The answer with the highest number must be selected in the case if (1) multiple answers apply to an element, (2) there is uncertainty between multiple answers about how elements are connected or (3) the type of the connection cannot be detected.

Table 6.1: Type of connection with answer options and grading. Adapted from Durmisevic [2006, p. 183].

Answer options adopted from Durmisevic (2006, p. 183)	Explanation	Grading	Sketch
1 - Indirect connection with additional fixing device (dry connection)	Two elements are independent in (dis)assembly (all elements could be reused or recycled)	1,0	
2 - Indirect connection via independent third component (dry connection)	Two elements are independent in (dis)assembly (all elements could be reused or recycled)	0,8	
3 - Indirect connection via dependent third component	Two elements are dependent in (dis)assembly with an internal removable or non-removable fixing device (reuse is restricted)	0,6	
4 - Direct connection with additional fixing device	Two elements are dependent in (dis)assembly with replaceable accessory. If one element has to be removed, whole connection needs to be disassembled (reuse is restricted).	0,5	
5 - Indirect connection via third chemical material (soft)	Two elements are permanently connected (reuse is restricted, no recycling)	0,4	
6 - Indirect connection via third chemical material (hard)	Two elements are permanently connected (reuse is restricted, no recycling)	0,2	
7 - Direct connection between two pre-made components	Two elements are dependent in (dis)assembly (no reuse)	0,1	
8 - Direct chemical connection	Two elements are permanently fixed (no reuse, no recycling)		
9 - Type of connection is not applicable, element is already deconstructed			

6.1.1.2 *Accessibility*

Since damage during removal has a negative effect on the reuse potential, this indicator can be seen as a deal-breaker (subsection 5.1.1.3). Additionally, the accessibility with grading can be found in Table 5.4.

6.1.1.3 *Equipment to disconnect*

For the full and partial removal of reinforced concrete structures, several demolition technologies are available. In Appendix D.3, the following demolition methods and corresponding equipment for concrete structures are studied, along with its advantages and disadvantages:

- Demolition by hand (wire cutter, jackhammer);
- Demolition by machine-mounted attachments (crusher, hammer);
- Saw cutting (diamond blade saw, diamond wire cutter);
- Splitting (mechanical, chemical);
- Deliberate collapse (pre-cuts);
- Blasting (explosives);
- Ball and crane (wrecking ball);
- Hydrodemolition (water jet machine);
- Thermal demolition (thermal boring and cutting, electric heating).

For each equipment to disconnect, it is stated if reuse of the removed element is possible or not (Appendix D.3). The demolition technologies which are suitable to disconnect elements made of concrete for reuse are demolition by hand, demolition by machine-mounted attachments, saw cutting, hydrodemolition and thermal demolition. This results in nine options for the equipment to disconnect: wire cutter, jackhammer, crusher, hammer, diamond blade saw, diamond wire cutter, water jet machine, electric heating and thermal boring and cutting. However, the possibility that a demolition company does not possess particular equipment should be considered. Additionally, recent studies show that deconstruction results in approximately 60% extra costs in respect to the demolition of a similar structure [Volkov, 2019]. This makes reusing an unfavourable practice.

The advantages and disadvantages per equipment to disconnect are shown in Table D.21. The most important aspects for reuse are graded per equipment to disconnect in Table 6.2. The damage to the element is listed, followed by the accurate removal since this affects the material handling (Stage 6). The damage to the (protruding) rebars is investigated, because deconstruction of reinforced concrete can be performed with or without protruding rebars out of the cross-section. The latter is referred to as a net cut and requires additional steel bars/provisions for reconnecting, which are not required with protruding rebars. Additionally, protruding rebars ease reconnecting and can ensure reinforcement continuity. However, equipment that preserves rebars is more expensive compared to equipment that saws or cuts, because additional work of the demolition company is needed [Volkov, 2019]. The average grading on the right in Table 6.2 indicates the reuse potential of the equipment to disconnect, since the disconnecting and reconnecting of harvested (structural) elements is affected. Because the methods to deconstruct differ per project, the structural engineer of the project can choose the preferred equipment to deconstruct based on the advantages and disadvantages in Table D.21. With literature study (Appendix D.3), the demolition technologies which are suitable to disconnect elements for reuse are allocated for the type of connection and accessibility. This is shown in Table 6.3. When it is possible to use several kinds of equipment to disconnect, the concept coloured in orange is the suggested equipment based on the method and effort to reconnect the element. This concept is displayed as a suggestion in the Decision Support Tool. The structural engineer can choose the preferred equipment with or without considering the suggested equipment. In all cases, the method to reconnect should be taken into account, especially when the design of the new building is known. The reconnecting of the harvested (structural) element is further explored in Stage 7: Construction (Section 7.1).

Table 6.2: Overview of equipment to disconnect with important aspects for reuse, based on Table D.21. Adapted from Abudayyeh et al. [1998]; Glias [2013]; Hyland and Ouwejan [2017]; Warner [1998]; Zhu et al. [2019].

	Damage during deconstruction						
	Damage to the element?	Comment(s)	Accurate removal?	Comment(s)	Damage to (protruding) rebars?	Comment(s)	Average grading
1 Wire cutter (by hand)	0,75		0,75	Extra sawing needed	0	Protruding rebars are cut	0,50
2 Jackhammer (by hand)	0,5	Microcracks in remaining concrete Degraded bond between rebar and remaining concrete	0,5	Extra sawing needed	0	Protruding rebars are burned (hack) or destroyed (drill)	0,33
3 Crusher (machine-mounted)	0,5	Microcracks in remaining concrete Degraded bond between rebar and remaining concrete	0,5	Extra sawing needed	0	Wrecked ends of rebars	0,33
4 Hammer (machine-mounted)	0,5	Microcracks in remaining concrete	0,5	Extra sawing needed	0	Wrecked ends of rebars	0,33
5 Diamond blade saw (saw cutting)	0,75		0,75		0	Protruding rebars are cut	0,50
6 Diamond wire cutter (saw cutting)	0,75		0,75		0	Protruding rebars are cut	0,50
7 Water jet machine (hydro)	1		1	Irregular concrete allows for good mechanical bonding	1	Rebars are cleaned of scale and rust Rebars can suffer low cycle flexural fatigue	1,00
8 Boring and cutting (thermal)	0,5	Microcracks in remaining concrete Degraded bond between rebar and remaining concrete	0,5	Extra sawing needed	1	Rebars have been heated	0,67
9 Electric heating (thermal)	0,5	Microcracks in remaining concrete Degraded bond between rebar and remaining concrete Concrete cover needs to be repaired	0,5	Extra sawing needed	1	Rebars have been heated	0,67

Table 6.3: Determination of equipment to disconnect with accessibility (column) and type of connection (row).

	0 – Accessibility is not applicable, element is already deconstructed	1 - Accessible without additional operation	2 - Accessible with additional operation which causes no damage to the element	3 - Accessible with additional operation which causes repairable damage to the element	4 - Accessible with additional operation which causes partly repairable damage to the element	5 - Not accessible without causing total damage to the element
1 - Indirect connection with additional fixing device (dry connection)	No equipment to disconnect is needed, because the element is already deconstructed.	No equipment to disconnect is needed, because the indirect connection is accessible.	No equipment to disconnect is needed, because the indirect connection is accessible.	No equipment to disconnect is needed, because the indirect connection is accessible.	No equipment to disconnect is needed, because the indirect connection is accessible.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.
2 - Indirect connection via independent third component (dry connection)	No equipment to disconnect is needed, because the element is already deconstructed.	No equipment to disconnect is needed, because the indirect connection is accessible.	No equipment to disconnect is needed, because the indirect connection is accessible.	No equipment to disconnect is needed, because the indirect connection is accessible.	No equipment to disconnect is needed, because the indirect connection is accessible.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.
3 - Indirect connection via dependent third component	No equipment to disconnect is needed, because the element is already deconstructed.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	1 - Wire cutter (by hand); 5 - Diamond blade saw (saw cutting); 6 - Diamond wire cutter (saw cutting); 7 - Water jet machine (hydro); 8 - Boring and cutting (thermal); 9 - Electric heating (thermal);	2 - Jackhammer (by hand); 3 - Crusher (machine-mounted); 4 - Hammer (machine-mounted);	The element is not accessible without causing total damage, which has a negative effect on the reuse potential. No equipment to disconnect is suggested.
4 - Direct connection with additional fixing device	No equipment to disconnect is needed, because the element is already deconstructed.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	1 - Wire cutter (by hand); 5 - Diamond blade saw (saw cutting); 6 - Diamond wire cutter (saw cutting); 7 - Water jet machine (hydro); 8 - Boring and cutting (thermal); 9 - Electric heating (thermal);	2 - Jackhammer (by hand); 3 - Crusher (machine-mounted); 4 - Hammer (machine-mounted);	The element is not accessible without causing total damage, which has a negative effect on the reuse potential. No equipment to disconnect is suggested.
5 - Indirect connection via third chemical material (soft)	No equipment to disconnect is needed, because the element is already deconstructed.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	7 - Water jet machine (hydrodemolition)	1 - Wire cutter (by hand); 5 - Diamond blade saw (saw cutting); 6 - Diamond wire cutter (saw cutting); 8 - Boring and cutting (thermal); 9 - Electric heating (thermal);	2 - Jackhammer (by hand); 3 - Crusher (machine-mounted); 4 - Hammer (machine-mounted);	The element is not accessible without causing total damage, which has a negative effect on the reuse potential. No equipment to disconnect is suggested.
6 - Indirect connection via third chemical material (hard)	No equipment to disconnect is needed, because the element is already deconstructed.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	7 - Water jet machine (hydrodemolition)	1 - Wire cutter (by hand); 5 - Diamond blade saw (saw cutting); 6 - Diamond wire cutter (saw cutting); 8 - Boring and cutting (thermal); 9 - Electric heating (thermal);	2 - Jackhammer (by hand); 3 - Crusher (machine-mounted); 4 - Hammer (machine-mounted);	The element is not accessible without causing total damage, which has a negative effect on the reuse potential. No equipment to disconnect is suggested.
7 - Direct connection between two pre-made components	No equipment to disconnect is needed, because the element is already deconstructed.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	1 - Wire cutter (by hand); 5 - Diamond blade saw (saw cutting); 6 - Diamond wire cutter (saw cutting); 7 - Water jet machine (hydro); 8 - Boring and cutting (thermal); 9 - Electric heating (thermal);	2 - Jackhammer (by hand); 3 - Crusher (machine-mounted); 4 - Hammer (machine-mounted);	The element is not accessible without causing total damage, which has a negative effect on the reuse potential. No equipment to disconnect is suggested.
8 - Direct chemical connection	No equipment to disconnect is needed, because the element is already deconstructed.	Combination is not possible. Select different answer(s) or indicate the preferred equipment to disconnect.	7 - Water jet machine (hydrodemolition)	1 - Wire cutter (by hand); 5 - Diamond blade saw (saw cutting); 6 - Diamond wire cutter (saw cutting); 8 - Boring and cutting (thermal); 9 - Electric heating (thermal);	2 - Jackhammer (by hand); 3 - Crusher (machine-mounted); 4 - Hammer (machine-mounted);	The element is not accessible without causing total damage, which has a negative effect on the reuse potential. No equipment to disconnect is suggested.

6.2 Stage 4: Transport

After the element is disconnected, the element needs to be hoisted and transported to either the deconstruction site, the new construction site or a storage yard. During Stage 4, any particularities of transport by road and by crane are investigated considering the dimensions and weight of the element, which are linked to Stage 1 (subsection 5.1.1). Transport by water, air, and rail are out of scope. The subsequent section analyses the indicator (transportation) of Stage 4, followed by Stage 5: Storage.

6.2.1 From deconstruction site to next destination

According to Figure 3.8 and the research of Glias [2013, p. 76], five transportation routes can be distinguished:

- Deconstruction site –> Construction site;
- Deconstruction site –> Storage site;
- Deconstruction site –> Recycling plant for material handling;
- Storage site –> Construction site;
- Storage site –> Recycling plant for material handling;

However, transportation comes with financial costs and environmental impacts which lead to negative effects regarding circularity. In order to minimize these drawbacks, transportation distances have to be as small as possible. Therefore, the supply and demand locations preferably have to be close to each other [Volkov, 2019, p. 13]. The type of transport and method of hoisting depend on the dimensions and weight of the element, or loading scheme (if governing).

6.2.1.1 *Method of hoisting*

Four methods exist to hoist beams, columns, slabs, and walls from a concrete building. An overview of the advantages and disadvantages is shown in Table 6.4. The first method makes use of the former lifting points after they have been detected (only for pre-cast elements). Usually, the lifting points are destroyed after primary use or due to damage or corrosion problems. The condition must be assessed on site to determine if it is possible to reuse the former lifting points. However, this makes it not possible to reassure if this method can be used in the design phase. If the former lifting points can be used, it is the cheapest hoisting method as no additional work is needed. The second method makes use of a crane with a fork to grab an element and to hoist it to ground level. However, the order of removal of elements has to be taken into account. Additionally, the fork is not able to go deep inside the building. This method is more expensive compared to using the former lifting points. The third method drills holes which can be used as lifting points. Steel chains are inserted in the drill holes and connected under the element in order to hoist it. An advantage is that the elements can be hoisted from anywhere in the building. However, this method is time-consuming and expensive. A similar method (the fourth method) is to drill chemical anchors in the element. However, this is more expensive and time-consuming. The drilling and drying take one day, after which the chemical anchors can be used as lifting points. The number and position of anchors depend on the geometry of the element. In the case an element is modified to the desired dimensions, it should be taken into account to drill at a place that can be used again for the new construction [Glias, 2013, p. 64-67].

For this research, three assumptions have been made. Firstly, prefab elements in the building can be hoisted with the same method as they arrived during construction. Secondly, harvested (structural) elements can be considered with the same features as prefab elements after hoisting. Thirdly, the method of hoisting during deconstruction will also be used to hoist the harvested (structural) elements during construction.

Table 6.4: Methods to hoist elements. Adapted from Glias [2013, p. 64-67].

Answer options		Decide in design phase?	Cost?	Hoist from anywhere?	Time-consuming?	Damage to the element?
Former lifting points	all	No	€	Yes	Yes	No
Crane with fork		Yes	€€	No	No	No
Drilled holes		Yes	€€€	Yes	Yes	Yes
Chemical anchors		Yes	€€€€	Yes	Yes	Yes

6.2.1.2 *Transport by road and crane*

The dimensions and weight for 'normal' transport by road have been analysed in the deal-breaker questions (subsection 5.1.1.3) with the report of Minister van Verkeer en Waterstaat [2021]:

- Length (L) $\leq$ 22,0 m;
- Width (w) $\leq$ 3,0 m;
- Height (h) $\leq$ 4,0 m;
- Weight (G) $\leq$ 50.000 kg.

However, the capacity of a "normal" crane on site is about 15.000 kg and thus governing. A larger or more advanced crane can be applied, but this will increase the deconstruction and construction costs. Therefore, this research considers the maximum weight of an element to be transportable by crane and truck to be 15.000 kg. As can be seen in Table 6.5, an element within 3,0x4,0x22,0 m which weighs less than 15.000 kg is preferred in order to reduce difficulty and costs. In the Decision Support Tool, green cells are graded with 1 while red cells are graded with 0. The cells with colours in between get a grading of 0,5.

Table 6.5: Transport by road determined by dimensions and weight. The green and red cells respectively indicate a positive and negative effect on the reuse potential.

	Dimensions within 3,0x4,0x22,0 m	Dimensions not within 3,0x4,0x22,0 m
Weight less than 15.000 kg	'Normal' transport by road; 'Normal' crane on site.	'Exceptional' transport by road; 'Normal' crane on site.
Weight in between 15.000 and 35.000 kg	'Normal' transport by road; Large or advanced crane on site.	'Exceptional' transport by road; Large or advanced crane on site.
Weight more than 35.000 kg	'Exceptional' transport by road; Large or advanced crane on site.	'Exceptional' transport by road; Large or advanced crane on site.

6.3 Stage 5: Storage

Storage of harvested (structural) elements is needed when the new project is unknown or when elements cannot be brought directly to the construction site. If an element is stored, it is important to determine how long an element has been at the storage site since this can cause (external) deterioration. Therefore, Stage 5 considers the susceptibility to external influences. The subsequent section analyses this indicator of Stage 5, followed by Stage 6: Material handling.

6.3.1 Susceptibility to external influences

If an element is stored, it is important to determine how long an element has been at the storage site since this can cause (external) deterioration. When a concrete element has been stored outside for quite some time, deterioration can occur due to external sources (Appendix D.2.2). This research considers external influences at the storage site as rain/water, wind and frost (other influences are out of scope). Additionally, storage at or near the sea (< 25 km inland) forms a risk. In the Decision Support Tool, the susceptibility to external influences is analysed by the location and the number of years the element was stored outside (if so). Based on the findings in Appendix D.2.2, risks are given in Table 6.6. In the Decision Support Tool, green cells are graded with 1 while red cells are graded with 0. The cells with colours in between get a grading of 0,5. Besides the susceptibility to external influences, the reason why an element has been stored for this long should be determined (e.g., nobody wants to reuse the element due to its poor condition or due to high final costs). However, these subjects are out of the scope of this research.

Table 6.6: Deterioration at storage site determined by external influences at or near the sea (<25 km inland). The green and red cells respectively indicate a positive and negative effect on the reuse potential.

	Stored far from the sea (>25 km inland)	Stored at or near to the sea (<25 km inland)
Not stored	-	-
Stored inside	Susceptibility to external influences forms no risk	Investigate the risk of penetration of sulphates, and chlorides.
Stored outside (depending on amount of years)	Investigate the risk of internal sulphate attack, Alkali-Silica Reaction (ASR) and penetration of carbonation.	Investigate the risk of internal sulphate attack, Alkali-Silica Reaction (ASR) and penetration of sulphates, chlorides, carbonation.

6.4 Stage 6: Material Handling

After deconstruction, the harvested (structural) elements are modified in order to be able to reuse them in a new project. During Stage 6, modifications of the element are investigated considering a 'new' prefab concrete element. In addition, the condition and related risks of the (structural) element are analysed. The subsequent sections each analyse an indicator of Stage 6, followed by Stage 7: Construction.

As mentioned in the definition of reuse (page 19), the highest possible material quality is reached without the need for modifications, reprocessing or treatment. In case of necessary treatment, harvested (structural) elements can be temporarily stored and modified at either the deconstruction site, the storage site or the new construction site: [Jabeen, 2020]

- At the deconstruction site
  After removal from the building, the elements are placed on the ground to be modified. Next, the elements are transported to the new construction site where they can be reused without further modifications. This implies that at the time of demolition, the design of the new project is known and that the elements can be modified according to the requirements of the new design. In order to avoid delays or an excessive number of elements at the new construction site, transportation has to be planned in detail. Elements that will not be reused in the new project but are possible to be reused in another project need to be transported to a storage site. When the design of the new project is not known, elements can be virtually stored in the demolition project (so without getting deconstructed until a buyer is found). This saves extra transportation of the elements, damage, and costs. However, one needs to pay operational costs for the elements to be reused. Also, traditionally, space is quite limited at these sites (e.g., in the centre of a city) hence material handling of harvested (structural) elements at the deconstruction site can become quite expensive. After, the elements can be transported to the storage site or to the new construction site (when the new project is known).

- At the storage site
  After deconstruction, the harvested (structural) elements are transported to the storage site where they are stored and modified later. Storage happens without modifications if the new project is yet unknown since the elements will be modified according to the requirements of the new project. After modification, the elements can be transported to the new construction site where they can be reused without further modifications. Since storage is expensive, this option is not preferred.

- At the new construction site
  After deconstruction, the reusable elements are transported to the new construction site where they are modified. When modification(s) of the elements are ready, they can immediately be constructed in the new project. However, this demands extra space and planning at the new construction site. Therefore, material handling at the new construction site is not preferred and only minor modifications occur at the new construction site.

6.4.1 Modifications, reprocessing and treatments

As described, an element has to be removed and hoisted from a building (Stage 3). Assumed for this research is that after hoisting, harvested (structural) elements can be considered with the same properties as prefab elements. Additionally, the most efficient way to reuse harvested (structural) elements in the design of a new building is to use them as prefabricated elements (see Appendix B.2 for advantages of constructing with prefab compared to cast in-situ). However, the term prefab indicates an element comes from a factory and is thus 'unused'. Therefore, the term 'new' is used to refer to the treatment of harvested (structural) elements. As mentioned, the goal of material handling is to reuse harvested (structural) elements as new (prefabricated) elements. This is indicated by modifications, reprocessing and treatment, which distinguishes:

- Modify to 'new';
- Fire resistance.

6.4.1.1 *Modify to 'new'*

In order to use harvested (structural) elements (e.g., beams, columns, walls and slabs) as new elements, various types of modifications can be needed. For example, the removal for reuse or hoisting method can destroy the connections between elements and as consequence the edges of the element when not handled with care. When reinforcing bars are exposed (e.g. at the edges) the rebar is not covered at all sides and thereby not protected from the environment. In order to reuse such an element, it needs to be determined if repair is needed by checking the concrete cover of the element. When an element needs to be repaired, the surface can be *painted or coated* to protect e.g. the exposed reinforcement against (further) degradation. A (special corrosion resistance) coating can be done with grout/mortar or with epoxy/polyurethane to protect an element against wear and tear. However, it should be considered that a reusable element with a damaged surface can create a contrast between new and old, thereby decreasing the aesthetics. Additionally, refurbishment can increase the final costs of a reusable element.

Other examples for reuse are the *filling of openings and holes* which are not needed anymore (especially in walls and slabs). Small holes in elements that do not affect the structural integrity can be filled with insulation, while larger ones can be filled with either concrete, masonry or insulation. This depends on the function of the element and if the holes (with or without filling) affect the element. Additionally, the surface of elements can be damaged by several *fixings* (e.g., screws, nails, etc). In order to reuse, these fixings must be removed.

In the case connections can not be reused, *holes have to be drilled* for the reconnection. Additionally, elements can be *sawn to resize*. Since all depend on the requirements of the (new) design the following modifications should be taken into account in order to reuse a harvested (structural) element: [Glias, 2013; Jabeen, 2020; Bleuel, 2019]

- The element needs painting
- The element needs coating
- Holes need to be filled
- Fixings (e.g. screws/nails/etc) need to be removed
- The element needs to be sawn to resize
- Holes need to be drilled for new connections (further analysed in Stage 7)

In addition, the Decision Support Tool includes the modification 'Nothing'. This means an element is in proper condition for reuse without any modifications. Depending on the requirements of the (new) design, one can opt for different combinations of modifications. However, the modification costs increase when more modifications are needed.

6.4.1.2 *Fire resistance*

The fire resistance is described in Appendix D.1.2. However, the fire resistance of existing buildings can degrade due to deterioration. Zandbergen [2016] declares that more research is needed to predict which factors influence the fire resistance of concrete structures and to what extent. In any way, he concludes that at least the concrete cover and carbonation should be taken into account. Firstly, the concrete cover protects the reinforcing steel (as described in subsection 5.1.2.2). However, if the thickness of the concrete is not sufficient, the strength of the reinforcing steel can degrade which can form a risk under fire conditions. Therefore, the concrete cover influences the fire resistance of concrete structures. The strength of reinforcing steel can also degrade due to corrosion. Additionally, corrosion can substantially increase the risk of spalling, which means corrosion forms a risk under fire conditions. Therefore, corrosion influences the fire resistance of concrete structures. As described in Appendix D.2.2, internal reinforcing bars can corrode due to carbonation and chlorides (respectively environmental class XC and XD/XS).

In the decision support tool, the (origin) fire resistance is revised in Phase II, based on the occurred deterioration (Table 6.7). The outcome of the performance criteria is compared to the required fire resistance of the new design (Phase III), which is determined by the structural engineer or a fire expert. In case the concrete cover of the element is damaged or there is a chance of corrosion, the structural engineer of the new design can consider applying an additional concrete cover, fire-resistant coating, plaster ceiling or sprinkler system in the new design.

Table 6.7: Revised fire resistance determined by chance of corrosion and damage to concrete cover. The green and red cells respectively indicate a positive or negative effect on the reuse potential.

	No damage to concrete cover	Damage to concrete cover
No chance of corrosion	The revised fire resistance is assumed to be the same as the origin	The revised fire resistance is assumed to be the same as the origin
Small chance of corrosion	The revised fire resistance is assumed to be the same as the origin	The revised fire resistance is assumed to be the same as the origin, but more research is needed.
Great chance of corrosion	The revised fire resistance is assumed to be the same as the origin, but more research is needed.	The revised fire resistance is assumed to be 30 min less than the origin, but more research is needed.

6.4.2 Risk score

In addition to a condition assessment (as explained in subsection 5.1.1.3), a risk assessment can be performed to gain insight into the possible risks of observed defects. The risk score is determined by the RAMS- or RAMSSHEEP list, being: *Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economics, Politics.* When repair of observed defects is postponed or not resolved additional effects may occur, e.g., use effects, cost effects, image or safety. The risk score is expressed in a score of 1 to 3 [NEN 2767, 2013]. In Table 6.8, the risk score is adjusted to the same scale as the condition score.

It should be considered that damages can occur during performance testing, deconstruction, transportation, storage and material handling. Possible risks and damages which make reuse in a new project inapplicable need to be discussed per stage.

Table 6.8: Risk score with answer options and grading. Adapted from NEN 2767 [2013].

Option	Explanation	Grading
1	No effect	1,0
2	Slight effect	0,8
3	Mild effect	0,6
4	Moderate effect	0,4
5	Strong effect	0,2
6	Very severe effect	0

6.5 Overview of Phase II

The relations between the stages and indicators of Phase II are made visible in a decision tree (Figure 6.2). Each indicator represents a node which includes the grading of the needed information. From right to left, the decision tree distinguishes the needed information in the input and formulae, the indicators and the four stages of Phase II. The grading of the needed information (colored in grey) results in the output of Phase II which is the reuse potential per stage carried out in Phase I and II. This is shown on page 78. After generating the output of Phase II, the executor of the Decision Support Tool can continue to Phase III (Re-Assembling). The total overview of the relations between Phase I, II and III can be found in the decision tree on page 82.

The preliminary versions of the Decision Support Tool are validated and verified with the case-study of De Nederlandsche Bank (DNB) and with the feedback of experts throughout the research. The validity of Phase II can be found in Appendix H.1.2. Additionally, Chapter 8 provides an overview of the processed improvements of Phase I, II and III which make the Decision Support Tool useful in practice.

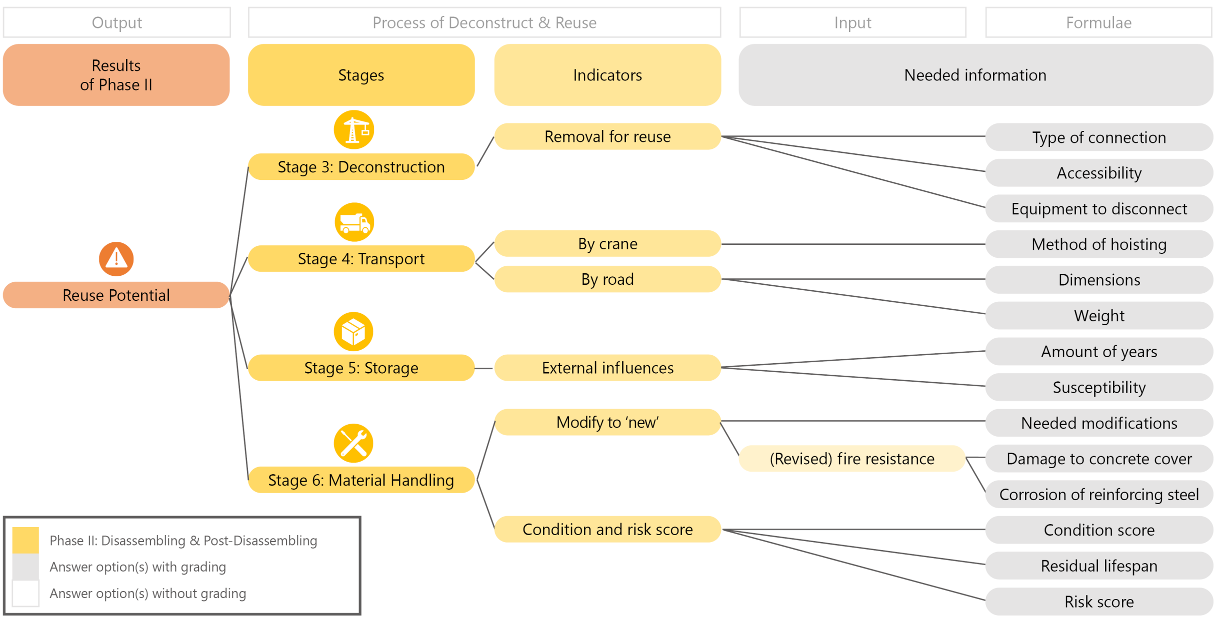


Figure 6.2: Decision tree of Phase II with the graded indicators relating to the assessment of the reuse potential (own figure).

7 | Phase III: Re-Assembling

The first Phase of the process of 'Deconstruct & Reuse', namely Stage 7: Construction, as highlighted in Figure 6.1. Stage 7 is analysed in Section 7.1. An overview of the input and grading of all three phases can be found in Appendix G.

7.1 Stage 7: Construction

When harvested (structural) elements are selected for the design of a new building, construction can start. Construction considers the requirements of the new design, the properties of the second-hand element and the implementation of the harvested (structural) element (Figure 7.1). The subsequent sections each analyse an indicator of Stage 7. More information about Stage 7 can be found in Appendix D.4.

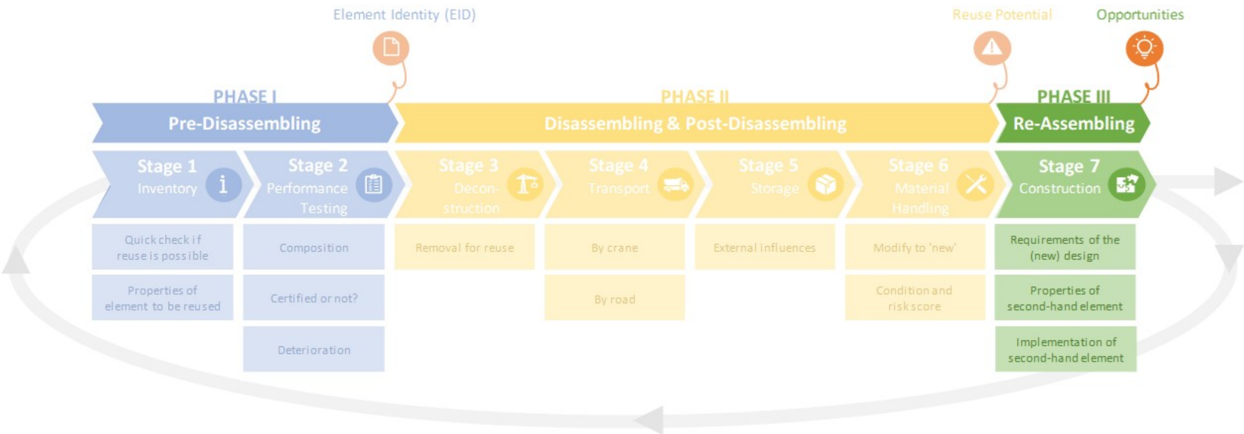


Figure 7.1: Assessment of reuse potential of existing concrete with Phase III highlighted in green (own figure).

7.1.1 Requirements of the new design

This section investigates if the harvested (structural) element is sufficient for the requirements of the new design. Therefore, Stage 7 starts by questioning if the design of the new building is known. In this section, general information about the (new) building is gathered based on the following:

- Project name and location;
- Construction year;
- Design service life.

Project name and location

The (new) building is analysed with the project name and location. For this research, only locations in the Netherlands are considered. As mentioned in Section 6.2, transportation distances have to be as small as possible. Therefore, a question is added to the Decision Support Tool about the distance from the location of the element (in building or at storage site) to the new construction site.

Construction year

The construction year indicates in which year the (new) building will be constructed. A check indicates if the element is already deconstructed and available at a storage site, or if the element is still in a building. If the element is stored, the check indicates for how long the element has been stored by comparing the deconstruction year of Phase I (subsection 5.1.1.2) with the construction year of the new building. If the element is still in a building, the construction of the new building will have to be postponed.

Design service life

As described earlier, the reference service life (RSL) of structural elements made of concrete can be 100+ years [Vissering et al., 2011; Brand, 1994]. However, most buildings are designed for 50 years (Appendix H.1.3). A check indicates if the design service life of the new building is in line with the residual lifespan of the element (subsection 5.1.1.3). If the design service life exceeds the residual lifespan, the advice is given to strengthen the element.

7.1.2 Properties of the second-hand element

This section analyses the required properties of the second-hand element in the new design. Per property, a check indicates if the element is in line with the requirement of the new design. If the element is not sufficient, the check gives an advice for implementation in the new design.

Fire resistance

As described in Appendix D.1.2, this research considers the fire resistance of new and existing buildings which are implemented in the Decision Support Tool as 30 min, 60 min, 90 min and 120 min. A check indicates if the required fire resistance is in line with the revised fire resistance of Phase II (subsection 6.4.1.2). If the element is not sufficient, the height and function of the new design need to be reconsidered, as described in Appendix D.1.2, or the concrete cover needs to be enlarged [Zandbergen, 2016].

Environmental class

As described in Appendix D.1.4, this research considers the environmental classes which are implemented in the Decision Support Tool as X0, XC1, XC3, XC4, XD1 and XS1. A check indicates if the required environmental class is less aggressive than the origin (or of the same). If the element is not sufficient, the element needs to be protected or the concrete cover needs to be enlarged. Additionally, a check gives a warning in case the new building is at or near the sea (environmental class XS1) which forms a risk for penetrating species.

Concrete cover

As described in Appendix D.1.5, the minimum concrete cover ($c_{min,dur}$) can be determined by the environmental class and the strength class with the assumed construction class S4 [Eurocode 2, 2013]. By adding the design allowance for deviation ($\Delta\ c_{dev}$) of 5 mm to $c_{min,dur}$, an assumption can be determined for the final concrete cover (c_{nom}) in equation D.2. The minimum concrete cover needed in the new design is determined with the (origin) strength class and (new) environmental class. A check indicates if the needed concrete cover is in line with the current concrete cover of Phase I (subsection 5.1.2.2). If the (minimum) concrete cover is not sufficient, a less aggressive environmental class needs to be reconsidered or the concrete cover needs to be enlarged. More information about the concrete cover can be found in Appendix D.1.5.

In the case of reuse, it should also be checked whether the concrete cover withstands the durability requirements of the new design according to Eurocode 2 [2013], being the environmental class and construction class with relating service life, strength class, geometry and quality control [Braam et al., 2011; Van Berlo, 2019]. Additionally, if the concrete cover is locally damaged, the possibility that the element has to transfer the load via another route within the element, partly determines the size of the concrete cover required. This is out of the scope of the research.

Function
The function of the (new) building is linked to the categories and loads in NEN-EN 1992, as described in subsection 5.1.1.1. A check indicates if the design load of the (new) function at the location of the second-hand element is in line with the design load of the origin function. If the element is not sufficient, the advice is given to check the reinforcement or to strengthen the element.

Design loads
A check indicates if the design loads of the (new) building are in line with the design loads of the origin building (subsection 5.1.2.4). Therefore, the design loads at midspan and at the support are considered. An example calculation of the required reinforcement area of a beam can be found in Appendix D.4. However, this calculation is only possible if the reinforcement drawings are available.

Holes for services
Holes for services can be present in the element, especially in slabs and beams. If holes are present, it is important to determine in which area: at midspan/length, at the support or at non-critical spot. The holes for services form a risk for the strength of the element in case they are not located at a non-critical spot and if the diameter is more than more than 20 mm (Appendix H.1.3). If the element is not sufficient, the advice is given to test the performance and the possibly need for strengthening. Additionally, a question is added to determine if the holes can be reused for new services.

7.1.3 Implementation of second-hand element

In this section, the implementation of the harvested (structural) element is considered with the change of function and type of reconnection, which is referred to as 're-element' (subsection 7.1.3.1). Next, the equipment to reconnect the second-hand element is analysed with relative merits, the general procedure and the adaptation of the element. This is referred to as 're-connect' (subsection 7.1.3.2).

7.1.3.1 *Re-element*

Change of function
As described in Appendix C.1, the database of Madaster does not take a possible change of function for reuse into account. This means in-situ does not necessarily have to be reused 1-on-1 (e.g., a damaged slab from a higher floor can be placed on ground level or used as a wall). This section determines which other functions can be assigned to a harvested (structural) element, based on the interpretation of experts and the researcher (Appendix H.1.3. Due to differences in dimensions and span, it is hard to reuse a concrete beam as a column and vice versa [BELTON, 1992]. Moreover, a concrete wall cannot be reused as a slab due to the insufficient amount of reinforcement. Therefore, the function of a concrete beam, column or wall cannot change. On the other side, it is possible to reuse a concrete wall as a wall or slab due to its sufficient length and amount of reinforcement. However, in order to reuse a slab as a wall additional material handling is needed. For this research, the following changes of function are considered:

- Reuse beam as beam;
- Reuse column as column;
- Reuse wall as wall;
- Reuse slab as slab;
- Reuse slab as wall.

For this research, only the dimensions and reinforcement are taken into account which means more options can be made possible with further research. Additionally, only structural elements are considered (e.g. beam, column, slab and wall) and aesthetically changes are out of scope.

Type of reconnection

With the change of function in mind, it is possible to reconnect a harvested (structural) element to another element. The type of reconnection is requested by the structural engineer of the new project and plays a role in reconnecting. Reconnections considered for this research are the connections that often occur in construction projects, based on interpretation of experts and the researcher (Appendix H.1.3):

- Reuse beam as beam; (1) Beam-to-column;
  (2) Beam-to-beam;
- Reuse column as column; (3) Column-to-beam;
  (4) Column splice joint;
  (5) Column foot joint;
- Reuse wall as wall; (6) Wall-to-wall (vertical);
  (7) Wall-to-wall (horizontal);
  (8) Wall foot joint;
- Reuse slab as slab; (9) Slab-to-wall;
  (10) Slab-to-slab (longitudinal);
  (11) Slab-to-beam;
- Reuse slab as wall; (12) Slab as wall-to-wall (vertical);
  (13) Slab as wall-to-wall (horizontal);
  (14) Slab as wall foot joint.

Next, the second-hand element can be reconnected to another second-hand element or to a newly-made element. In most connections between second-hand (structural) elements, the continuity of the longitudinal reinforcement needs to be ensured. Therefore, the protruding rebars of the second-hand element play a role. The following two ways can be applied to bare the reinforcement at the end of an element: [Volkov, 2019]

- Steel-avoiding adaptation
  A concrete element is deconstructed with protruding reinforcement which means the element can be treated as a normal precast element. However, modification of the element is needed to bare the reinforcement at the ends resulting in high costs and a relatively shorter element, since extra space is needed. Additionally, there is no need for additional steel bars or provisions to ensure longitudinal reinforcement.

- Net cut
  A concrete element is deconstructed without protruding reinforcement. The ends of the element have to be modified to ensure longitudinal reinforcement resulting in high costs and the need for additional steel bars or provisions. Additionally, no extra space is needed resulting in a relatively longer element.

Both options are laborious achievements of reinforcement continuity which depend on the equipment to disconnect and related damage to the protruding rebars (subsection 6.1.1.3). Additionally, steel bars or provisions can be present inside the second-hand element which have no structural role (anymore). In order to predispose an element for a reconnection, these useless connection bars can interfere with the drilling of holes or baring reinforcement at the ends. Additionally, modifications of the structural scheme can take place, especially for beams and slabs. An example is the reduction of continuous beams across columns to one-span beams. In the new design, these beams can be reconstructed as continuous or simply supported. However, changing the structural system also changes the internal bending moments and shear forces. If a beam was extracted from a continuous structural system the best option would be to reconstruct it in the new design by providing bending moment resistance at the connections to prevent higher actions in other parts of the beam. However, a reconnection with second-hand elements that can transfer bending moment(s) is hard to achieve. In addition, the research of Volkov [2019] analysed the limitations and boundaries of reuse per second-hand beam, column, wall and slab. An overview is shown in Table 7.1.

Table 7.1: Limitations and boundaries of reusing (structural) concrete elements. Adapted from Volkov [2019].

Second-hand beams	Second-hand columns	Second-hand walls	Second-hand slabs
Laborious achievement of reinforcement continuity	Laborious achievement of reinforcement continuity	Laborious achievement of reinforcement continuity	Laborious achievement of reinforcement continuity
Eventual presence of useless connection bars	Eventual presence of useless connection bars	Eventual presence of useless connection bars	
Eventual insufficiency of shear reinforcement		Absence of indentation or protruding steel provisions	Non-hollow core issue
Need for a totally different connecting than newly-made beams			Absence of lateral "keyed" void
Modification of the structural scheme			Modification of the structural scheme

7.1.3.2 *Re-connect*

In Appendix D.4, the following equipments to reconnect are studied, along with its advantages and disadvantages: (in alphabetic order)

- (A) Anchor bottom reinforcement;
- (B) Anchor bottom and top reinforcement;
- (C) Anchored end-plate;
- (D) C-gaps;
- (E) Corbel;
- (F) External pocket;
- (G) Hollowed-out cores;
- (H) L-profile;
- (I) Recast concrete cover;
- (J) Sleeve coupler(s);
- (K) Steel column shoes;
- (L) U-voids;
- (M) V-gaps;
- (N) Welded U-loops.

An overview of the advantages and disadvantages per equipment to reconnect is shown in Table 7.3. With literature study (Appendix D.4), the equipment to reconnect is allocated per type of reconnection taking into account if the second-hand element is reconnected to another second-hand element or to a newly-made element. The overview in Table 7.2 shows the possible options (with a maximum of five) per type of reconnection based on the advantages and disadvantages.

Besides the relative merits, each equipment to reconnect comes with a general procedure that requires adaptation of the second-hand element. Based on the relative merits, general procedure and adaptation, the person who executes the method can select the preferred equipment to reconnect. The table works similarly as described with the equipment to disconnect (Table 6.3). The equipments to reconnect only serve as an indication / first impression for structural engineers with the overarching goal to show that reuse does not have to be complicated.

Table 7.2: Possible equipment to reconnect per type of reconnection. Adapted from Volkov [2019].

				Similar to	Option nr.	Ref. nr.	Reconnect second-hand element to another second-hand	Option nr.	Ref. nr.	Reconnect second-hand element to newly-made element
Beam	Reuse beam as beam	(1)	Beam-to-column	(3) (9)	1 2 3 4	A B C J	Anchor bottom reinforcement Anchor bottom and top reinforcement Anchored end-plate Sleeve coupler(s)	1 2 3 4 5	A B C E J	Anchor bottom reinforcement Anchor bottom and top reinforcement Anchored end-plate Corbel Sleeve coupler(s)
		(2)	Beam-to-beam	(10)	1 2	A B	Anchor bottom reinforcement Anchor bottom and top reinforcement	1 2	A B	Anchor bottom reinforcement Anchor bottom and top reinforcement
Column	Reuse column as column	(3)	Column-to-beam	(1) (9)	1 2 3 4	A B C J	Anchor bottom reinforcement Anchor bottom and top reinforcement Anchored end-plate Sleeve coupler(s)	1 2 3 4	A B C J	Anchor bottom reinforcement Anchor bottom and top reinforcement Anchored end-plate Sleeve coupler(s)
		(4)	Column-to-column	(5) (7) (8)	1 2	C J	Anchored end-plate Sleeve coupler(s)	1 2 3 4	C I J K	Anchored end-plate Re-cast concrete cover Sleeve coupler(s) Steel shoes
		(5)	Column foot joint	(4) (7) (8)	1		Combination is out of scope (foundation is not reused)	1 2 3 4 5	C F I J K	Anchored end-plate External pocket Re-cast concrete cover Sleeve coupler(s) Steel shoes
Wall	Reuse wall as wall	(6)	Wall-to-wall (vertical)		1	N	Welded U-loops	1	N	Welded U-loops
		(7)	Wall-to-wall (horizontal)	(4) (5) (8)	1 2	C J	Anchored end-plate Sleeve coupler(s)	1 2 3 4	C I J K	Anchored end-plate Re-cast concrete cover Sleeve coupler(s) Steel shoes
		(8)	Wall foot joint	(4) (5) (7)	1		Combination is out of scope (foundation is not reused)	1 2	F J	External pocket Sleeve coupler(s)
Slab	Reuse slab as slab	(9)	Slab-to-wall	(1) (3)	1 2	G H	Hollowed-out cores L-profile	1 2	G H	Hollowed-out cores L-profile
		(10)	Slab-to-slab (longitudinal)	(2)	1 2	D M	C-gaps V-gaps	1 2	D M	C-gaps V-gaps
		(11)	Slab-to-beam		1	L	U-voids	1	L	U-voids
	Reuse slab as wall	(12)	Slab as wall-to-wall (vertical)	(6)	1	J	Sleeve coupler(s)	1	J	Sleeve coupler(s)
		(13)	Slab as wall-to-wall (horizontal)	(7)	1	G	Hollowed-out cores	1	G	Hollowed-out cores
		(14)	Slab as wall foot joint	(8)	1		Combination is out of scope (foundation is not reused)	1 2	F G	External pocket Hollowed-out cores

Table 7.3: Overview of equipment to reconnect with advantages, disadvantages and other where V = 1 and X = 0. Adapted from Volkov [2019]; Van den Brink [2020]; Holly and Abrahoim [2020]; Engström [2008].

		Easy mounting on site	Simple design	Aesthetically attractive	No need to drill sleeves	Suitable for eventual further reuse	Laborious achievement	Ductile joint behaviour	Need to bare reinforcement	Need for formwork	Need for precise drilling or breaking	Need for precise welding and quality	Failure possibility	Design for disassembly?	Dry or wet joint?	With or without added (steel) provisions?	Complexity?	Other advantages	Other drawbacks + risks
A	Anchor bottom reinforcement	✓	✓						×					×	Wet	With	Simple	No reduction of beam length.	
B	Anchor bottom and top reinforc	✓		✓	×				×			✓	×	×	Wet	With	Medium		Reduction of beam length; Mostly applicable between beams with similar bar layouts.
C	Anchored end-plate	✓			✓				×			✓	×	✓	Dry	With	Medium		
D	C-gaps		✓	✓		×									Wet	Without	Simple		Requires further studies on effectiveness.
E	Corbel	✓	✓	✓	×										Wet	Without	Simple		Only suitable for connection with new element.
F	External pocket	✓		×	✓		✓			×				✓	Wet	Without	Medium		
G	Hollowed-out cores		✓	✓		×									Wet	With	Simple		Not suitable for use with second-hand wall; Need to add U-voids or shear studs.
H	L-profile			×				✓							Wet	With	Medium	Adds freedom of architectural design.	Dimensioning of L-profile needed.
I	Re-cast concrete cover			×	✓					×	×				Wet	Without	Simple	Allows for reinforcement inspection.	Increased concrete cover.
J	Sleeve couplers	✓		✓		×					✓			×	Wet	Without	Medium	Completely monolithic result.	Compromised out-of-plane stability.
K	Steel shoes	✓									✓		×	✓	Dry	With	Complex		
L	U-voids	✓	✓			×					×			✓	Wet	With	Medium	Most of the adaptation is done in factory.	
M	V-gaps			×		✓		✓			×				Wet	With	Complex	Good horizontal shear resistance.	
N	Welded U-loops			✓								✓		×	Wet	With	Complex		Need to remove concrete from side; Need to re-cast a wall portion.

7.2 Overview of Phase III

The relations between the stages and indicators of Phase III are made visible in a decision tree (Figure 7.2). Each indicator represents a node which includes the grading of the needed information. From right to left, the decision tree distinguishes the needed information in the input and formulae, the indicators and the two stages of Phase I. The output of Phase III are the opportunities of the second-hand element in the design of a new building, as shown on page 81. The total overview of Phase I, II and III can be found in the decision tree on page 82.

The preliminary versions of the Decision Support Tool are validated and verified with the case-study of De Nederlandsche Bank (DNB) and with the feedback of experts throughout the research. The validity of Phase III can be found in Appendix H.1.3. Additionally, Chapter 8 provides an overview of the processed improvements of Phase I, II and III which make the Decision Support Tool useful in practice.

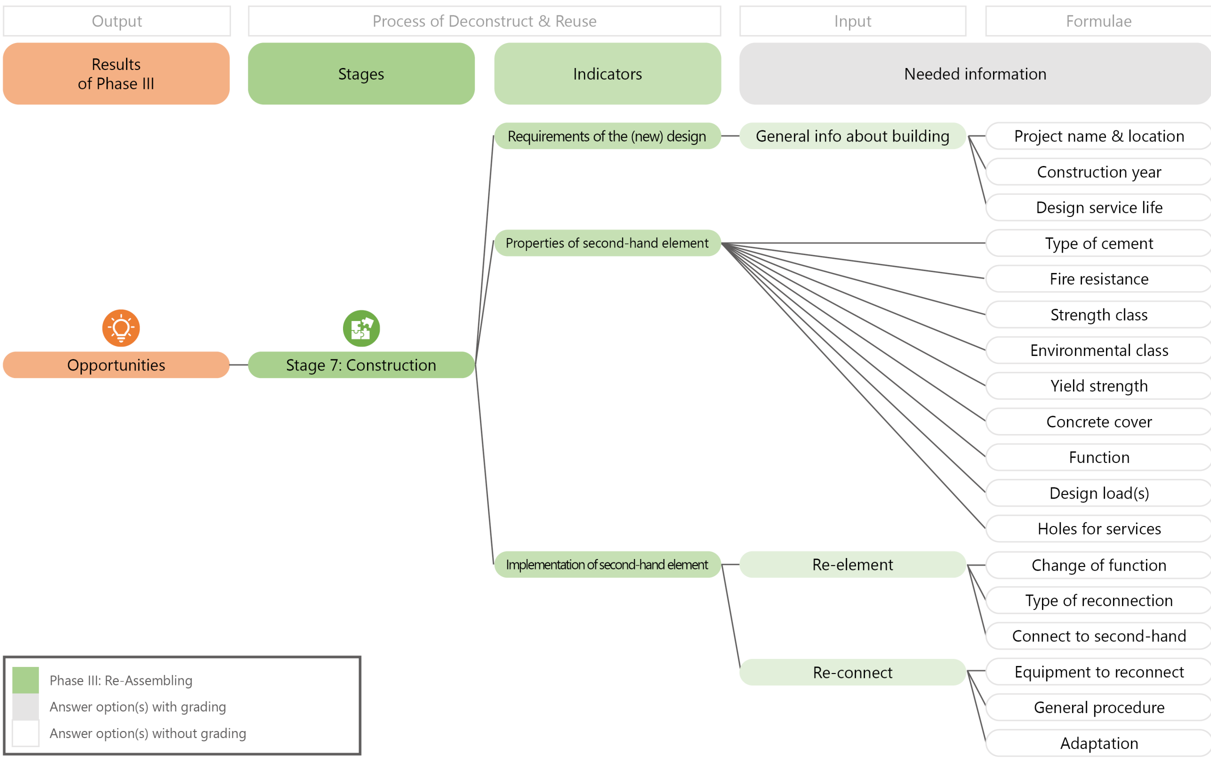


Figure 7.2: Decision tree of Phase III with the graded indicators relating to the assessment of the reuse potential (own figure).

Part III
Results and Final Remarks

The third and last part of the research describes results and final remarks of the research, which follows the research framework and methods of respectively the first and second part.

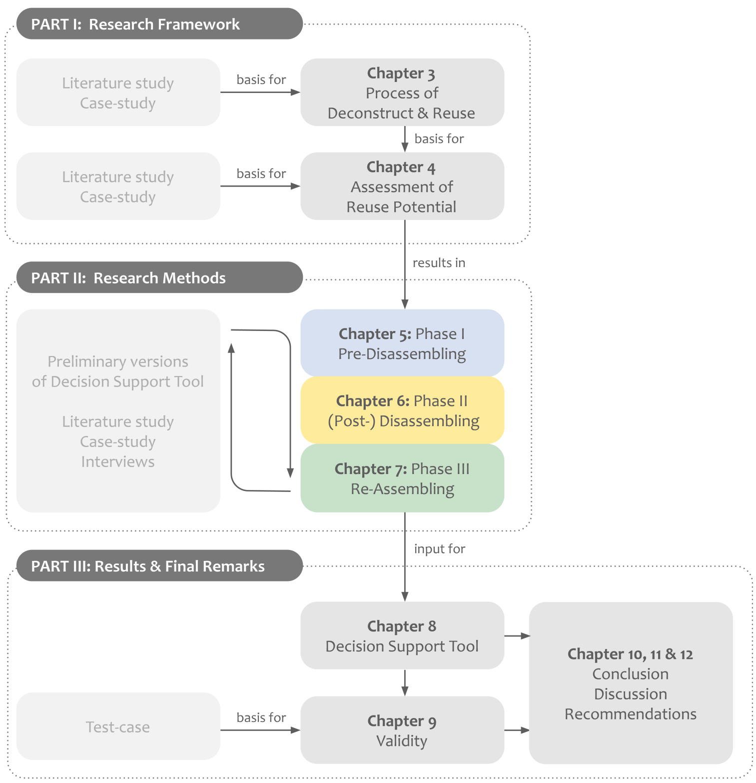


Figure 7.3: Research Parts with chapters (own figure).

8 Decision Support Tool

The Decision Support Tool is an executable method to assess the reuse potential of harvested elements of existing concrete structures. The aim of the Decision Support Tool is to allow structural engineers to make use of these elements in the design of new buildings. This Chapter analyses how the preliminary versions of the Decision Support Tool led to the final version (Section 8.1). The final version of the Decision Support Tool is explored in Section 8.2.

8.1 Preliminary versions

As described in subsection 3.3.3, the process of 'Deconstruct & Reuse' is set-up by information found in literature study and the case-study. In order to translate this process in the Decision Support Tool, interviews and feedback sessions are conducted throughout the research. This is done with structural engineers of Pieters Bouwtechniek and with the contractor and demolition company of the case-study. All conversations considered (parts of) the process of 'Deconstruct & Reuse' and were based on open-ended questions. After each discussion, notes were written down regarding the given feedback. These notes (and thoughts) form the basis for the results in this Chapter.

The interviews and feedback sessions resulted in valuable information for the development of the Decision Support Tool for the structural engineer. All feedback is processed in the preliminary versions of the Decision Support Tool, resulting in the final version. An overview of the most valuable improvements which make the Decision Support Tool useful in practice is shown in Table 8.1. This overview recapitulates all received and processed feedback of the preliminary versions in the most valuable improvements. All feedback of Phase I (Pre-Disassembling), Phase II (Disassembling and Post-Disassembling) and Phase III (Re-Assembling) can be found respectively in Appendix H.1.1, Appendix H.1.2 and Appendix H.1.3.

As can be seen in Table 8.1, the most valuable improvements of preliminary versions consist of four aspects. Firstly, the main and side information of the process of Deconstruct and Reuse were distinguished from the point of view of the structural engineer. Secondly, the feedback regarding the preliminary versions of the Decision Support Tool consists of displaying the theory behind the indicators, to extend the Decision Support Tool with more information. Thirdly, the formulation of the Decision Support Tool is enhanced by analysing the interpretations of the executors of the Decision Support Tool. Lastly, the Graphical User Interface (GUI) is developed by analysing what executors of the Decision Support Tool encountered.

In conclusion, the preliminary versions of the Decision Support Tool are improved by conducting interviews and feedback sessions throughout the research. All feedback is processed in the preliminary versions of the Decision Support Tool, resulting in the final version.

Table 8.1: Overview of the most valuable improvements of the preliminary versions of the Decision Support Tool based on the received and processed feedback during interviews and feedback sessions throughout the research.

Most valuable improvements of preliminary versions	Explanation of received and processed feedback	Retrieved from
Distinguishing main and side information	• Adding and eliminating indicators in Stages from the point of view of the structural engineer • Changing order of the process of 'Deconstruct & Reuse' • Identifying indicators and calculations • Supporting the decisions of structural engineers, because everyone gives his or her twist to the design of connections and calculations	Feedback sessions at Pieters Bouwtechniek Interviews with (external) parties of case-study
Extending the research with more information	• Processing of where information to understand an indicator can be found (e.g. by adding foldout buttons in the Decision Support Tool) • Processing the need for further research in case an indicator has a negative effect on the reuse potential (or perform research in another Stage) • Implementing 'unknown' answer options in the Decision Support Tool by suggesting a conservative lower limit • Including assumptions from point of view of the structural engineer	Feedback sessions at Pieters Bouwtechniek Interviews with (external) parties of case-study
Enhancing the formulation of the Decision Support Tool	• Clarifying answer options in the Decision Support Tool with figures • Formulating only one element with one connection can be tested at a time in the Decision Support Tool • Formulating questions in the Decision Support Tool • Formulating definitions in the Decision Support Tool • Implementing answer options for additional comment(s) in the Decision Support Tool • Implementing answer options to overrule calculated results • Simplifying calculations	Feedback sessions at Pieters Bouwtechniek
Developing Graphic User Interface (GUI)	• Implementing an introductory manual to the Decision Support Tool • Setting up an overview of the Phases and Stages (with colours and icons) • Displaying all answer options in the Decision Support Tool (instead of drop-down menus) • Implementing open-ended and closed-ended questions (e.g. to ensure the executor remains accountable) • Indicating the positive and negative effect on the reuse potential in the answer options of the Decision Support Tool • Displaying output / advice in the Decision Support Tool after answer is filled-in	Feedback sessions at Pieters Bouwtechniek

8.2 Final version

As described in Section 4.3, the Decision Support Tool is set up in Excel with worksheets for Input, Formulae and Output. The input and output are referred to as the front-end of the Decision Support Tool, whereas the formulae is referred to as the back-end. In this section, the front-end and back-end of the final version of the Decision Support Tool are demonstrated with a test-case executed by the researcher.

8.2.1 Results based on test-case

This section demonstrates the front-end of the Decision Support Tool, followed by the back-end based on a test-case. However, the output of the Decision Support Tool may differ per executor due to different interpretations. Therefore, validation and verification is needed which is described in Chapter 9.

8.2.1.1 *Front-end of Decision Support Tool*

The front-end of the Decision Support Tool consists of the input and the output. As described, the information in the Decision Support Tool is determined with extensive literature study, interviews and a case-study. All sources are indicated in the Graphical User Interface (GUI). However, in some cases the answer options are based on 'own interpretation' due to lack of literature. These assumptions are analysed in Chapter 11: Discussion.

8.2.1.2 *Back-end of Decision Support Tool*

The back-end of the Decision Support Tool consists of worksheets for the input and the formulae. Input shows the filled-in answers of the Graphical User Interface (GUI) in a more structured way. Formulae grades all answer options according to a Fuzzy calculation and range of uncertainty. An overview of all answer options with corresponding grading of Phase I, II and III can be found respectively in Figure G.1, Figure G.2 and Figure G.3. Next to the grading, dependences consist between the indicators of the three Phases. This is shown on page 82, where the decision trees of Phase I, II and III are united. With the grading and dependences, calculations can be made to generate the output per Phase.

8.2.1.3 *Test-case executed by researcher*

For the test-case, a double tee slab of the case-study of De Nederlandsche Bank (DNB) is considered. In subsection 8.2.1.1 and subsection 8.2.1.2, the front-end and back-end of the Decision Support Tool are analysed with a test-case that is executed by the researcher. This test-case serves as a reference for the validation in subsection 9.1.1. A general description of the test-case can be found in Appendix E.

The flowchart in Figure 8.1 displays the execution of the Decision Support Tool relating to the worksheets for Input, Formulae and Output. The front-end, which consists of the input and output, is subdivided in fourteen steps. These steps are described in the introductory manual for the execution of the Decision Support Tool on page 71. Additionally, the steps link to the next pages on A3 format (page 71 to page 81) where the final version of the Decision Support Tool is shown for the test-case executed by the researcher. The output of Phase I, II and III can be found respectively on page 75, page 78 and page 81.

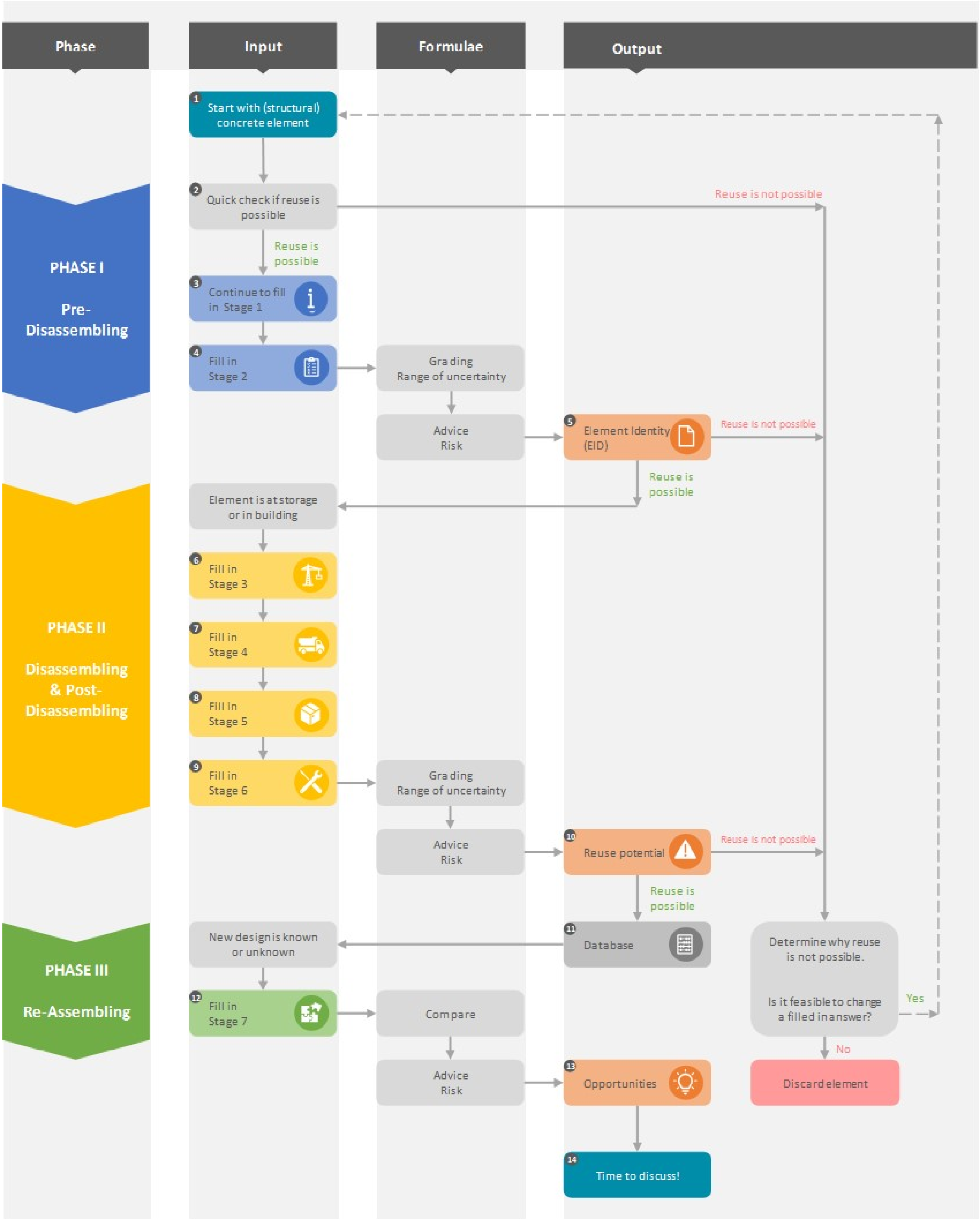


Figure 8.1: Flowchart of the process of 'Deconstruct & Reuse' for the execution of the Decision Support Tool (own figure).

Decision Support Tool

Author: B. (Bente) R. Kamp
Version: 8
Last edited: 1-6-2021

Pieters BOUWTECHNIEK TU Delft

What does the Decision Support Tool do?

The Decision Support Tool is a method to qualitatively and quantitatively assess the reuse potential of existing concrete. By harvesting structural elements from demolition projects and reusing them in the design of new buildings, critical environmental issues of the construction industry (such as the disposal of waste, resource depletion and emissions of greenhouse gasses) can be reduced. By keeping products in use and by designing out waste, the Circular Economy (CE) in the building sector is enhanced. This is referred to as the process of 'Deconstruct & Reuse' that is based on an extensive literature study, a case-study and interviews with structural engineers at Pieters Bouwtechniek. The goal of the Decision Support Tool is to guide structural engineers who want to test or reuse a harvested (structural) element in the design of a new building. In order to realize this, the Decision Support Tool considers three phases, indicated by the following colours:

I Pre-Disassembling II Disassembling & Post-Disassembling III Re-Assembling

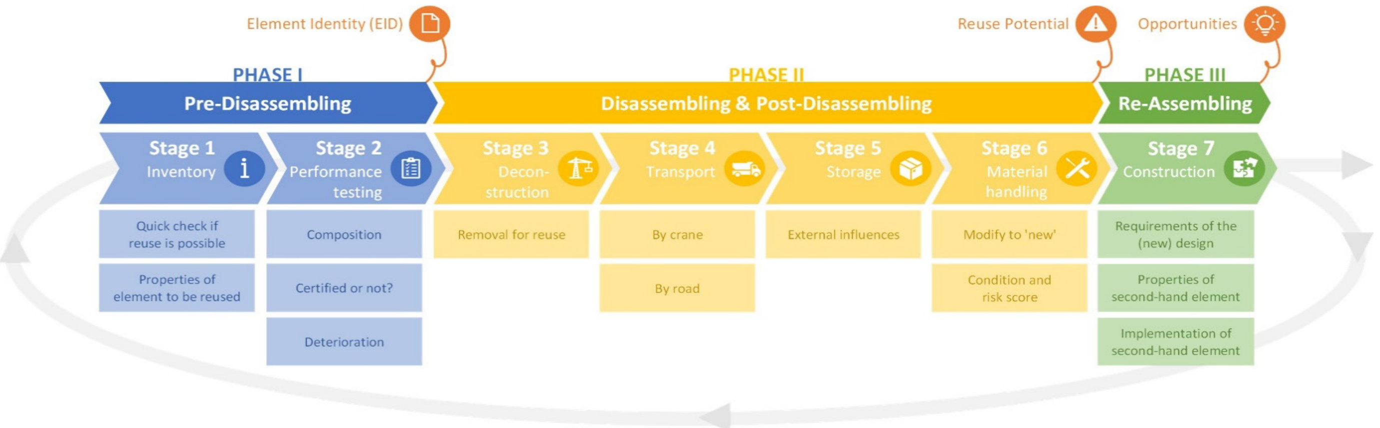
Who can make use of the Decision Support Tool?

The Decision Support Tool can be used by structural engineers who want to test the reuse potential of a (structural) concrete element and reuse this element in the design of a (new) building. Moreover, the second-hand (structural) element to be tested and reused can originate from a storage site, a demolition project or a building to be demolished. However, basic knowledge about (structural) concrete is expected for the input that makes the Decision Support Tool particularly useful for structural engineers.

How is the Decision Support Tool set up?

The Decision Support Tool distinguishes three phases which are set up based on the information provided during respectively **Pre-Disassembling**, **Disassembling & Post-Disassembling** and **Re-Assembling**. The three phases each categorize several stages. An overview of the Decision Support Tool is shown in the figure below, where all phases and stages are indicated with the corresponding colours.

The Decision Support Tool is set up in Excel, consisting of worksheets for (1) Input, (2) Formulae and (3) Output. Firstly, the input is linked to a Graphic User Interface (GUI) which can be executed easily. Next, the filled-in information is processed in Formulae that makes use of a Fuzzy calculation. The grading and range of uncertainty result in **Output per Phase** which assesses the reuse potential. For simplicity, only the input and output are visible for the executor of the Decision Support Tool. More information can be found in the report at the repository of Delft University of Technology.



What results can be expected from the Decision Support Tool?

At the end of each Phase, results can be obtained which outline the assessment of the reuse potential so far. As shown in the figure above, the outputs that can be obtained at the end of Phase I, II and III are respectively:

- Element Identity (EID) with first and second signature of the executor
- Reuse potential of a harvested (structural) element per Stage carried out in Phase I and II
- Opportunities of second-hand (structural) element in the design of a (new) building

page 71

The output per Phase is generated in a PDF file that can be saved locally. The reuse potential (or output) is easy to understand, which makes it a subject for discussion with other parties of new building designs. Especially during the initial phase, the results of the Decision Support Tool can influence the implementation of harvested (structural) elements in a building instead of new elements. The results can thus lead to more reuse of concrete (structural) elements and accelerate the Circular Economy (CE) in the building sector.

How to make use of the Decision Support Tool?

A manual to execute the Decision Support Tool is described below, where all steps relate to the flowchart on the right. In order to assess the reuse potential, all stages need to be filled in. The assessment questions can have open or fixed answer options, with further instructions if the answer is unknown. In that case, the Decision Support Tool takes a conservative lower limit. Additionally, each question explains where or how information can be retrieved. However, if an answer is left blank an empty label is generated in the output giving in skewed results. Therefore, the executor of the Decision Support Tool should try to fill in all questions (in some cases with information of other parties).

Manual for the Decision Support Tool

1. Start with (structural) concrete element to be reused
2. Quick check if reuse is possible
3. If reuse is possible, continue to fill in Stage 1 (Inventory)
4. Fill in Stage 2 (Performance Testing)
5. Generate output of Phase I: Element Identity (EID)
6. If reuse is possible, fill in Stage 3 (Deconstruction)
7. Fill in Stage 4 (Transport)
8. If element is already deconstructed, fill in Stage 5 (Storage)
9. Fill in Stage 6 (Material Handling)
10. Generate output of Phase II: Reuse potential
11. If reuse is possible, add element to database
12. Fill in Stage 7 (Construction)
13. Generate output of Phase III: Opportunities
14. Discuss the implementation of a harvested (structural) element in the initial phase of a (new) building with other construction parties

What is the scope of the Decision Support Tool?

The Decision Support Tool is part of a graduation project conducted at Delft University of Technology, in collaboration with Pieters Bouwtechniek. The Decision Support Tool is validated and verified with experienced structural engineers which showed four limitations for use in practice. Firstly, the assessment depends on the judgement of the executor which means the output of the Decision Support Tool can only be seen as advice. Secondly, unfamiliarity, sensitivity and lacking information to answer assessment questions can generate skewed results. The fixed and 'unknown' answer options, explanations and range of uncertainty deal with this. Thirdly, only individual elements can be assessed in the Decision Support Tool. Especially, beams and slabs are considered during the development and validation which can limit the assessment of columns and walls. Lastly, the Decision Support Tool has not been used in practice yet. However, with these limitations for use in practice, this research tries to provide valuable insights with which a structural engineer can decide if a harvested (structural) element can be reused and implemented in a new building. Thereby, the assessment of the reuse potential is considered to be a step towards circularity in the construction industry.

Click here to start the assessment and to go to the next sheet
(Phase I - Pre-Disassembling)

① Start with (structural) concrete element to be reused

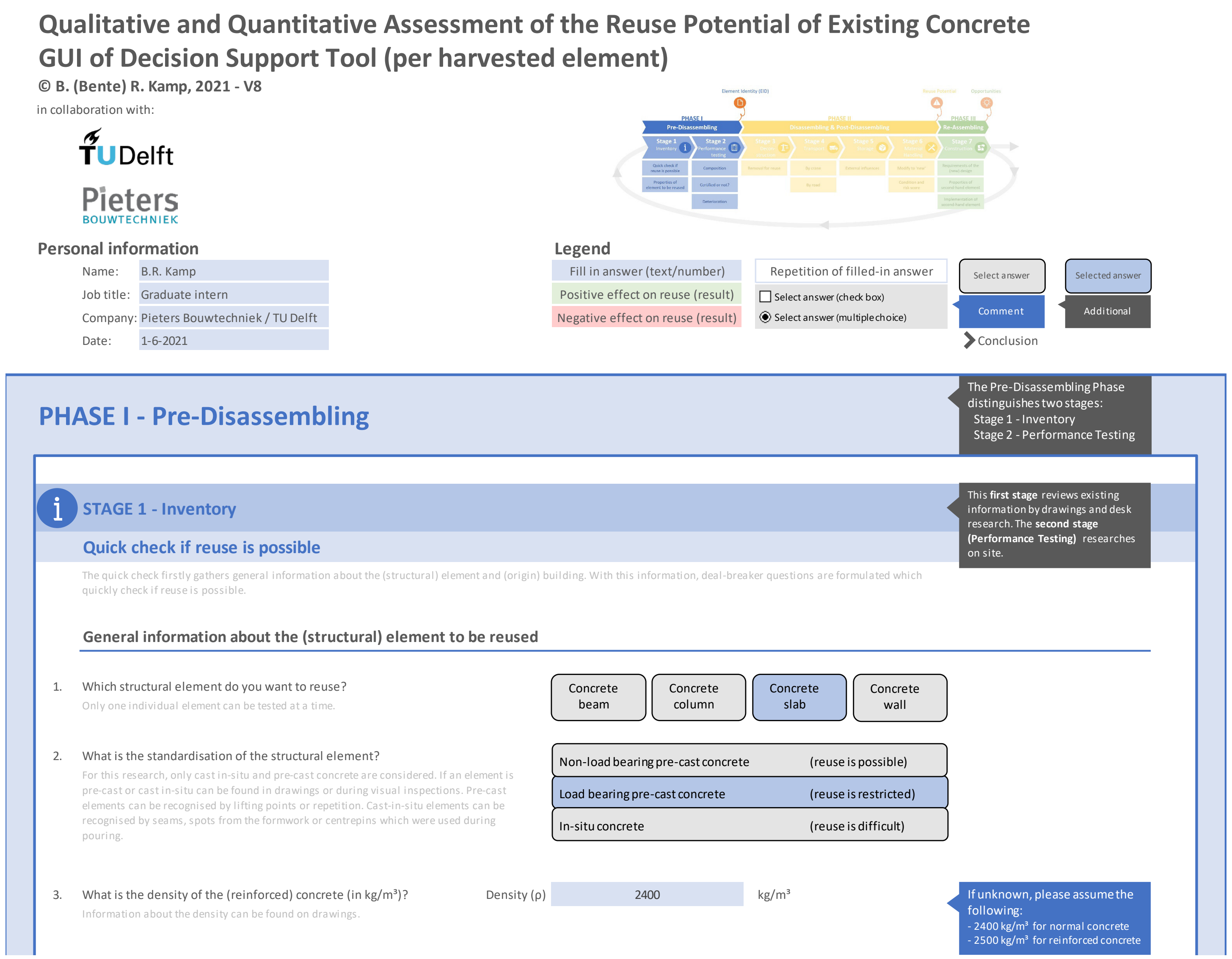
In the first step, the executor of the Decision Support Tool choses a concrete element to assess the reuse potential. This element can originate from a building to be demolished, or from a storage site in case the building is already deconstructed.

② Quick check if reuse is possible

In order to determine if reuse of a harvested (structural) element in a new design is possible, a quick check is implemented at the start of the Decision Support Tool. The quick check firstly gathers general information about the (structural) element and (origin) building. Therefore, assessment questions about the structural element, standardisation, density, dimensions, project name, project location and (de-)construction year need to be filled in by the executor. Information to answer these assessment questions can be gathered by drawings and desk research.
After gathering general information about the (structural) element and (origin) building, deal-breaker questions are formulated which quickly check if reuse is possible. The questions are compiled considering the negative effects among all stages, together with the interpretation of experts and the researcher. Therefore, the questions are a combination of desk research and research on site. The following deal-breakers are considered (in between brackets indicates the corresponding stage):

- Technical condition of the element (Stage 2: Performance Testing)
- Residual lifespan (Stage 2: Performance Testing)
- Accessibility of the connection(s) of the element (Stage 3: Deconstruction)
- Transport by road (Stage 5: Transport)

The answers to the deal-breaker questions directly indicate the positive or negative effect on the reuse potential by highlighting respectively in green or red. If reuse is possible, the executor can continue to fill in Stage 1 in the next step. If reuse is not possible, the reason for rejection is indicated by the answer(s) highlighted in red.



Qualitative and Quantitative Assessment of the Reuse Potential of Existing Concrete
GUI of Decision Support Tool (per harvested element)
© B. (Bente) R. Kamp, 2021 - V8
in collaboration with:
TU Delft
Pieters BOUWTECHNIEK

Personal information
Name: B.R. Kamp
Job title: Graduate intern
Company: Pieters Bouwtechniek / TU Delft
Date: 1-6-2021

Legend
Fill in answer (text/number)
Positive effect on reuse (result)
Negative effect on reuse (result)
Repetition of filled-in answer
Select answer (check box)
Select answer (multiple choice)
Select answer
Selected answer
Comment
Additional
Conclusion

PHASE I - Pre-Disassembling
The Pre-Disassembling Phase distinguishes two stages:
Stage 1 - Inventory
Stage 2 - Performance Testing

STAGE 1 - Inventory
This **first stage** reviews existing information by drawings and desk research. The **second stage (Performance Testing)** researches on site.

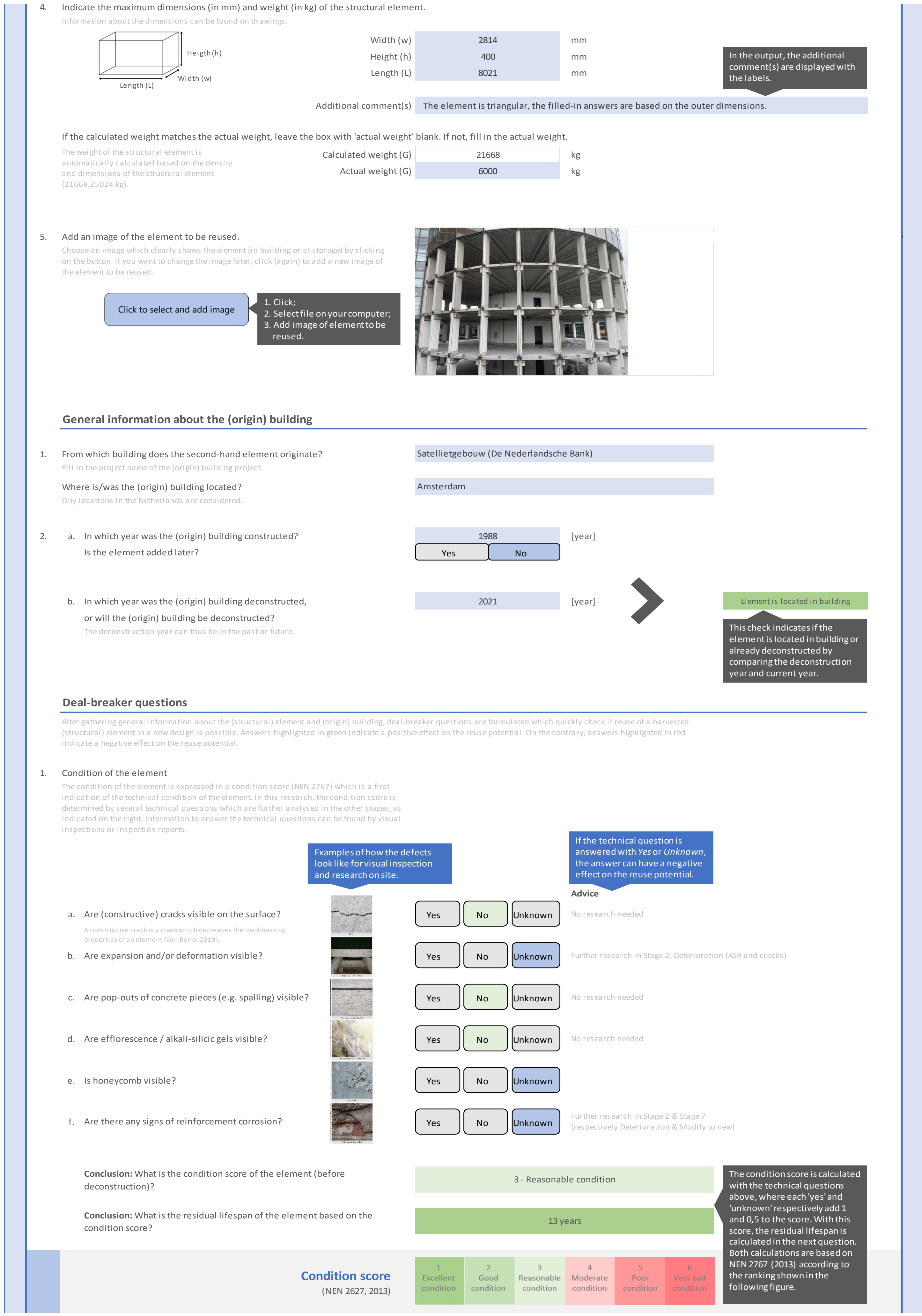
Quick check if reuse is possible
The quick check firstly gathers general information about the (structural) element and (origin) building. With this information, deal-breaker questions are formulated which quickly check if reuse is possible.

General information about the (structural) element to be reused

1. Which structural element do you want to reuse? — Concrete beam / Concrete column / Concrete slab / Concrete wall
Only one individual element can be tested at a time.

2. What is the standardisation of the structural element?
For this research, only cast in-situ and pre-cast concrete are considered. If an element is pre-cast or cast in-situ can be found in drawings or during visual inspections. Pre-cast elements can be recognised by lifting points or repetition. Cast-in-situ elements can be recognised by seams, spots from the formwork or centrepins which were used during pouring.
Non-load bearing pre-cast concrete (reuse is possible)
Load bearing pre-cast concrete (reuse is restricted)
In-situ concrete (reuse is difficult)

3. What is the density of the (reinforced) concrete (in kg/m³)? Density (ρ) 2400 kg/m³
Information about the density can be found on drawings.
If unknown, please assume the following:
- 2400 kg/m³ for normal concrete
- 2500 kg/m³ for reinforced concrete



4. Indicate the maximum dimensions (in mm) and weight (in kg) of the structural element.
Information about the dimensions can be found on drawings.
Heigth (h) Width (w) Length (L)
Width (w) 2814 mm
Height (h) 400 mm
Length (L) 8021 mm
In the output, the additional comment(s) are displayed with the labels.
Additional comment(s) The element is triangular, the filled-in answers are based on the outer dimensions.

If the calculated weight matches the actual weight, leave the box with 'actual weight' blank. If not, fill in the actual weight.
The weight of the structural element is automatically calculated based on the density and dimensions of the structural element (21668,25024 kg).
Calculated weight (G) 21668 kg
Actual weight (G) 6000 kg

5. Add an image of the element to be reused.
Choose an image which clearly shows the element (in building or at storage) by clicking on the button. If you want to change the image later, click (again) to add a new image of the element to be reused.
Click to select and add image
1. Click;
2. Select file on your computer;
3. Add image of element to be reused.

General information about the (origin) building

1. From which building does the second-hand element originate? Satellietgebouw (De Nederlandsche Bank)
Fill in the project name of the (origin) building project.
Where is/was the (origin) building located? Amsterdam
Ony locations in the Netherlands are considered.

2. a. In which year was the (origin) building constructed? 1988 [year]
Is the element added later? Yes / No
b. In which year was the (origin) building deconstructed, or will the (origin) building be deconstructed? 2021 [year]
The deconstruction year can thus be in the past or future.
Element is located in building
This check indicates if the element is located in building or already deconstructed by comparing the deconstruction year and current year.

Deal-breaker questions
After gathering general information about the (structural) element and (origin) building, deal-breaker questions are formulated which quickly check if reuse of a harvested (structural) element in a new design is possible. Answers highlighted in green indicate a positive effect on the reuse potential. On the contrary, answers highlighted in red indicate a negative effect on the reuse potential.

1. Condition of the element
The condition of the element is expressed in a condition score (NEN 2767) which is a first indication of the technical condition of the element. In this research, the condition score is determined by several technical questions which are further analysed in the other stages, as indicated on the right. Information to answer the technical questions can be found by visual inspections or inspection reports.
Examples of how the defects look like for visual inspection and research on site.
If the technical question is answered with *Yes* or *Unknown*, the answer can have a negative effect on the reuse potential.

Question	Answer	Advice
a. Are (constructive) cracks visible on the surface? A constructive crack is a crack which decreases the load-bearing properties of an element (Van Berlo, 2019).	Yes / No / Unknown	No research needed
b. Are expansion and/or deformation visible?	Yes / No / Unknown	Further research in Stage 2: Deterioration (ASR and cracks)
c. Are pop-outs of concrete pieces (e.g. spalling) visible?	Yes / No / Unknown	No research needed
d. Are efflorescence / alkali-silicic gels visible?	Yes / No / Unknown	No research needed
e. Is honeycomb visible?	Yes / No / Unknown	
f. Are there any signs of reinforcement corrosion?	Yes / No / Unknown	Further research in Stage 2 & Stage 7 (respectively Deterioration & Modify to new)

Conclusion: What is the condition score of the element (before deconstruction)? 3 - Reasonable condition
Conclusion: What is the residual lifespan of the element based on the condition score? 13 years
The condition score is calculated with the technical questions above, where each 'yes' and 'unknown' respectively add 1 and 0,5 to the score. With this score, the residual lifespan is calculated in the next question. Both calculations are based on NEN 2767 (2013) according to the ranking shown in the following figure.

Condition score (NEN 2627, 2013)
1 Excellent condition | 2 Good condition | 3 Reasonable condition | 4 Moderate condition | 5 Poor condition | 6 Very bad condition

3 If reuse is possible, continue to fill in Stage 1 (Inventory)

After the quick check to determine if reuse of a harvested (structural) element in a new design is possible, the properties of the (structural) element are investigated by drawings and desk research in Stage 1. Firstly, general properties are analysed such as type of cement, fire resistance, strength class, environmental class and yield strength of the reinforcing steel. Next, the concrete cover is checked. Lastly, the function of the (origin) building and the design values of the total load on the element are analysed. If the filled-in answers of Stage 1 are correct and researched by drawings and desk research, the executor of the Decision Support Tool can set a first signature below the Element Identity (EID), which is the output of Phase I.

2. Residual lifespan

What is the age of the element?	2021 - 1988 = 33	[years]
What is the (origin) design service life of the element?	50	[years]

The theoretical lifespan of concrete has a maximum of 100+ years (Vissering et al, 2011). Most buildings are designed for 50 years, so if the design service life of the element is unknown, assume 50 years as a conservative lower limit.

Conclusion: Is the design service life of the element exceeded? — No, the element can be reused for minimal 17 years (= 50 - 33)

3. Considering one connection of the element to be reused you demand to disconnect, What is the accessibility of the connections you want to disconnect?

The accessibility of an element refers to the level of access without causing damage to the element or other surrounding elements. The answers are ordered from 'most accessible' to 'less accessible'. The answer with the highest number must be selected in the case if the accessibility cannot be detected.
Additional operation is specified as operations for which equipment to disconnect the element from the structure is needed. Repairable damage is specified as modifications to restore the element (on small and large scale). Information about the accessibility can be found by drawings, inspection reports or visual inspections.

- 1 - Accessible without additional operation
- 2 - Accessible with additional operation which causes no damage to the element
- 3 - Accessible with additional operation which causes repairable damage to the element
- 4 - Accessible with additional operation which causes partly repairable damage to the element
- 5 - Not accessible without causing total damage to the element

4. 'Normal' transport by road and a 'normal' crane on site

For this research, transport by air, rail or water are not considered (further researched in Stage 4: Transport).

a. Does the element weigh less than 15.000 kg?	Yes	The weight of the element is 6000 kg.
b. Does the element fit within the dimensions of 3,0x4,0x22,0 m?	Yes	The dimensions of the element are 2,814 x 0,4 x 8,021 m.

Conclusion: Can the element be transported by road? — 'Normal' transport is possible

5. **Is reuse of second-hand element possible?** — REUSE IS POSSIBLE

What to do next? — Continue to fill in.

Properties of the (structural) element to be reused

1. Indicate the following properties of the concrete and the reinforcing steel of the structural element, as assumptions before 'Performance Testing' in Stage 2. If the answer is unknown by drawings and desk research, you can select 'unknown' for a conservative lower limit. The blue coloured boxes display your selected answers.

a. What is the type of cement of the element?

For this research, only the types of cement most used in the Netherlands (CEM I, CEM II/A, CEM II/B, CEM III/A, CEM III/B and CEMIII/C) are considered. These are simplified as CEM I, CEM II and CEM III.

CEM I (portlandcement) | CEM II (portland-composite cement) | CEM III (blast furnace cement) | Unknown

If the type of cement is unknown, this research assumes CEM I (Portlandcement) as a conservative lower limit.

b. What is the fire resistance of the element?

In the case of a deficiency of information, the performance criteria of existing buildings can be applied according to NEN-EN 13501-2 which can be found by clicking on the button. If the fire resistance is (still) unknown, 30 min is assumed as a conservative lower limit which can be certified in Stage 2 (Performance Testing).

Click to show — Click on these buttons for more information.

30 min | 60 min | 90 min | 120 min | Unknown

If the fire resistance is unknown, this research assumes 30 min as a conservative lower limit.

c. What is the strength class of the element (at construction)?

For this research, only 'normal' concrete and corresponding strength classes are considered. If the strength class of the structural element does not refer to NEN-EN 1992-1-1, you can find the corresponding strength class of older codes by clicking on the button.

Click to show

C20/25 | C25/30 | C30/37 | C35/45 | C40/50 | C45/55 | C50/60 | Unknown

If the strength class is unknown, this research assumes the following (minimum):
- C20/25 for in-situ concrete;
- C35/45 for pre-cast concrete.

d. What is the environmental class of the element?

For this research, only the environmental classes which correspond to superstructures of buildings in the Netherlands are considered. If the environmental classes of NEN-EN 1992-1-1 are unclear, you can find descriptions, informative examples or codes before 2005 of the environmental classes by clicking on the button.

Click to show

X0 | XC1 | XC3 | XC4 | XD1 | XS1 | XF1 | Unknown

If the environmental class is unknown, this research assumes the environmental class with the highest chance of damage to the reinforcement and concrete (XD1).

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e. What is the yield strength of the reinforcing steel (corresponding to NEN-EN 199 — 500 N/mm² | Unknown

In the case an older code is used and it is unknown how the yield strength corresponds to NEN-EN 1992-1-1, you can find the designations of reinforcing steel and corresponding yield strengths by clicking on the button.

Click to show

If the yield strength of the reinforcing steel is unknown, this research assumes 220 N/mm² if the building is constructed before 1960; 400 N/mm² is the building is constructed between 1960 and 1990; and 500 N/mm² if the building is constructed after 1990.

2. What is the (average) thickness of the concrete cover? — 20 mm

For this research it is assumed the concrete cover is uniform on all sides. If the thickness is unknown, the minimum concrete cover can be assumed to be 20 mm (Eurocode 2, 2013). This thickness is based on the filled-in strength class (C30/37), the environmental class (X0) and the construction class (S4).

Conform current regulations in Eurocode 2 (2013) regarding the origin environmental class (X0) and the minimum concrete cover. More research is needed regarding the environmental class of the new design (probably equal or less aggresive than the origin).

3. What is/was the function of the (origin) building at the location of the (structural) element to be reused?

The functions are in accordance with the categories and loads in Eurocode 2.

- Residential areas
- Office areas
- Congregation areas
- Shopping areas
- Storage areas

4. Indicate the design value of the total load on the element

Total permanent loading (without self-weight)	G	1,5	kN/m²
Partial factor permanent loading	γ_G	1	
Total variable loading	Q	3,0	kN/m²
Partial factor variable loading	γ_Q	0,4	

(self-weight of the element is 58,8399 kN)

What is/was the design value of the total load on the element? q_d = 2,7 kN/m² (without self-weight)

The design load(s) can be determined with the standards corresponding to the construction year (1988) and function of the (origin) building.

Additional comment(s): The filled-in answers are based on the double tee slab of the 2nd floor (connection to the facade column).

Indicate the design loads at midspan or support of the element. In case no loads occur, leave blank or fill in 0.

For the design load(s), please consider the elastic theory and stress distribution for statically determinate structures.

a. Design load(s) at midspan	Bending moment	M_{Ed}	393,9	kNm
	Shear force	V_{Ed}	0,0	kN
	Normal force	N_{Ed}	0,0	kN
b. Design load(s) at support (of the connection to be considered)	Bending moment	M_{Ed}	0,0	kNm
	Shear force	V_{Ed}	1109,1	kN
	Normal force	N_{Ed}	0,0	kN

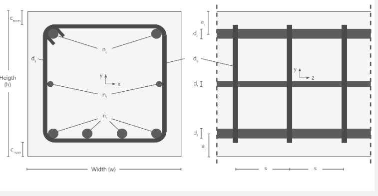
c. Are reinforcement drawings available? (e.g. to determine maximum capacity) — Yes | No

Indicate the dimensions of the reinforcing steel according to the figure on the right.

Per structural element, only the dimensions considered in the output need to be filled in, as indicated below. Dimensions which are not present inside the element need to be filled in with '0'.
- For **beams**: rebars in tension (main), rebars in flank and stirrups;
- For **columns**: rebars in tension, rebars in compression and stirrups;
- For **walls**: rebars in tension and compression;
- For **slabs**: rebars in tension (main) and compression layer.

Rebars at bottom (at midspan)	Number of rebars	n_b	2	
	Diameter	d_b	20	mm
	Distance to outer	a_b	36	mm
	Area	A_b	628	mm²
Rebars at top (at support)	Number of rebars	n_t	4	
	Diameter	d_t	10	mm
	Distance to outer	a_t	31	mm
	Area	A_t	314	mm²
Compression layer	Thickness	c_c		mm
Rebars in flank	Number of rebars	n_f	2	
	Diameter	d_f	12	mm
Stirrups	Diameter	d_s	6	mm
	Spacing	s	50	mm
	Number of sections per stirrup	n_s	2	

If multiple rows of rebars (in tension, compression or flank) are present, fill in:
- the total amount of bars (n);
- the average diameter (d).



5. **First signature for Element Identity (EID)** — I hereby state that the filled-in answers are correct and researched by drawings and desk research.

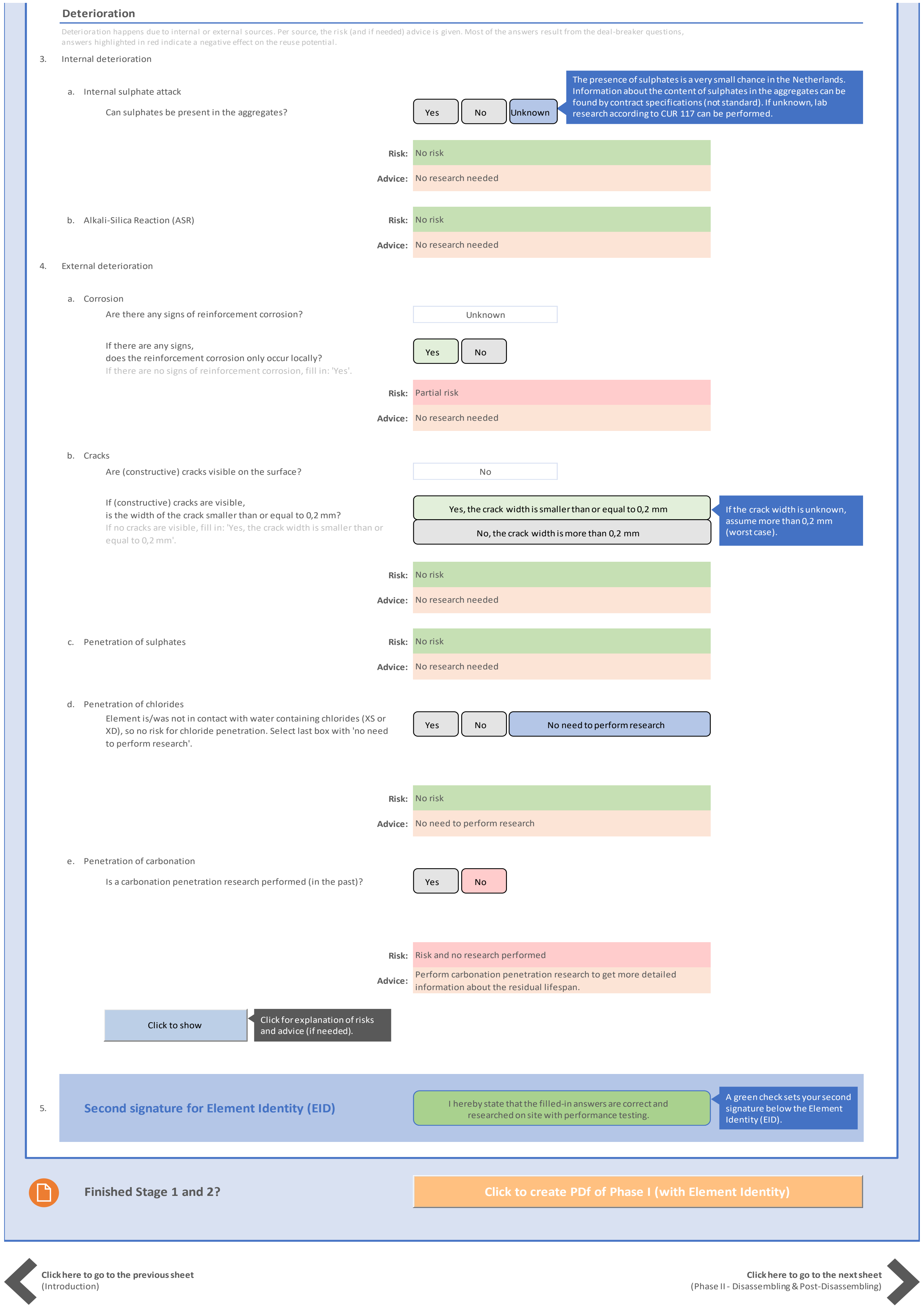
A green check sets your first signature below the Element Identity (EID).

4 Fill in Stage 2 (Performance Testing)

The desk research of Stage 1 is followed up by research on site to check the existing information or, in case desk research was unavailable or insufficient, to obtain lacking information. In Stage 2, the presence of toxic materials in the composition of the (structural) element is investigated. Next, it is important to determine if the filled-in properties of Stage 1 are certified by performance testing. Last, internal and external deterioration of the element are investigated. If the filled-in answers of Stage 2 are correct and researched on site with performance testing, the executor of the Decision Support Tool can set a second signature below the Element Identity (EID), which is the output of Phase I.

5 Generate output of Phase I: Element Identity (EID)

Phase I (Pre-Disassembling) distinguishes two stages, namely Stage 1: Inventory and Stage 2: Performance Testing. As decribed, these two stages consider if reuse of a harvested (structural) element is possible before an element is deconstructed. Therefore, the gathered and reviewed information of Stage 1 and 2 is summarized in the Element Identity (EID), which is shown on the next page. The output of Phase I is generated in a PDF file that can be saved locally. After generating the output of Phase I, the executor of the Decision Support Tool can continue to Phase II (Disassembling and Post-Disassembling).



Qualitative and Quantitative Assessment of the Reuse Potential of Existing Concrete

In collaboration with: TU Delft, Pieters Bouwtechniek

Filled-in by: B.R. Kamp
Graduate intern
Pieters Bouwtechniek / TU Delft

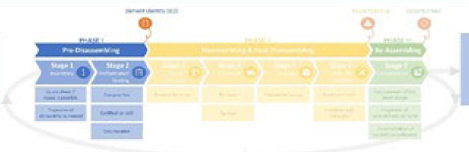
Filled-in on: 1-6-2021

Legend:
- Filled-in answer
- Result of filled-in answer(s)
- Positive effect on reuse potential
- Negative effect on reuse potential

Phase I - Pre-Disassembling — Output

Quick check if reuse is possible

(by drawings and desk research)



General information about the (structural) element to be reused

Structural element		Slab
Material		Concrete
Standardisation		Load bearing pre-cast concrete
Density	ρ	2400 kg/m³
Width	w	2814 mm
Height	h	400 mm
Length	L	8021 mm
Weight	G	6000 kg
Additional comment(s) by executor		The element is triangular, the filled-in answers are based on the outer dimensions.

General information about the (origin) building

Project name and location	Satellietgebouw (De Nederlandsche Bank) at Amsterdam
Function	Shopping areas
Build in	1988
(To be) deconstructed	2021 → Element is located in building

Deal-breaker questions

Answers highlighted in green indicate a positive effect on the reuse potential. On the contrary, answers highlighted in red indicate a negative effect.

		1	2	3	4	5	6
Condition score before Phase I and II (NEN 2627, 2013)	C_I	1 (Excellent condition)	2	**3**	4	5	6 (Very bad condition)
Accessibility		1 (Not applicable)	2 (Accessible)	3	**4**	5	6 (Not accessible)

'Normal' transport: 'Normal' transport by road and crane is possible (based on dimensions and weight)

Residual lifespan
- Based on design service life — SL_d — 17 years
- Based on condition score before deconstruction — C_I — 13 years

With a marge between 6,25 and 50 years (respectively - and + uncertainty of C_I), which can be extended with treatment.

Is reuse possible? REUSE IS POSSIBLE

Properties of the (structural) element to be reused

(by on site research)

Type of cement		CEM I	Certified	
Fire resistance		60 min	Not certified	Investigate fire resistance by concrete properties and NEN-EN 13501-2
Strength class (maximum)		C30/37	Certified	
Environmental class		X0	Not certified	Determine environmental class according to NEN-EN 1992-1-1
Yield strength	f_y	500 N/mm²	Certified	
Concrete cover	c_{nom}	20 mm		Conform current regulations in Eurocode 2 (2013) regarding the origin environmental class (X0) and the minimum concrete cover. More research is needed regarding the environmental class of the new design (probably equal or less aggresive than the origin).

Design load(s)

Design value of total load — q_d — 2,7 kN/m²

Additional comment(s) by executor: The filled-in answers are based on the double tee slab of the 2nd floor (connection to the facade col

		At midspan	At support
Bending moment	M_{Ed}	393,9 kNm	0,0 kNm
Shear force	V_{Ed}	0,0 kN	1109,1 kN
Normal force	N_{Ed}	0,0 kN	0,0 kN

Are reinforcement drawings available? Available

Composition

	Risk	Advice
Iron fibres	Presence is unknown	Investigate the presence of iron fibres
Composite fibres	Presence is unknown	Investigate the presence of composite fibres
Asbestos	Not present	No research needed
Chlorides	Presence is unknown	Investigate the presence of chlorides

Deterioration

	Risk	Advice
Internal deterioration		
Internal sulphate attack	No risk	No research needed
Alkali-Silica Reaction (ASR)	No risk	No research needed
External deterioration		
Corrosion	Partial risk	No research needed
Cracks	No risk	No research needed
Penetration of sulphates	No risk	No research needed
Penetration of chlorides	No risk	No need to perform research
Penetration of carbonation	Risk and no research performed	Perform carbonation penetration research to get more detailed information about the residual lifespan.

Signatures below Element Identity (EID) of Stage 1 and 2

In Stage 1, existing information is researched by desk research. This first signature shows the filled-in answers are correct.	In Stage 2, more information is researched on site. This second signature shows the filled-in answers are correct.
Signed by B.R. Kamp	Signed by B.R. Kamp

6 If reuse is possible, fill in Stage 3 (Deconstruction)

In order to safely deconstruct existing buildings, the sequence of disassembling is important. Therefore, Stage 3 considers the removal for reuse by disconnecting the connections. The equipment to disconnect elements for reuse is affected by the type of connection and the accessibility (deal-breaker). Based on a literature study, a suggestion for the equipment to disconnect is made which limits damage to the connection. Next, the executor of the Decision Support Tool can select the preferred equipment to disconnect based on the advantages and disadvantages.

Qualitative and Quantitative Assessment of the Reuse Potential of Existing Concrete GUI of Decision Support Tool (per harvested element)

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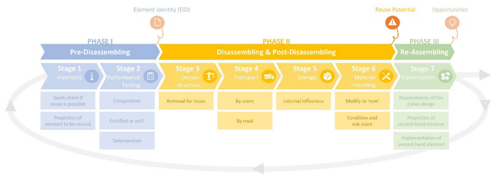
in collaboration with:

TU Delft

Pieters BOUWTECHNIEK



Personal information

Name:	B.R. Kamp
Job title:	Graduate intern
Company:	Pieters Bouwtechniek / TU Delft
Date:	1-6-2021

Legend

Fill in answer (text/number)
Positive effect on reuse (result)
Negative effect on reuse (result)
Result of Phase I
Result of filled-in answer(s)
☐ Select answer (check box)
○ Select answer (multiple choice)
Select answer
Selected answer
Comment
Additional
Conclusion

PHASE II - Disassembling and Post-Disassembling

The Disassembling and Post-Disassembling Phase distinguishes four stages:
Stage 3 - Deconstruction
Stage 4 - Storage
Stage 5 - Transport
Stage 6 - Material Handling

Indicate if the second-hand element is located in building or already deconstructed:

- Element is located in building
- Element is already deconstructed and at storage site

STAGE 3 - Deconstruction

Removal for reuse

1. What is the type of connection to be deconstructed?
   The type of connection implies the level of difficulty to disconnect the element. The answers are ordered from 'easily to remove' (flexible) to 'hard to remove' (fixed). Information can be found by drawings, inspection reports or visual inspections. The answer with the highest number must be selected in the case if (1) multiple answers are applicable to an element, (2) there is uncertainty between multiple answers about how elements are connected or (3) type of the connection cannot be detected.

   - 1 - Indirect connection with additional fixing device (dry connection)
   - 2 - Indirect connection via independent third component (dry connection)
   - 3 - Indirect connection via dependent third component
   - 4 - Direct connection with additional fixing device
   - 5 - Indirect connection via third chemical material (soft)
   - 6 - Indirect connection via third chemical material (hard)
   - 7 - Direct connection between two pre-made components
   - 8 - Direct chemical connection

   If the element has multiple connections to be disconnected, please assume one. Other connections can be added and tested by changing your filled-in answer(s).

   Click to show examples — Click here to see examples of type of connection

2. What is the equipment to disconnect the connection?
   With literature study, the demolition technologies which are suitable to disconnect elements for reuse are allocated based on the accessibility and type of connection. A suggestion for the equipment to disconnect is made (2a). In the next question (2b), you can select the preferred equipment with or without considering the suggested equipment.

   a. Suggested equipment(s) to limit damage to the connection
   Based on filled-in answers of accessibility and type of connection, respectively:
   4 - Accessible with additional operation which causes repairable damage to the element
   3 - Indirect connection via dependent third component

   1 - Wire cutter (by hand);
   5 - Diamond blade saw (saw cutting);
   6 - Diamond wire cutter (saw cutting);
   7 - Water jet machine (hydrodemolition);
   8 - Boring and cutting (thermal demolition);
   9 - Electric heating (thermal demolition);

   b. Indicate which equipment to disconnect is preferred
   (or if equipment is already known)

   - 1 - Wire cutter (by hand)
   - 2 - Jackhammer (by hand)
   - 3 - Crusher (machine-mounted)
   - 4 - Hammer (machine-mounted)
   - 5 - Diamond blade saw (saw cutting)
   - 6 - Diamond wire cutter (saw cutting)
   - 7 - Water jet machine (hydrodemolition)
   - 8 - Boring and cutting (thermal demolition)
   - 9 - Electric heating (thermal demolition)
   - No equipment to disconnect is needed

   The equipment to disconnect depends on the demolition contractor. Therefore, the selected equipment can be used as an advice regarding the damaging and reconnecting the element.

   Click to show (dis-)advantages — Click here to see the advantages and disadvantages of the equipment to disconnect

   Advantages and disadvantages of preferred equipment to disconnect

		Advice
Damage to element?	Almost no damage: reuse is possible	-
Accurate removal?	Partly accurate	-
Damage to (protruding) rebars?	Protruding rebars are cut	-

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7 Fill in Stage 4 (Transport)

After the element is disconnected, the element needs to be hoisted and transported to either the deconstruction site, the new construction site or a storage yard. During Stage 4, any particularities of transport by road and by crane are investigated considering the dimensions and weight of the element, which are linked to Stage 1. Additionally, four methods are considered to hoist beams, columns, slabs, and walls from a concrete building.

8 If element is already deconstructed and at a storage site, fill in Stage 5 (Storage)

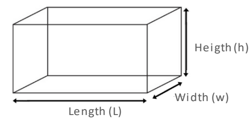
Storage of harvested (structural) elements is needed when the new project is unknown or when elements cannot be brought directly to the construction site. If an element is stored, it is important to determine how long an element has been at the storage site since this can cause (external) deterioration. Therefore, Stage 5 considers the susceptibility to external influences. Since the elements of the test-case are located in the building, storage is not needed. Therefore, an example of Stage 5 is shown below.

STAGE 4 - Transport

From deconstruction site to ...

1. Are 'normal' transport by road and a 'normal' crane on site possible?
   For this research, transport by air, rail or water are not considered. Also, only 'normal' transport by crane and by road is considered.

   Filled-in dimensions of the structural element



Width (w)	2814	mm
Height (h)	400	mm
Length (L)	8021	mm
Density (p)	2400	kg/m³
Weight (G)	6000	kg

If 'normal' transport by road is not possible, 'exceptional' transport is needed which increases the transportation costs. More information can be found on RDW (2021).

		Advice
a. Does the element weigh less than 15.000 kg?	Yes	'Normal' crane on site is possible.
b. Does the element fit within the dimensions of 3,0x4,0x22,0 m?	Yes	'Normal' transport by road is possible.

Conclusion: 'Normal' transport by road and 'normal' crane on site are possible.

Advice:

2. What kind of system is needed to hoist the element?

   - 1 - Former lifting points
   - 2 - Crane with fork
   - 3 - Drilled holes
   - 4 - Chemical anchors

   Click to show examples — Click here to see examples of hoisting

STAGE 5 - Storage

External influences

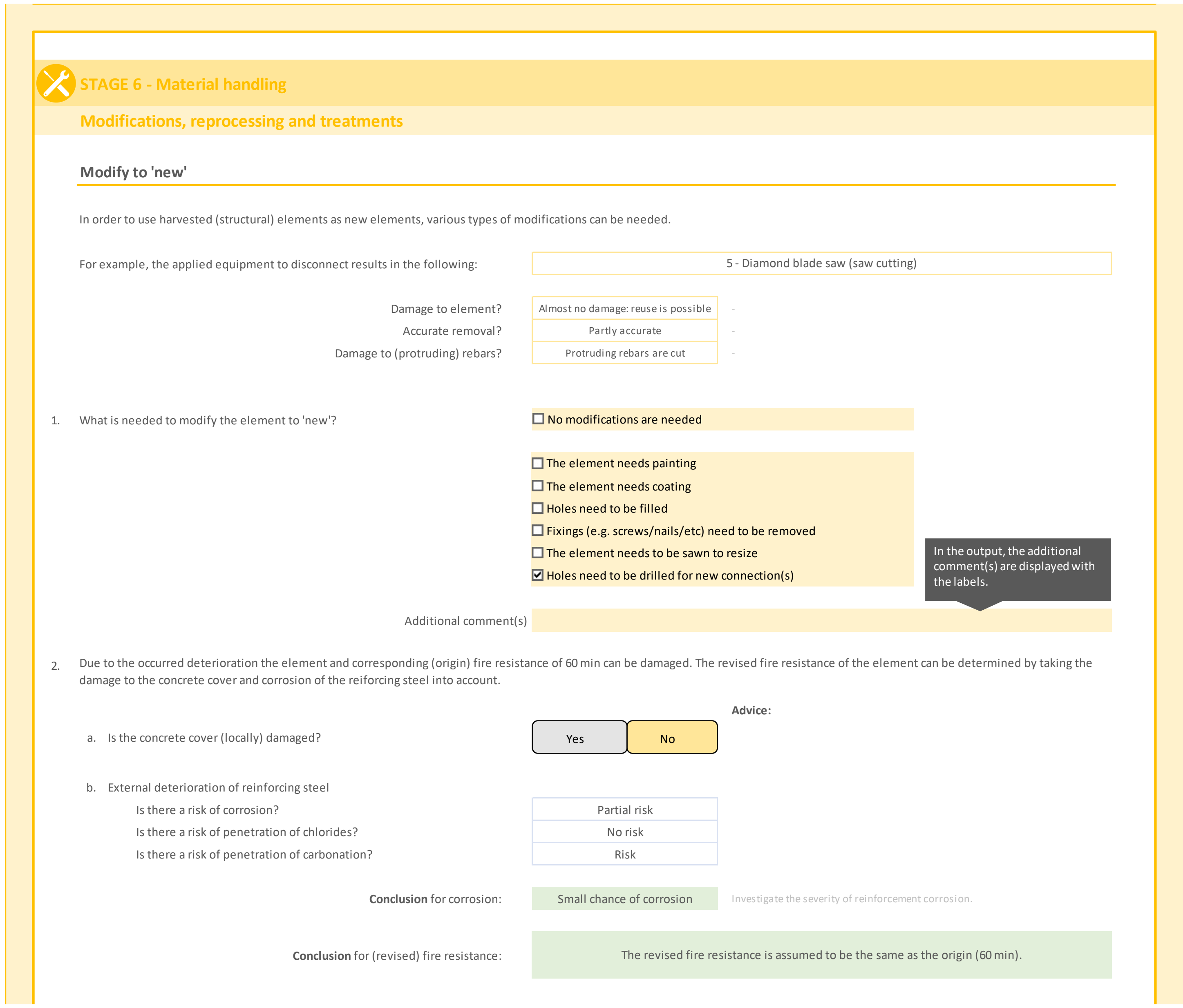
1. How many years is the element located at the storage site? 10 [years]
   Based on current year and the year the (origin) building is deconstructed. The element will be stored longer if the (new) design is constructed in the distant future.

2. Susceptibility to external influences
   a. Is/was the element stored outside and susceptible to external influences (e.g. r — Yes / No
   b. Is the element stored at or near to the sea (< 25 km inland)? — Yes / No

Conclusion: Susceptibility to external influences forms no risk.

9 Fill in Stage 6 (Material Handling)

After deconstruction, the harvested (structural) elements are modified in order to be able to reuse them in a new project. During Stage 6, modifications of the element are investigated considering a 'new' prefab concrete element. If the new design is known, the harvested (structural) elements can be modified to the requirements of the design (Stage 7). In addition, the fire resistance of the element is investigated. Lastly, the condition and related risks of the element after Phase I and Phase II are analysed.



STAGE 6 - Material handling

Modifications, reprocessing and treatments

Modify to 'new'

In order to use harvested (structural) elements as new elements, various types of modifications can be needed.

For example, the applied equipment to disconnect results in the following: 5 - Diamond blade saw (saw cutting)

Damage to element? Almost no damage: reuse is possible -
Accurate removal? Partly accurate -
Damage to (protruding) rebars? Protruding rebars are cut -

1. What is needed to modify the element to 'new'?

- ☐ No modifications are needed
- ☐ The element needs painting
- ☐ The element needs coating
- ☐ Holes need to be filled
- ☐ Fixings (e.g. screws/nails/etc) need to be removed
- ☐ The element needs to be sawn to resize
- ☑ Holes need to be drilled for new connection(s)

In the output, the additional comment(s) are displayed with the labels.

Additional comment(s)

2. Due to the occurred deterioration the element and corresponding (origin) fire resistance of 60 min can be damaged. The revised fire resistance of the element can be determined by taking the damage to the concrete cover and corrosion of the reiforcing steel into account.

Advice:

a. Is the concrete cover (locally) damaged? Yes No

b. External deterioration of reinforcing steel
Is there a risk of corrosion? Partial risk
Is there a risk of penetration of chlorides? No risk
Is there a risk of penetration of carbonation? Risk

Conclusion for corrosion: Small chance of corrosion — Investigate the severity of reinforcement corrosion.

Conclusion for (revised) fire resistance: The revised fire resistance is assumed to be the same as the origin (60 min).

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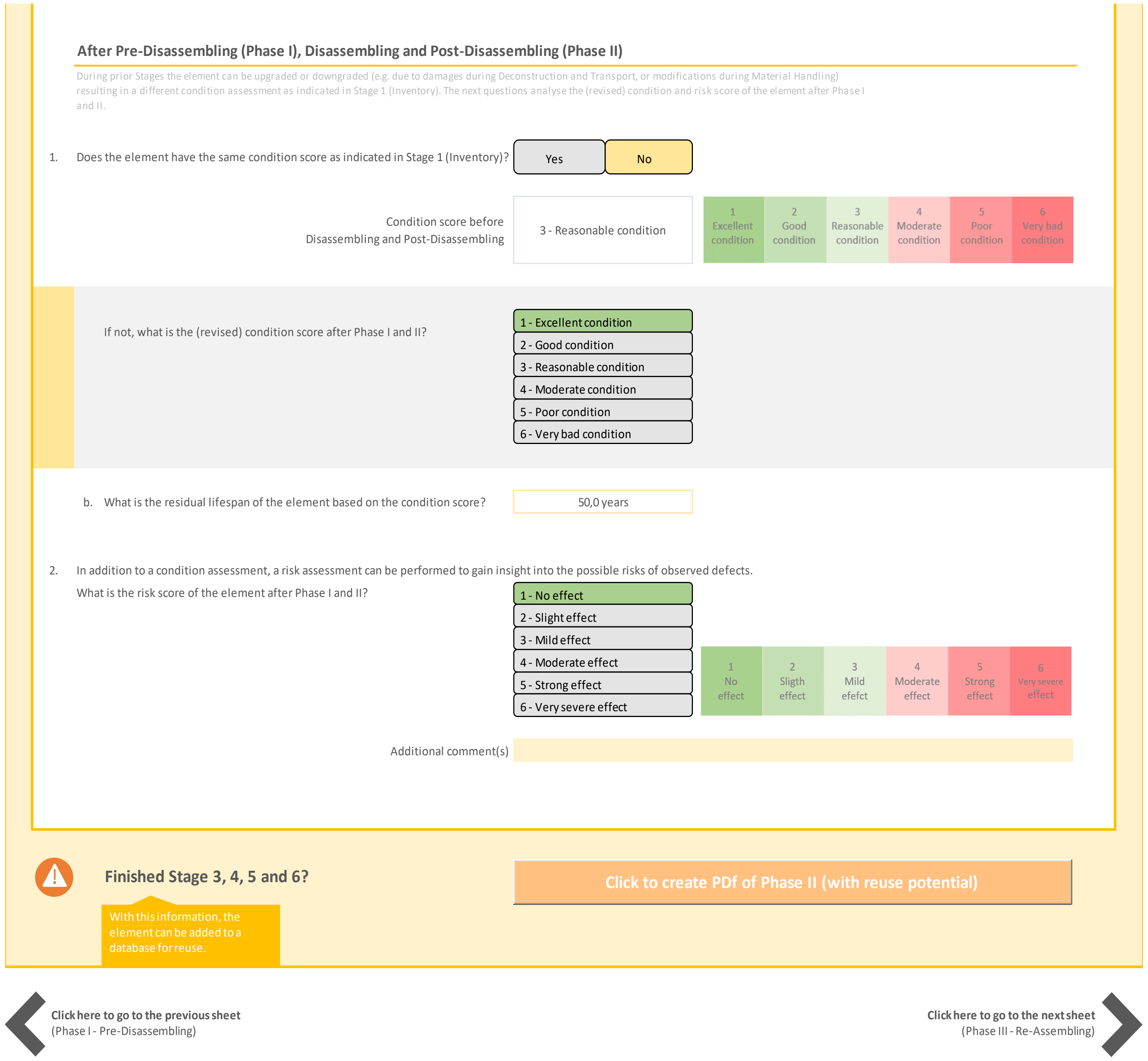
10 Generate output of Phase II: Reuse Potential

Phase II (Disassembling and Post-Disassembling) distinguishes four stages, namely Stage 3: Deconstruction, Stage 4: Transport, Stage 5: Storage and Stage 6: Material Handling. The output of Phase II is the reuse potential per stage carried out in Phase I and II, which is shown on the next page. The output of Phase II is generated in a PDF file that can be saved locally. After generating the output of Phase II, the executor of the Decision Support Tool can continue to Phase III (Re-Assembling).

11 If reuse is possible, add element to database

With the output of Phase I and Phase II, the Decision Support Tool can be linked to a database which can predict when and where elements can be harvested. Thereby, the database brings together the supply and demand of harvested (structural) elements which means a long-term construction planning can be created based on harvested elements. The database is out of the scope of this research, but recommended for further research.



After Pre-Disassembling (Phase I), Disassembling and Post-Disassembling (Phase II)

During prior Stages the element can be upgraded or downgraded (e.g. due to damages during Deconstruction and Transport, or modifications during Material Handling) resulting in a different condition assessment as indicated in Stage 1 (Inventory). The next questions analyse the (revised) condition and risk score of the element after Phase I and II.

1. Does the element have the same condition score as indicated in Stage 1 (Inventory)? Yes No

Condition score before Disassembling and Post-Disassembling: 3 - Reasonable condition

1 Excellent condition	2 Good condition	3 Reasonable condition	4 Moderate condition	5 Poor condition	6 Very bad condition

If not, what is the (revised) condition score after Phase I and II?

- 1 - Excellent condition
- 2 - Good condition
- 3 - Reasonable condition
- 4 - Moderate condition
- 5 - Poor condition
- 6 - Very bad condition

b. What is the residual lifespan of the element based on the condition score? 50,0 years

2. In addition to a condition assessment, a risk assessment can be performed to gain insight into the possible risks of observed defects.
What is the risk score of the element after Phase I and II?

- 1 - No effect
- 2 - Slight effect
- 3 - Mild effect
- 4 - Moderate effect
- 5 - Strong effect
- 6 - Very severe effect

1 No effect	2 Sligth effect	3 Mild efefct	4 Moderate effect	5 Strong effect	6 Very severe effect

Additional comment(s)

Finished Stage 3, 4, 5 and 6?

With this information, the element can be added to a database for reuse.

Click to create PDf of Phase II (with reuse potential)

Click here to go to the previous sheet
(Phase I - Pre-Disassembling)

Click here to go to the next sheet
(Phase III - Re-Assembling)

Qualitative and Quantitative Assessment of the Reuse Potential of Existing Concrete

In collaboration with: TU Delft, Pieters Bouwtechniek

Filled-in by: B.R. Kamp
Graduate intern
Pieters Bouwtechniek / TU Delft

Filled-in on: 1-6-2021

Legend:
- Filled-in answer
- Result of filled-in answer(s)
- Positive effect on reuse
- Negative effect on reuse

PHASE II - Disassembling & Post-Disassembling   Output

General information about Disassembling

(Element is located in building)

Deconstruction — STAGE 3.

Preferred equipment to disconnect	5 - Diamond blade saw (saw cutting)	
Damage to element?	Almost no damage: reuse is possible	-
Accurate removal?	Partly accurate	-
Damage to (protruding) rebars?	Protruding rebars are cut	-

Transport — STAGE 4.

Method of hoisting	Chemical anchors	
Transport by road — Dimensions (w x h x l)	Within 3,0x4,0x27,0 m	'Normal' transport by road and 'normal' crane on site are possible.
Weight (G)	Less than 15.000 kg	

Storage — STAGE 5.

(element is located in building, so storage is not applicable)

Material handling — STAGE 6.

Modifications needed	Holes need to be drilled for new connection(s)

Additional comment(s) by executor: No comment(s)

Fire resistance

Damage to concrete cover?	No	
Chance of reinforcement corrosion?	Small chance of corrosion	Investigate the severity of reinforcement corrosion.
Fire resistance (revised)	60 min	The revised fire resistance is assumed to be the same as the origin (60 min).

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Reuse Potential of Phase I and II — 72,6 %

is the average Reuse Potential of Phase I & II for the element considered regarding the (), (+) and (-) uncertainty range.

Overview of (), (+) and (-) uncertainty range

The percentages of the (), (+) and (-) uncertainty ranges are based on the filled-in answers during Phase I & II.
A percentage close to 100% indicates a higher reuse potential, and vice versa.

Phase I: Pre-Disassembling	()	(+)	(-)
During Inventory (Stage 1)	74,5 %	81,0 %	72,3 %
During Performance Testing (Stage 2)	81,9 %	97,5 %	66,3 %

Phase II: Disassembling & Post-Disassembling	()	(+)	(-)	
During Deconstruction (Stage 3)	53,3 %	58,9 %	47,8 %	
During Transport (Stage 4)	75,0 %	100,0 %	50,0 %	
During Storage (Stage 5)	-	-	-	Element is located in building, so storage is not applicable
During Material Handling (Stage 6)	74,7 %	97,2 %	58,9 %	

After Phase I and II

Condition score (revised)	C_{II}	1	2	3	4	5	6
(Before Phase I and II, C_I was 3)		Excellent condition					Very bad condition
Risk score	R_{II}	1	2	3	4	5	6
(NEN 2627, 2013)		No effect					Very severe effect

Additional comment(s) by executor: No comment(s)

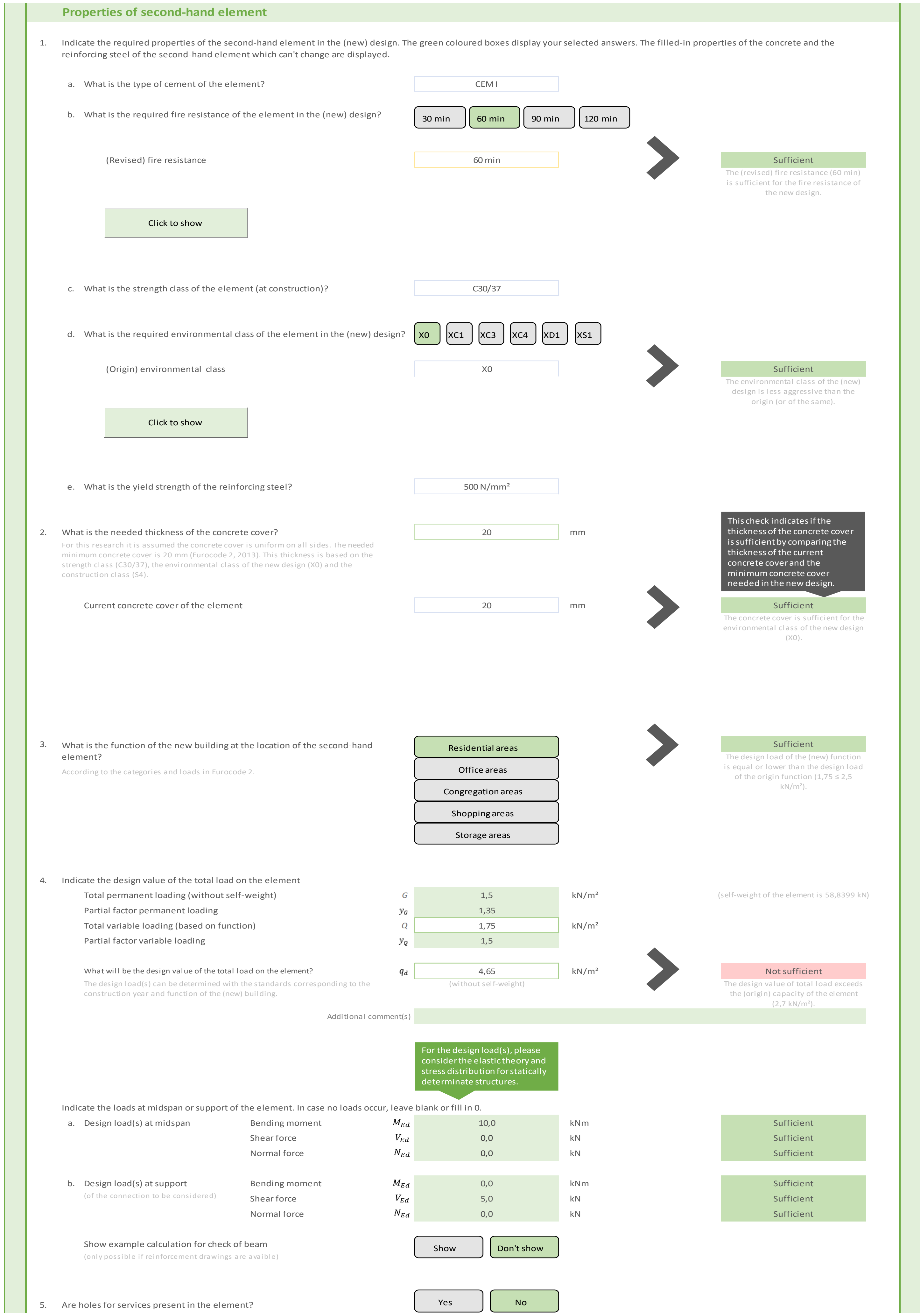
Residual lifespan

Based on design service life	SL_d	17 years
Based on condition score before deconstruction	C_I	13 years
Based on condition score after deconstruction	C_{II}	25 years

With a marge between 12,5 and 50 years (respectively - and + uncertainty of C_II).

12 Fill in Stage 7 (Construction)

When harvested (structural) elements are selected for the design of a new building, construction can start. Stage 7 investigates the requirements of the new design considering the properties of the second-hand element, as assessed in the previous stages. Assessment questions which need to be filled to consider if the second-hand element is sufficient are related to the construction year, design service life, fire resistance, environmental class, concrete cover, function, design loads, and holes for services. Next, the implementation of the second-hand element is considered with the change of function and type of reconnection, which is referred to as 're-element'. Next, the equipment to reconnect the second-hand element is analysed with relative merits, the general procedure and the adaptation of the element. This is referred to as 're-connect'. Based on a literature study, suggestions for the equipment to reconnect are made after which the executor of the Decision Support Tool can select the preferred equipment to reconnect.



Implementation of second-hand element

Re-element

1. Is it possible to change the original function of the second-hand element? — Yes, reuse slab as slab or wall

Reuse slab as slab | Reuse slab as wall

2. Type of reconnection
   a. How do you want to reconnect the second-hand element?

Slab-to-wall | Slab as wall-to-wall (vertical)
Slab-to-slab (longitudinal) | Slab as wall-to-wall (horizontal)
Slab-to-beam | Slab as wall foot joint

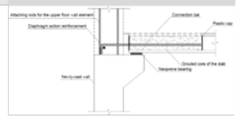
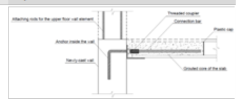
   b. What do you want to reconnect to the second-hand element?

RE-connect second-hand element to another second-hand element
RE-connect second-hand element to a newly-made element

The second-hand element is disconnected with: 5 - Diamond blade saw (saw cutting) (Stage 3: Deconstruction)
This resulted in the following damage: Protruding rebars are cut
(Stage 3: Deconstruction)

Re-connect

3. Possible options to reconnect the second-hand element are shown below.
Select the preferred equipment to reconnect (one at a time).

Option		Advantages	Disadvantages	Other
OPTION 1	Hollowed-out cores 	(+) Simple design (+) Aesthetically attractive	(-) Not suitable for further reuse (-) Not suitable for use with second-hand (-) Need to add U-voids or shear studs	Simple of putting in practice Wet joint With added (steel) provisions
OPTION 2	L-profile 	(+) Adds freedom of architectural design	(-) Not aesthetically attractive (-) Ductile joint behaviour (-) Dimensioning of L-profile needed	Medium easiness of putting in practice Wet joint With added (steel) provisions

Click to show — Overview with advantages, disadvantages and other of equipment to reconnect.

What is the preferred equipment to reconnect? — L-profile
(selected by the option buttons above)
Additional comment(s)

13 Generate output of Phase III: Opportunities

Phase III (Re-Assembling) distinguishes one stage, namely Stage 7: Construction. The output of Phase III are the opportunities of the second-hand element in the design of a new building, which is shown on the next page. The output of Phase III is generated in a PDF file that can be saved locally.

14 Time to discuss!

As described, results can be obtained at the end of each phase which outline the assessment of the reuse potential. The output is easy to understand for construction parties, which makes it a subject for discussion. Therefore, the last step of the Decision Support Tool is to discuss the implementation of a harvested (structural) element in the initial phase of a (new) building with other construction parties. This can lead to more reuse of concrete (structural) elements in the construction industry, thereby accelerating the transition towards a Circular Economy (CE).

4. What is the general procedure for the preferred equipment to reconnect?

Step 1. Break the top of the hollow cores;
Step 2. Block the ends of these hollowed-out cores with plastic caps;
Step 3. Embed anchors inside the other element and connect L-profile by tightening the nuts;
Step 4. Place second-hand element on the L-profile of the other element;
Step 5. Screw threaded couplers on the embedded anchors and nuts;
Step 6. Insert connection bars and tighten with threaded couplers;
Step 7. Grout with low-shrinkage concrete;
Step 8. The connection is achieved.

5. What needs to be done to accomplish adaptation of the second-hand element?

Break the top of the hollow cores in which the connection bars will be positioned
Block the ends of these hollowed-out cores with plastic caps to prevent the grouting concrete from spreading or pouring

Click to show — General procedure of equipment to reconnect with adaptation of second-hand element.

Finished Stage 7? — Click to create PDF of Phase III (with opportunities)

Click here to go to the previous sheet
(Phase II - Disassembling & Post-Disassembling)

Qualitative and Quantitative Assessment of the Reuse Potential of Existing Concrete

In collaboration with: TU Delft, Pieters Bouwtechniek

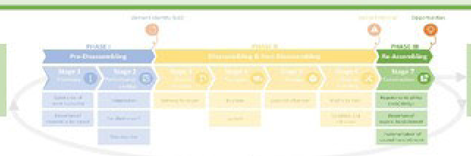
Filled-in by:	B.R. Kamp
	Graduate intern
	Pieters Bouwtechniek / TU Delft
Filled-in on:	1-6-2021

Legend:
- Filled-in answer
- Filled-in answer of Phase I & II
- Comment / advice
- Sufficient or not sufficient

PHASE III - Re-Assembling — Output

Requirements of the (new) design

(New design is not yet known)



Project name and location	Zorginstelling at Amsterdam		(10 km of element)
Additional comment(s) by executor	No comment(s)		
Function	Residential areas	›	Sufficient — The design load of the (new) function is equal or lower than the design load of the origin function (1,75 ≤ 4 kN/m²).
Construction year	2022	›	Sufficient — Element is available since 2021 (stored for 1 year(s)).
Reference service life	50 years	›	Not sufficient — The reference service life exceeds the residual lifespan of the element (based on residual lifespan of 17 years). Advice: strenghten element.

Properties of the second-hand element

Type of cement	CEM I		
Strength class	C30/37		
Environmental class	X0	›	Sufficient
	The environmental class of the (new) design is less aggressive than the origin (or of the same).		
Concrete cover c_{nom}	20 mm	›	Sufficient
	The concrete cover is sufficient for the environmental class of the new design (X0).		
Fire resistance	60 min	›	Sufficient
	The (revised) fire resistance (60 min) is sufficient for the fire resistance of the new design.		
Holes for services	Not present		

Design load(s)

			(new design)	(origin)	
Design value of total load		q_d	4,7 kN/m²	2,7 kN/m²	Not sufficient
Additional comment(s) by executor			No comment(s)		
At midspan	Bending moment	M_{Ed}	10,0 kNm	393,9 kNm	Sufficient
	Shear force	V_{Ed}	0,0 kN	0,0 kN	Sufficient
	Normal force	N_{Ed}	0,0 kN	0,0 kN	Sufficient
At support	Bending moment	M_{Ed}	0,0 kNm	0,0 kNm	Sufficient
	Shear force	V_{Ed}	5,0 kN	1109,1 kN	Sufficient
	Normal force	N_{Ed}	0,0 kN	0,0 kN	Sufficient

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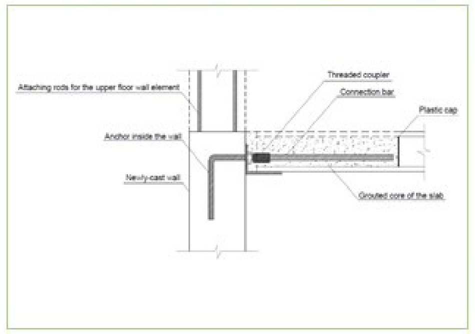
Implementation of the second-hand element

RE-element	
Change of function	Yes, reuse slab as slab or wall
(Protruding) rebars?	Protruding rebars are cut
RE-connect second-hand element	to another second-hand element
Type of RE-connection	Slab-to-wall
Preferred equipment to reconnect	L-profile

Illustration of preferred equipment to reconnect



Advantages	Disadvantages	Other
(+) Adds freedom of architectural design	(-) Not aesthetically attractive	Wet joint
	(-) Ductile joint behaviour	With added (steel) provisions
	(-) Dimensioning of L-profile needed	Medium easiness of putting in practice

General procedure for preferred equipment to reconnect: L-profile

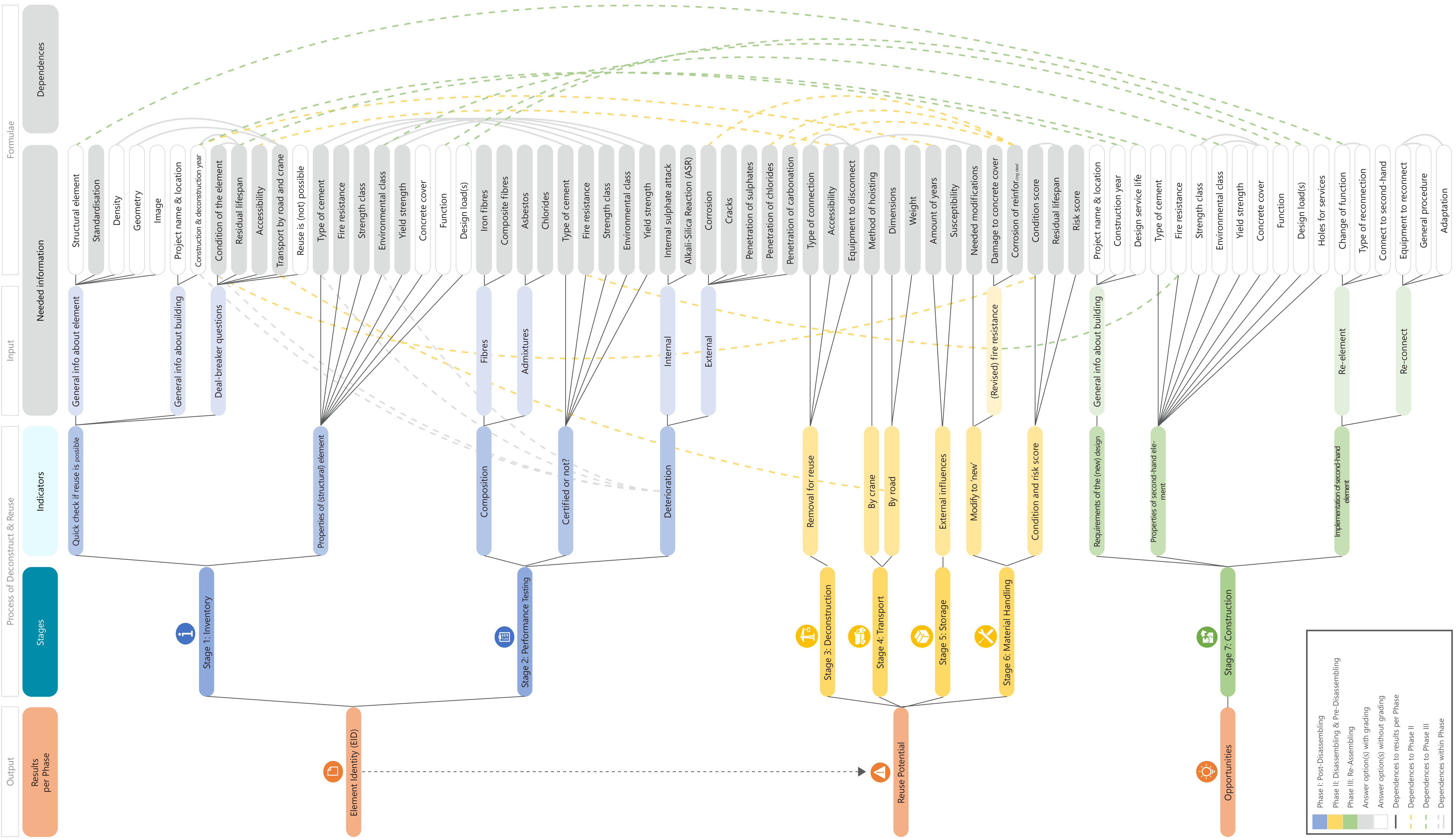
Step 1. Break the top of the hollow cores;
Step 2. Block the ends of these hollowed-out cores with plastic caps;
Step 3. Embed anchors inside the other element and connect L-profile by tightening the nuts;
Step 4. Place second-hand element on the L-profile of the other element;
Step 5. Screw threaded couplers on the embedded anchors and nuts;
Step 6. Insert connection bars and tighten with threaded couplers;
Step 7. Grout with low-shrinkage concrete;
Step 8. The connection is achieved.
-

Adaptation of second-hand element according to preferred equipment to reconnect: L-profile

Break the top of the hollow cores in which the connection bars will be positioned
Block the ends of these hollowed-out cores with plastic caps to prevent the grouting concrete from spreading or pouring out
-
-
-
-
-
-
-

Additional comment(s) by executor: No comment(s)

Figure 8.2: Graphical representation of dependences relating to the reuse potential of harvested (structural) elements made of concrete (own figure).



9 | Validity of Final Version

Validity refers to the validation and verification of the Decision Support Tool, which is carried out with the preliminary versions and final version. This section analyses the validity of the final version of the Decision Support Tool. In Section 9.1, validation is carried out with a test-case which is executed by experts. In Section 9.2, verification is carried out according to the specifications of the Decision Support Tool, as described in Section 2.4. Lastly, the results of the validation and verification are summarized in Section 9.3.

9.1 Validation

Validation refers to the process to assure that the Decision Support Tool represents reality to a sufficient level of accuracy. Validation of the final version of the Decision Support Tool is carried out with a test-case. In this section, the test-case is executed by experienced structural engineers where the test-case executed by the researcher serves as a reference (subsection 8.2.1.3). In subsection 9.1.1, the execution of the test-case by experts is described. Therefore, the results of the test-case, the feedback of the experts and the overall vision of the experts are analysed in the subsections. The goal of this section is to validate the Decision Support Tool regarding the use in practice.

9.1.1 Test-case executed by experts

In total, the test-case is executed by five experienced structural engineers. During each individual execution, the process of 'Deconstruct & Reuse' was briefly introduced. After the introduction, the executors were provided with a general description of the test-case which can be found in Appendix E. Next, the Decision Support Tool was shown to each executor to give a first impression of the assessment of the reuse potential. If there were no questions about the test-case or assessment, the executor could start the execution of the Decision Support Tool. During execution, each executor gave feedback regarding the assessment of the reuse potential. At the end of the individual executions of the test-case, each executor was asked to give an overall vision on the Decision Support Tool based on two additional questions.

9.1.1.1 *Results of the test-case*

As described, all filled-in answers are graded resulting in output per phase. An overview of the filled-in answers and corresponding grading of the test-case executed by the researcher and the five experienced structural engineers can be found in Figure H.1, Figure H.2 and Figure H.3. Only Phase I and Phase II are considered for the results, because Phase III consists of many open-ended questions resulting in varying answers filled-in. This section analyses the filled-in answers and the output of Phase I and II of the five experienced structural engineers in accordance with the reference test-case. In order to draw a conclusion considering the results of the test-case in Appendix H.2, four points of attention are addressed.

Firstly, some of the gradings per indicator differ for Phase I and Phase II, as indicated in the last column in Figure H.1, Figure H.2 and Figure H.3. For Stage 1 (Inventory), the largest difference is found for the 'deal-breaker questions'. Considering the filled-in answers, this can be assigned to the technical questions of the condition score (and corresponding residual lifespan) and to the accessibility of the connection. Other significant differences are found for the 'properties of the structural element to be reused'. This can be assigned to the filled-in 'unknown' answers of some of the executors. As a result, varying answers are filled in for the 'certification' of the properties in Stage 2 (Performance Testing). Additionally, some of the executors believed certification of the properties can be done with existing information by drawings resulting in varying answers filled-in. For Stage 2, the differences of the 'composition' and 'deterioration' can be assigned to unfamiliarity of the assessment questions. For Stage 3 (Deconstruction), significant differences are found for the 'removal for reuse'. Considering the filled-in answers, this can be assigned to the type of connection and to the accessibility of the connection (Stage 1). For Stage 4 (Transport) and Stage 5 (Storage) no significant differences were found. For Stage 6 (Material Handling), significant differences are found for the condition and risk score. This can be assigned to varying interpretations of the answer options of NEN 2767 [2013]. In conclusion, the significant differences of the filled-in answers of Phase I and Phase II can be assigned to 'unknown' answer option(s), unfamiliarity of the indicator(s) or the formulation of the assessment questions with relating answer options.

Secondly, the assessment questions with relating answer options are differently interpreted by the executors. Definitions to be considered are the significant differences as mentioned above together with 'geometry' (Stage 1), 'design loads' (Stage 1 and Stage 7) and 'first and second signature below Element Identity (EID)' (Stage 1). Additionally, it should be taken into account that some of the definitions are easily understood by structural engineers, but can be misunderstood by other parties (e.g. client of a project) which complicates the execution leading to (more) skewed results. For further development of the Decision Support Tool, the definitions of the assessment questions and relating answer options can be re-formulated or clarified with images.

Thirdly, the explanation of grading in answer options about what leads to a positive (1) or negative (0) effect on the reuse potential can be questioned. The execution of the test-case shows that displaying the grading to the executors in some cases lead to selecting an answer option with a (more) positive effect on the reuse potential. However, not displaying the grading to the executors can lead to different interpretations. For further development of the Decision Support Tool, the effect of (not) displaying the grading to the executors can be analysed.

Lastly, the output of the test-case executed by the researcher and the five experienced structural engineers is compared, where the test-case executed by the researcher serves as a reference (subsection 8.2.1.3). The chart in Figure 9.1 shows the reuse potential and range of uncertainty per Stage, where the (+) uncertainty is indicated in green and the (-) uncertainty in red. The percentages of the reuse potential show and range of uncertainty show that no significant differences occur in the output of the reference and the five experts. The percentages which relate to the output can be found in Figure 9.2, where the last column indicates the largest difference between the reference and the five experts. The difference is calculated per Stage for the reuse potential and the range of uncertainty. The percentages per Stage result in the reuse potential after Phase I and II, as indicated on the right of Figure 9.1 and in the last row of Figure 9.2. Based on the percentages of the reuse potential after Phase I and II, it can be concluded no significant differences occur to the results of the test-case.

In conclusion, the analysis of the filled-in answers of all executors and the output of the executions in accordance with the reference test-case indicate that the Decision Support Tool can be executed generating unambiguous and comparable results. Significant differences of the filled-in answers can be assigned to 'unknown' answer option(s), unfamiliarity of the indicator(s) or the formulation of the assessment questions with relating answer options leading to different interpretations. For further development of the Decision Support Tool, re-formulating can be considered. Additionally, the effect of (not) displaying the grading to the executor(s) can be analysed. The results are further explored in the specifications of the Decision Support Tool (Section 9.2).

Figure 9.1: Comparison of the reuse potential and range of uncertainty of the test-case executed by the researcher and the five experts per Stage. Percentages can be found in Figure 9.2 (own figure).

		Reference by researcher	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Difference to reference
Phase I: Pre-Disassembling								
Stage 1 (Inventory)	()	74,5%	75,5%	72,4%	74,5%	70,3%	60,4%	14,1%
	(+)	81,0%	79,8%	81,0%	81,0%	76,8%	62,5%	18,5%
	(-)	72,3%	75,5%	68,1%	71,0%	63,9%	58,3%	14,0%
Stage 2 (Performance Testing)	()	81,9%	87,5%	72,9%	57,5%	71,8%	52,5%	29,4%
	(+)	97,5%	97,5%	92,5%	72,5%	87,5%	67,5%	30,0%
	(-)	66,3%	77,5%	50,0%	42,5%	51,3%	37,5%	28,8%
Phase II: Disassembling & Post-Disassembling								
Stage 3 (Deconstruction)	()	53,3%	45,0%	46,7%	53,3%	53,3%	38,3%	15,0%
	(+)	58,9%	50,6%	52,2%	58,9%	58,9%	43,9%	15,0%
	(-)	47,8%	39,4%	41,1%	47,8%	47,8%	32,8%	15,0%
Stage 4 (Transport)	()	75,0%	75,0%	75,0%	75,0%	75,0%	75,0%	0,0%
	(+)	100%	100%	100%	100%	100%	100%	0,0%
	(-)	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	0,0%
Stage 5 (Storage)	()	-	-	-	-	-	-	0,0%
	(+)	-	-	-	-	-	-	0,0%
	(-)	-	-	-	-	-	-	0,0%
Stage 6 (Material Handling)	()	74,7%	74,7%	70,6%	60,3%	74,7%	60,3%	14,4%
	(+)	97,2%	97,2%	93,1%	76,1%	97,2%	76,1%	21,1%
	(-)	58,9%	58,9%	54,7%	44,4%	58,9%	44,4%	14,5%
Reuse Potential after Phase I and II	()	71,9%	71,5%	67,5%	64,1%	69,0%	57,3%	14,6%
	(+)	86,9%	85,0%	83,8%	77,7%	84,1%	70,0%	16,9%
	(-)	59,0%	60,3%	52,8%	51,1%	54,4%	44,6%	14,4%
Average reuse potential		**72,6%**	**72,3%**	**68,0%**	**64,3%**	**69,2%**	**57,3%**	**15,3%**

Figure 9.2: Percentages of the reuse potential and range of uncertainty of Figure 9.1. The last column indicates the largest difference between the test-case executed by the researcher (reference) and the five experts (own figure).

9.1.1.2 *Feedback of the experts*

During the test-case executed by five experienced structural engineers, the process of 'Deconstruct & Reuse' is discussed based on the final version of the Decision Support Tool. An overview of the feedback on the test-case is shown on page 176, page 177 and page 178 (A3 format). The overview is ordered in Phase I, Phase II, Phase III, output and general. In order to draw a conclusion considering the feedback of the test-case, points of attention are addressed for remarks, opportunities, challenges and further research. Table 9.1 and Table 9.2 outline the most important remarks, opportunities, challenges and further research.

Table 9.1: Received feedback of the test-case with experts considering the final version of Decision Support Tool [1/2]

Points of attention
Remarks • The executors found the Graphical User Interface (GUI) clear, especially the colours and images to explain answer options were found to be insightful; • The executors considered the assessment of the reuse potential to be a step towards circularity in the construction industry; • The assessment includes all information needed to assess the reuse potential. However, some indicators were questioned whether they were necessary; • The input and output of the Decision Support Tool are easy to understand for structural engineers, but require structural knowledge; • The assessment can be improved regarding the formulation of the assessment questions and relating answer options. Additionally, some answer options can be expressed differently (e.g. in percentage); • Unfamiliarity of assessment questions results in unknown answer options and skewed results due to the range of uncertainty. However, these questions create awareness about the risks for reuse and are thus important for the assessment. • Adding more answer options for additional comment(s) by the executor (e.g. at the end of each Phase) can be a solution to the above-mentioned issue. Additionally, for some indicators suggestions were made to add more answer options. However, most of the suggestions concern the scope limitations of the research and are thus part of further research. • All executors want to know where a filled-in answer is used for and to understand how the results are generated (e.g. especially if a combination of information is used); • The needed information to answer assessment questions can depend on other parties which can hinder the execution of the Decision Support Tool. It is suggested to further research the legal liabilities, warranties and responsibilities of reuse; • The reuse of concrete (structural) elements also depends on indicators that are out of the scope of this research (e.g. economic value in practice).
Opportunities • The Decision Support Tool can automatically determine answers by integrating (current) standards. Additionally, it can be convenient to integrate (regular) inspections in the assessment or to link the condition and risk score to a maintenance plan; • The input of the Decision Support Tool can be linked to BIM (Building Information Models) to automatically generate the output. If, for all new and harvested (structural) elements the needed information of the assessment questions is documented during its service life, the reuse potential can be easily determined; • Investigate different circularity strategies in the output. Currently, the percentages of the output make it only possible to compare the reuse potential of different elements.

Table 9.2: Received feedback of the test-case with experts considering the final version of Decision Support Tool [2/2]

Points of attention
Challenges • Speculation of the answer occurs in case information is lacking. This results in a range of uncertainty and skewed results of the percentages of the reuse potential after Phase I and II; • Investigate what can be done to improve the reuse potential; • Investigate from what percentage reuse is not recommended; • Investigate if a reuse potential close to 0% results in higher costs to enable reuse.
Further research • Extending the Decision Support Tool for buildings as a whole, for multiple connections, for other (concrete) elements and materials; • Link Decision Support Tool to a database to combine the supply and demand of harvested (structural) elements with a Dynamic Final Design (in Dutch: Dynamisch Definitief Ontwerp (DDO)); • Investigate the integration of (current) standards, (regular) inspections or maintenance plans to the assessment (see opportunities). A lot of the other options for further research in the overview on page 178 concern scope limitations of this research; • Phase I and II determine if reuse is possible according to the reuse potential. These phases should be applied at the start of demolition or deconstruction. Phase III supports the decisions of a structural engineer about the implementation in a (new) design which comes year(s) later. At that time, a structural engineer is probably already involved giving his or her twist to the design of connections and calculations. Therefore, Phase III can be considered separately (e.g. with design strategies); • The current added value in practice is in Phase I and II, especially in the deal-breaker questions. For further research the first draft of Phase III can be extended. • Adding more indicators (especially liabilities, economic value in practice and advantages of reuse).

9.1.1.3 *Overall vision of the experts*

At the end of the execution of the test-case, each executor was asked to give a vision on the Decision Support Tool based on two additional questions. In this section, the findings of the provided visions are analysed.

> *Can the Decision Support Tool add value in practice to reuse more concrete (structural) elements in the construction industry?*

The Decision Support Tool assesses the reuse potential of harvested (structural) elements reaching their end of life cycle. All executors considered the assessment of the reuse potential to be a step towards circularity in the construction industry, because the assessment of the reuse potential was new to all executors which creates awareness. However, the reuse and implementation of such elements in a new design mainly depend on the fact if the client of a project is willing to consider reusing concrete (structural) elements. In the design phase of a project, a structural engineer can advise the client and change the design requirements. This can be realized by for example offering the Decision Support Tool as an extra service to the client or by making it mandatory.

Since the output is relatively easy to understand, the output can be discussed with other parties which can lead to more reuse of concrete (structural) elements. Thereby, the output motivates towards (more) circularity in the construction industry which enhances the chance that the assessment will be used in practice. Additionally, the assessment includes all information required to reuse (structural) elements made of concrete. Moreover, the process of 'Deconstruct & Reuse', the Graphical User Interface (GUI) and the unambiguous and comparable results make it likely that the Decision Support Tool will be used in practice to test the reuse potential of an element. However, the feedback of the test-case (subsection 9.1.1.2) and the specifications of the Decision Support Tool (Section 9.2) should be taken into account.

> *Would you make use of the Decision Support Tool or recommend it to others?*

All executors answered: yes! The Decision Support Tool makes it is possible to get a first indication of the reuse potential of a harvested (structural) element made of concrete. As shown in validation (subsection 9.1.1.2), especially the deal-breaker questions were found to be useful to check if reuse is possible. In addition, the Decision Support Tool makes it is possible to get advice on the implementation of a second-hand element in a (new) design. Since every structural engineer gives his or her twist to the design of connections and calculations, the first draft of Phase III can be extended (subsection 9.1.1.2).

The Decision Support Tool offers support to the process of 'Deconstruct & Reuse' and can be executed in a relatively quick manner. Additionally, the Decision Support Tool is easy to execute by the Graphical User Interface (GUI), even if an executor has no prior knowledge. Especially the quick checks which indicate the positive or negative effects on the reuse potential with colours were found to be insightful. One of the executors suggested that the process of 'Deconstruct & Reuse' is also relevant for building owners and contractors because they are reached out to for demolition. However, the Decision Support Tool is set up for structural engineers which means some assessment questions require basic structural knowledge.

9.2 Verification

Verification refers to the process to assure that the Decision Support Tool is correct and works as designed for [Van Berlo, 2019]. In order to analyse this, the specifications of the Decision Support Tool (Table 2.1) are discussed with the executors of the test-case. The feedback in conformance with the specifications is shown in Table 9.3.

Table 9.3: Conformance with the specifications of the Decision Support Tool, described in Table 2.1.

Subject	Description
Practical guideline	The assessment of the reuse potential is made operational in the Decision Support Tool. • The Decision Support Tool makes it is possible to get a first indication of the reuse potential of a harvested (structural) element made of concrete. • The Decision Support Tool makes it is possible to get advice on the implementation of a second-hand element in a (new) design.
End-user	The Decision Support Tool is set up from the pioneering role of structural engineers. • The end-user of the Decision Support Tool is considered to have basic structural knowledge to answer some assessment questions.
Execution	The Decision Support Tool can be executed in a relatively quick manner. • Some assessment questions require structural knowledge, which means not all parties can execute the Decision Support Tool in a relatively quick manner. The 'unknown' answer options and explanations deal with this issue; • The needed information to answer some assessment questions depends on other parties which can hinder the execution of the Decision Support Tool. Preferably one party can properly answer all assessment questions of the Decision Support Tool and assess the reuse potential.
Software design	The Decision Support Tool is set up in Excel with a Graphical User Interface (GUI). • The Decision Support Tool is easy to execute by the Graphical User Interface (GUI), even if an executor has no prior knowledge. Additionally, the output is relatively easy to understand which increases the chance that the assessment will be used in practice. • Other software (in 3D) can be considered for further research, because some remarks are missing due to limitations of Excel (analysed in subsection 9.1.1.2, e.g. linking to database). • Excel makes the Decision Support Tool easily alterable for further developments, because assessment questions or indicators can be easily changer or added to Excel.
Results	The Decision Support Tool can be uniformly executed generating unambiguous and comparable results in the form of a final score for the reuse potential. • Figure 9.1 showed that all executors of the test-case were able to generate the same results, which makes the Decision Support Tool unambiguous. • Validation (subsection 9.1.1.1) showed that the Decision Support Tool gives skewed results if information is lacking, because each executor might handle lacking information differently depending on the knowledge and experience. Therefore, the Decision Support Tool depends on the availability of existing information. The fixed answer options, 'unknown' answer options, explanations and range of uncertainty deal with this issue. However, as analysed in subsection 9.1.1.1, there is still some room for an executor's judgement which means the output can only be interpreted as advice.; • The results of the Decision Support Tool make it easy to compare the reuse potential of different elements, especially after Phase I and II where the reuse potential is allocated in percentages per Stage. This final score makes it easy to discuss with other parties; • The Fuzzy calculation with the grading and range of uncertainty makes the assessment of the reuse potential rational.

9.3 Results of validation and verification

Validity refers to the validation and verification of the Decision Support Tool. Validation of the final version has been carried out by a test-case executed by the researcher and by five experienced structural engineers. With the test-case executed by the researcher (subsection 8.2.1.3), the front-end and back-end of the Decision Support Tool have been analysed. Additionally, this test-case served as a reference for the test-case executed by the experienced structural engineers. In subsection 9.1.1, the results of the test-case, feedback of the experts and overall vision of the experts have been analysed. Next, verification of the final version has been carried out by discussing the specifications of the Decision Support Tool with the experts (Section 9.2). The results of the validation and verification of the Decision Support Tool are concluded in this section. The most important results are summarized in Figure 9.3.

Firstly, the analysis of the filled-in answers of all executors and the output of the executions in accordance with the reference test-case has indicated that the Decision Support Tool can be executed generating unambiguous results. Significant differences of the filled-in answers can be assigned to 'unknown' answer options, unfamiliarity of the indicators or the formulation of the assessment questions with relating answer options leading to different interpretations. For further development of the Decision Support Tool, re-formulating the significant differences and the effect of (not) displaying the grading to the executor(s) can be considered. Additionally, the Decision Support Tool gives skewed results in case information is lacking. The fixed and 'unknown' answer options, explanations and range of uncertainty deal with this issue. However, the Decision Support Tool ultimately depends on the judgement of the executor. Therefore, the output can only be interpreted as advice and it is recommended to analyse further the processing of lacking information. Furthermore, the Decision Support Tool generates comparable results, especially after Phase I and II where the reuse potential is allocated in percentages per Stage. Additionally, the final score of the reuse potential makes it easy to understand and discuss with other parties which can lead to more reuse of concrete (structural) elements in the construction industry. Additionally, the interpretation of the reuse potential can be clarified with recommendations to improve the percentage.

Secondly, the feedback of the experts indicate that the assessment includes all information required to reuse (structural) elements made of concrete. Especially the displaying of the positive and negative effects on the reuse potential in the Graphical User Interface (GUI) was found to be clarifying during execution. Other feedback has been subdivided in remarks, opportunities, challenges and further research. *Remarks* include the unfamiliarity of the indicators about composition, certification and deterioration (Stage 2). However, these indicators create awareness about the risk for reuse and are thus important for the assessment. *Opportunities* are the integration of (current) standards, (regular) inspections or maintenance plans to the assessment to automatically determine answers. Additionally, the input of the Decision Support Tool can be linked to 3D models (BIM) to automatically assess the reuse potential of harvested (structural) elements. If, for all new and existing buildings the needed information of the assessment questions is documented during its service life, the output can be easily generated. The Decision Support Tool can also be linked to a database to combine the supply and demand of harvested (structural) elements. As described, *challenges* are the processing of lacking information resulting in skewed results. Additionally, needed information to answer some assessment questions depends on other parties which can hinder the execution of the Decision Support Tool. Therefore, it is suggested to *further research* the legal liabilities, warranties and responsibilities. Additionally, the reuse of concrete (structural) elements can depend on indicators that are out of the scope of this research. For example, the economic value in practice can be investigated by analysing if a reuse potential close to 0% results in higher costs to enable reuse. Furthermore, the assessment can be extended for buildings as a whole, for multiple connections, for other (concrete) elements and materials.

Thirdly, the added value of the Decision Support Tool in practice is analysed based on the overall vision of the five experienced structural engineers. It was found that the assessment of the reuse potential was new to all executors. By guiding the executors through the process of 'Deconstruct & Reuse' in the Decision Support Tool, awareness was created. The input of the Decision Support Tool is easy to execute by the Graphical User Interface (GUI), and the output in the form of a PDF is relatively easy to understand. This means the Decision Support Tool can be discussed with other parties which can lead to more reuse of concrete (structural) elements in the construction industry. Additionally, structural engineers can advise the client about the use of second-hand elements instead of new elements in the construction, by offering the Decision Support Tool as an extra service. Especially during the initial phase, where structural engineers have the greatest potential to affect the design of a new building due to big decisions being made (Section 3.2). Additionally, the guidance through the process of Deconstruct & Reuse makes it possible to generate unambiguous and comparable results in the Decision Support Tool (subsection 9.1.1.1). The guidance through the input, output and formulae of the Decision Support Tool makes it likely that the assessment will be used in practice to test the reuse potential of an element. Moreover, the Fuzzy calculation which includes the grading and range of uncertainty makes the assessment of the reuse potential rational for use in practice. The vision of the experts also showed that all executors would make use of the Decision Support Tool and recommend it to others. Therefore, it can be stated that the Decision Support Tool is a step towards circularity in the construction industry. However, for use in practice the feedback of the test-case of the Decision Support Tool (Section 9.2) should be taken into account, as described in subsection 9.1.1.2.

Next to the validation, verification of the final version has been carried out. Verification has shown that the Graphical User Interface (GUI) makes the assessment easy to execute. Additionally, the assessment can be executed in a relatively quick manner by structural engineers. However, some assessment questions require structural knowledge which can make it difficult to execute the Decision Support Tool for other parties. The unknown answer options and explanations deal with this issue, but for further research the execution of the Decision Support Tool can be made more accessible for other parties. This research is the first method to scientifically assess the reuse potential of a harvested (structural) element made operational in a Decision Support Tool, based on extensive literature study, interviews and a case-study. Therefore, more research is recommended which is described in Chapter 12: Recommendations.

Figure 9.3: Overview of the results of the validity of the final version of the Decision Support Tool (own figure).

10 | Conclusion

The main research objective of this research as stated in Section 2.1:

> *to qualitatively and quantitatively assess the reuse potential of harvested elements of existing concrete structures in such a way to allow structural engineers to make use of these elements in the design of new buildings.*

In order to reach the main research objective, a total of three sub-research questions have been formulated in Section 2.2. This Chapter firstly provides answers to each sub-research question in Section 10.1. Subsequently, the main research question is answered in Section 10.2.

10.1 Sub-research questions

> *1. Which phases and indicators of the process of Deconstruct & Reuse affect the reuse potential of harvested concrete (structural) elements in the design of new buildings?*

In Chapter 3 and Chapter 4, the answer can be found for this sub-question.

The definitions of Deconstruct & Reuse have been analysed from the point of view of structural engineers. Deconstruct means it is technically feasible and viable to recover the residual value of harvested elements of existing (to-be-demolished) structures. Reuse is an operation by which a product, its components or materials can be used again for the same purpose/function for which they were conceived. Following these definitions, the process of Deconstruct & Reuse aims to assess the reuse potential, which is the possibility to reuse a harvested concrete (structural) element in the design of a new building.

For this research, the process of Deconstruct & Reuse is set up from the point of view of structural engineers with an extensive literature study, interviews and a case-study. Thus, the process of Deconstruct & Reuse has been subdivided into three phases. Here, Deconstruct is represented by Phase I (Pre-Disassembling) and Phase II (Disassembling & Post-Disassembling), and Reuse by Phase III (Re-Assembling). Next, the three phases of the process of 'Deconstruct & Reuse' have been subdivided into indicators that affect the reuse potential of harvested concrete (structural) elements in the design of new buildings. The indicators consist of a quick check if reuse is possible and considers information about the element to be reused (composition, deterioration, properties and related certification). Additionally, the removal for reuse and transport by crane and by road need to be considered. Other indicators required for reuse are the modifications and the condition of the second-hand element. Moreover, the requirements and the implementation of a harvested (structural) element in the design of a new building affect the reuse potential.

Next, all indicators have been arranged in seven Stages where Phase I distinguishes (1) Inventory and (2) Performance Testing; Phase II distinguishes (3) Deconstruction, (4) Transport, (5) Storage and (6) Material Handling and Phase III distinguishes (7) Construction. An overview of the phases, stages and indicators which affect the reuse potential of harvested concrete (structural) elements in the design of new buildings is shown in Figure 3.7.

2. How to assess the reuse potential of harvested concrete (structural) elements in the design of new buildings based on the indicators of the process of Deconstruct & Reuse?

In Chapter 5, Chapter 6 and Chapter 7, the answer can be found for this sub-question.

As described in the problem definition (Section 1.3), none of the existing methods takes into account the process of 'Deconstruct & Reuse'. Additionally, analysed gaps of the existing methods state that a practical guideline to assess the reuse potential of harvested concrete (structural) elements in the design of new buildings is currently missing. Therefore, this research has made the assessment of the reuse potential of harvested (structural) elements operational in a Decision Support Tool.

The indicators of the process of 'Deconstruct & Reuse' have been written into assessment questions. The needed information to answer each assessment question has been analysed in combination with how this information can be retrieved during the process of 'Deconstruct & Reuse'. The retrieved information per assessment question is translated in answer options in the Decision Support Tool. Next, a Fuzzy calculation is assigned to all answer options with the use of grading and a range of uncertainty. This means each answer option has been assigned any number between 0 and 1, where 1 stands for the most favourable value regarding the reuse potential of an element. An overview of the grading and range of uncertainty per answer option can be found in Appendix G, which has been determined with extensive literature study and the interpretation of experts and the researcher. If all assessment questions of a Stage of the process of 'Deconstruct & Reuse' are answered in the Decision Support Tool, the Fuzzy calculation has made it possible to determine percentages for the reuse potential per Stage. Additionally, at the end of each phase a final score and the related risks and advises are addressed.

3. How can the Decision Support Tool add value in practice?

In Chapter 8 and Chapter 9, the answer can be found for this sub-question.

The assessment of the reuse potential of harvested concrete (structural) elements in the design of new buildings has been made operational in the Decision Support Tool. Besides indicating if reuse of a harvested (structural) element made of concrete is possible, the Decision Support Tool advises on the implementation of a second-hand element in a (new) design. Preliminary versions of the Decision Support Tool have been validated by conducting interviews throughout the research resulting in the development of the Decision Support Tool. The most valuable improvements which make the Decision Support Tool useful in practice have been the distinction of main and side information, the extension with more information, the enhancement of formulations and the development of the Graphical User Interface (GUI). All feedback has been processed in the preliminary versions of the Decision Support Tool, resulting in the final version which has been verified and validated with a test-case regarding the added value in practice.

The validity of the Decision Support Tool showed that the assessment includes all information required to reuse (structural) elements made of concrete. By guiding the executors through the process of 'Deconstruct & Reuse' in the Decision Support Tool, awareness is created about the positive and negative effects on the reuse potential. Additionally, the input is easy to execute by the Graphical User Interface (GUI) and the assessment can be executed in a relatively quick manner by structural engineers.

The Decision Support Tool can be uniformly executed generating unambiguous results, making the output easy to understand. Moreover, the Fuzzy calculation with the grading and range of uncertainty makes the assessment of the reuse potential rational for use in practice. The guidance through the input, output and formulae of the Decision Support Tool makes it likely that the assessment will be used in practice to test the reuse potential of an element. Furthermore, the Decision Support Tool generates comparable results of the reuse potential which makes the output easy to understand and discuss with other parties which can lead to more reuse of concrete (structural) elements in the construction industry. Additionally, structural engineers can advise the client about the use of second-hand elements instead of new elements in the construction, by offering the Decision Support Tool as an extra service. Especially during the initial phase, structural engineers have the greatest potential to affect the design of a new building due to big decisions being made.

10.2 Main research question

How can the reuse potential of harvested (structural) elements of the existing concrete building stock be assessed to allow structural engineers to make use of these elements in the design of new buildings?

This research proposes an assessment of the reuse potential based on the process of 'Deconstruct & Reuse' which has been made operational in the Decision Support Tool. By executing the Decision Support Tool, it is made possible to determine percentages for the reuse potential per Stage. The validity of the Decision Support Tool has pointed out that the assessment has a high practical value as it stimulates the reuse of concrete elements through an operational method. Therefore, the assessment of the reuse potential is considered to be a step towards circularity in the construction industry. However, for use in practice, several remarks and opportunities can be made. Firstly, the Decision Support Tool depends on the judgement of the executor, and so the output can only be interpreted as advice. Secondly, the validity of the Decision Support Tool showed that skewed results can occur due to unfamiliarity, sensitivity and lacking information to answer assessment questions. The fixed and 'unknown' answer options, explanations and range of uncertainty deal with this issue. However, the required information to execute the Decision Support Tool can depend on other parties. Therefore, it is suggested to further research the legal liabilities, warranties and responsibilities for the reuse of concrete (structural) elements. Thirdly, the economic value needs to be investigated for use in practice by analysing if a reuse potential close to 0% results in higher costs to enable reuse.

Opportunities of the assessment are the extension for buildings as a whole, for multiple connections, for other (concrete) elements and materials. Additionally, the assessment can integrate (current) standards, (regular) inspections or maintenance plans to automatically determine answers. The input of the Decision Support Tool can be linked to a database to combine the supply and demand of harvested (structural) elements. The input can also be linked to 3D models (BIM) to automatically assess the reuse potential of harvested (structural) elements. If, for all new and existing buildings the required information to assess the reuse potential is documented during its service life, the output of the Decision Support Tool can be easily generated which stimulates the reuse of concrete.

11 | Discussion

In this Chapter, the relevance and limitations of this research are discussed resulting in suggestions for further research.

11.1 Research relevance

The *'Transition Agenda'* in the Netherlands aims to accelerate the transition of the building sector towards a Circular Economy (CE). The ambitions for 2030 and 2050 are to reach 50% and 100% respectively of the final objective to be fully circular. However, the opportunities of circularity in the construction industry remain difficult to implement. By considering the design process of the Circular Economy, this research focuses on the elimination of residual waste and the different ways of dealing with raw materials. Thus, this research helps parties in the building sector achieve the goals of 2030 and 2050. Additionally, this research contributes to the Sustainable Development Goals (SDG), which have been drawn up by the United Nations, specifically the fifth target of SDG12. This target ensures sustainable consumption and production patterns by reducing waste generations through prevention, reduction, recycling and reuse (United Nations, 2018).

The process of 'Deconstruct & Reuse' is investigated in this research. Since none of the existing methods takes into account all indicators, this research combines existing methods and adds new ones to assess the reuse potential. Based on extensive literature study, interviews with experienced structural engineers and a case-study, the selected indicators provide relevant information needed for the process of 'Deconstruct & Reuse'. However, for some of the selected indicators theoretical research and practical experiences were lacking. With the interpretation of experts and the researcher, a first draft to fill these research gaps is investigated which is further explored in subsection 11.2.1. Additionally, analysed gaps of the existing methods state that a practical guideline to assess the reuse potential of harvested concrete (structural) elements in the design of new buildings is missing. Therefore, this research has made the assessment of the reuse potential of a harvested (structural) element operational in a Decision Support Tool, which has a high practical value as it stimulates the reuse of concrete elements through an operational method. The insights and output of the Decision Support Tool can easily be discussed with other parties. Thus, the Decision Support Tool creates awareness which makes it more likely (structural) elements will be reused.

This research is the first method to scientifically assess the process of 'Deconstruct & Reuse' in a Decision Support Tool. The assessment of the reuse potential is considered to be a step towards circularity in the construction industry, especially for structural engineers who have a pioneering role in making reuse possible.

11.2 Research limitations

Next to the scope limitations (Section 2.4), limitations of the research were encountered by the researcher and the five experienced structural engineers during validation and verification.

- *Interpretation of experts and the researcher due to literature gap*
  Due to the lack of theoretical research and practical experiences, parts of the following indicators are analysed with the interpretation of experts and the researcher. A first draft to fill these research gaps is investigated, but more research to gain knowledge and experiences is required.
  - *Quick check if reuse is possible (Stage 1)*
    The deal-breaker questions are based on interviews with structural engineers (e.g. calculation of condition score based on technical questions). For further research, interviews can be conducted with experts from other fields resulting in a more complete list of the indicators as well as more information in depth.
  - *Equipment to disconnect (Stage 3)*
    A suggestion for the equipment to disconnect is given regarding the reuse of an element and related damaging of the element. This is based on the advantages and disadvantages extracted from a literature study as well as the interpretation of experts and the researcher. After the suggestion, the Decision Support Tool gives the option to the executor to select the preferred equipment. For further research, Stage 3 (Deconstruction) can be extended with more assessment questions to better determine the equipment to disconnect.
  - *Equipment to reconnect (Stage 7)*
    This research only considers the most common types of reconnections. The 'reconnecting design proposals' per type of reconnection are based on the advantages and disadvantages from literature study but classified according to the interpretation of experts and the researcher. However, connections are project dependent due to specific requirements and internal forces which makes Phase III (Re-Assembling) challenging to assess. For further research, the first draft of Phase III can be extended with more assessment questions to determine the equipment to reconnect.

- *Existing information*
  This research considers existing information to be sufficient for the individual assessment of the Decision Support Tool since performance testing is not always possible due to the requirements of the project, advanced equipment and costs. However, the severity of internal and external deterioration (Stage 2) and the susceptibility to external influences on the storage site (Stage 5) depend on parameters retrieved during laboratory research, (regular) inspections or maintenance plans. For further research, the assessment can be linked to these sources instead of only the existing information.

11.2.1 Decision Support Tool

Considering the relevance and limitations of this research, the following limitations can be addressed for the assessment of the reuse potential in the Decision Support Tool. In the next Chapter (Recommendations), suggestions for further research are discussed.

- *Non-uniform answers*
  The filled-in answers of the test-case indicate significant differences, which can be assigned to 'unknown' answer options and unfamiliarity of the indicators. Unfamiliarity refers to the formulation of the assessment questions with relating answer options leading to different interpretations. Validation showed that the unfamiliar indicators create awareness about the risk for reuse and are thus important for the assessment. For further development of the Decision Support Tool, the definitions of the assessment questions and relating answer options can be re-formulated or clarified with images.

- *Judgement of the executor*
  The Decision Support Tool depends on the availability of existing information. However, each executor might handle lacking information differently depending on their knowledge and experience. In case information is lacking or an answer is unknown, the input of the Decision Support Tool depends on the interpretation and judgement of the executor leading to skewed results. Therefore, the output can only be interpreted as advice.

- *Skewed results*
  The validity of the Decision Support Tool showed that skewed results can occur due to sensitivity, lacking information and displaying of the grading. Firstly, sensitivity refers to the different amount of assessment questions per Stage which means the grading of Stages with only one or two indicators are more sensitive to adjustments. This sensitivity can be reduced if the stages include an equal amount of indicators or if weighing between the stages is applied. Secondly, lacking information refers to the needed information to answer assessment questions. The fixed and 'unknown' answer options, explanations and range of uncertainty deal with this. However, it is recommended to analyse further the processing of lacking information. Lastly, the effect of displaying the grading to the executors can also lead to skewed results. The execution of the test-case showed that displaying the grading to the executors in some cases lead to selecting answer options with a (more) positive effect on the reuse potential. However, not displaying the grading to the executors can lead to different interpretations. For further development of the Decision Support Tool, the effect of not displaying the grading to the executor(s) can be analysed.

- *Validity of the Decision Support Tool*
  The validity of the preliminary and final version of the Decision Support Tool showed that the assessment is useful in practice and that the assessment includes all aspects associated with the process of 'Deconstruct & Reuse'. However, limitations occur for the validity of the Decision Support Tool since the test-case is only executed with five experienced structural engineers due to time constraints. Next, only one test-case is used for the validity which can lead to the chance of coincidences or the possibility not all issues are addressed. Additionally, the test-case executed by the researcher serves as a reference. However, it has not been demonstrated whether the filled-in answers correspond to reality because the disassembling and reusing of the case-study has not been realised yet.
- *Execution by structural engineer*
  The Decision Support Tool is mainly set up for structural engineers. However, some of the needed information depends on other parties which can make it difficult to execute the Decision Support Tool. Therefore, it is suggested to further research the legal liabilities, warranties and responsibilities for the reuse of concrete (structural) elements.

12 | Recommendations

This research is the first method to scientifically assess the reuse potential of a harvested (structural) element made operational in a Decision Support Tool, based on extensive literature study, interviews and a case-study. Based on the Discussion (Chapter 11), more research is recommended. The most significant recommendations of this research are described in this Chapter.

- *Weighing between stages*
  In the Decision Support Tool, the indicators are graded and a range of uncertainty is applied according to Fuzzy. However, skewed results can occur due to sensitivity of different amount of indicators per Stage. For further research, weighing can be applied between the stages, which consider the different influences that stages have on the reuse potential. These relations can be obtained by adding individual weighing factors to the decision tree on page 82.

- *Validity of the Decision Support Tool*
  For further research, the validity of the Decision Support Tool can be enhanced. This can be achieved by executing more test-cases, or at least a test-case which is already realised. Additionally, the test-case can be executed with experts from other fields resulting in a more complete list of the indicators as well as more information in depth.

- *Development of the Decision Support Tool*
  The test-case showed that significant differences of the filled-in answers can be assigned to 'unknown' answer option(s) and unfamiliarity of the indicator(s). For further development of the Decision Support Tool, the definitions of the assessment questions and relating answer options can be re-formulated or clarified with images. Additionally, only individual elements can be tested in the Decision Support Tool, especially beams and slabs are considered during the development and test-case. Therefore, the Decision Support Tool can be extended for buildings as a whole, for multiple connections, for other (concrete) elements and materials. Moreover, the scope of the research can be broadened by including the substructure and other strategies than reuse (e.g., recycling of concrete by crushing the aggregates). Lastly, validation showed that the current added value in practice is in Phase I and II (respectively Post-Disassembling and Disassembling). For further research, the first draft of Phase III (Re-Assembling) can be extended to ease the implementation of harvested (structural) elements in the design of new buildings.

- *Include other expertises*
  The process of 'Deconstruct & Reuse' is researched from the perspective of structural engineers. For further research, interviews can be conducted with experts from other fields resulting in a more complete list of the indicators as well as more information in depth. Furthermore, the Decision Support Tool can be executed in a relatively quick manner by structural engineers. However, some assessment questions require structural knowledge which can make it difficult to execute the Decision Support Tool for other parties. The 'unknown' answer options and explanations deal with this, but for further research the execution of the Decision Support Tool can be made more accessible for e.g. building owners and contractors because they are reached out to for demolition.

- *Liability*
  The needed information to execute the Decision Support Tool can depend on other parties. Therefore, it is suggested to further research the legal liabilities, warranties and responsibilities for the reuse of concrete (structural) elements.

- *Advantages of reuse*
  Validation showed that the Decision Support Tool has a high practical value as it stimulates the reuse of concrete elements through an operational method. Reuse can be enhanced even more by comparing a second-hand element to a similar newly-made element regarding the environmental impact, waste savings and costs. The extra effort of reuse must also be taken into account. Also, deconstruction can be compared to the demolition of a similar building to map the advantages. However, reuse only increases when raw materials become scarce or when the prices of newly-made elements increase. The influence on reuse can be investigated for further research. However, it should be taken into account that most incentives are related to government regulations (e.g. certificates for CO_2 pricing or the CO_2 ladder program).

- *Economic value*
  For use in practice, the economic value needs to be investigated for further research. This can be done by analysing if a reuse potential close to 0% results in higher costs to enable reuse.

- *Automate Decision Support Tool*
  Validation showed that the integration of (current) standards, (regular) inspections or maintenance plans to the assessment can be an opportunity to automatically determine answers. Additionally, the input of the Decision Support Tool can be linked to 3D models (BIM) to automatically assess the reuse potential of harvested (structural) elements. The assessment of the reuse potential can also be linked to existing methods, such as the material passport of Madaster (Appendix C.1).

- *Combine supply and demand*
  The reuse of harvested (structural) elements in new designs depends on the supply of elements which come from demolition projects or storage sites. However, if the supply changes during construction of a new building, the design continuously needs to adapt (a 'Dynamisch Definitief Ontwerp (DDO)' [Superuse Studios, 2019], in English: Dynamic Final Design). This should to be prevented. For further research, the Decision Support Tool can be linked to a database to combine the supply and demand of harvested (structural) elements. Figure 12.1 shows that the database can be linked to the assessment of the reuse potential before reusing harvested (structural) elements in new designs (Phase III).

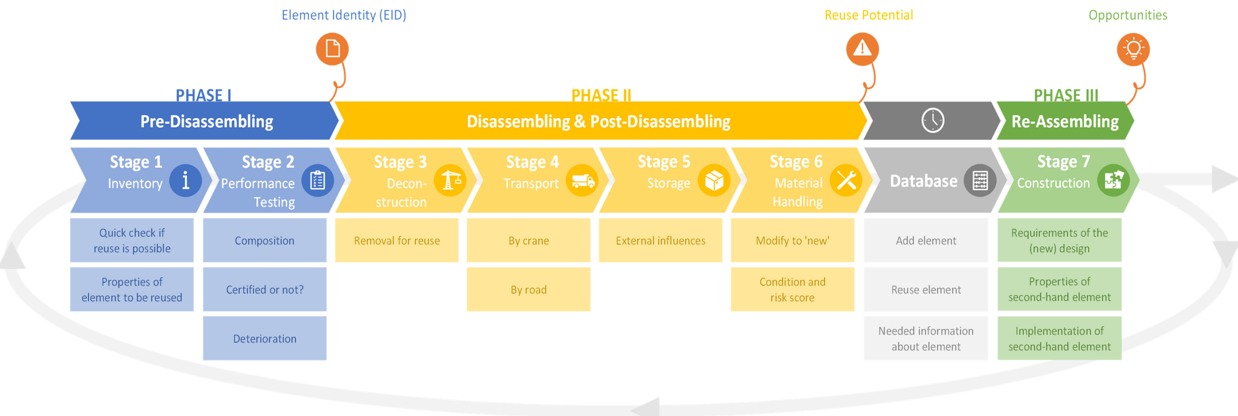


Figure 12.1: Assessment of reuse potential of existing concrete with Phases, Stages and Indicators. The database can be linked to the Decision Support Tool for further research (own figure).

- *Pieters Bouwtechniek*
  This research is carried out on behalf of Delft University of Technology and Pieters Bouwtechniek. Therefore, additional advice is given to engineering firms for use in practice. The reuse and implementation of harvested (concrete) elements in a new design mainly depend on the fact if the client of a project is willing to consider reusing concrete (structural) elements. In the initial phase of a project, a structural engineer can advise the client and change the design requirements. For instance, by offering the Decision Support Tool as an extra service to the client (or by making it mandatory). Then, the output can be discussed with other parties leading to more reuse of concrete (structural) elements. Therefore, the output motivates towards (more) circularity in the construction industry.

List of References

Abudayyeh, O., Sawhney, A., El-Bibany, H., and Buchanan, D. (1998). Concrete Bridge Demolition Methods and Equipment. *Journal of Bridge Engineering, 3(3):117-125. https://doi.org/10.1061/(asce)1084-0702.*

Akanbi, L., Oyedele, L., Akinade, O., Ajayi, A., Davila, M., Bilal, M., and Bello, S. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling, 129:175-186. Elsevier B.V. http://doi.org/10.1016/j.resconrec.2017.10.026.*

Architectuur Centrum Amsterdam (2019). De Nederlandsche Bank | ARCAM. Retrieved on October 1, 2020 from https://www.arcam.nl/de-nederlandsche-bank/.

Backx, S. (2020). *Structural sustainability in the early design phase - A parametric environmental impact assessment of various construction materials, including the design for deconstruction and donor structural framework concepts*. Master thesis, Delft University of Technology.

BELTON (1992). *Verbindingen in prefab - Binnenspouwbladen, balken en kolommen in de utiliteitsbouw*. Spruyt, Van Mantgem & De Does BV, Leiden.

Bertin, I., Lebrun, F., Braham, N., and Le Roy, R. (2019). Construction, deconstruction, reuse of the structural elements: The circular economy to reach zero carbon. *IOP Conference Series: Earth and Environmental Science. 323(1). Institute of Physics Publishing. https://10.1088/1755-1315/323/1/012020.*

Bijleveld, M. and Beeftink, M. (2020). *Klimaatimpact van betongebruik in de Nederlandse bouw - Vergelijking 1990, 2010 en 2017*. CE Delft, commissioned by Rijkswaterstaat.

Bijleveld, M., Bergsma, G., Krutwagen, B., and Afman, M. (2015). *Meten is weten in de Nederlandse bouw - Milieu-impact van de Nederlandse bouw- en sloopactiviteiten in 2010*. CE Delft, commissioned by Bouwend Nederland.

Bleuel, D. (2019). *A decision support model for analysing the reuse potential of hollow-core slab floor components*. Master thesis, Delft University of Technology.

Braam, C., Lagendijk, P., and Dees, W. C. (2011). *Constructieleer Gewapend Beton*. Cement&BetonCentrum. Aeneas, 7th edition. ISBN: 978-94-6104-006-0.

Brand, S. (1994). *How Buildings Learn: What Happens After They're Built*. Viking Press. ISBN: 978-0-670-83515-7.

Cai, G. and Waldmann, D. (2019). A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study. *Clean Technologies and Environmental Policy. 21(10):2015-2032. Springer Science and Business Media Deutschland GmbH. https://10.1007/s10098-019-01758-1.*

Corporaal, H. (2016). *Cementgebonden afstandhouders in een betonconstructie met een ontwerplevensduur van 100 jaar*. Institute of Concrete Technology, 's-Hertogenbosch.

Council for the Environment and Infrastructure (2015). *Circular Economy - From wish to practice*. (in Dutch: Raad voor de Leefomgeving en Infrastructuur), Den Haag.

Cramer, J. (2015). *Circulaire economie: van visie naar realisatie - Resultaten van negen Circular Economy Labs*. Utrecht Sustainability Institute.

De Nederlandsche Bank (2019). Renovatie hoofdkantoor DNB. Retrieved on October 1, 2020 from https://www.dnb.nl/over-ons/renovatie/.

Disseldorp, W. (2018). *(RE)develop the future: An instrument to develop and implement the concept of circularity for the redevelopment initiation phase*. Master thesis, Delft University of Technology.

Duffy, F. (1990). Measuring building performance. *Facilities, 8(5):17-20. https://doi.org/10.1108/EUM0000000002112. ISSN: 0263-2772*.

Durmisevic, E. (2006). *Transformable building structures: design for dissassembly as a way to introduce sustainable engineering to building design & construction*. PhD thesis, Delft University of Technology.

Durmisevic, E. and Brouwer, J. (2002). Design aspects of decomposable building structures. In *International Council for Research and Innovation in Buildings and Construction (TG39 - Deconstruction)*, Karlsruhe, Germany. Delft University of Technology.

Ellen MacArthur Foundation (2013). *Towards the Circular Economy: Economic and business rationale for an accelerated transition*.

Ellen MacArthur Foundation (2017). What is a Circular Economy? Retrieved on August 10, 2020 from https://www.ellenmacarthurfoundation.org/circular-economy/concept.

ENCI (2013). Globale cementkeuze gebaseerd op technologische aspecten. *Arko Catalogus Bouwwereld, 580-581*.

Engström, B. (2008). *Structural connections for precast concrete buildings*. International Federation for Structural Concrete (fib Bulletin 43), Lausanne, Switzerland. ISBN: 9782883940833, ISSN: 1562-3610.

Eurocode 2 (2013). *EN 1992-1-1: Ontwerp en berekening van betonconstructies*.

Figueira, R., Silva, C., Peveira, E., and Salta, M. (2014). Corrosion of hot-dip galvanized steel reinforcement. *Corrosion and Protection of Materials*, 33(3):44–54.

Geldermans, R. (2016). Design for Change and Circularity - Accommodating Circular Material & Product Flows in Construction. *Energy Procedia, 96:301-311. Elsevier Ltd.*

Geraedts, R. and Van der Voordt, T. (2007). A tool to measure opportunities and risks of convering empty offices into dwellings. In *International Conference on Enhancing Housing Residencies*. Delft University of Technology.

Glias, A. (2013). *The "Donor Skelet" - Designing with reused structural concrete elements*. Master thesis, Delft University of Technology.

Heidrich, O., Kamara, J., Maltese, S., Re Cecconi, F., and Dejaco, M. (2017). A critical review of the developments in building adaptability. *International Journal of Building Pathology and Adaptation, 35(4):284-303. Emerald Group Publishing Ltd. https://doi.org/10.1108/IJBPA-03-2017-0018. ISSN: 23984708.*

Holly, I. and Abrahoim, I. (2020). Connections and Joints in Precast Concrete Structures. *Slovak Journal of Civil Engineering. 28(1):49-56. https://doi.org/10.2478/sjce-2020-0007. ISSN: 1338-3973*.

Hradil, P., Talja, A., Wahlström, M., Huuhka, S., Lahdensivu, J., and Pikkuvirta, J. (2014). *Re-use of structural elements - Environmentally efficient recovery of building components*. VTT Technology 200.

Hyland, C. and Ouwejan, A. (2017). Fatigue of reinforcing bars during hydro-demolition. *Conference Series: Fracture, Fatigue and Wear, 843. Institute of Physics Publishing (IOP), Auckland. https://doi.org/10.1088/1742-6596/843/1/012033. ISSN: 17426596*.

Iacovidou, E. and Purnell, P. (2016). Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. *Science of the Total Environment. 557-558:791-807. Elsevier B.V. https://1doi.org/0.1016/j.scitotenv.2016.03.098. ISSN:18791026*.

Jabeen, I. (2020). *Economic Feasibility of Reusing Structural Components*. Master thesis, Delft University of Technology.

Jiang, L. (2020). *Measuring product-level circularity performance based on the Material Circularity Indicator: An economic value-based metric with the indicator of residual value*. Master thesis, University of Twente.

Kanters, J. (2020). Circular Building Design: An analysis of barriers and drivers for a circular building sector. *Buildings, 10(4). Lund University. https://doi.org/10.3390/BUILDINGS10040077. ISSN: 20755309*.

Kent, J., Gerard, E., Church, L., and Miranda, F. (2019). Thornton Tomasetti Shares Results of Comprehensive Embodied Carbon Measurement Study. Retrieved on September 11, 2020 from https://www.thorntontomasetti.com/news/embodied-carbon-measurement-study.

Khasreen, M., Banfill, P., and Menzies, G. (2009). Life Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability, 1:674-701. Heriot Watt University. https://doi.org/10.3390/su1030674. ISSN: 20711050*, 1:674–701.

Lesmes Mendoza, C. (2020). *Closing the Loop: A Decision Support Framework for Circular Economy implementation to the adaptive reuse of buildings in the Netherlands*. Master thesis, Delft University of Technology.

MacNamara, E. (2020). Applying circular principles to the design process. *The Structural Engineer*, 8:9–11.

Madaster services (2018). *Toelichting Madaster Circulariteit Indicator (versie 0.2)*.

Madaster services (2020). *Stappenplan Madaster Gebouwpaspoort - Procesbeschrijving voor het opmaken van een gebouwpaspoort in het Madaster Platform*.

Mayor of London (2019). *Design for a circular economy: primer*. Circular Economy Sounding Board. Greater London Authority (GLA).

Mecanoo (2018). Mecanoo selected for the renovation of the DNB (De Nederlandsche Bank) in Amsterdam. Retrieved on October 1, 2020 from https://www.mecanoo.nl/News/ID/432/Mecanoo-selected-for-the-renovation-of-the-DNB-De-Nederlandsche-Bank-in-Amsterdam.

Minister van Verkeer en Waterstaat (2021). Regeling voertuigen. Retrieved on February 22, 2021 from https://wetten.overheid.nl/BWBR0025798/2021-01-21#Hoofdstuk5.

Morren, M., Wijte, S., Lucas, S., and Minartz, P. (2020). Minder CO dankzij doorgaande sterkteontwikkeling. *CEMENT. ISSN: 0008-8811*, 2:54–62.

Najah, M. (2012). *Conserveren, renoveren, transformeren of sloop, gevolgd door vervangende nieuwbouw? zoektocht naar een geschikt alternatief in de sociale woningbouw*. Master thesis, Eindhoven University of Technology.

NEN 2767 (2013). *Condition Assessment*.

NRP Gulden Feniks (2020). Een prijs om van te leren. Retrieved on September 22, 2020 from https://www.nrpguldenfeniks.nl/.

NU (2020). Bijgebouw van De Nederlandsche Bank in de verkoop. Retrieved on August 4, 2020 from https://www.nu.nl/economie/6068536/bijgebouw-van-de-nederlandsche-bank-in-de-verkoop.html.

Nussbaumer, A., Borges, L., and Davaine, L. (2018). *Fatigue Design of Steel and Composite Structures - Eurocode 3 - Design of Steel Structures; Part 1-9 - Fatigue Eurocode 4 - Design of Composite Steel and Concrete Structures (2nd Edition)*. European Convention for Constructional Steelwork, European Convention for Constructional Steelwork. ISBN: 9783433608814.

Pieters Bouwtechniek (2020). Duurzaamheid. Retrieved on November 1, 2020 from https://www.pietersbouwtechniek.nl/constructie-adviesbureau/duurzaamheid.

Pieters Bouwtechniek Internal Document (2021a). Figure: Disassembling sequence. Amsterdam, unpublished.

Pieters Bouwtechniek Internal Document (2021b). Figure: Double Tee slab of Satellietgebouw (type: V1). Amsterdam, unpublished.

Pieters Bouwtechniek Internal Document (2021c). Figure: Floor plan of Satellietgebouw. Amsterdam, unpublished.

Pieters Bouwtechniek Internal Document (2021d). Figure: Impression of De Nederlandsche Bank (DNB) made in 1987 by Adviesbureau D3BN Civiele Ingenieurs. Amsterdam, unpublished.

Pieters Bouwtechniek Internal Document (2021e). Figure: Section of Satellietgebouw. Amsterdam, unpublished.

Pieters Bouwtechniek Internal Document (2021f). Plan van Aanpak Demontage Satelliet (V2) drafted by Kruijswijk Sloopwerk. Amsterdam, unpublished.

Platform CB23 (2020a). Lexicon Circulaire Bouw - Eenduidige termen en definities (versie 2.0).

Platform CB23 (2020b). Meten van circulariteit - Werkafspraken voor een circulaire bouw (versie 2.0).

Potting, J., Hekkert, M., Worrell, E., and Hanemaaijer, A. (2017). *Circular Economy: Measuring Innovation in the Product Chain*. Number 2544. PBL Publishers, The Hague.

Rademaker, E., Bakker, J., Kaptijn, N., and Appels, H. (2002). *Handboek voor oriënterende inspectie ASR*. Bouwdienst Rijkswaterstaat, Tilburg.

Rakhshan, K., Morel, J., Alaka, H., and Charef, R. (2020). Components reuse in the building sector: A systematic review. *Waste Management and Research. 38(4): 347-370. SAGE Publications Ltd. https://10.1177/0734242X20910463*, 38(4):347–370.

Rijksdienst Voor Ondernemend Nederland (2014). Transformatie en het Bouwbesluit 2012 - van het Expertteam (kantoor)transformatie.

Rodgers, L. and Chatham House (2018). Climate change: the massive CO2 emitter you may not know about. Retrieved on December 3, 2020 from https://www.bbc.com/news/science-environment-46455844.

Salama, W. (2017). Design of concrete buildings for disassembly: an explorative review. *International Journal of Sustainable Built Environment, 6:617-635. Elsevier B.V. https://doi.org/10.1016/j.ijsbe.2017.03.005. ISSN: 22126104*.

Schmidt III, R. and Austin, S. (2016). *Adaptable Architecture: Theory and Practice*. Routledge, Abingdon. ISBN: 978-0-415-52258-8.

Schmidt III, R., Eguchi, T., Austin, S., and Gibb, A. (2010). What is the meaning of adaptability in the building industry? In *16th International Conference on Open and Sustainable Building*, Bilbao, Spain.

Somerville, G., Andrade, C., Fagerlund, G., Lagerblad, B., and Tuutti, K. (1995). The Residual Service Life of Reinforced Concrete Structures.

Stofberg, F. and Duijvestein, K. (2008). Basisdoc: XS 2 duurzaam bouwen. Technical report, BOOM-SI, Milieukundig Onderzoek- & OntwerpBuro, Delft.

Stolk, I. (2018). Een inventariserend onderzoek naar een uniforme meetmethode voor circulair bouwen - in opdracht van Rijksdienst voor Ondernemend Nederland.

Stubeco (2017). Beknopte betontechnologie. Hoofdstuk 9. Retrieved on April 7, 2021 on https://www.stubeco.nl/9-beknopte-betontechnologie.html.

Superuse Studios (2019). Buitenplaats Brienenoord (project informatie).

Suzyo, L. (1996). *In-situ vs precast concrete construction - A Comparative Investigation of their Effectiveness of on Housing Development Projects*. Master thesis, Copperbelt University, Zambia.

Täljsten, B., Paulsson, B., and Elfgren, L. (2019). *Prestressed Concrete Bridges Condition Assessment and Future Challenges - A State-of-Art Report*. Lulea University of Technology.

Tijssens, R. (2011). *Doorexploiteren , duurzaam renoveren of sloop gevolgd door vervangende nieuwbouw? Aanzet tot een multicriteria-analyse*. Master thesis, Eindhoven University of Technology.

TNO (2018). Online database of (circular) building materials. Retrieved on October 16, 2020 from https://www.tno.nl/en/focus-areas/circular-economy-environment/roadmaps/circular-economy/circular-building/online-database-of-circular-building-materials/.

Treacy, D. (2020). Time for a structural change? *The Structural Engineer*, 8:18–19.

Turntoo (2018). Turntoo begeleidt klanten bij de totstandkoing van een materialenpaspoort in het Madaster platform. Retrieved on July 26, 2020 from http://turntoo.com/nl/materialenpaspoort/.

Van Belzen, T. (2020). Circulaire architecten verenigen zich: Dit gaat de markt pijn doen. Retrieved on 16 October, 2020 from https://www.cobouw.nl/duurzaamheid/nieuws/2020/10/circulaire-architecten-verenigen-zich-we-willen-de-markt-pijn-doen-101289076.

Van Berlo, S. (2019). *Assessing the circularity of infrastructure assets: A methodology to inspect and assess 1 on 1 reuse of concrete components*. Master thesis, University of Twente.

Van den Brink, G. (2020). *Designing with recovered precast concrete elements - A study on the possibilities of reusing structural precast concrete elements, from disassembled office buildings, in new apartment buildings*. Master thesis, Delft University of Technology.

Van der Weij, E. (2020). Rekenen met doorgaande sterkteontwikkeling. *CEMENT, 2:63-67. Aeneas Media B.V. ISSN: 0008-8811*, 2:63–67.

Van Dijk, E., Houben, T., and Verheul, J. (2018). *Circulair sturen op hoogwaardig hergebruik van toegepaste en toe te passen materialen*. Royal Haskoning DHV, commissioned by Rijkswaterstaat Water, Verkeer en Leefomgeving.

Van Dijk, K., Boediante, P., te Dorsthorst, J., and Kowalczyk, A. (2000). State of the Art Deconstruction in the Netherlands. In *Overview of Deconstruction in Selected Countries*, chapter 6, pages 95–143. CIB, International Council for Research and Innovation in Building Construction Task Group 39: Deconstruction (CIB TG 39).

Vandenbroucke, M. (2018). *Technische levensduur van gebouwcomponenten*. Vlaanderen is materiaalbewust. OVAM.

Verberne, J. (2016). *Building Circularity Indicators - An approach for measuring circularity of a building*. Master thesis, Eindhoven University of Technology.

Verhagen, T., Sauer, M., van der Voet, E., and Sprecher, B. (2021). Matching Demolition and Construction Material Flows, an Urban Mining Case Study. *Sustainability, 13(2): 653. MDPI AG. Leiden University.*

Vissering, C., Straub, A., Van Nunen, H., Janssen, R., and Liebregts, M. (2011). *Levensduur van bouwproducten: methode voor referentiewaarden*. Standard Business Reporting (SBR).

Volkov, M. (2019). *Structural connections in circular concrete*. Master thesis, Delft University of Technology.

Warner, J. (1998). Hydrodemolition for Removing Concrete. *Concrete International*, 20(8):47–50.

Watson, N. (2020). Lean design: 10 things to do now. *The Structural Engineer*, 8:12–14.

Zandbergen, T. (2016). *Fire Resistance of Existing Structures - Assessing the fire resistance of existing concrete buildings*. Master thesis, Delft University of Technology.

Zhu, J., Zheng, W., Sneed, L., Xu, C., and Sun, Y. (2019). Green Demolition of Reinforced Concrete Structures: Review of Research Findings. *Global Journal of Researches in Engineering, 19(4). Global Journals, Harbin University of Science. ISBN: 2249-4596*.

Part IV
Appendices

The last part of this research provides the Appendices, which follow the Research Framework (Part I), Research Methods (Part II) and Results (Part III).

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A | Definitions of the R-list

This Chapter defines the concepts of the R-list of Potting et al. [2017], based on the lexicon of Platform CB23 [2020a]. The concepts are subdivided in the design phase, the use phase and the discard phase. The latter two can be implemented in the design phase (as shown in Figure 3.4).

Concepts of the design phase:

- Refuse (R0)
  Preventing the use of products, elements, or materials.
- Reduce (R1)
  Reducing the use of new raw materials while guaranteeing the same functionality and quality.
- Renew (R2)
  Redesigning a product based on circular design principles.

Concepts of the use phase (in the design phase):

- Reuse (R3), as defined on page 19.
  Reuse means an operation by which a product, its components or materials can be used again for the same purpose/function for which they were conceived. The waste is prepared by checking, cleaning, or repairing recovery activities to be reused without the need for any modifications, reprocessing or treatment.
- Repair (R4)
  Returning a faulty product to a condition where it can fulfil its initial function. The service life of a product or structure can be extended by applying preventive or corrective maintenance during its use phase.
- Refurbish (R5)
  Improving or modernizing an existing (construction) product or material to a satisfactory working condition with a similar function.
- Remanufacture (R6)
  Using parts of a discarded product in a new product with a similar function.
- Re-purpose (R7)
  Using a product, its components or materials in a role that they were not originally designed to perform without the need for any reprocessing or treatment (which falls under recycling). Augmentation of the product might be required to fulfil its new role.

Concepts of the discard phase (in the design phase):

- Recycle (R8)
  An operation of any kind, where a product, component or material is reprocessed for the original or other purposes. This can be done for the same or less quality (respectively up- or downcycling). Energy recovery is not included.

- Recover (R9)
  An operation of any kind, where waste serves a useful purpose by replacing other materials which would otherwise be used to fulfil a particular function, or where waste is prepared to fulfil that function in the plant or the wider economy. Energy recovery means the production of useful energy through direct and controlled combustion or other processing of waste.

B Concrete

This Chapter provides a short introduction of concrete, considering the properties and varieties respectively in Appendix B.1 and Appendix B.2.

B.1 Properties

Concrete is a composite material composed of aggregates, cementitious binders and water which determine the physical, mechanical, chemical, and thermal properties of the finished concrete. The mechanical properties, strength and stiffness, are of great importance for concrete construction. Strength, the more important one, is expressed in strength classes based on the compressive strength of concrete (f_{ck}). NEN-EN 1992-1-1, NEN-EN 206-1 and NEN 8005 describe the following strength classes: C12/15, C16/20, C20/25, C25/30, C30/37, C35/45, C40/50, C45/55, C50/60, C55/67, C60/75, C70/85, C80/95 and C90/105 (for properties see Table D.4).

Concrete can be formulated with high compressive strength and considerably lower tensile strength. To enhance this, concrete usually includes steel rebars (reinforcement). The properties of concrete and reinforcing steel are described in Appendix D.1. Reinforced concrete derives many application possibilities from the cooperation between concrete and steel. For example, during bending of a beam supported on two sides compressive stresses are created at the top (the concave side) and tensile stresses at the bottom (the convex side). In order to prevent wear, tear, and obsolescence, reinforcement must be applied on the tension side of the beam as far as possible from the neutral axis (the boundary line between tensile and compressive stresses).

Additionally, the reinforcement must always be surrounded by a layer of concrete of sufficient thickness and density (the concrete cover). This causes a sound adhesion of the reinforcement to the concrete. Therefore, cast-in rebars can only be pulled out of the concrete with a lot of effort and damage. Moreover, the expansion coefficients of concrete and steel correspond, which means the materials similarly expand due to e.g., temperature differences. Therefore, no significant stresses are generated [Braam et al., 2011, p. 12-14]. However, the concrete cover can be attacked by environmental forces such as wind, raining and freezing. This is further explored in subsection 5.1.2.2 (Figure D.2).

B.2 Varieties

Concrete elements can be casted in two ways: in-situ or pre-cast. The first way (in-situ) means casting and hardening are done on site. The second way (pre-cast) means casting is done in factories, after which the hardened elements are transported and assembled on the construction site. This means pre-casting requires a longer design process, whereas casting in-situ on site requires a longer construction process tangible by weather conditions. The latter can increase costs, delay production, or undervalue the compromised quality of elements. Next to the production, another significant difference between the two methods is the flexibility as in-situ construction can be poured in all formworks, whereas pre-cast construction offers repetitive production of prefabricated elements resulting in standardised structures. The repetitive production of prefabricated elements can reduce production and erection costs, guarantee quality, and speed construction on site, because the elements only have to be assembled on site [Suzyo, 1996, p. 34-35].

Guidelines to identify if an element is pre-cast or in-situ: [Van Berlo, 2019]

- Pre-cast elements can be recognised by lifting points on the element or by repetition of the same elements.
- Cast-in-situ elements can be recognised by seams, by spots from the formwork or by centrepins which were used during pouring.

Besides in-situ or pre-cast elements, concrete can be pre-stressed and post-tensioned. Firstly, in pre-stressed concrete elements, tension cables are implemented before the concrete is cast and hardened. During demolition, tension is released after which the bounded cables in pre-stressed concrete require a similar demolition technique as in-situ casting.

Secondly, in post-tensioned concrete elements, tubes made out of plastic or metal are cast in concrete. The tubes are filled with unconstrained tension cables which means the cables are not bounded to the concrete. The cables are tensioned when the concrete reaches a certain design strength. Demolition of post-tensioned elements requires a special design because when the concrete is demolished cables are violently released. This can result in collapse of the element or launch of the anchors [Glias, 2013, p. 30]. Due to these special requirements, post-tensioned elements are out of the scope of this research.

C | Process of Deconstruct & Reuse

Existing methods to assess the reuse potential of concrete are researched with extensive literature study (Appendix C.1). Additionally, the gaps of the existing methods are analysed which form the problem definition of this research (Section 1.3). In Appendix C.1.1, the indicators and stages are analysed and a selection is made for the process of 'Deconstruct & Reuse' to assess the reuse potential for this research.

C.1 Existing methods

Madaster is a web-based platform where existing buildings are documented, registered and archived. Thereby, a depot for reuse of materials of existing buildings is created. A material passport can be made in Madaster which contains information about the quality, origin and location of buildings. This data can make use of various data sources about products and materials (such as life cycle assessment or CO2 data), but also financial sources (what is the value of materials) and data sources about the health of materials (toxicity). The material passport thus provides insight into the material, circular and financial (residual) value of a building. However, these insights cannot be seen as a certificate Madaster services [2018].

The data can also be automatically registered from BIM (Building Information Models). However, since each party has its own model it is often unclear who is responsible for the correct information in Madaster. In addition, differences between the construction and the design model are often not implemented. It is also not possible to select an individual element in a 3D/IFC model. The materials passport therefore applies at building level, and not at element level [TNO, 2018; Stolk, 2018; Madaster services, 2018, 2020; Turntoo, 2018].

Other existing methods to assess the reuse potential are analysed in the research of [Van Berlo, 2019]. He develops an assessment method to assess concrete infrastructure components on their ability to be reused (Appendix C.1.1). In addition, Closing the Loop is a consortium with Nebest, Antea Group, Strukton Civiel en GBN Groep which aims to reuse existing infrastructure in the form of new infrastructure (`https://www.nebest.nl/producten/closing-loop`).

The bob-model (*Bouwmaterialen in Beeld*) developed by TNO in collaboration with Madaster documents materials and buildings for reuse based on public databases and profiles. Additionally, land partitioning and ownership in land registry are documented in order to realize circular building projects. The model includes a Residual Value Calculator of building products which considers the price of raw materials, quality, detachability and the costs of transport, maintenance and repairs [TNO, 2018].

Other examples of platforms that bring together the supply and demand of building materials are Matching Materials of Heijmans (`https://www.matchingmaterials.com/`) and the Oogstkaart of New Horizon (`https://www.oogstkaart.nl/about/`). The provision of insights into the stock of used and/or circular materials and raw materials can be referred to as the urban mining potential. The Urban Mining Collective (UMC: `https://urbanminingcollective.nl/`) and Circular Design Collective (CDC) are examples of associations which focus on circularity in the construction industry [Van Belzen, 2020]. Additionally, Platform CB'23 is a foundation in the Netherlands which focuses on the first Stage of the *'Transition Agenda'* and thus on the period till 2023 (Section 1.2).

C.1.1 Indicators and Stages of existing methods

C.1.1.1 *Research of Durmisevic, E. (2006)*

The research of Durmisevic [2006, p. 206-212] develops a conceptual framework for the transformation capacity in a knowledge model. This can be translated in a decision tree, where the disassembly sub-aspects are distinguished in input level:

- Functional decomposition (with as input the functional separation and dependence);
- Systematisation (with as input the structure of material levels and type of clustering);
- Base elements (with as input the type of base element);
- Life cycle coordination (with as input the use life cycle coordination, technical life cycle coordination, coordination of life cycle and size);
- Relational patterns (with as input the type of relational patterns);
- Assembly process (with as input the assembly direction and sequence);
- Geometry (with as input the geometry and standardisation of product edge);
- Connections (with as input the type of connections, accessibility to fixings, tolerance and morphology of joints).

C.1.1.2 *Research of Glias, A (2013)*

In collaboration with IMd Raadgevende Ingenieurs, the research of [Glias, 2013, p.42-80] analysed the feasibility level of reusing existing structural concrete elements. Therefore, he analysed the whole reuse process in order to identify the technical obstacles of reusing structural elements. The following basic actions are found to determine the reuse percentage, the total costs and the environmental impacts.

- Inventory:
  Existing drawings have to be examined in order to determine if an existing building is suitable for deconstruction. If a building is suitable, information has to be recorded for the inventory, which can be referred to as the Bill of Materials (BOM). The BOM contains basic information such as the general/material/structural properties of the building, type and amount of elements, dimensions, reuse percentage, deconstruction costs, and environmental impact.
- Quality Check:
  The condition has to be examined before reuse with existing drawings, visual inspection and performance testing. Additionally, it has to be examined if the building is constructed according to the existing drawings. The results of the Inventory and Quality Check create the Element Identity (EID) which contains details about the properties of the element and can be used as a certificate that proves if an element is suitable for reuse (subsection 4.2.1). A signed Element Identity (EID) reassures all prospective users that the element is safe to be reused.
- Deconstruction:
  A planning and attention are required in order to safely deconstruct existing buildings. Different ways exist to remove an element, criteria can be based on the costs and the loss of structural mass. Additionally, deconstruction comes with high costs and environmental impacts.
- Transportation:
  In order to minimize environmental impacts, it is suggested to reuse harvested components in a new project close to the deconstruction site.
- Storage:
  Harvested components require storage when facing structural vacancy or when the value of the building depreciates. However, it is suggested to only deconstruct a building when the new project is known to avoid storage and extra costs.
- Modification:
  Harvested components have to be modified in order to be reused in a new building. Therefore, it might be needed to reconnect or saw to component on size in order to fit in the new building.
- Construction:
  The construction process of harvested components is similar to the process of new components.

C.1.1.3 *Research of Geldermans, R. (2016)*

In order to assess the reuse potential, the research of Geldermans [2016] distinguishes intrinsic and relational properties. First, intrinsic properties indicate the functional performance, sustainability, toxicity and consistency with biological and technical cycles of the (structural) element. Second, relational properties indicate the dimensions, connections and performance time of the (structural) element. Geldermans [2016] states that the overlapping of the intrinsic and relational properties has a significant impact on the reuse potential. Therefore, he distinguishes seven categories:

- Exact composition;
- Performance quality;
- Deployment;
- Intended (re)use path;
- Performance time;
- Connections;
- Dimensions;
- Quality of the system.

C.1.1.4 *Research of Iacovidou, E. & Purnell, P. (2016)*

In order to assess the reuse potential, the research of Iacovidou and Purnell [2016] states that clarifications are needed by developing a topology system, which can provide confidence in reuse and assist construction parties in the selection and performance of second-hand elements. The typology system of Iacovidou and Purnell [2016] focuses on the properties of an element and the nature of the recovery process and original use:

- Action;
- Material;
- Deployment;
- Loading;
- Recovery;
- Residual;
- Connections;
- Availability;
- Generation.

The research of Iacovidou and Purnell [2016, p. 801] discusses that the guidance on the theoretical reuse potential of (structural) elements and states a successful implementation is hard to achieve. Currently, on-site assessment is the only way to evaluate the physical performance and ability for reuse. By assessing and documenting the service life of (structural) elements, the time-consuming on-site assessment could be avoided. This extra information can be introduced by e.g. labels which enable the recovery for reuse at the End of Life (EoL). However, Iacovidou and Purnell [2016] concludes more research is needed about which indicators affect the reuse potential during the service life of an element.

C.1.1.5 *Research of Van Berlo, S. (2019)*

In collaboration with Witteveen+Bos, the research of Van Berlo [2019] develops a method to assess the reuse potential. As a starting point, the decomposition (NEN 2767) of a bridge is considered to determine if an element can be reused, recycled (as raw material or as granulate) or discarded. The seven indicators to assess the reuse potential are:

- Toxic materials;
- Overall condition;
- Residual lifespan;
- Dismountable;
- Transportable;
- Current requirements;
- Standardisation.

However, the method of Witteveen+Bos is only a rough outline which lacks justification and qualification. Therefore, the research of Van Berlo [2019] develops an inspection and assessment method to assess concrete infrastructure components on their ability to be reused. He distinguishes three categories which arrange seven circular indicators:

- Material Quality (toxicity, condition, residual lifespan);
- Disassembly (connections, retrieval);
- Applicability (design requirements, dimensions).

C.1.1.6 *Research of Jabeen, I. (2020)*

Deconstruction is a complex process compared to the process of demolition. Therefore, the research of Jabeen [2020, p. 37-50] analysed the process of component reuse. Thereby, she distinguishes the deconstruction, material handling and consumption. Figure C.1 shows the stages for the disassembly of a concrete slab, where the deconstruction is split in preparation and execution of deconstruction.

Figure C.1: Process of component reuse with preparation of deconstruction, execution of deconstruction, material handling and consumption [Jabeen, 2020, p. 37].

Before deconstruction of a (partial) building can start preliminary actions are required, such as obtaining the permit and doing the site audit. Additional, both an inventory of the elements to be reused and a plan for the deconstruction waste needs to be drafted. By making a general and structural description of the building, a buyer for reuse can be found. Next, the internal and external non-structural elements are removed from the building to make visual inspection and testing easier and cheaper to perform. This process is also known as stripping which means that the building is reduced to only main load-bearing elements by recovering the elements from temporary layers of the building. After the building is stripped, performance testing of the components can be carried out. Since no protocol exists for performance testing, the level of testing depends on the available documents and the requirements of the user. Performance testing can be carried out by visual inspection, Non-Destructive Testing (NDT) and Destructive Testing. Before disassembly starts, it is important to support elements by propping, bracing, shoring and scaffolding to avoid unexpected collapse. An example of the sequence of disassembling of the case-study is described in Appendix F.1.1. For the research of Jabeen [2020], the slab is made accessible by removing the concrete cover and disconnecting connections. Once the component is lifted, the material handling stage starts. First, the component needs to be modified to fit the requirements of the new use. However, by reusing the component as it is costs can be reduced. A harvested component is then stored at either the deconstruction site, the new construction site or a storage yard. This means the component is transported from the deconstruction site to either the end-user, the new construction site or a storage yard. Before reuse, the harvested component should be repaired and certified. However, no protocol or guideline exists for this. When the component is ready, a buyer reuses the component in a new design. This is referred to as the consumption stage.

Within the deconstruction stage, the material handling stage and the consumption stage, the research of Jabeen [2020] developed a Feasibility Calculation Tool to determine if it is feasible to reuse a component or not. Thereby, various factors that affect the reuse cost were found (from high to low influence):

- Market (can hinder deconstruction due to time constraints of the owner to find a buyer for reuse);
- Type of connection (influences the removal for reuse);
- Method of construction (affects the method of deconstruction);
- Available documents (reduces the time and effort of the needed preliminary actions to deconstruct);
- Accessibility on site (influences the removal for reuse);
- Quantity (eases deconstruction);
- Age (influences the residual lifespan and performance).

C.1.2 Conclusion of existing methods

The extensive literature study resulted in indicators which affect the reuse potential, an overview is shown in Figure C.2. As described in subsection 3.3.3, indicators are selected for the process of 'Deconstruct & Reuse'. This is done in combination with the case-study, where this research analyses what structural engineers want to know before applying a harvested element for reuse in a new project.

Analysed gaps of the existing methods state that a few methods consider one or more indicators of the process of 'Deconstruct & Reuse', which means these methods can be used to assess the reuse potential. However, none of the existing methods takes into account all indicators of the process of 'Deconstruct & Reuse'. Additionally, no protocol exists for harvested elements considering the performance testing, repair or certifications. Lastly, a practical guideline to assess the reuse potential of harvested concrete (structural) elements in the design of new buildings is currently missing. Therefore, this research makes the assessment of the reuse potential of a harvested (structural) element operational in a Decision Support Tool. This research is the first of its kind, based on extensive literature study, interviews with experienced structural engineers and a case-study.

Indicator	Durmisevic (2006)	Glias (2013)	Geldermans (2016)	Iacovidou & Purnell (2016)	Van Berlo (2019)	Jabeen (2020)
Accessibility					✓	✓
Age						✓
Action				✓		
Assembly (retrieval/removal)	✓	✓			✓	✓
Availability				✓		✓
Certification		✓				✓
Composition			✓		✓	
Condition		✓			✓	
Connection	✓	✓	✓	✓	✓	✓
Costs		✓				✓
Deterioration					✓	
Implementation (deployment)		✓	✓	✓		✓
Design requirements		✓			✓	
Dimensions (geometry)	✓		✓		✓	
Environmental impact		✓				
Execution						✓
Function	✓					
Generation				✓		
Hoisting						✓
Intended (re)use path			✓			
Inventory		✓				✓
Life cycle coordination	✓					
Loading				✓		
Material (base element)	✓			✓		
Material properties		✓			✓	
Market		✓				
Method of construction						✓
Modification		✓				✓
Performance time			✓			
Planning		✓				✓
Preparation						✓
Quality check		✓				
Quality of system			✓			
Quick check					✓	
Recovery (repair)				✓		✓
Relational patterns	✓					
Residual performance			✓	✓	✓	
Storage		✓				✓
Soft stripping						✓
Structural system and mass		✓				
Time constraints						✓
Transport		✓				✓

Figure C.2: Overview of the indicators which affect the reuse potential of Durmisevic [2006]; Glias [2013]; Geldermans [2016]; Iacovidou and Purnell [2016]; Van Berlo [2019]; Jabeen [2020] in alphabetical order (own figure).

D | Information behind Process

In this Chapter, the information behind the Process of 'Deconstruct & Reuse' is analysed. Per Stage, indicators are elaborated in more detail. Phase I (Pre-Disassembling) is distinguished in Stage 1 (Inventory) and Stage 2 (Performance Testing) which are analysed respectively in Appendix D.1 and Appendix D.2. This is followed by Phase II (Disassembling and Post-Disassembling), which is distinguished in Stage 3 (Deconstruction), Stage 4 (Transport), Stage 5 (Storage) and Stage 6 (Material Handling). Additional information of Stage 3 can be found in Appendix D.3. Phase III (Re-Assembling) analyses Stage 7 (Construction), which is investigated in Appendix D.4.

D.1 Stage 1: Inventory

In this section, the properties of the (structural) element are investigated.

D.1.1 Type of cement

Concrete is a composite material composed of:
- Aggregate: usually a rocky material (e.g., coarse gravel or crushed rocks along with fine sand);
- Binder: cementitious (most commonly Portland cement) or non-cementitious (asphalt).
  Sometimes, admixtures (mineral or conspicuous materials) are added to the binder to modify the cure rate or properties of concrete;
- Water.

Determined by the type of aggregates and the formulation of binders, 27 types of concrete exist (NEN-EN 197-1). The exact composition of concrete depends on the type of structure being built, how the concrete is mixed and delivered and how the concrete is constructed. For the production of concrete with cementitious binders, water is mixed with the dry powder and aggregate. Typically, the mushy mixture is poured into a formwork mould to shape. The water reacts with the cement, which bonds the other components together. Through a chemical process (*hydration*) the concrete solidifies and hardens (cures) over time.

For cementitious binders, the type of cement is indicated by CEM, followed by the number of the main type in Roman numerals. According to NEN EN 197-1, the following main types of cement exist: [ENCI, 2013]
- CEM I Portland cement;
- CEM II Portland-composite cement;
- CEM III Blast furnace cement;
- CEM IV Pozzolanic cement;
- CEM V Slag and ash cement.

This designation is followed by a slash and a letter that indicates the vowel content (A, B or C). Next, a horizontal line and one (or more) capital letter(s) indicate which ingredient(s) is used in addition to Portland cement. This is followed by the strength class and strength development of cement [Stubeco, 2017].

In conclusion, the designations of the types of cement differ in main type, vowel content, ingredient(s), strength class and strength development. Additionally, the performance of hardening after long-term exposure, grey tone and resistance against sulphates differ. Cement is considered sufficient if it meets the requirements of NEN-EN 206-1 or NEN 3550. However, the research of Van Berlo [2019, p. 17] describes the possibility of insufficient cement causing internal deterioration. Cement is considered insufficient if sulphate, magnesium oxide or chalk are present in surplus. app-sec:typeofcement

For the simplicity of this research, only the main types of cement are considered, which all contain some Portland clinker. This is indispensable for any concrete structure with long service life. On the one hand, Portland clinkers harden quickly and are necessary to achieve sufficient resistance against frost-thaw salt. On the other hand, Portland clinker is a raw material with a high CO2 emission.

For applications without special requirements imposed on the concrete, CEM I and CEM III are the most commonly used types of cement in the Netherlands. Firstly, Portland cement (CEM I) consists of more than 95% Portland clinker, which means that CEM I hardens quickly, is resistant against sulphates and has high CO2 emissions. Additionally, the initial and final strength of CEM I are high. This in combination with fast hardening makes CEM I very suitable for quick demolding or prestressing. The colour of CEM I is grey after demolding and turns out lighter than CEM III.

Secondly, blast furnace cement (CEM III/A, CEM III/B and CEM III/C) consists of Portland clinker and 40-90% blast furnace slag. The clinker content is considerably lower than CEM I. Blast furnace slag is a waste product from iron production in blast furnaces. Additionally, the initial and final strength of CEM III are normal, which makes CEM III suitable for use in structures where the strength requirements are not too high. Moreover, CEM III is resistant against ASR or sulphates that occur in seawater, wastewater and manure. Therefore, CEM III can be applied in e.g., structures at or near the sea. The colour of CEM III is blue after demolding and turns out darker than CEM I.

Lastly, CEM I and CEM III can be mixed as Portland-composite cement (CEM II/A-M and CEM II/B-M). In general, CEM II consists of at least 65% Portland clinker and a filler that can be partly hydraulic. CEM II is regularly applied for road surfaces and is less resistant against sulphates, which can form a problem in the case of ASR or external sulphate attack (Appendix D.2.2).

In conclusion, this research considers CEM I, CEM II/A, CEM II/B, CEM III/A, CEM III/B and CEM III/C which are implemented in the Decision Support Tool as CEM I, CEM II and CEM III.

D.1.2 Fire resistance

The fire resistance of load-bearing elements in a building is conducted in the building regulations. These regulations are part of the 'Wet algemene bepalingen omgevingsrecht' or 'Wabo' (Dutch Environmental Permitting Act). Additionally, technical regulations in terms of safety are given in the 'Woningwet' (Dutch Housing Act) and 'Bouwbesluit' (Dutch Building Decree) which aims to prevent casualties and fire from spreading to another plot. In order to meet these objectives, functional requirements and performance criteria are set which provide a distinction between safe and unsafe situations [Zandbergen, 2016].

Fire resistance is defined as a certain time in which a compartment in which a fire occurs should not collapse or lead to progressive (structural) collapse, which gives people the ability to escape or search the building. For load-bearing structures, NEN-EN 13501-2 distinguishes three performance criteria concerning fire safety: the load-bearing capacity (criterion R), the integrity (criterion E), and the thermal insulation (criterion I). These performance criteria are given in minutes, where the terms R30-, E30- and I30- indicate that an element needs to fulfill the criteria R, E, or I for at least 30 minutes. In case the term REI30 is applied, the most critical performance criteria is governing [Zandbergen, 2016].

The performance criteria can be determined based on the performance level, function type of the building and the building height. First, the performance level can be new buildings, alteration/renovation, and existing buildings. Second, the function type can be housing or utility buildings with/without sleeping accommodation. Third, the building height is the height of the highest floor of an area to the measurement level (the level of the adjacent terrain at the location of the building entrance). However, in order to determine the fire resistance for reuse, current building regulations do not state which performance level should be applied.

The performance criteria for new and existing buildings are respectively shown in Table D.1 and Table D.2 at permanent fire load density of 500 Mj/m^2 (expressed in minutes) [Zandbergen, 2016, p. 19-40]. It can be seen that all performance criteria for existing buildings are reduced by one hour compared to new buildings. Additionally, no requirements are set for housing and utility buildings without sleeping accommodation if the (existing) building height is respectively up to 7 and 5 m above measurement level.

For the simplicity of this research, the fire resistance is implemented in the Decision Support Tool as 30, 60, 90 or 120 min. In Phase I, the (origin) fire resistance of a harvested (structural) element can be determined by drawings and desk research. In the case of a deficiency of information, the performance criteria of existing buildings can be applied (Table D.2). However, the research of Zandbergen [2016] states that requirements in the Dutch Building Decree are unclear regarding the fire resistance, which can hinder a correct application.

Table D.1: Fire resistance of existing buildings. Table originates from Decision Support Tool and is adapted from NEN-EN 13501-2.

Housing

Highest floor of accomodation area above measurement level	Fire resistance (performance criteria)
	-
7-13 m	30 min
> 13 m	60 min

Non-Housing

Highest floor of accomodation area above measurement level	Fire resistance (performance criteria)
	-
5-13 m	30 min
> 13 m	60 min

Table D.2: Fire resistance of new buildings. Table originates from Decision Support Tool and is adapted from NEN-EN 13501-2.

Housing

Highest floor of accomodation area above measurement level	Fire resistance (performance criteria)
	30 min
< 7 m	30 min
7-13 m	60 min
> 13 m	90 min

Non-Housing (e.g. utility buildings with sleeping accomodations)

Highest floor of accomodation area above measurement level	Fire resistance (performance criteria)
	30 min
< 5 m	30 min
5-13 m	60 min
> 13 m	90 min

D.1.3 Strength class

As described in Appendix B.1, strength is the most important mechanical property of concrete and expressed in strength classes based on the compressive strength of concrete (f_c). NEN-EN 1992-1-1, NEN-EN 206-1 and NEN 8005 describe the following strength classes: C12/15, C16/20, C20/25, C25/30, C30/37, C35/45, C40/50, C45/55, C50/60, C55/67, C60/75, C70/85, C80/95 and C90/105 (for properties see Table D.4). The first number indicates the characteristic value of the cylinder compressive strength and the second number indicates the characteristic value of the cube proof compressive strength.

'Normal concrete' indicates the strength classes up to and including C50/60, of which C12/15 and C16/20 are rarely or never applied as structural concrete because the strength is extremely low. Strength classes above C50/60 are indicated by 'high-strength concrete' (HSC) which is often more expensive and requires more attention during processing. The choice of which concrete strength class will be applied depends on the design, the method of implementation and costs. In recent years, a trend has been observed that more and more concrete of higher strength classes is developed [Braam et al., 2011]. This is also visible in the practice of in-situ and prefab concrete (Appendix B.2). However, since this research focuses on existing structures only 'normal' concrete is implemented in the Decision Support Tool (C20/25, C25/30, C30/37, C35/45, C40/50, C45/55, and C50/60). Concrete can be formulated with high compressive strength and considerably lower tensile strength (1/10 to 1/15). Table D.4 shows the material properties of concrete in N/mm^2, where

f_{ck} is the characteristic cylinder compressive strength of concrete at 28 days,
f_{cd} is the design value of the compressive strength of concrete,
f_{ctd} is the design value of the axial tensile strength of concrete (f_{ctk}/γ_c),
f_{ctm} is the average axial tensile strength of concrete (plays a role in checking for cracking and deflection),
E_{cm} is the secant modulus of elasticity of concrete (between $\sigma_c = 0$ and $\sigma_c = 0{,}4 f_{cm}$).

In the prefab industry higher strength classes are used, because people work under significantly better working conditions (indoor) than on the construction site. Besides, when manufacturing prefab concrete the aim is to reuse one formwork mould as often as possible in as little time as possible. Therefore, the concrete must harden quickly to be able to demold quickly [Braam et al., 2011, p. 25-33]. In the past, the concrete quality was designated by B-classes and K-classes. These correspond to strength classes nowadays as shown in Table D.3.

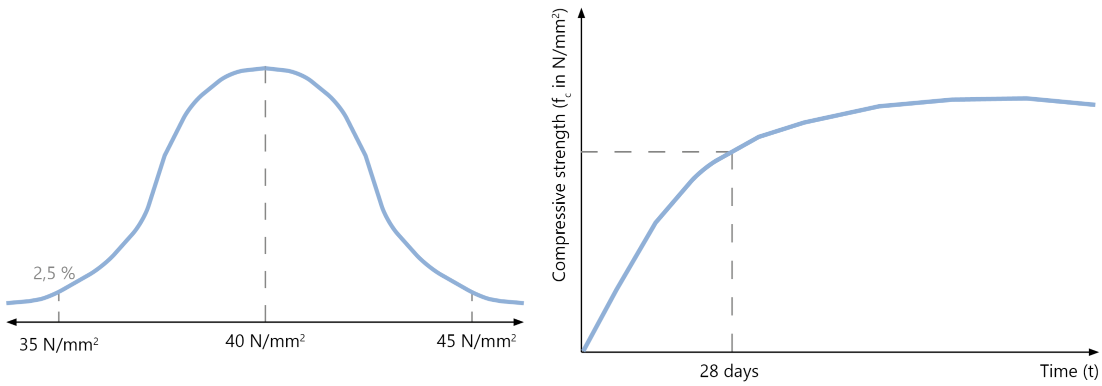
Table D.3: Strength classes of NEN-EN 1992-1-1 corresponding to older codes. Table originates from the Decision Support Tool and is adapted from this website. Abbreviations (in Dutch): VB = Voorschriften Beton; VBC = Voorschriften Beton - Constructieve eisen en rekenmethoden; GBV = Gewapend Beton Voorschriften

NEN EN 1992-1-1 Eurocode 2	VBC 1990 VBC 1995	VB 74 VB 74/84	GBV-1962
C20/25	B25		K300 (rounded up)
C25/30	B35 (rounded down)	B30	K400 (rounded down)
C30/37		B37,5	K450 (rounded down)
C35/45	B45	B45	
C40/50			
C45/55	B55	B52,5 (rounded down)	
C50/60	B65 (rounded down)	B60	

Table D.4: Material properties of concrete in N/mm^2. Adapted from Braam et al. [2011, p. 28].

Strength class	f_{ck}	f_{cd}	f_{ctd}	f_{ctm}	$f_{ctk;0,05}$	E_{cm}
C20/25	20	13,3	1,03	2,21	1,5	30000
C25/30	25	16,7	1,20	2,56	1,8	31000
C30/37	30	20,0	1,35	2,90	2,0	33000
C35/45	35	23,3	1,50	3,21	2,2	34000
C40/50	40	26,7	1,64	3,51	2,5	35000
C45/55	45	30,0	1,77	3,80	2,7	36000
C50/60	50	33,3	1,90	4,07	2,9	37000

Suppliers of concrete work with margins between 2 to 3%. On the left side in Figure D.1 an example is shown for C40/50. On the one hand, approximately 2 to 3% of the strength is lost over time. On the other hand, the compressive strength of concrete increases by about 10 to 30% after 28 days, shown on the right side in Figure D.1. This means the strength (e.g., at the compressive zone at the top of a beam) is always more than requested. The question is whether a structural engineer can assume this increased strength for reuse of concrete elements [Van der Weij, 2020; Morren et al., 2020].



(a) Suppliers of concrete work with margins for the compressive strength of concrete (example for C40/50)

(b) The compressive strength of concrete increases by 10 to 30% after 28 days

Figure D.1: Properties of concrete after 28 days (own figure).

The design service life of concrete elements must meet the requirements of Eurocode 2, which consist of: [Corporaal, 2016]

1. A concrete composition that meets the requirements of the environmental classes;
2. A correct concrete cover;
3. A concrete composition that is resistant to ASR.

D.1.4 Environmental class

Durable concrete elements offer sufficient resistance to all external influences that can be expected during its life cycle. Based on the chance of damage to the reinforcement (corrosion) and the concrete (degradation), NEN-EN 206-1 describes the following six different environments:

- X0 (0 = 'zero risk') No risk of corrosion or damage;
- XC (C = 'carbonation') Corrosion caused by carbonation;
- XD (D = 'de-icing salts') Corrosion caused by chlorides, such as de-icing salts;
- XS (S = 'seawater') Corrosion caused by chlorides from seawater;
- XF (F = 'frost') Degradation caused by frost and thaw changes, with or without de-icing salts;
- XA (A = 'aggressive') Degradation by aggressive chemicals.

These six different environments are further specialised in X0, XC (1/2/3/4), XD (1/2/3), XS (1/2/3), XF (1/2/3/4), XA (1/2/3). The environmental class is indicated with 'X' (e**x**posure). The second letter refers to the attack mechanism. The number indicates the degree of water saturation of the concrete [Braam et al., 2011]. Depending on the environmental class, requirements are set in NEN-EN 206-1 and NEN 8005 for the concrete composition in order to guarantee durability considering the maximum permissible Water-Cement Factor (WCF), the minimum cement content and the minimum additional air content [Corporaal, 2016]. According to Braam et al. [2011], only in specific cases an extra requirement is set for the type of cement. Since this research focuses on the superstructure of buildings in the Netherlands, environmental classes applying to foundations, bridges, industrial waters or marine structures are out of scope. Therefore, only the following exposures are considered: concrete inside buildings with air low/moderate/high humidity (X0 / XC1 / XC3), concrete surfaces exposed to chlorides (XD1), concrete structures at or near to the sea (XS1) and vertical surfaces without de-icing salts (XF1). A comprehensive table of all environmental classes and which of them are implemented in this research can be found in Table D.5. An overview of the implemented environmental classes is shown in Table D.6. The table also shows how other codes than NEN-EN 206-1 translate to the environmental classes considered for this research.

Table D.5: Environmental classes of NEN-EN 1992-1-1. Adapted from Corporaal [2016].

Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: All exposures except where there is freeze/thaw, abrasion or chemical attack. For concrete with reinforcement or embedded metal: Very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation		
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows:		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity; Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact; Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity; External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
3 Corrosion induced by chlorides other than from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts, from sources other than from sea water, the exposure shall be classified as follows:		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools; Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides. Pavements, Car park slabs
4 Corrosion induced by chlorides from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure shall be classified as follows:		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/thaw attack with or without de-icing agents		
Where concrete is exposed to significant attack by freeze/thaw cycles whilst wet, the exposure shall be classified as follows:		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents; Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zones of marine structures exposed to freezing
6 Chemical attack		
Where concrete is exposed to chemical attack from natural soils and ground water, the exposure shall be classified as follows:		
XA1	Slightly aggressive chemical environment	Concrete exposed to natural soil and ground water according to Table 2
XA2	Moderately aggressive chemical environment	Concrete exposed to natural soil and ground water according to Table 2
XA3	Highly aggressive chemical environment	Concrete exposed to natural soil and ground water according to Table 2

Table D.6: Environmental classes of NEN-EN 1992-1-1 corresponding to older codes with descriptions, informative examples and Water-Cement Factor wcf. Table originates from the Decision Support Tool and is adapted from Braam et al. [2011]; Corporaal [2016].

NEN EN 206-1		Description	Informative examples	Code before 2005		Water cement factor (wcf)
X0	(0 = no risk)	Very dry	Concrete inside buildings with low air humidity	1	(dry, inside)	0,65
XC1	(C = carbonation)	Dry	Concrete inside buildings with low air humidity	2A	(dry, outside)	0,55
XC3	(C = carbonation)	Moderate humidity	Concrete inside buildings with moderate or high air humidity	2A	(dry, outside)	0,55
XC4	(C = carbonation)	Cyclic wet/dry	Concrete subject to short-term water contact	2A	(dry, outside)	0,55
XD1	(D = de-icing salts)	Moderate humidity	Concrete exposed to airborne chlorides	3	(wet, de-icing salts)	0,45
XS1	(S = seawater)	Exposed to airborne salt, but not in direct contact with sea	Concrete at or near to the sea (< 25 km inland)	4A/B	(seawater)	0,45-0,55
XF1	(F = frost)	Moderate water saturation without de-icing agent	Vertical concrete surfaces exposed to rain and freezing	2B	(wet, outside)	0,55

D.1.5 Concrete cover

The correct concrete cover protects the reinforcement against external influences, such as rust and fire. The greater the distance from the concrete surface to the reinforcement is (the cover), the better the reinforcement is protected against penetrating harmful substances and high temperatures. The size of the concrete cover depends on the environment in which the concrete is located. For example, a smaller concrete cover can be applied in a dry environment than in an aggressive environment, since there is a lower risk of rusting [Corporaal, 2016]. Additionally, the concrete cover transfers the forces between the tensile loaded concrete and the reinforcement [Braam et al., 2011].

This means the concrete cover is based on all aspects that play a role during the design service life of a structure. Through a system of construction classes and environmental classes, a structural engineer can determine the correct concrete cover in two steps.

As a first step, the structural engineer determines the so-called construction class of a concrete structure (S1 - S6). The starting point for any concrete structure with a service life of 50 years is S4. Depending on the actual service life, the strength class, the geometry and quality control, the construction class is 'reduced' or 'increased' resulting in a different concrete cover. This revision of the construction class is shown in Table D.7 [Eurocode 2, 2013].

As a second step, the minimum concrete cover ($c_{min,dur}$) for reinforcing steel can be found in Table D.8 with the construction class and environmental class. In this table can be seen that the higher the class, the more stringent the requirements for the concrete cover. Environmental classes XA and XF are not considered, because they relate to the deterioration of the concrete itself. Additionally, XA and XF occur in combination with environmental classes that relate to the protection of the reinforcing steel [Eurocode 2, 2013; Braam et al., 2011]. For example, if XF occurs in combination with XC, the latter is decisive with regards to the minimum concrete cover. In this case XC must be adhered to in order to determine $c_{min,dur}$.

In order to determine the minimum concrete cover by the environmental class and strength class (instead of construction class), this research assumes construction class S4 for concrete structures. Table D.9 shows the minimum concrete cover ($c_{min,dur}$) for reinforcing steel, which can be determined by the environmental class and the strength class [Eurocode 2, 2013].

Table D.7: Construction classes with starting point S4 for any concrete structure with a service life of 50 years. Adapted from Eurocode 2 [2013].

	X0	XC1	XC3	XC4	XD1	XS1
Service life (100+ years)	+2	+2	+2	+2	+2	+2
Strength class	≥ C30/37 - 1	≥ C30/37 - 1	≥ C35/45 - 1	≥ C40/50 - 1	≥ C40/50 - 1	≥ C40/50 - 1
Element with plate-geometry (position of reinforcement not affected by construction)	- 1	- 1	- 1	- 1	- 1	- 1
Quality control of the concrete production is guaranteed	- 1	- 1	- 1	- 1	- 1	- 1

Table D.8: Minimum concrete cover ($c_{min,dur}$) in mm, regarding durability. Adapted from Eurocode 2 [2013].

	X0	XC1	XC3	XC4	XD1	XS1
S1	10	15	15	20	25	25
S2	10	15	20	25	30	30
S3	10	15	25	30	35	35
S4	10	20	30	35	40	40
S5	15	25	35	40	45	45
S6	20	30	40	45	50	50

Table D.9: Minimum concrete cover ($c_{min,dur}$) in mm, considering S4. Adapted from Eurocode 2 [2013].

	X0	XC1	XC3	XC4	XD1	XS1
C20/25	15	15	30	35	40	40
C25/30	15	15	30	35	40	40
C30/37	15	15	30	35	40	40
C35/45	15	15	25	35	40	40
C40/50	15	15	25	30	35	35
C45/55	15	15	25	30	35	35
C50/60	15	15	25	30	35	35

Next to the minimum concrete cover regarding durability ($c_{min,dur}$), the concrete cover is needed to bond the reinforcement to the concrete ($c_{min,b}$). This allows the forces in the reinforcement to be properly transferred to the surrounding concrete. The minimum concrete cover regarding bonding ($c_{min,b}$) must be at least equal to the bar diameter (∅ or $∅_n$). The final concrete cover (c_{nom} in Figure D.2) can be calculated using the following relation in *mm*: [Braam et al., 2011, p. 41-43]

$$c_{nom} = max(c_{min,dur}; c_{min,b}; 10) + \Delta c_{dev} \tag{D.1}$$

where

c_{nom}	is the nominal/final concrete cover,
$c_{min,dur}$	is the minimum concrete cover regarding durability,
$c_{min,b}$	is the minimum concrete cover regarding bonding ($\geq$ ∅ or $∅_n$),
$\Delta\ c_{dev}$	is the design allowance for deviation.

For this research, the relation to determine the final concrete cover is simplified, because $c_{min,dur}$ for S4 is always more than 10 mm and $c_{min,b}$ is out of the scope of this research. Additionally, for simplicity of this research the concrete cover is assumed to be uniform on all sides. The simplified relation according to Eurocode 2 [2013] is as follows:

$$c_{nom} = c_{min,dur} + \Delta c_{dev} \tag{D.2}$$

where

c_{nom}	is the nominal/final concrete cover,
$c_{min,dur}$	is the minimum concrete cover regarding durability, considering S4 (Table D.9),
$\Delta\ c_{dev}$	is the design allowance for deviation (5 *mm* in the Netherlands according to NEN-EN 1992-1-1).

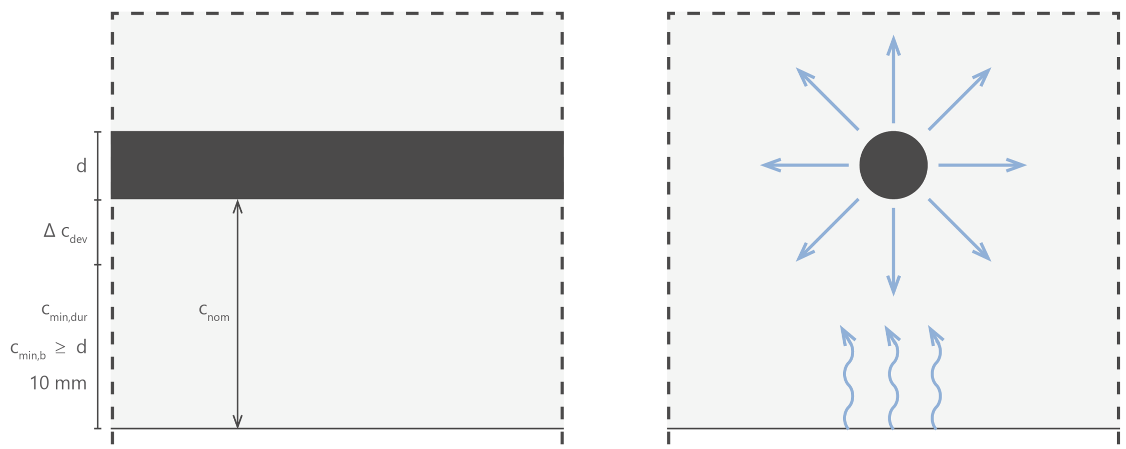


Figure D.2: Concrete cover. Left figure with c_{nom}, $c_{min,dur}$, $c_{min,b}$ and $\Delta\ c_{dev}$, right figure with bonding and penetrating species. Adapted from Braam et al. [2011, p. 42].

D.1.6 Reinforcing steel

Concrete usually includes steel rebars (reinforcement) to enhance its low tensile strength (Table D.4). Reinforcing steel has a characteristic yield strength (f_{yk}). From 2008, only yield strengths of 500 N/mm^2 are used in NEN-EN 1992-1-1. This is indicated by B500A, B500B and B500C which respectively indicate smooth, dented and ribbed surface. For the simplicity of this research, only the yield strength of reinforcing steel is considered.

In the case of reuse, different yield strengths occur due to older codes. As an example, in VB 74/84 and VBC 1990/1995 reinforcing steel was successively indicated by the letters FeB (where **Fe**rrum indicates iron and the **B** indicates Beton (= concrete in Dutch)) and a number which relates to the characteristic yield strength (f_{yk}) [Braam et al., 2011, p. 33-38]. How the material properties of reinforcing steel originating from 1950 till 2008 correspond to the yield strengths described in NEN-EN 1992-1-1 can be found at this website. Table D.10 shows the material properties of the different steel grades in N/mm^2, where

f_{yk} is the characteristic yield strength of reinforcing steel,
f_{yd} is the design value of the yield strength of reinforcing steel.

Table D.10: Material properties of reinforcing steel in N/mm^2 corresponding to older codes. Table originates from the Decision Support Tool and is adapted from Braam et al. [2011, p. 37].

Eurocode from 2008 (NEN-EN 206-1)	VB 74/84 VBC 1990/1995	GBV 1950 GBV 1962	f_yk [N/mm²]	f_yd [N/mm²] (= f_yk / 1,15)
	FeB 220	QR22	220	191
		QR24	240	209
		QR30	300	240*
		QR32	320	270*
		QR36	360	270*
	FeB 400	QRn40	400	348 / 330*
		QRn42	420	300*
		QRn48	480	330*
B500 (A/B/C)	FeB 500		500	435
		QRn54	540	330*

* A lower value for f_yd is determined than would follow from the allowable stresses in the original code and f_yk corresponding to NEN-EN 1992-1-1. Values are derived from Rijkswaterstaat (RWS).

D.2 Stage 2: Performance Testing

In this section, the composition and deterioration of the (structural) element are investigated.

D.2.1 Composition of the (structural) element

In order to assess the reuse value of components, it is relevant to know the exact composition of the material [Geldermans, 2016; Iacovidou and Purnell, 2016]. This section analyses which toxic materials can be present in the composition of (structural) concrete elements and which of them make reuse in a new project inapplicable. For example, if certain toxic materials were used in the production of the concrete, from which it is not preferred or allowed to use them anymore. The research of Van Berlo [2019] defines this as toxicity, where toxic materials are defined as unwanted materials inside the concrete which can affect the quality, health and environment. Materials that can form a risk for reuse are e.g., iron and composite fibres, asbestos, chlorides, immobilized waste material and, steel, phosphorous and blast furnace slag. For some elements information about the applied toxic materials is stored. If this is not the case, lab research is necessary to find out the exact composition, which is out of the scope of this research. However, toxic materials do not always affect concrete and are therefore not necessarily a bad feature regarding the composition. Subsequent subsections discuss the composition of concrete and the presence of toxic materials in fibres, admixtures and/or, slag. An overview is shown in Table D.11.

D.2.1.1 *Fibres*

Iron fibres
Iron fibres in building materials do not usually form a big risk for reuse. However, the fibres can corrode when visible on the surface of concrete and exposed to water, causing degradation to the concrete. Fortunately, these iron fibres can be visually detected on the surface of concrete as corrosion, as shown in Table D.11 [Van Dijk et al., 2018; Van Berlo, 2019].

Composite fibres
Composite fibres in concrete exist of multiple different materials which can make the concrete stronger, such as steel, glass, macro plastic and microplastic fibres. However, some composite fibres increase the risk of carbonation in concrete which can form a risk for reuse. Fortunately, these composite fibres can be visually detected on the surface of concrete as small strands, as shown in Table D.11 [Van Dijk et al., 2018; Van Berlo, 2019].

D.2.1.2 *Admixtures*

Asbestos
Asbestos has been used in the production of concrete and can mainly be found in cable tubes or water drainage systems. It can be assumed that no asbestos is present in concrete, if an asbestos-free declaration has been given after research or if concrete is produced after 1983 because since then asbestos in concrete was not allowed anymore [Van Berlo, 2019].

Chlorides
Until 1975, 1% to 2% chlorides were allowed as an admixture to the binder. These chlorides made the concrete harden faster and increased the production capacity. Therefore, chlorides were mainly added to prefab components. However, mixed-in chlorides seemed to have negative effects regarding the corrosion of the reinforcement. Therefore, elements containing chlorides should not be reused. In lab research, the exact amount of mixed-in chlorides can be measured, which is out of the scope of this research [Van Berlo, 2019].

Immobilized waste material
Immobilized waste material in concrete forms a risk for other building materials if the immobilized waste material is broken. However, it is possible to reuse only individual concrete elements with immobilized waste material in it [Van Dijk et al., 2018].

D.2.1.3 *Slag*

Steel slag

Steel slag is formed during the process of transforming raw steel or scrap into steel. This residue is recycled by adding it to the binder and coarse aggregates. Steel slag in building materials can form a risk for reuse because it has negative effects regarding the pH value of concrete. A lower pH value decreases the alkalinity of concrete, which means reinforcement is less protected and can therefore be more easily affected by external influences (e.g., corroding) [Van Dijk et al., 2018].

Phosphorous slag

Phosphorous slag is formed during the process of transforming phosphor ores into phosphor. This stone-like residue is recycled by adding it to the binder. In 1968, it was discovered that phosphorus slag is slightly radioactive depending on the used ores from certain production periods. The amount of radioactivity from phosphorous slags differs a lot which can form a risk for reuse. In order to make sure the radioactivity does not exceed a critical value, regulations were set [Van Dijk et al., 2018].

Blast furnace slag

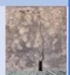
Blast furnace slag is formed during the blast furnace process in which iron is produced from iron ore. This residue is often recycled in the production of blast furnace cement (CEM III). Blast furnace slag in building materials can form a risk for reuse because it seems to have negative effects regarding the pH value of concrete which means it can have a strong effect on the leachability [Van Dijk et al., 2018].

D.2.1.4 *Conclusion*

As stated in the specifications of the Decision Support Tool, structural engineers should be able to perform the assessment in a relatively quick manner. Since all fibres, admixtures and slags form a different risk for reuse, not all need to be assessed for reuse of an element [Van Berlo, 2019]. Firstly, some of the toxic materials only form a risk for reuse if the element is crushed and recycled. These do not harm if kept inside the concrete. Secondly, some of the toxic materials require lab research to determine the presence inside concrete. This means it is unfeasible to retrieve needed information only by regular inspection (Stage 2). Thirdly, some of the toxic materials do not form a risk in buildings, but mostly for infrastructure or parking lots. Based on these criteria, only the following toxic materials are implemented in the Decision Support Tool (Table D.11):

- Iron fibres;
- Composite fibres;
- Asbestos;
- Chlorides.

Table D.11: Information about toxic materials which can be present in the composition of (structural) concrete elements. Table originates from the Decision Support Tool (own table).

	Toxic materials	Risk for reuse	Conditions	Where to find information?
Fibres	Iron fibres 	Iron fibres can degrade concrete when corroded	- Visible on the surface of concrete and exposed to water - Corrosion is detected on the surface	- Visual inspections - Inspection reports
	Composite fibres 	Some composite fibres can increase the risk of carbonation	- Visible on the surface of concrete by small strands - Materials in the composition cause carbonation	- Visual inspections - Inspection reports
Admixtures	Asbestos	The fibres of asbestos form a risk when concrete is worn, damaged or sawn	- The concrete is produced before 1983 - Cable tubes or water drainage systems are present - The element does not contain an asbestos-free declaration	- Material passport / drawings - Inspection reports
	Chlorides	Mixed-in chlorides can corrode reinforcing steel in concrete	- The concrete is produced before 1975 - The element is pre-cast - Negative effects on reinforcement corrosion are detected	- Material passport / drawings - Inspection reports
	Immobilized waste material		*- The admixture is broken (other materials can not be reused)*	For this research some toxic materials are out of scope, *(immobilized waste material, steel-, phosphorous- and blast furnace slag)*, because: - Some of them do no harm if kept inside the concrete; - Some of them require lab research to determine the presence inside the concrete; - Some of them do not form a risk in buildings, but mostly for infrastructure or parking lots.
Slags	*Steel slag*		*- Steel residue is recycled in binder and aggregates* *- Negative effects on pH value of concrete are detected*	
	Phosporous slag		*- Phospor residue is recycled in binder* *- The element is slightly radioactive (depending on production period)* *- The concrete is produced before 1968*	
	Blast furnace slag		*- Iron residue is recycled in binder* *- The type of cement is CEM III (blast furnace cement)* *- Negative effects on pH value of concrete are detected*	

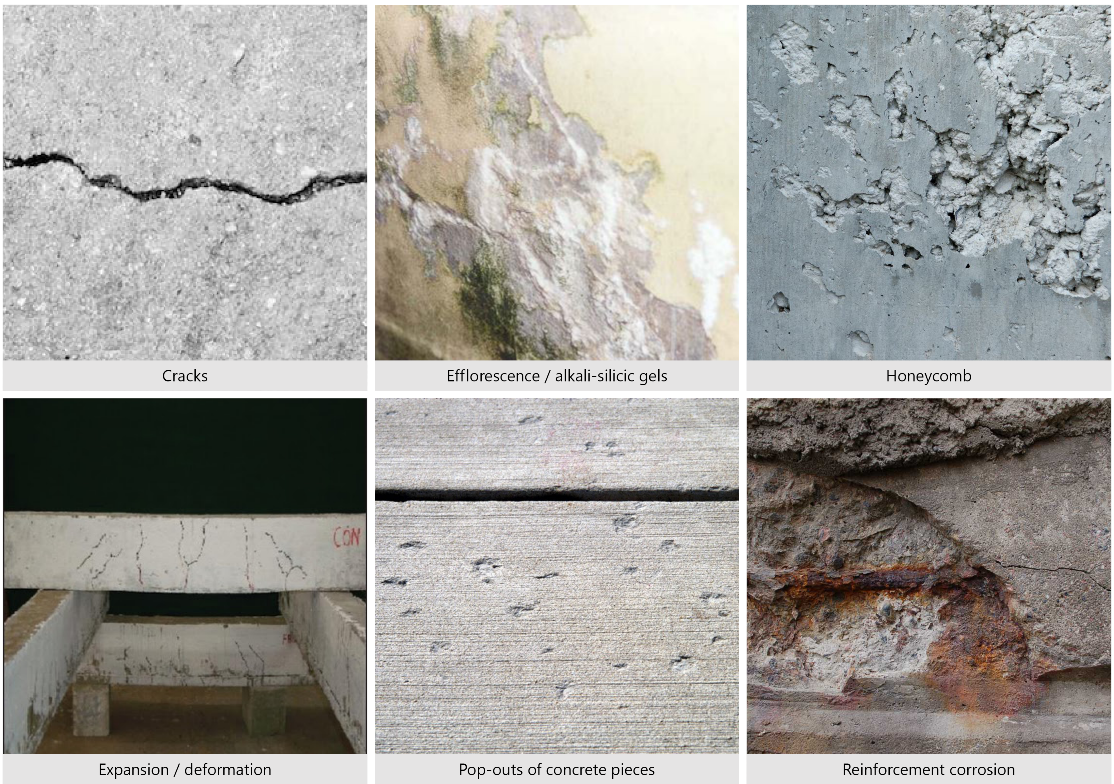


Figure D.3: Defects on the surface of existing concrete, which relates to the deal-breaker questions in subsection 5.1.1.3 (own figure).

D.2.2 Deterioration

Over time, concrete deteriorates due to internal or external sources. This section describes possible sources which make reuse in a new project inapplicable regarding internal and external deterioration.

D.2.2.1 *Internal deterioration*

The research of Van Berlo [2019] describes the following possible internal sources that can cause deterioration of concrete:

- Insufficient cement;
- Internal sulphate attack;
- Alkali-Silica Reaction (ASR).

<u>Insufficient cement</u>
As described in Appendix D.1.1, cement is considered insufficient if sulphate, magnesium oxide or chalk are present in surplus. Since this research only considers the main types of cement (CEM I, CEM II and CEM III) of NEN-EN 1992-1-1, it can be assumed that the requirements of NEN-EN 206-1 or NEN 3550 are met.

<u>Internal sulphate attack</u>
Sulphate attack can cause an expansive reaction. Internal sulphate attack forms a risk if the following three conditions are present: [Van Berlo, 2019, p. 18]

1. Cracks on the surface of concrete;
2. Sufficient sulphates in the aggregates;
3. Water.

In the Decision Support Tool, questions are formulated for each condition. Firstly, cracks are always present on the surface, because an internal sulphate attack can already happen through microcracks. Secondly, information about the presence of sulphates in the aggregates can be found by contract specifications (not standard). If unknown, lab research can be performed. However, sulphates have a very small chance in the Netherlands. Thirdly, the presence of water relates to e.g., a humid environment that can be exposed to at least fog or dew [Van Berlo, 2019]. Considering the environment of the element, this can be the case with environmental class XC3, XC4, XD1, XS1 or XF1.

If the three conditions are met, the Decision Support Tool warns for the risk of internal sulphate attack. Additionally, the advice is given to investigate the presence of internal sulphate attack.

<u>Alkali-Silica Reaction (ASR)</u>
Some aggregates in concrete can react with alkalis in the cementitious binder causing an Alkali-Silica Reaction (ASR), deteriorating the concrete. ASR often only shows itself after 5 to 10 years and is a combination of internal and external conditions. ASR became a known problem in 1989. However, the official recommendations to prevent ASR have been drawn up in 2002 [Van Berlo, 2019, p. 66]. Therefore, this research considers elements produced after 2002 to be resistant to ASR. ASR forms a risk if the following three conditions are present within the concrete: [Van Berlo, 2019, p. 17]

1. Temporarily or permanently moist (XC3, XC4, XD1, XS1, XF1);
2. Sufficient reactive silica in the aggregates (e.g., sodium or potassium ions);
3. Sufficient alkalis in the aggregates.

The presence of moist relates to the environmental class, whereas the presence of silica and alkalis in the aggregates depends on the type of cement. As an example, the chance of ASR is much lower in blast furnace cement (CEM III) than in Portland cement (CEM I or CEM II). However, it is not always known which type of cement has been applied in existing structures. Therefore, the handbook of ASR gives a guideline to easily justify the suspicion of the presence of ASR [Rademaker et al., 2002].

The four signs for visual inspection of ASR are based on:

- Cracks on the surface of the concrete (Figure D.4a);
- Presence of efflorescence or alkali-silicic gels (Figure D.4b);
- Expansion or deformation of the concrete;
- Pop-outs of concrete pieces.

In the Decision Support Tool, these signs for visual inspection are added to the deal-breaker questions of the condition of the element. If one of these questions is answered with "yes" (Figure 5.2), it is advised to investigate the presence of ASR. Additionally, the Decision Support Tool warns for the risk of ASR if the element is produced before 2002 and if moisture is present. However, in order to know for sure if ASR is present, field tests and drill samples need to be performed. Therefore, the Decision Support Tool advises investigating the presence of ASR and performing lab research.

(a) Typical crack pattern and brown-colour after ASR

(b) Flake-shaped efflorescence of ASR gels

Figure D.4: Visual inspection of the surface of concrete on Alkali-Silica Reaction [Rademaker et al., 2002, p. 25 & 51].

D.2.2.2 *External deterioration*

The research of Van Berlo [2019] describes the following possible external sources that can cause deterioration of concrete:

- Frost in combination with de-icing salts;
- Corrosion;
- Cracks;
- External sulphate attack;
- Penetration of chlorides;
- Penetration of carbonation.

<u>Frost in combination with de-icing salts</u>
The most important factor to determine if frost in combination with de-icing salts forms a risk is the Water-Cement Factor (wcf). No risks occur if wcf $< 0{,}45$. In case a higher factor is present in the concrete composition, the additional air content should be around 3,5-4,5 % [Van Berlo, 2019, p. 18]. Since de-icing salts are mostly used at infrastructure or parking lots, frost in combination with de-icing salts is out of the scope of this research.

<u>Corrosion</u>
Internal reinforcing bars can corrode due to chlorides or carbonation (Figure D.2). These penetrating species can deteriorate a concrete element and endanger the structural safety. Moreover, a corrosive or humid environment (air, water, acids etc.) increases the crack propagation rate and can thus reduce the fatigue life of reinforcement [Nussbaumer et al., 2018, p. 6]. Corrosion of internal reinforcing bars can be detected by visual inspections, or by knocking on the concrete (hollow sound). However, after corrosion has been detected it is recommended to investigate its severity because corrosion does not necessarily mean that the concrete element is endangered.

For example, when corrosion is only detected on a small part of an element, the severity is less compared to when corrosion is detected throughout the element [Van Berlo, 2019]. Examples of damage to the reinforcement due to corrosion are spalling, cracking and delamination (Figure D.5).

Therefore, the deal-breaker questions of the condition of the element also include corrosion. If there are any signs, the Decision Support Tool warns for the risk of corrosion and advises investigating the severity of reinforcement corrosion. A more accurate measurement can be done by Non-Destructive Testing (NDT). For corrosion, NDT can be done by 'potential measurements' where at one specific point reinforcement is opened as a reference value for the measurement. After the measurement has been carried out, the values are assessed and deviations are compared to the reference value. In this way, the presence and severity of corrosion can be determined accurately at the location of the measurement.

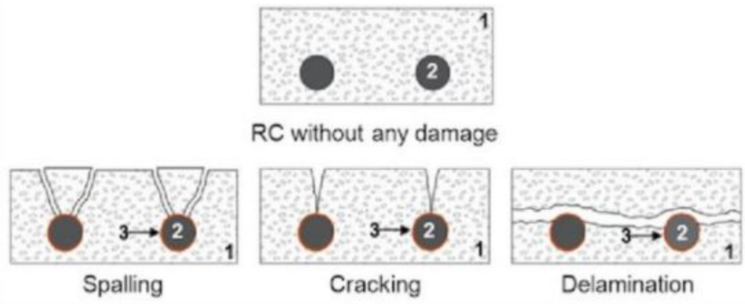


Figure D.5: Spalling, cracking and delamination of reinforced structures, with (1) concrete; (2) steel rebar; (3) corrosion oxides [Figueira et al., 2014, p. 45].

Cracks

Cracks indicate an element is constructively damaged. During visual inspection, cracks on the concrete surface are easily detected as described in the deal-breaker questions. After detection, it is recommended to investigate the severity of cracks, because cracks do not necessarily mean that the concrete element is endangered. This research analyses constructive cracks which are cracks that decreases the load-bearing properties of an element (e.g., due to a constructive overload). Regarding the severity of cracks, two relevant parameters are the cause and the width of the crack.

The cause means a constructive crack can be more dangerous than a regular crack. If the cause of the crack is detected, in most cases cracks can be repaired. Concrete can self-heal due to silting, hydration and swelling if the crack width is smaller than or equal to 0,2 mm. Therefore, these crack widths are considered the same as if there are no cracks visible [Van Berlo, 2019, p. 18].

However, if the crack width is more than 0,2 mm the structure needs to be checked from the point of view of the suitability for use of the structure. For reinforced elements, the crack width depends on the steel stress, bar diameter, bar distance, concrete cover, reinforcement ratio, concrete crack stress and loading situation (normal force and/or bending). NEN-EN 1992-1-1 section 7.3.1 gives limit values for the calculated crack width in regards to the environmental class: 0,4 mm for X0 and XC1, 0,3 mm for XC2-4 and 0,2 mm for XD1-3 and XS1-3.

The crack width can be measured with a crack map, crack magnifier, measurement grid or by monitoring (a so-called 'crack width meter'). In case an element is reused where (constructive) cracks are visible with a crack width of more than 0,2 mm, the Decision Support Tool warns for the risk of cracks. In this case, the crack width should be geared to the environmental class of the new design. Since lower limit values apply for a dry environment, a limit to the crack width is only set to ensure an acceptable appearance (according to NEN-EN 1992-1-1, section 7.3.1). In an aggressive climate, it can be more challenging to meet the crack width requirement. If the requirement is not met in the new design, several options are available: [Braam et al., 2011, p. 65-78].

- Apply more reinforcement (reduces steel stress)
- Apply a larger concrete cover than c_{nom} (leads to less strict crack width requirement). However, this is often uneconomical and should be avoided as much as possible, because (much) extra concrete is needed.

External sulphate attack

Besides internal sulphate attack, sulphate can penetrate from the outside causing an expansive reaction. According to NEN-EN 197-1, the following types of cement are sulphate resistant: CEM I-SR, CEM III/B-SR, CEM III/C-SR, CEM IV/A-SR and CEM IV/B-SR (= CEM I, CEM III/B and CEM III/C). Since the Decision Support Tool only states CEM I and CEM III to be sulphate resistant (so without any further specifications), an additional comment is given in the Decision Support Tool if the type of cement is not certified. It is then recommended to perform lab research to determine the type of cement.

In addition, concrete at or near the sea (< 25 km inland, indicated by environmental class 'XS'), is most susceptible to suffer external sulphate attack [Van Berlo, 2019, p. 18]. If CEM II is used, the Decision Support Tool warns for the risk of external sulphate attack and advises to investigate the penetration of sulphates. Additionally, in the new design (Stage 7) a question is added if the element is reused at or near the sea.

Penetration of chlorides

As described earlier, mixed-in chlorides seemed to have negative effects regarding the corrosion of the reinforcement. Besides admixtures, chlorides can penetrate through the surface in the case of de-icing salts or seawater. Since de-icing salts are mostly used at infrastructure or parking lots, penetration of chlorides does not often occur in buildings (especially not for indoor climate). This research considers that chloride penetration can only occur if an element has been used at or near the sea.

If the penetrating substance reaches the reinforcement, the reinforcement may begin to corrode. As described earlier, the residual lifespan can be determined based on the design service life, NEN 2627 and penetration of chlorides or carbonation. In the case of chlorides, it is calculated how much time it takes until the penetrating substance reaches the reinforcement [Van Berlo, 2019]. The residual lifespan based on chloride penetration can be calculated using the following relation: (CUR 121)

$$C(x,t) = C_s - (C_s - C_i) \cdot erf(\frac{x}{2 \cdot \sqrt{D_a \cdot t}} \tag{D.3}$$

where

C_s is the apparent chloride content,
C_i is the initial chloride content,
x is the chloride depth,
t is the age of the element,
D_a is the diffusion coefficient.

In order to retrieve this information, extensive research needs to be performed (with crushed drill samples and lab research). This is out of the scope of this research. If an element has been used at or near the sea, the Decision Support Tool asks if chloride penetration research is performed (in the past). If information is already available, it is worthwhile to include these results in the tool [Van Berlo, 2019]. If chloride penetration research has not been performed, it is recommended to perform such research to get more detailed information about the residual lifespan.

Penetration of carbonation

Carbonation can form a risk for reuse because it has negative effects regarding the pH value of concrete. A lower pH value decreases the alkalinity of concrete, which means reinforcement is less protected and can therefore be more easily affected by external influences. If the penetrating substance reaches the reinforcement, the reinforcement may begin to corrode. Additionally, a small concrete cover or low concrete quality increases the risk of corrosion due to carbonation reaching the reinforcement quicker [Volkov, 2019, p. 13].

The risk of carbonation-induced corrosion of the reinforcement is determined on site or in a laboratory by drill samples. Measures to prevent damage or to stop the penetrating substance can be e.g., the application of a new preservation layer every 5 to 10 years [Van Berlo, 2019].

The residual lifespan based on carbonation penetration can be calculated using the following relation: (CUR 121)

$$r = \left(\frac{c_{nom}}{\frac{x_c}{\sqrt{t}}}\right)^2 \tag{D.4}$$

$$x_c = A \cdot \sqrt{t} \tag{D.5}$$

where
r is the residual lifespan,
c_{nom} is the nominal concrete cover,
x_c is the carbonation depth (determined using phenolphthalein),
A is the empirical determined factor,
t is the age of the element.

Information for the residual lifespan based on carbonation penetration is not time-consuming and can easily be retrieved on site. Therefore, the Decision Support Tool asks if carbonation penetration research is performed (in the past). If information is already available, it is worthwhile to include these results in the tool. If carbonation penetration research has not been performed yet, it is recommended to perform a carbonation penetration research to get more detailed information about the residual lifespan. Additionally, the Decision Support Tool shows three questions related to equation D.4 which make it relatively easy to perform such research on site. According to CUR 72, the carbonation penetration depth (x_c) can be measured by drill samples. Another method is by a small massive drill, which takes less time to perform but is less accurate. It is also necessary to know how deep the reinforcement lies beneath the concrete (concrete cover). This can be measured with a reinforcement scanner which measures electromagnetic fields [Van Berlo, 2019].

In the ROK (Rijkswaterstaat, 2017) it is stated that the application of blast furnace cement with a percentage of more than 50% slag, or Portland fly ash cement (CEM II / BV) with a percentage of more than 25% coal fly ash gives (just as for ASR) the best resistance against chlorides and carbonation [Van Berlo, 2019]. In general, the damage caused by chlorides and carbonation will be less than expected in buildings. This is because penetrating substances (such as de-icing salts) especially occur at infrastructure or parking lots. However, the future development of damage should be taken into account in all cases.

D.2.2.3 *Conclusion*

As stated in the specifications of the Decision Support Tool, structural engineers should be able to perform the assessment in a relatively quick manner. Since the internal and external sources cause a different degree of deterioration, not all need to be assessed for reuse of an element [Van Berlo, 2019].

Firstly, some of the sources do not form a risk for buildings, but mostly for infrastructure or parking lots. Secondly, for some of the sources it is unfeasible to retrieve the needed information by only regular inspection (Stage 2), e.g. the wcf of concrete. Additionally, some of the sources are taken into account in environmental classes (Stage 1), e.g. the resistance against frost [Van Berlo, 2019]. Based on these criteria, only the following internal and external sources are implemented in the Decision Support Tool:

- Internal sulphate attack;
- Alkali-Silica Reaction (ASR);
- Corrosion;
- Cracks;
- External sulphate attack;
- Penetration of chlorides;
- Penetration of carbonation.

D.3 Stage 3: Deconstruction

In this section, the equipment to disconnect for reuse is investigated.

D.3.1 Equipment to disconnect

For the full and partial removal of reinforced concrete structures, several demolition technologies are available. The following demolition methods and corresponding equipment for concrete structures are studied, along with its advantages and disadvantages. For each equipment to disconnect, it is stated if reuse of the removed element is possible or not. An overview of the advantages and disadvantages is shown in Table D.21, which forms the basis for subsection 6.1.1.3.

- Demolition by hand (wire cutter, jackhammer);
- Demolition by machine-mounted attachments (crusher, hammer);
- Saw cutting (diamond blade saw, diamond wire cutter);
- Splitting (mechanical, chemical);
- Deliberate collapse (pre-cuts);
- Blasting (explosives);
- Ball and crane (wrecking ball);
- Hydrodemolition (water jet machine);
- Thermal demolition (thermal boring and cutting, electric heating).

Demolition by hand

In the past, one of the most applied demolition technologies for concrete structures was by hand. This was a labour-intensive activity where concrete structures were dismantled on a floor-by-floor downward sequence by equipped workers who cut and removed the (reinforced) concrete [Glias, 2013, p. 26-30]. Examples of hand-held percussion tools to partially remove concrete are wire cutters and jackhammers [Abudayyeh et al., 1998]. Their advantages and disadvantages are described in the following table.

A compressor with hammers can hack or drill connections. By hacking, the steel rebars are revealed and burned after which the element can be easily removed. Drilling also destroys the rebars and requires drawings to locate the rebars. Thereby, it should be taken into account that differences can occur between the project on site, construction and production drawings and calculations. An advantage of drilling compared to hacking is time. Additionally, drilling creates less damage to the connection. However, both methods need extra sawing later to modify the element to the desired dimensions [Glias, 2013, p. 65-66]. In the case of the removal of columns, the drilling machine has to be placed as low as possible to generate the least amount of damage. In order to aid the hoisting, a hammer can be used to disconnect thin layers [Jabeen, 2020].

Table D.12: Demolition by wire cutter or jackhammer (by hand).

	Advantages (Abudayyeh, 1998; Glias, 2013, p. 26-30; Zhu, 2019)	Disadvantages (Abudayyeh, 1998; Glias, 2013, p. 26-30; Zhu, 2019)	Is reuse possible?
1 Wire cutter (by hand)	• Limited skills required of operator (easy to operate) • Strong mobility • Effective in narrow and localised areas • Accurate removal • Well recycled materials	• Noise, dust and vibration • Time-consuming and labour-intensive (low efficiency) • Expensive (high demolition cost) • Crowd tactics (so requirements for engineering management are higher)	Yes
2 Jackhammer (by hand)	• Limited skills required of operator (easy to operate)	• Noise, dust and vibration • Time-consuming and labour-intensive (low efficiency) • Drawings needed • Need for protective measures for operator • Potential damage: microcracks in remaining concrete and degraded bond between rebar and remaining concrete Hack: burned rebars Drill: destroyed rebars	Yes

Nowadays, personnel are replaced by machinery which means demolition companies use expensive machines and hire less but more skilled workers, resulting in quicker, safer and cheaper demolition. Demolition by hand is still applied, e.g., on sites where machines cannot have access or where noise and vibration are restricted [Glias, 2013, p. 26-30].

Demolition by machine-mounted attachments

Demolition by machine-mounted attachments are excavators with specialist attachments. These can be used for small or larger demolition projects, but their use is restricted on sites with limited space due to the generation of large amounts of noise, dust, and vibrations [Zhu et al., 2019]. Crushers or hammers can be mounted on excavators or machines with high-reach booms. The latter allows for the demolition of areas not reachable by excavator booms or with restricted access [Glias, 2013, p. 26-30].

Firstly, crushers apply opposing forces on either side of a concrete member or reinforcement to demolish it effectively. These jaw-like attachments can remove large sections of concrete, cut through concrete and reinforcement and separate the concrete from the reinforcement [Abudayyeh et al., 1998]. The most used method in the Netherlands is a crane with a shear.

Secondly, hammers on excavators or high-reach booms should be properly matched. A hammer that is too heavy can damage an excavator and a hammer that is too small can unintentionally be damaged by an excavator operator. Hammers can be mounted on a heavily restrained leaf spring arm which is raised and swung downwards adding to the force with which the hammer strikes the concrete. Examples are hydraulic hammers, pneumatic hammers (powered by compressed air) or whip hammers (operated by fluid) [Abudayyeh et al., 1998]. With the use of hammers, complicated site conditions and other constraints should be taken into account.

Table D.13: Demolition by machine-mounted crusher or hammer.

	Advantages (Abudayyeh, 1998; Zhu, 2019)	**Disadvantages** (Abudayyeh, 1998; Zhu, 2019)	**Is reuse possible?**
3 Crusher (machine-mounted)	• No dust and vibration • Strong mobility • High production rate • Operable in inclement weather • Rapid cutting of reinforcement (not time-consuming) • Effective ability to separate concrete from steel • Can be used for loading debris into trucks for removal	• Noise • Degraded bond between rebar and remaining concrete	Yes
4 Hammer (hydraulic -, pneumatic -, whip-)	• Strong mobility • High production rate • Operable in inclement weather • Rapid cutting of reinforcement (not time-consuming)	• Noise, dust and vibration • Requires high energy unit per blow (whiphammers) • Can only be applied to buildings on relatively flat ground (so mind complicated site conditions and other constraints) • Need for adequate counter-weight • Need for protective measures for operator • Need for water spraying before and during demolition	Yes

Saw cutting

Saw cutting can be used to cut concrete elements into large segments, which can be easily hoisted by a crane or a winch to the ground for further demolition. For example, reinforced slabs and wall elements can be cut into segments, varying in thickness [Zhu et al., 2019]. Saw cutting generally includes blade saws or wire cutters which both are time-consuming and do not create a lot of damage. The most used blade saws are diamond-shaped which can be powered or driven by a combustion engine, electrically or hydraulically. The weight of the element may break the diamond blade. In order to avoid this, an option is to lift the element during sawing. On the one hand, this method is expensive, but on the other hand modifications costs can be reduced in case the desired dimensions are known, because it is possible to saw the element on size straight away [Glias, 2013, p. 65-66].

Another method to cut concrete is with (diamond) wire cutting. For the cutting process, a diamond-shaped wire is passed through a drilled hole in the concrete element. With the use of a steel coupling bead, the wire is then strung together and placed on the drive wheel. Production rates depend on the type of wire used, the type of aggregate and the amount of reinforcement.

In both methods a water source is needed during cutting to wash away the slurry and to cool the blade or wire, thereby preventing overheating [Abudayyeh et al., 1998]. A water collecting system can be applied to discharge polluted water and to minimize the negative impact on the project and the surrounding environment.

A case-study in China applied saw cutting during the demolition of a viaduct in combination with BIM technology. This resulted in faster cutting speed & shortening of the deconstruction period (without noise, dust and vibration). Both are great benefits for the design and implementation of saw cutting [Zhu et al., 2019].

Of the above cutting techniques, the most suitable for deconstruction is the diamond blade saw [Volkov, 2019, p. 10-11], which advantages and disadvantages are shown in the following table. During deconstruction safety measures should be taken for the loading of the remaining structure where the pieces are cut from and for the hoisting and lowering of the pieces to the ground for further demolition [Glias, 2013, p. 26-30]. Additionally, the diamond blade saw avoids damages to other elements [Volkov, 2019].

Table D.14: Demolition by saw cutting.

	Advantages (Abudayyeh, 1998; Zhu, 2019)	**Disadvantages** (Abudayyeh, 1998; Zhu, 2019)	**Is reuse possible?**
5 Diamond blade saw (saw cutting)	• No dust and vibration • Leaves clean, straight edges (accurate removal) • Reduced damage to other elements • Cutting and removal of large pieces preventing the creation of debris • Efficient dismantling • Limited skills required of operator (easy to operate) • Light and easy to transport the equipment • Economic	• Noise (plus additional safety requirements) • Slow procedure • Expensive • Cutting depths are limited • Not all shapes or patterns can be cut • Need for cooling water (and clean up) • Blade wear • Difficulties can arise when the blade comes in contact with reinforcement running parallel to the cut • The size and location of the reinforcement should be determined before starting (drawings needed)	Yes
6 Diamond wire cutter (saw cutting)	• All above mentioned advantages • Cutting depths are not limited (by e.g. the amount of reinforcement)	• Noise • Slow procedure • Expensive • Not all shapes or patterns can be cut • Need for cooling water (and clean up) • The diameter of the bead is slowly reduced as the cut progresses	Yes

Deliberate collapse

Another demolition technology is the deliberate collapse method, where key structural elements are weakened by pre-cuts leading to collapse of the structure by a crane with a wrecking ball or shear. This can also be done with pulling-/pushing forces, where the structure is dragged down by attached cables and a winching machine or hydraulic excavator. Both methods are fast techniques, but sufficient distance is needed from nearby structures. Additionally, the demolition procedure needs to be designed carefully to avoid accidents [Glias, 2013, p. 26-30].

Table D.15: Demolition by pre-cuts.

	Advantages (Glias, 2013, p. 26-30)	**Disadvantages** (Glias, 2013, p. 26-30)	**Is reuse possible?**
- Pre-cuts	• Fast speed	• Noise, dust and vibration • Need for substantial clear space • Careful design of procedure before starting	No

Splitting

Other demolition technologies can be mechanical or chemical splitting, where holes are drilled in the concrete in a predetermined pattern. Splitters can easily dismantle or pre-split large segments of concrete due to the low tensile strength [Zhu et al., 2019]. By mechanical splitting hydraulic pressure is applied in the drilled holes causing the concrete to expand and split. By chemical splitting agents which can expend (e.g., hydrated calcium oxide) are placed in the drilled holes [Abudayyeh et al., 1998]. The research of Zhu et al. [2019] refers to the chemical expansive agent as a green demolition method.

Table D.16: Demolition by mechanical or chemical splitter.

	Advantages (Abudayyeh, 1998; Zhu, 2019)	**Disadvantages** (Abudayyeh, 1998; Zhu, 2019)	**Is reuse possible?**
- Mechanical splitter	• No noise, dust and vibration • No flying debris (no explosive) • Small effect for surrounding environment • Non-expensive • Remaining concrete is undamaged • Accurate removal, efficient dismantling • High safety degree (lower hazards to operator) • Working continuously without interruption • Limited skills required of operator (easy to operate) • Can be used underwater	• Time-consuming • Requires the use of breakers to expose reinforcement for cutting • Splitter is usually employed as secondary means of separating and removing the concrete	No
- Chemical splitter	• All above mentioned advantages, except for non-expensive	• Time-consuming (more than mechanical splitters) • Expensive (more than mechanical splitters or explosives) • Need for adequate protective measures for operator • Reinforcement is cut	No

<u>Blasting</u>

Blasting is a method of complete structural removal which has been used for years. Blasting is ideal for deteriorated concrete structures that suffered prior damage (due to fire, earthquake or deteriorated concrete) or when time is critical. By blasting structural elements are demolished by the detonation of explosives in controlled fractures which ensures easy concrete removal [Zhu et al., 2019]. Blasting can be done with charged drill holes that are electrically detonated or by laying an explosive charge covered by sandbags on the element. After detonation, large volumes can be removed in one piece for later pulverizing in a controlled environment [Abudayyeh et al., 1998].

Blasting can also be used for partial demolition or localized cutting. This is referred to as mini-blasting which can ensure concrete removal without damaging the remaining concrete or surrounding environment. Additionally, mini-blasting is effective in areas with closely spaced reinforcement (unlike conventional hammering) and large volumes can be removed in one piece for later pulverizing in a controlled environment [Abudayyeh et al., 1998]. Blasting is considered to be very dangerous due to dangers in handling or usage, which make the process immensely complex. Therefore, blasting requires more stringent controls than any other method [Zhu et al., 2019]. Additionally, this method requires sufficient space and a careful assessment of the impacts on the area. The use of explosives is restricted in the Netherlands because the shock caused by the implosion can damage concrete piles of nearby buildings due to the soft soil [Glias, 2013, p. 26-30].

Table D.17: Demolition by explosives.

	Advantages (Glias, 2013, p. 26-30; Zhu, 2019)	**Disadvantages** (Glias, 2013, p. 26-30; Zhu, 2019)	**Is reuse possible?**
- Explosives (blasting)	• Fast speed • Non-expensive • Removing large volumes in one piece	• Noise, dust and vibration (shot duration) • Flying debris • Inherent danger associated with blasting	No

<u>Ball and crane</u>

One of the oldest methods for building demolition is a wrecking ball connected to a crane which is swung or dropped into the building to be demolished. Concrete elements break into smaller pieces. However, additional cutting of reinforcement may be necessary before the building can be removed from the site [Zhu et al., 2019]. This method requires an experienced crane operator to handle the ball and safety measures for the falling debris. Nowadays, this method is not used anymore in the Netherlands [Glias, 2013, p. 26-30].

Table D.18: Demolition by wrecking ball.

	Advantages (Zhu, 2019)	Disadvantages (Zhu, 2019)	Is reuse possible?
- Wrecking ball	• High safety degree (lower hazards to operator)	• Noise, dust and vibration (shot duration) • Need for water spraying before and during demolition • Need for sufficient clear space • Need for control of the swing of the ball (highly skilled operator is required)	No

Hydrodemolition

Another demolition technology is hydrodemolition, which removes and cleans deteriorated and sound concrete with the use of high-pressure water jet machines. The removal or cleaning of unwanted matter from the concrete surface involves a blast of water, with or without the addition of other liquids or solid particles, in a controlled manner [Warner, 1998]. In demolition the process is used, e.g., for cutting out concrete from around steel reinforcing bars where the latter are to remain. This means the water jet has the potential to preserve reinforcement for reuse within the concrete removal area [Zhu et al., 2019]. However, rebar shadow problems can occur in situations where the reinforcement acts as a shield, obstructing the removal of concrete below the bar [Abudayyeh et al., 1998].

Parameters that influence the depth of removal are the standoff (spacing between the nozzle and object to be cut), the number of passes, cutting speed and the strength of the concrete. Deteriorated concrete is easily removed by hydrodemolition, whereas dense, homogeneous concrete is not [Abudayyeh et al., 1998]. On one hand, hydrodemolition includes selective removal without damaging the remaining concrete, but on the other hand, surrounding concrete of lower quality or strength can be cut if the water jet is uncontrollably used [Warner, 1998]. It should also be considered that rebars exposed to high-pressure water can suffer low cycle flexural fatigue from vibration [Hyland and Ouwejan, 2017].

Over the last decade, the water jet has greatly improved, and it is now becoming competitive with some of the other removal devices. Modern machines can be programmed to remove as much or as little concrete as required [Abudayyeh et al., 1998]. The advantages of hydrodemolition over hammering are described in the following table.

Table D.19: Demolition by water jet machine.

	Advantages (Abudayyeh, 1998; Zhu, 2019)	Disadvantages (Warner, 1998; Zhu, 2019)	Is reuse possible?
7 Water jet machine (hydrodemolition)	• Not labour-intensive (minimum) • No noise, dust and vibration • High production rate • Very accurate removal • Reinforcement is cleaned of scale and rust • Remaining concrete surface is irregular allowing good mechanical bonding to new overlay	• 'Rebar shadow' problems • Expensive • Need of large quantities of water • Need clean up and safely disposal of the water mixed with debris • Dangerous due to high pressures used (highly skilled operator is required) • Need for adequate protective measures for operator	Yes

Thermal demolition

A fairly new technology with the potential to partially remove concrete is thermal demolition. Alloys are ignited to obtain high temperatures to heat and melt concrete and rebars [Zhu et al., 2019]. Thermal demolition can be grouped into three categories: thermal boring-cutting, cracking-peeling and breaking-peeling. Thermal boring and cutting at a high temperature is used to heat and melt concrete. The cutting speed depends on the quality of the concrete, type of aggregates, the amount of reinforcement, operator skill and the smoothness of discharge of the molten slag [Abudayyeh et al., 1998].

Cracking-peeling and breaking-peeling can be referred to as electric heating which is a green demolition method according to Zhu et al. [2019], where the concrete cover is cut open to expose the reinforcement. By using a hammer or chisel, concrete around a continuous crack can be e.g., easily removed. Next, the reinforcement is electrically heating resulting in expansion of the rebars and delamination of the surrounding concrete. This produces tensile stresses breaking the bond between the rebars and concrete. Instead of direct heating, the rebars can also be exposed to an alternating magnetic field with induction heaters on the concrete surface. The resulting loss of resistance is used to heat the steel reinforcement and crack the concrete.

Table D.20: Demolition by thermal boring/cutting and electric heating.

	Advantages (Abudayyeh, 1998; Zhu, 2019)	**Disadvantages** (Abudayyeh, 1998; Zhu, 2019)	**Is reuse possible?**
8 Thermal boring and cutting (thermal demolition)	• No noise, dust or vibration • Can be used in places that are not easily accessible • Can be used underwater • Not hampered by the presence of steel plates or steel frames	• Costly (compared to mechanical methods) • Generates large amount of fumes (fire hazard) • Need for adequate protective measures for operator	Yes
9 Electric heating (thermal demolition)	• No noise, dust or vibration • Limited skills required of operator (easy to operate) • Easier to set coils on the concrete surface (compared to thermal boring) • Non-explosive • High safety degree (lower hazards to operator) • Protect environment	• Need to cut open the concrete cover • Induction heaters are expensive and need cooling • Requires high-power equipment to heat steel reinforcement with a thick concrete cover • Need for additional equipment (e.g. hammer or chisel)	Yes

Green demolition methods

Traditional demolition technologies have many problems such as noise, dust, and vibration, which often lead to negative impacts on the project and surrounding environment. These bad effects conflict with the requirement of green environmental protection, especially in populated areas of cities. Therefore, green demolition technologies of reinforced concrete structures have been widely developed. Already discussed are the electric heating method and the chemical expansive agent. Other novel, eco-friendly green demolition technologies include: [Zhu et al., 2019]

- High-voltage pulse technology
- Resonance demolition method
- Cut & down construction method
- Drilled core demolition technology
- Intelligent robot demolition technology

Table D.21: Overview of advantages and disadvantages of equipment to disconnect where V = 1 and X = 0. Overview is useful if the structural engineer can affect decisions on how to disconnect (so when element is still in a demolition project). Adapted from Abudayyeh et al. [1998]; Glias [2013]; Hyland and Ouwejan [2017]; Warner [1998]; Zhu et al. [2019].

	Drawings needed?	Easy to operate?	Protective measures?	Mobility?	Production rate?	Time consuming?	Noise?	Dust?	Vibration?	Create debris?	Costs?	Weather dependent?	Applicability / accessibility?	Other?
1 Wire cutter (by hand)	×	✓	✓	✓	×	✓✓	✓✓	✓✓	✓	✓	€€	×	On sites where machines cannot have access or with restrictions	Effective in narrow and localised zone
2 Jackhammer (by hand)	✓	✓	✓	✓	×	✓✓	✓✓	✓✓	✓	✓	€	×	On sites where machines cannot have access or with restrictions	
3 Crusher (machine-mounted)	✓	✓	×	×	✓	×	✓✓	✓	×	✓✓	€€	✓	High-reach booms access more (restricted) areas Can only be applied to sites with enough space	Effective ability to separate concrete from steel Can also be used for loading debris into trucks for removal
4 Hammer (machine-mounted)	✓	✓	✓	✓	✓	✓	✓✓	✓	✓	✓✓	€	✓	Can only be applied to buildings on flat ground and to sites with enough space	Need for adequate counter-weight Need for cooling water Requires high energy per blow (whipham.)
5 Diamond blade saw (saw cutting)	✓	✓	✓	×	✓	✓	✓	×	×	✓	€	×		Need for cooling water (and clean up) Wear of blade
6 Diamond wire cutter (saw cutting)	×	✓	✓	×	✓	✓	✓	×	×	✓	€€	×		Need for cooling water (and clean up) Wear of bead's diameter
7 Water jet machine (hydro)	✓	×	✓	✓✓	✓	×	×	×	×	✓✓✓	€€€	×		Need of large quantities of water 'Rebar shadow' problems Need clean up
8 Boring and cutting (thermal)	✓	✓	✓	✓✓	×	✓	×	×	×	✓✓	€€€	×	Can be used in places that are not easily accessible Can be used underwater	
9 Electric heating (thermal)	✓	✓	×	✓✓	×	✓	×	×	×	✓✓	€€€€	×		Need for cooling induction heaters Requires high-power equipment to delaminate a thick concrete cover

D.4 Stage 7: Construction

In this section, the reconnecting of harvested structural elements is investigated.

D.4.1 RE-connect

As described in Section 7.1, a second-hand element can be reconnected to another second-hand element or to a newly-made element. The research of [Volkov, 2019, p. 14-16] shows the most relevant modular systems with prefabricated slabs and columns. The connections of these building systems form a starting point for his research on how second-hand elements can be connected to the rest of a (new) structure. For this research, options for connecting newly prefabricated elements to each other are analysed for each type of reconnection. Subsequently, it is analysed how the connection can be realized with second-hand elements. This is referred to as the 'reconnecting design proposal(s)' which takes into account the different equipment(s) to reconnect.

The equipments to reconnect are designated with the easiness of putting in practice, referred to as the 'complexity / laboriousness' of the reconnection. Regarding the easiness of putting the reconnection in practice, a level is given for each design proposal ranging between 'simple', 'medium' and 'complex'. These levels are subjectively assigned by the author of this research and based on the research of Volkov [2019]. Additionally, it is investigated if the reconnection is a wet or dry joint. Moreover, the adaptation of harvested (structural) elements can be identified as with or without added provisions like plates, anchors, bars, etc. The following combinations of reconnecting are possible: [Volkov, 2019, p. 28]

- Wet joint without added provisions;
  Only possible in case the original rebars are not disconnected at the same position as the concrete.

- Wet joint with added provisions;
  Possible in case the original rebars are disconnected at the same position as the concrete. Usually, steel parts have to be inserted and/or added.

- Dry joint without added provisions;
  Only possible in case the harvested (structural) element does not need any anchoring or grouting (i.e., mechanical dowel-type connection, difficult to put in practice).

- Dry joint with added provisions;
  Possible in case the harvested (structural) element is deliberately adapted.

D.4.1.1 *Beams*

Methods to reconnect a harvested (structural) beam.

(1) Beam-to-column. Adapted from Volkov [2019, p. 63-70].
Common methods for connecting newly made beams to columns:

- Half-beams on corbels

Reconnecting design proposals:

- Connection by anchoring the bottom reinforcement (simply supported)
  - Advantages: easy mounting on site, simple design, no reduction of beam length;
  - Drawbacks: need to bare reinforcement, need for adding couplers;
  - Other: simple complexity, wet joint, with added (steel) provisions.

(2) Beam-to-beam. Adapted from Volkov [2019, p. 70-72].
Common methods for connecting newly made beams to beams:

- Anchor reinforcement

Reconnecting design proposals: = simple/medium/complex

- Intermediate connection by anchoring the top reinforcement (continuous behaviour)
  - Advantages: relatively easy mounting on site, aesthetically attractive;
  - Drawbacks: need to bare reinforcement, precision and quality of welding is necessary, failure possibility of welds should be accounted for, reduction of beam length, mostly applicable between beams with similar bar layouts;
  - Other: medium complexity, wet joint, with added (steel) provisions.

D.4.1.2 *Columns*

Methods to reconnect a harvested (structural) column.

(3) Column-to-beam. Adapted from Volkov [2019, p. 44-45].
Common method for connecting newly made columns to beams:

- Columns are provided with corbels to lay beams on

Reconnecting design proposals:

- Connection in sleeve couplers
  - Advantages: no need for steel provisions, completely monolithic result, aesthetically attractive;
  - Drawbacks: need for precise concrete drilling, not suitable for eventual further reuse;
  - Other: medium complexity, wet joint, without added (steel) provisions.

(4) Column-to-column. Adapted from Volkov [2019, p. 35-59].
Common methods for achieving a column-to-column:

- Connection through anchored end-plates on both ends;
- Grouted connection by means of coupling sleeves.

Reconnecting design proposals:

- Connection in sleeve couplers
  - Advantages: no need for steel provisions, completely monolithic result, aesthetically attractive;
  - Drawbacks: need for precise concrete drilling, not suitable for eventual further reuse;
  - Other: medium complexity, wet joint, without added (steel) provisions.
- Connection by means of adding steel column shoes
  - Advantages: easy mounting on site, suitable for eventual further reuse;
  - Drawbacks: need for precise concrete drilling, need for steel provisions, failure of shoes should be accounted for;
  - Other: complex, dry joint, with added (steel) provisions.
- Connection by means of a steel end-plate
  - Advantages: easy mounting on site, no need to drill sleeves;
  - Drawbacks: need to bare reinforcement, precision and quality of welding is necessary, failure possibility of plates, bolts and welds should be accounted for;
  - Other: medium complexity, dry joint, with added (steel) provisions.
- Connection by re-casting the concrete cover
  - Advantages: less need to precisely cut concrete, no need to drill sleeves, allows for reinforcement inspection;
  - Drawbacks: need for formwork, increased concrete cover, aesthetically relatively unattractive;
  - Other: simple complexity, wet joint, without added (steel) provisions.

(5) Column foot joint. Adapted from Volkov [2019, p. 34-62].
Common methods for connecting newly made columns to foundation block:
- Connection through anchored end-plate;
- Grouted connection by means of coupling sleeves.

Reconnecting design proposals:
- Connection in sleeve couplers
  - Advantages: no need for steel provisions, completely monolithic result, aesthetically attractive;
  - Drawbacks: need for precise concrete drilling, not suitable for eventual further reuse;
  - Other: medium complexity, wet joint, without added (steel) provisions.
- Connection by means of adding steel column shoes
  - Advantages: easy mounting on site, suitable for eventual further reuse;
  - Drawbacks: need for precise concrete drilling, need for steel provisions, failure possibility of shoes should be accounted for;
  - Other: complex, dry joint, with added (steel) provisions.
- Connection by means of a steel end-plate
  - Advantages: easy mounting on site, no need to drill sleeves;
  - Drawbacks: need to bare reinforcement, precision and quality of welding is necessary, failure possibility of plates, bolts and welds should be accounted for;
  - Other: medium complexity, dry joint, with added (steel) provisions.
- Connection by re-casting the concrete cover
  - Advantages: less need to precisely cut concrete, no need to drill sleeves, allows for reinforcement inspection;
  - Drawbacks: need for formwork, increased concrete cover, aesthetically relatively unattractive;
  - Other: simple complexity, wet joint, without added (steel) provisions.
- Connection in external concrete 'pocket'
  - Advantages: easy mounting on site, no need to drill sleeves, non-laborious adaptation of column;
  - Drawbacks: need for formwork (for foundation block), laborious adaptation of foundation, aesthetically relatively unattractive (if pocket above floor level);
  - Other: medium complexity, wet joint, without added (steel) provisions.

D.4.1.3 *Shear walls*

Methods to reconnect a harvested (structural) wall.

(6) Wall-to-wall (vertical connection). Adapted from Volkov [2019, p. 80-85].
Common methods for connecting newly made walls to walls (shear walls):
- Loops of reinforcement bars at the end of the element ('shear keys')

Reconnecting design proposals:
- Connection by re-casting a whole side portion
  - Advantages: final result reminds a newly made element, aesthetically attractive;
  - Drawbacks: need to remove concrete from wall portion, precision and quality of welding is necessary, need to re-cast a wall portion, need for steel provisions;
  - Other: simple complexity, wet joint, without added (steel) provisions.

(7) Wall-to-wall (horizontal connection) Adapted from Volkov [2019, p. 75-80].
Common methods for connecting newly made walls to walls:
- Coupling bars

Reconnecting design proposals:
- Connection in sleeve couplers
  - Advantages: no need for steel provisions, easy/common mounting on site, aesthetically attractive;
  - Drawbacks: need for precise concrete drilling, not suitable for eventual further reuse, compromised out-of-plane stability;
  - Other: medium complexity, wet joint, without added (steel) provisions.

(8) Wall foot joint Adapted from Volkov [2019, p. 76-78].
Common methods for connecting newly made walls to foundation block:
- Coupling bars

Reconnecting design proposals:
- Connection in sleeve couplers
  - Advantages: no need for steel provisions, easy/common mounting on site, aesthetically attractive;
  - Drawbacks: need for precise concrete drilling, not suitable for eventual further reuse;
  - Other: medium complexity, wet joint, without added (steel) provisions.

D.4.1.4 *Slabs*

Methods to reconnect a harvested (structural) slab, considering Hollow Core Slabs (HCS) and predalles slabs (PS).

(9) HCS-to-wall. Adapted from Volkov [2019, p. 90-98].
Common methods for connecting newly made HCS to wall:
- Connection bars into hollowed-out cores

Reconnecting design proposals:
- Connection in hollowed-out cores
  - Advantages: simple design, aesthetically attractive;
  - Drawbacks: not suitable for eventual further reuse, not suitable for use with second-hand wall;
  - Other: simple complexity, wet joint, with added (steel) provisions.
- Connection to a wall by means of L-profile
  - Advantages: adds freedom of architectural design, ductile joint behaviour;
  - Drawbacks: need for steel provisions, aesthetically unattractive, dimensioning of L-profile needed;
  - Other: medium complexity, wet joint, with added (steel) provisions.

(10) HCS-to-HCS (longitudinal connection). Adapted from Volkov [2019, p. 98-103].
Common methods for connecting newly made HCS to HCS:
- Compression struts (vertical shear connection) and transversal bars (horizontal diaphragm action);
- Insertion of a steel bar in between the 'keyed joints' (lateral voids of the elements to be jointed).

Reconnecting design proposals:
- Connection in C-gaps
  - Advantages: simple design, no need for steel provisions, aesthetically attractive;
  - Drawbacks: not suitable for eventual further reuse, requires further studies on effectiveness;
  - Other: simple complexity, wet joint, without added (steel) provisions.
- Connection in V-gaps with added steel plate
  - Advantages: ductile joint behaviour, suitable for further reuse, good horizontal shear resistance;
  - Drawbacks: need for precise concrete drilling, need for steel provisions, aesthetically unattractive;
  - Other: complex, wet joint, with added (steel) provisions.

(11a) HCS-to-(shallow or integrated) beam. Adapted from Volkov [2019, p. 92-96].
Common methods for connecting newly made HCS to beam

- Connection bars into hollowed-out cores

Reconnecting design proposals:

- Connection in hollowed-out cores
  - Advantages: simple design, aesthetically attractive;
  - Drawbacks: not suitable for eventual further reuse;
  - Other: simple complexity, wet joint, with added (steel) provisions.
    * In case of shallow beam: need to perform U-voids into the beam
    * In case of integrated beam: need to add shear studs on the beam

(11b) PS-to-(shallow) beam. Adapted from Volkov [2019, p. 103-106].
Common methods for connecting newly made predalles slabs to (shallow) beam

- Protruding stirrups of the beam

Reconnecting design proposals:

- Connection in U-voids
  - Advantages: simple design, easy mounting on site, most of the adaptation is done in factory;
  - Drawbacks: not suitable for eventual further reuse, need for precise concrete breaking
  - Other: medium complexity, wet joint, with added (steel) provisions.

D.4.2 Conclusion of reconnect

An overview of the possible 'reconnecting design proposals' per type of reconnection can be found in Table 7.2. Additionally, an overview of the advantages, drawbacks and other per equipment to reconnect can be found in Table 7.3. Besides the relative merits, each equipment to reconnect comes with a general procedure that requires adaptation of the second-hand element. This is described in the following section, where the adaptation of the second-hand element is coloured in yellow. Based on the relative merits, general procedure and adaptation, the person who executes the method can select the preferred equipment to reconnect. This is described in Appendix D.4.

D.4.2.1 *General procedure to reconnect and adaptation*

Table D.22: Reconnecting with anchored bottom reinforcement (A).

Anchor bottom reinforcement	(Volkov, 2019, p. 67)
Applicable to	Beam-to-column, beam-to-beam, column splice joint
Step 1.	Remove the end margin quantity (e_m) to expose longitudinal rebars of the bottom and/or top bars. If present, also remove eventual shear stirrups.
Step 2.	Roughen the end surface of the second-hand element (if not rough enough after disassembling). This is done in order to ensure sufficient bonding in the (grouted) connection with the other concrete element.
Step 3.	Install the coupler and anchorage bar (on site).
Adaptation of the second-hand element is accomplished.	
Step 4.	Install the neoprene bearings on the other element (e.g. column edge).
Step 5.	Place the second-hand element (beam) on the bearings of the other element in its final position.
Step 6.	Grout the gap between the two elements with low-shrinkage concrete. Once fully hardened, the connection is achieved.

Table D.23: Reconnecting with anchored bottom and top reinforcement (B).

Anchor bottom and top reinforcement	(Volkov, 2019, p. 71, 73)
Applicable to	Beam-to-column, beam-to-beam, column splice joint
Step 1.	Remove the end margin quantity (e_m) to expose longitudinal rebars of the bottom and/or top bars. If present, also remove eventual shear stirrups.
Step 2.	Roughen the end surface of the second-hand element (if not rough enough after disassembling). This is done in order to ensure sufficient bonding in the (grouted) connection with the other concrete element.
Step 3.	Install the coupler and anchorage bar (on site). If welding is needed, this is more likely to be done in the factory.
Adaptation of the second-hand element is accomplished.	
Step 4.	Install the neoprene bearings on the other element or install the jacks which support the two elements during execution (if needed).
Step 5.	Place the second-hand element (beam) in its final position on the bearings of the other element or on the jacks.
(Step 6.)	If needed, install the connection bars to the correct length and in their final position between the bottom and top reinforcement.
(Step 7.)	If needed, weld the connection bars to the protrusions of the bottom and top reinforcement.
Step 8.	Grout the gap between the two elements with low-shrinkage concrete. Once fully hardened, the connection is achieved.

Table D.24: Reconnecting with anchored end-plate (C).

Anchored end-plate	(Middeldorp, 2017; Volkov, 2019, p. 52, 54)
Applicable to	Beam-to-column, column-to-beam, column splice joint, column foot joint, wall-to-wall (horizontal) Most common for push and pull rods (druk- en trekstaven)
Step 1.	Remove the end margin quantity (e_m) to expose longitudinal rebars. This is done in order to be able to reach the point where the end-plate will be welded. If present, also remove shear stirrups (sequal in step 3).
Step 2.	Weld the steel end-plate to the longitudinal rebars to ensure anchorage of the reinforcement.
Step 3.	Replace the (eventually) removed shear stirrups with new ones.
Step 4.	Re-cast this part of the second-hand element with new concrete. After this, the second-hand element looks exactly as in the connection between pre-cast elements.
Adaptation of the second-hand element is accomplished.	Two options are possible: the steel end-plate can be connected to another element or additional steel provisions are welded to the steel end-plate.
Step 5.	If needed, position a shim plate between the two elements to be connected or adjust the levelling nuts on the anchors.
Step 6.	Place the second-hand element on the other element in its final position (with threaded anchors).
Step 7.	Insert the bolts into the holes and tighten the nuts.
Step 8.	Grout the gap between the two elements with low-shrinkage concrete. Once fully hardened, the connection is achieved.

Table D.25: Reconnecting with C-gaps (D).

C-gaps	(Volkov, 2019, p. 101)
Applicable to	Slab-to-slab (longitudinal) Most common for hollow core slabs (HCS)
Step 1.	Cut the longitudinal side of the second-hand slab in a slight angle with the vertical (if this has not been achieved during disassembling). The cut should pass through a void of a hollow core;
Adaptation of the second-hand element is accomplished.	
Step 2.	Insert a steel bar into the achieved void.
Step 3.	Grout the C-gap with low-shrinkage concrete. Once fully hardened, the connection is achieved.

Table D.26: Reconnecting with external pocket (F).

External pocket	(Volkov, 2019, p. 60)
Applicable to	Column foot joint, wall foot joint
Step 1.	Prepare a reinforced concrete 'pocket' with an internal diameter slightly larger than the second-hand element and with holes for grouting (bottom part).
Step 2.	Position a shim plate between the two elements to be connected. This is done to keep the end slightly elevated for efficient grouting.
Step 3.	Place the second-hand element inside the 'pocket' in its final location.
Step 4.	Grout the column inside the 'pocket' with low-shrinkage concrete by injecting through the holes of the 'pocket'. Once fully hardened, the connection is achieved.

Table D.27: Reconnecting with hollowed out cores (G).

Hollowed-out cores	(Volkov, 2019, p. 91)
Applicable to	Slab-to-wall Most common for hollow core slab (HCS) to corbel or flange of beam
Step 1.	Break the top of the hollow cores in which the connection bars will be positioned to the required length to be grouted (usually around two per slab).
Step 2.	Block the ends of these hollow-out cores with plastic caps to prevent the grouting concrete from spreading or pouring out.
Adaptation of the second-hand element (HCS) is accomplished.	
Step 3.	Install the neoprene bearings in the correct position on the corbel or on the flange of the beam;
Step 4.	Place the second-hand slab on the bearings of the other element in its final position.
Step 5.	Insert the connection bars into the hollowed-out cores.
(Step 6.)	If needed, weld the connection bars to the protrusions of the other element;
Step 7.	Grout the gap between the elements and the hollowed-out cores and connection bars with low-shrinkage concrete. Once fully hardened, the connection is achieved.

Table D.28: Reconnecting with L-profile (H).

L-profile	(Volkov, 2019, p. 97)
Applicable to	Slab-to-wall Most common for hollow core slab (HCS) to corbel or flange of beam
Step 1.	Break the top of the hollow cores in which the connection bars will be positioned to the required length to be grouted (usually around two per slab).
Step 2.	Block the ends of these hollow-out cores with plastic caps to prevent the grouting concrete from spreading or pouring out.
Adaptation of the second-hand element (HCS) is accomplished.	
Step 3.	Embed anchors inside the other element (wall). Connect the L-profile on the outside of the wall by tightening the nuts.
Step 4.	Place the second-hand element on the L-profile of the other element in its final position.
Step 5.	Screw threaded couplers on the embedded anchors and nuts.
Step 6.	Insert the connection bars into the hollowed-out cores and tighten with the threaded steel couplers.
Step 7.	Grout the gap between the elements and the hollowed-out cores and connection bars with low-shrinkage concrete. Once fully hardened, the connection is achieved.

Table D.29: Reconnecting with re-cast concrete cover (I).

Re-cast concrete cover	(Volkov, 2019, p. 56)
Applicable to	Column splice joint, column foot joint, wall-to-wall (horizontal)
Step 1.	Break the concrete cover in which the overlapping rebars will be positioned (avoid damaging the reinforcement bars). If present, also remove eventual shear stirrups (sequal in step 4).
Step 2.	Position a shim plate between the two elements to be connected. This is done to keep the end slightly elevated for efficient grouting.
Step 3.	Place the second-hand element in its final location, with the protruding rebars just externally next to each longitudinal rebar.
Step 4.	Replace the (eventually) removed shear stirrups with new ones.
Step 5.	Re-cast this part of the second-hand element with new concrete. Once fully hardened, the connection is achieved.
Adaptation of the second-hand element is accomplished.	

Table D.30: Reconnecting with sleeve couplers (J).

Sleeve coupler(s)	(Volkov, 2019, p. 38, 42, 44, 77)
Applicable to	Beam-to-column, column-to-beam, column splice joint, column foot joint, wall foot joint, wall-to-wall (horizontal)
Step 1.	Drill coupling holes in the second-hand element, respecting all the requirements.
Step 2.	Drill air expelling holes perpendicular to each coupling hole. This hole should intersect the coupling sleeve in its top part (with sufficient precision). If needed, another hole (with a larger diameter) can be drilled in the lower part.
Step 3.	Roughen the end surface of the second-hand element (if not rough enough after disassembling). This is done in order to ensure sufficient bonding in the (grouted) connection with the other concrete element.
Adaptation of the second-hand element is accomplished.	
Step 4.	Position a shim plate between the two elements to be connected. This is done to acquire head-to-head bonding and efficient grouting.
Step 5.	Place the second-hand element in its final position, by inserting the connection bars of the other element into the coupling holes.
Step 6.	If present, brace the second-hand element.
Step 7.	Grout all around the gap between the second-hand column and other element with low-shrinkage concrete under pressure. The coupling sleeves are fully grouted when the concrete has filled the air expelling openings.
Step 8.	Once fully hardened and full bond is achieved between the anchors and the column, the connection is achieved.

Table D.31: Reconnecting with steel shoes (K).

Steel shoes	(Volkov, 2019, p. 46, 49)
Applicable to	Column splice joint, column foot joint, wall-to-wall (horizontal)
Step 1.	Cut 4 cubic or cylindrical parts from the coners of the second-hand element. The obtained niches can be called 'pockets'.
Step 2.	Drill 4 coupling holes in the pockets, with a diameter larger than the anchoring rods of the shoe.
Step 3.	Drill air expelling holes perpendicular to each coupling hole. This hole should intersect the coupling sleeve in its top part (with sufficient precision).
Step 4.	Embed 4 shoe anchors inside the coupling holes.
Step 5.	Grout from the bottom of the sleeve hole (where the shoe anchors were inserted) with low-shrinkage concrete under pressure. The coupling sleeves are fully grouted when the concrete has filled the air expelling openings.
Adaptation of the second-hand element is accomplished.	
Step 6.	Position a shim plate between the two elements to be connected.
Step 7.	Place the second-hand element in its final position, by tightenin the nuts on the threaded anchors of the other element.
Step 8.	Grout the gap between the elements. Once fully hardened and full bond is achieved between the shoe and the second-hand element, the connection is achieved.

Table D.32: Reconnecting with U-voids (L).

U-voids	(Volkov, 2019, p. 105)
Applicable to	Slab-to-beam Most common for hollow core slabs (HCS)
Step 1.	Perform U-voids in the upper part of the second-hand element (slab).
Adaptation of the second-hand element is accomplished.	
Step 2.	Place the second-hand element in its final position on the other element, e.g. on the flange of the shallow beam.
Step 3.	Insert the connection bars into each void.
Step 4.	Grout the U-voids with low-shrinkage concrete. Once fully hardened and full bond is achieved between the bars and slab, the connection is achieved.

Table D.33: Reconnecting with V-gaps (M).

V-gaps	(Volkov, 2019, p. 102)
Applicable to	Slab-to-slab (longitudinal) Most common for hollow core slabs (HCS)
Step 1.	Cut the longitudinal side of the second-hand slab in a slight angle with the vertical (if this has not been achieved during disassembling). The cut should pass through a void of a hollow core;
Step 2.	Drill coupling holes in the top and bottom of the second-hand element for the anchors of the longitudinal jointing plate.
Step 3.	Drill filling holes in the top face for grouting the anchors of the longitudinal jointing plate.
Adaptation of the second-hand element is accomplished.	
Step 4.	Place the jointing plate between the two element (at the bottom face) and insert anchors in the holes (sticking out at the top face).
(Step 5.)	Eventually, insert the connection bars into each void and grout the V-gap with low-shrinkage concrete.
Step 6.	Grout (through the filling holes at the top) the anchors of the jointing plate with low-shrinkage concrete.
Step 7.	Once fully hardened, locate another jointing plate with holes on the sticking out anchors (at the top face) and tighten the nuts. The connection is achieved.

Table D.34: Reconnecting with welded U-loops (N).

Welded U-loops	(Volkov, 2019, p. 83)
Applicable to	Wall-to-wall (vertical)
Step 1.	Remove end margin to expose horizontal rebars. The amount of concrete to be removed is dictated by the length of the welds to be performed (which depend on the diameter of the bars and the forces to transmit).
Step 2.	Adjust the length of the protruding rebars dictated by efficient welding to the connection bars;
Step 3.	Roughen the end surface of the second-hand element (if not rough enough after disassembling). This is done in order to ensure sufficient bonding in the (grouted) connection with the other concrete element.
Step 4.	Weld the connection bars of the friction-resistant strip to all needed protruding rebars.
Step 5.	Cast concrete to the friction-resistant strips. After this, the second-hand element looks exactly as in the connection between pre-cast elements.
Adaptation of the second-hand element is accomplished.	
Step 6.	Insert vertical jointing bar in the loops between two wall elements.
Step 7.	Cast concrete to the whole connection. Once fully hardened, the connection is achieved.

D.4.3 Adaptive structure

The physical capacity of a building, foundation and load-bearing elements need to be adaptable. According to the scale of Schmidt III et al. [2010] in Figure D.6 six types of adaptive measures are identified: adjustable, versatile/flexible, refitable, convertible, scalable and movable. An *adjustable* building corresponds to equipment and/or furnishing changes as a result of changes in task or use. *Versatility* represents the physical change of space (e.g., spatial layout). It is about the possibility to divide spaces in a building differently, for example with movable walls or panels. A *refitable* building has elements (for example a facade or floor) that can be replaced, moved, or removed and signifies a change of performance. A building is *convertible* if its use can change through internal or external adaptation of the building. A *scalable* building can be resized, usually by expanding the building. Finally, a building is *movable* if it can be transferred to another physical location [Platform CB23, 2020a, p. 112]. Each of the six strategies was given a correlation to a type of change, a decision level (e.g., stakeholder), a built-environment scale, a time scale and the layers of Brand [1994]. The overview in Figure D.6 shows that an adaptive structure (or building) should be scalable and movable. For this reason, dry joints with or without added provisions are preferred for the reconnection. However, if a structural beam is cast to other elements (wet joint), this is more suitable for a design with a long service life because the element will be difficult to detach once fixed. As mentioned, circularity strategies of the new design are out of the scope of this research, because this is the decision of the structural engineer.

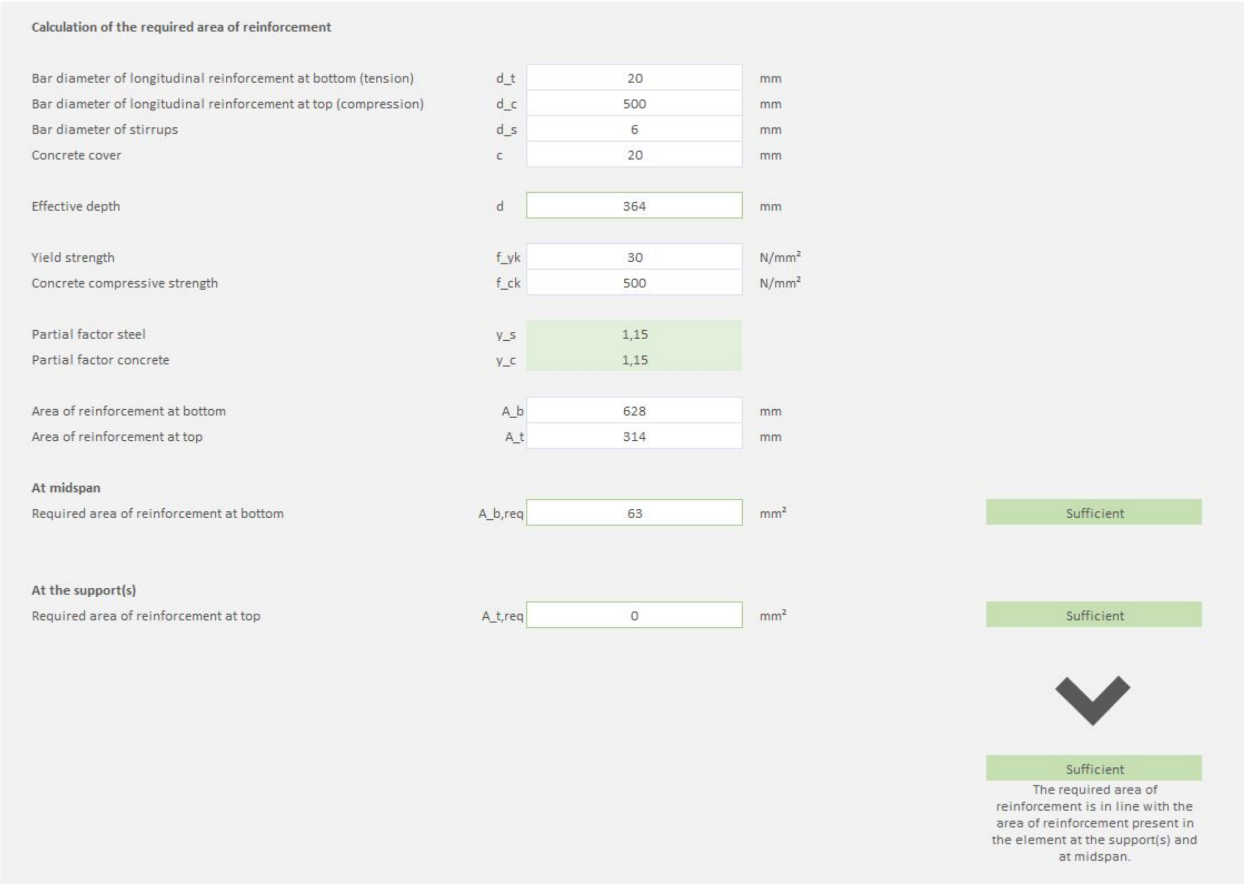
able	type of change	decision-level	B-E scale	Time (cycle speed)	Brand's layers					
					Stuff	Space	Services	Skin	Structure	Site
adjustable	change of task	user	components	daily/ monthly	O					
versatile (flexible)	change of space	user	components	daily/ monthly	O	O				
refitable	change of performance	user/ owner	components	7 years		O	O	O		
convertible	change of function	user/ owner	building	15 years		O	O	O		
scalable	change of size	owner	building	15 years		O	O	O	O	
movable	change of location	owner	building	30 years					O	O

Figure D.6: The layers of Brand [1994] in relation to strategies of Schmidt's Scale [Schmidt III et al., 2010, p. 7].

D.4.4 Calculations

Moreover, structural connections should fulfil the requirements of the Eurocode (EC). As described in Stage 6 (Material Handling), a harvested (structural) element needs to be adapted according to Eurocode, since the element was designed according to former codes. In order to convince a client to reuse harvested (structural) elements, a structural engineer can prove with modelling and calculations that an element is safe and reliable. Governing prescriptions from Eurocode which are likely to consider during the design of connections with harvested (structural) elements are: [Volkov, 2019, p. 27-32]

- Bending verification (same as for newly-made elements);
- Shifting bending moment;
- Bending-compression interaction (same as for newly-made elements);
- Bearing capacity (same as for newly-made elements);
- Shear (with presence of shear reinforcement) (same as for newly-made elements);
- Shear verification at the interface between concrete cast at different times;
- Design anchorage length of longitudinal reinforcements;
- Overlapping length of longitudinal reinforcement;
- Transverse reinforcement (concentration in overlap zone);



Calculation of the required area of reinforcement

Bar diameter of longitudinal reinforcement at bottom (tension)	d_t	20	mm	
Bar diameter of longitudinal reinforcement at top (compression)	d_c	500	mm	
Bar diameter of stirrups	d_s	6	mm	
Concrete cover	c	20	mm	
Effective depth	d	364	mm	
Yield strength	f_yk	30	N/mm²	
Concrete compressive strength	f_ck	500	N/mm²	
Partial factor steel	y_s	1,15		
Partial factor concrete	y_c	1,15		
Area of reinforcement at bottom	A_b	628	mm	
Area of reinforcement at top	A_t	314	mm	
At midspan				
Required area of reinforcement at bottom	A_b,req	63	mm²	Sufficient
At the support(s)				
Required area of reinforcement at top	A_t,req	0	mm²	Sufficient

Sufficient

The required area of reinforcement is in line with the area of reinforcement present in the element at the support(s) and at midspan.

Figure D.7: Example calculation of the required reinforcement area of a beam where the required area of reinforcement is calculated with M / (d * (f_{yk} y_s). Specifications can be found in Figure 5.4.

E | Case-study

This Chapter elaborates the case-study of the Satellietgebouw in more detail with a test-case, which is used to validate and verify the Decision Support Tool (Appendix E.1). In Appendix E.2, a photo report is given of the disassembling.

E.1 Satellietgebouw

The case-study of Pieters Bouwtechniek is introduced in subsection 3.3.1. A bird's eye view of De Nederlandsche Bank (DNB) is shown in Figure E.1. As described, the round cylindrical tower, also called the 'Satellietgebouw', is disassembled with the purpose of reuse. This construes to the process of 'Deconstruct & Reuse'. Additionally, this research assesses the reuse potential of the harvested (structural) elements. The Satellietgebouw consist of a post-tensioned concrete structure (1st floor), concrete prefab elements (2nd-14th floor) and a steel topping (15th floor). The structure, skin and service layers are reused in a new design at another location in Amsterdam. This research focuses on the disassembling and reuse of the prefab elements in a new design. Therefore, a test-case of the Satellietgebouw is set up to assess the reuse potential. This section describes the test-case which is used to validate and verify the Decision Support Tool.

Figure E.1: Bird's eye view of De Nederlandsche Bank (DNB) taken from the intersection of Stadhouderskade and Westeinde [De Nederlandsche Bank, 2019].

E.1.1 Test-case

The test-case of the Satellietgebouw focuses on the double Tee slabs of the outer ring of 2nd floor. This (prefab) element is chosen due to its large dimensions and weight and because it occurs most often in the Satellietgebouw.

In order to validate and verify the Decision Support Tool, the test-case is executed by the researcher and five experienced structural engineers (respectively in subsection 8.2.1.3 and subsection 9.1.1). During validation with the latter, the test-case was explained with the following figures. The figures show the double Tee slab and ensure each individual executor considers the same element (in order to compare the answers for validation). Additionally, existing information of the Satellietgebouw and properties of the double Tee slab are provided to reduce the difficulty of the test-case. Due to time constraints, only one element is assessed as a test-case.

Figure E.2: Perspective of De Nederlandsche Bank (DNB) from Stadhouderskade anno 2020. Adapted from NU [2020].

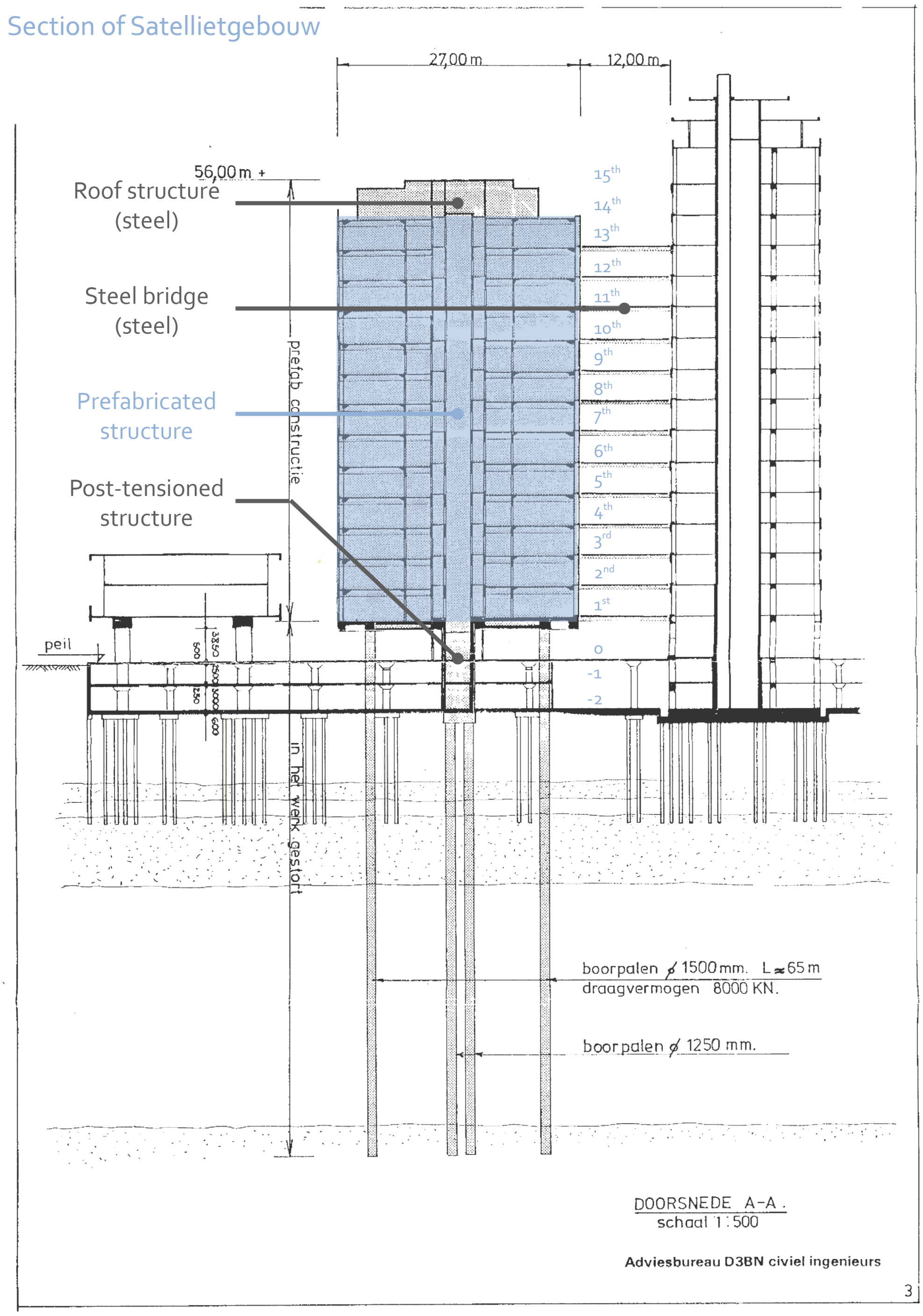


Figure E.3: Section of Satellietgebouw, where the prefabricated structure of the 2nd-14th floor is indicated in blue. Adapted from Pieters Bouwtechniek Internal Document [2021e].

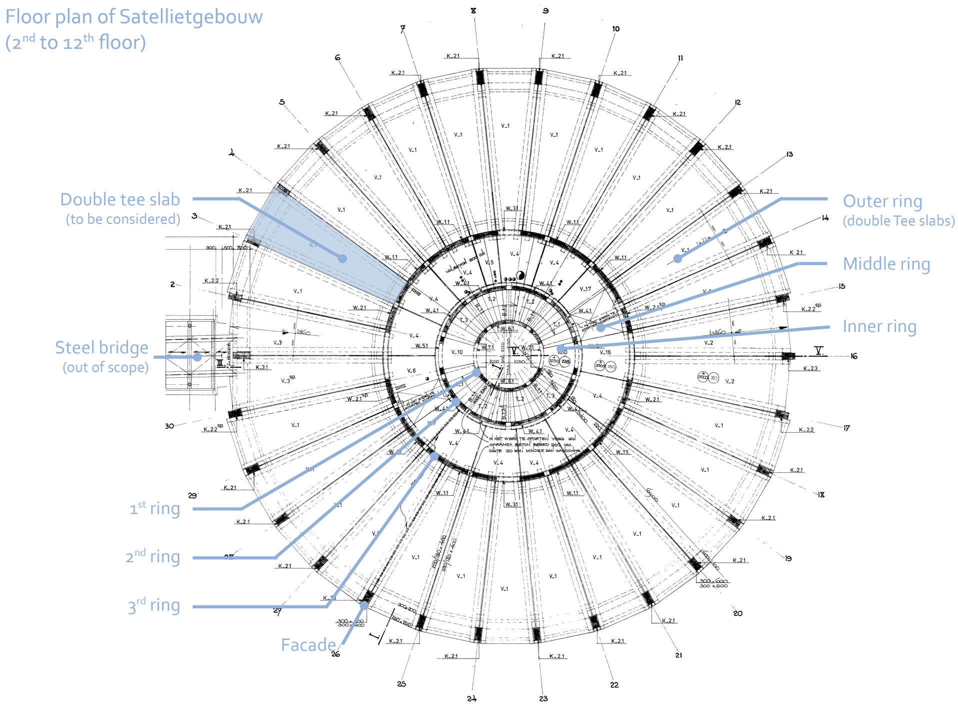


Figure E.4: Floor plan of Satellietgebouw (2nd floor, same up to 12th floor). The Double Tee slab considered for the test-case is indicated in blue (between axis 3 and 4, type: V1). Adapted from Pieters Bouwtechniek Internal Document [2021c].

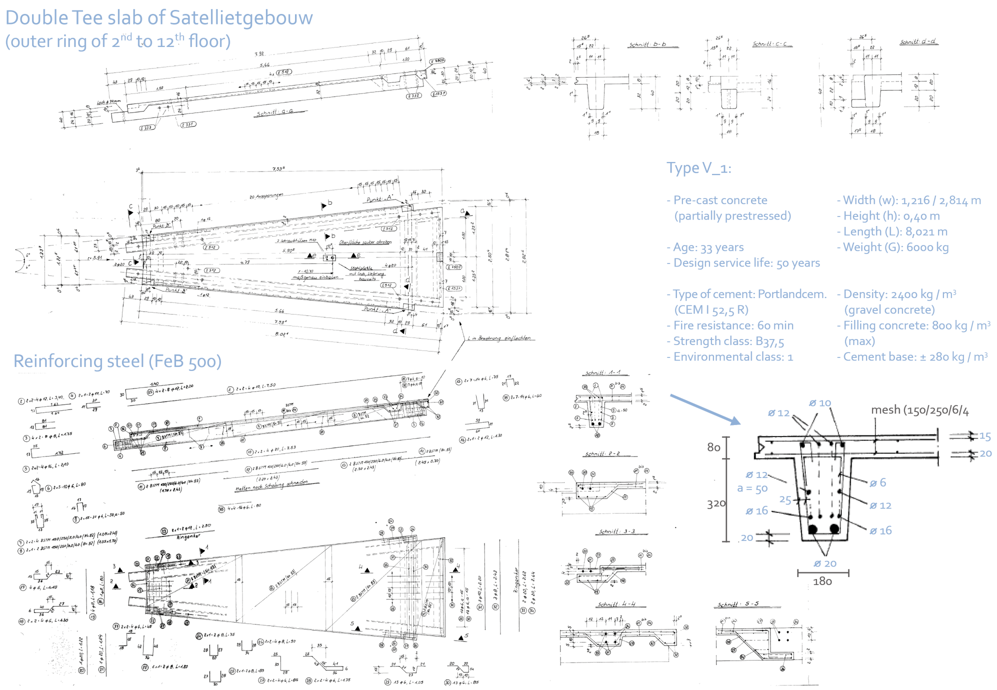
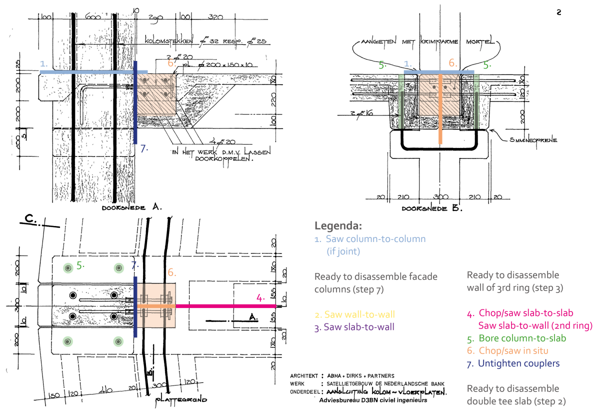
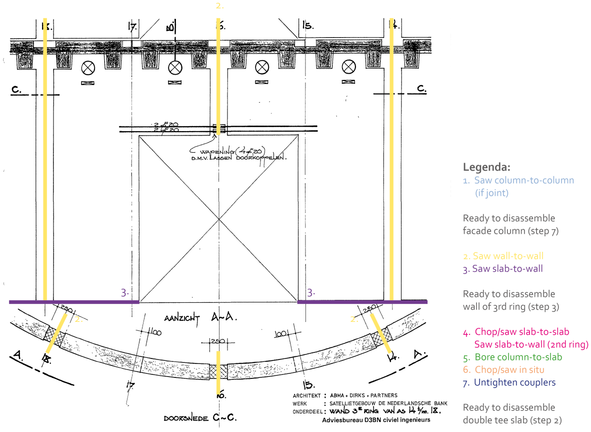


Figure E.5: Double Tee slab of Satellietgebouw (type: V1). Adapted from Pieters Bouwtechniek Internal Document [2021b].

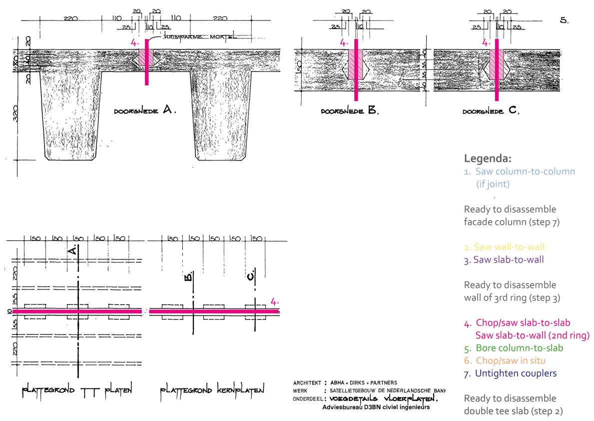


(a) Double Tee slab to column

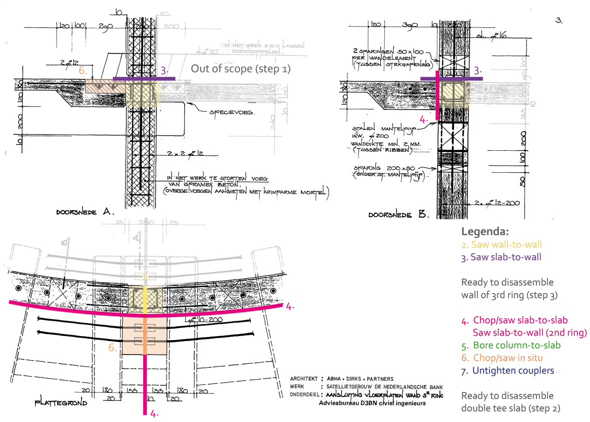


(b) 3rd ring

Figure E.6: Disconnecting the connections of the test-case [1/2]. Adapted from Pieters Bouwtechniek Internal Document [2021a].



(a) Double Tee slab to double Tee slab



(b) Double Tee slab to 3rd ring

Figure E.7: Disconnecting the connections of the test-case [2/2]. Adapted from Pieters Bouwtechniek Internal Document [2021a].

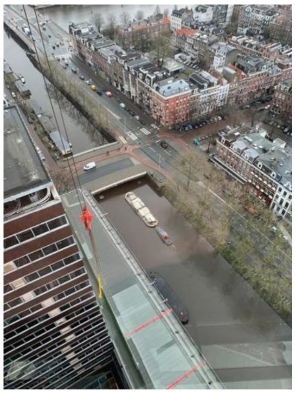
E.2 Photo report of disassembling

On the next page, a photo report of the disassembling of the Satellietgebouw is shown. The photos are taken in the period from February 2021 to June 2021 by Pieters Bouwtechniek, Kruijswijk Sloopwerk and the author of this research.

(Photo taken by Thijs van Schenk Brill
on the 23rd of February 2021)

(Photos taken by Kruiswijk Sloopwerk
in February 2021)

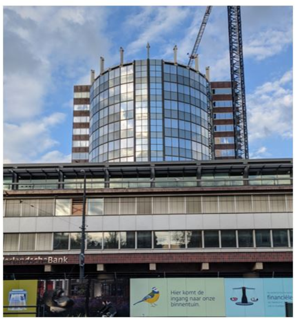
(Photo taken by Bente Kamp
on the 5th of March 2021)



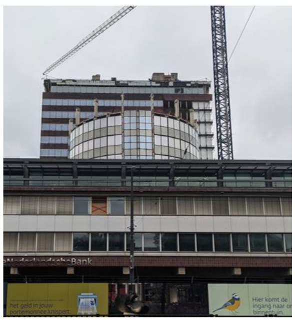
(Photos taken by Kruiswijk Sloopwerk
in February 2021)

(Photos taken by Bente Kamp
on the 4th of April 2021)

(Photo taken by Bente Kamp
on the 4th of April 2021)



(Photo taken by Bente Kamp
on the 6th of May 2021)



(Photo taken by Bente Kamp
on the 25th of June 2021)

Figure E.8: Photo report of the disassembling of the Satellietgebouw in Amsterdam in the period from February 2021 to June 2021.

F | Sequence of disassembling

F.1 General sequence

The deconstruction of concrete structures is significantly different from the deconstruction of e.g., steel structures, where elements can often be disconnected by 'just' untightening a few bolts. Additionally, no codes or prescriptions exist about the most suitable way to deconstruct or how to prepare a concrete structure for further reuse, which complicates the deconstruction of these structures even more. According to recent studies, it is only known that the deconstruction phase has approximately 60% extra costs in respect to the demolition of a similar structure [Volkov, 2019].

Usually, demolition or deconstruction of any kind of structure goes in the reversed order the structure has been constructed (from top to bottom). According to the Code of Practice for Demolition of Buildings, a general sequence can be: [Glias, 2013, p. 30]

- Removal of all cantilevered structures before removal of internal structures;
- Removal of floor slabs (begin at mid-span and work towards the supporting beams);
- Removal of floor beams (start with cantilevered beams, followed by secondary beams and lastly main beams);
- Removal of non-load bearing walls;
- Removal of columns and load-bearing walls.

Standardised structures can be easily reused due to the repetitive production of prefabricated elements. The procedure of deconstruction and demolition work of the prefabricated structure of De Nederlandsche Bank (DNB) is analysed in Appendix F.1.1. In general, an element is removed for reuse, hoisted to ground level, transported, and eventually stored till a structural engineer needs the element for the design of a new building. This is described in more detail in the subsequent sections. Moreover, the selling of an element is out of the scope of this research.

Another solution suggested by the research of Glias [2013] is to only deconstruct when the new project is known, so e.g., if the owner of the new building wants to rebuild the same building at another place. Besides the marking of every harvested element, this requires a deconstruction plan since the upper elements (i.e., the roof) will be available first for the design of a new building.

F.1.1 Sequence of case-study

The subsequent section describes the procedure of deconstruction and demolition work, based on the deconstruction of the prefabricated structure of De Nederlandsche Bank (DNB). Demolition of the roof structure (15th and 14th floor) and the bridge (13th to 2nd floor) are not taken into account, because these are made of steel. The demolition of the post-tensioned concrete structure (in Dutch: tafelconstructie) at the 1st floor is also disregarded. The following information is adapted from the demolition company of DNB: Kruiswijk Sloopwerk [Pieters Bouwtechniek Internal Document, 2021f].

<u>Step 1: Evacuate the building</u>
In this phase, the building will be emptied (partly for reuse).

- Furniture and loose furnishings will be removed;
- All services are disconnected (e.g., de-energized, shut down, drained, free from coolant / oil, etc.).

Step 2: Strip the inside of the building (i.e., soft stripping)

In this phase, all interior walls, window frames, suspended ceilings, computer floors and elevators will be removed including the services included therein. The harvested (non-structural) elements are transported by ship to temporary storage (e.g., carpet tiles, computer floors, cable trays, handrails, finishing strips, services, etc.).

Step 3: Strip the outside of the building

In this phase, the (non-structural) facade elements are deconstructed and made safe to prevent damage and contamination to these elements. Beforehand, the cover strips on the outer sides (at bending points of facade elements) must be removed. The method to deconstruct a facade element is as follows:

- Placing edge protection behind facade element;
- Bracing the facade element with tension/compression struts to the underlying floor (the same principle applies to facade columns and wall elements). Keep in mind that a facade element can run over two storeys;
- Removing elements on top;
- Attaching the facade element to the tower crane;
- Disconnecting joints and anchoring points of facade element to the underlying floor;
- Drilling the remaining bars (in Dutch: stekkenparen) to the underlying floor;
- Loosening tension/compression bracing;
- Hoisting of facade element with tower crane;
- Lowering the column horizontally on the ground (e.g., with clamp in the ship). The harvested facade elements are transported by ship to temporary storage.

In the case of DNB the facade elements at the higher floors are kept intact for as long as possible. The facade then serves as a wind barrier, edge protection and noise barrier that greatly reduces the nuisance for the environment (e.g. due to sawing, chopping and sawing water).

Step 4: Deconstruct frame

After the building has been emptied and stripped, elements are removed for reuse or taken to a waste processor for further recycling. The structure is deconstructed from "top to bottom". By disconnecting, the structure is divided into individual elements which are then hoisted by the tower crane. The harvested elements are transported by ship to temporary storage.

As mentioned, DNB is predominantly constructed of prefab concrete elements (walls / slabs / columns). The connections where the prefab elements are linked together (wet connections) are disconnected with a sawing cut. In addition, the stability walls per storey are removed from "outside to inside", while the slabs are removed from "inside to outside" (Figure F.1). The method to deconstruct a floor is as follows:

- Removing slabs;
  - Bracing the underlying column or wall to the underlying floor (take into account that a column can run over two storeys). In case an element is cast on-site, scaffolding is placed
  - Disconnecting joints between slabs (while retaining reinforcement as much as possible)
  - Checking lifting holes. In the case of prefabricated elements, existing lifting holes can be used. In case an element is cast on-site, lifting holes must be drilled (for hoisting chains)
  - Hoisting
- Removing stairs and landings;
- Removing walls;
  - Bracing
  - Disconnecting
  - Checking lifting holes
  - Hoisting
- Removing facade elements (if kept intact for as long as possible). The same method applies as the removing of walls;
- Removing facade columns.

In the case of DNB, the bridge (13th to 2nd floor) is removed at the same time. After the 13th to 2nd floor are deconstructed, the final step is the demolition of the post-tensioned construction at the 1st floor (in Dutch: tafelconstructie). An example for the procedure of deconstruction of DNB for the 12th floor is shown in Figure F.1, including an indication of the duration. In total, the dismantling of one floor will take 12 days. Extra time has been allocated for the deconstruction of the highest floors.

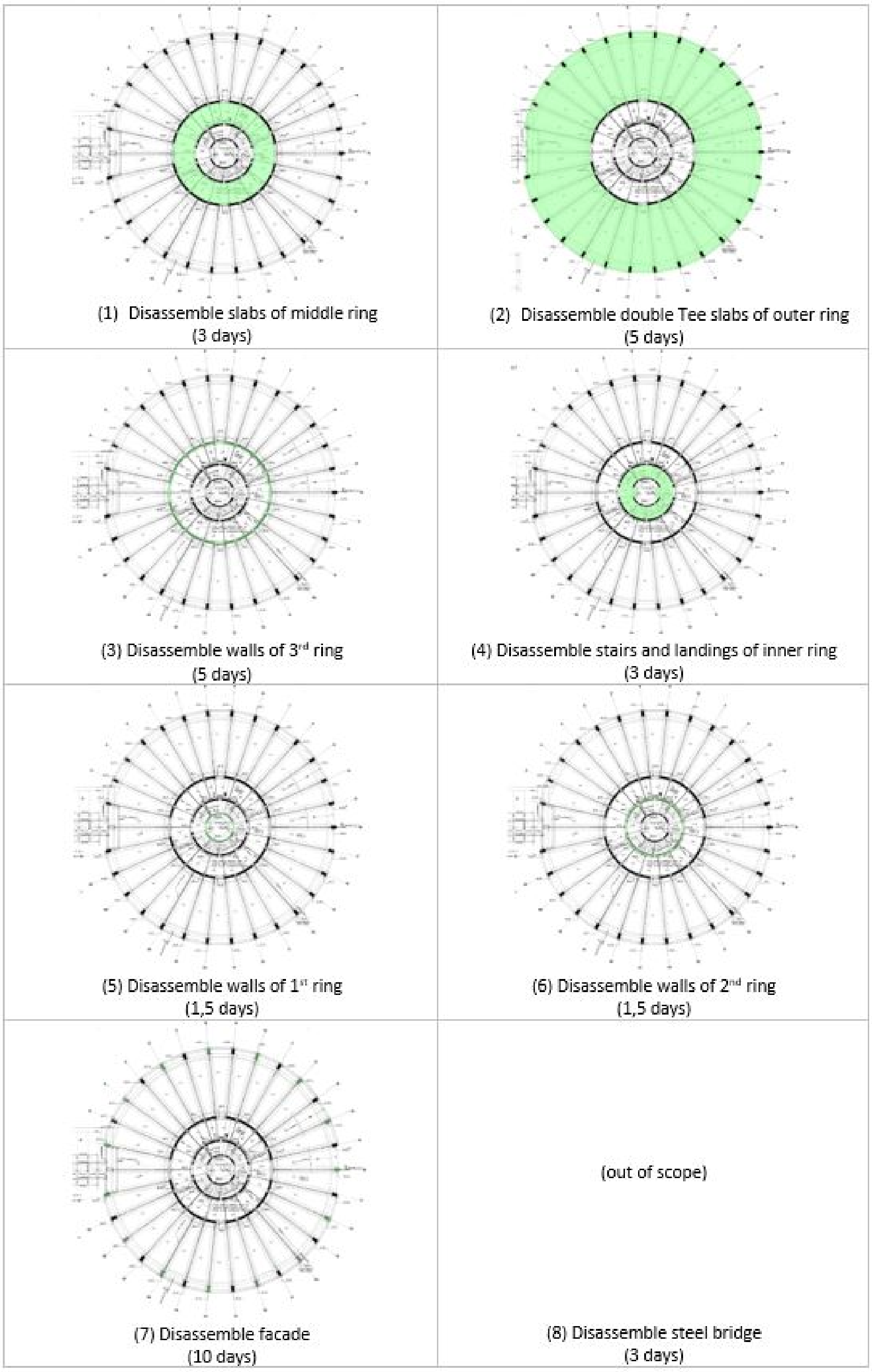
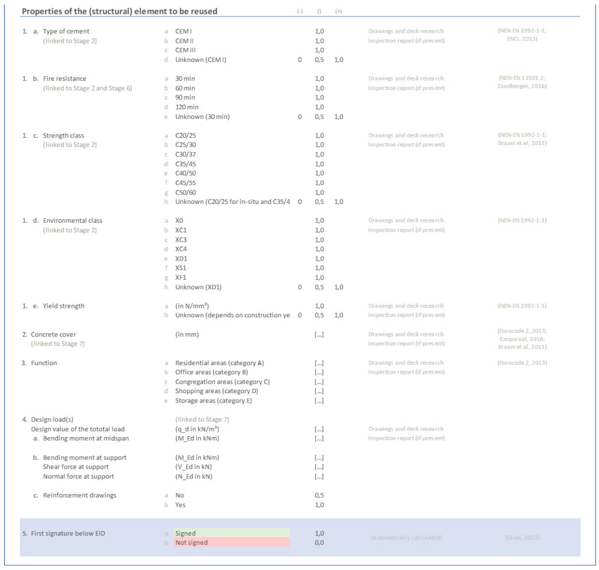


Figure F.1: Procedure of deconstruction of the Satellietgebouw for the 12th floor. Step 2, 3 and 7 are of importance for the disassembling of the double Tee slabs. Adapted from Pieters Bouwtechniek Internal Document [2021f].

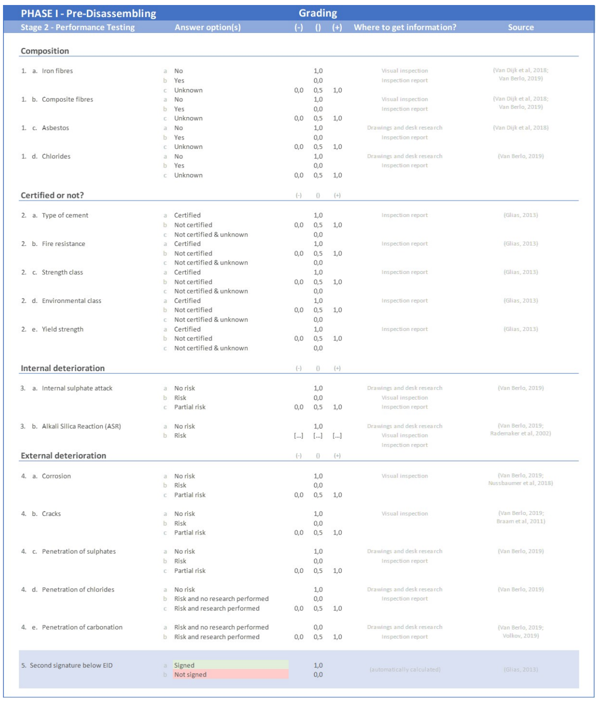
G Overview of input with grading

An overview of the indicators of Phase I, Phase II and Phase III is respectively shown in Figure G.1, Figure G.2 and Figure G.3. As described, the indicators are based on what structural engineers need to know for the implementation of a second-hand element in a (new) design. For the Decision Support Tool, the indicators are translated into assessment questions. The overviews in Figure G.1, Figure G.2 and Figure G.3 show the answer options and related grading per assessment question. Additionally, the source of the answer options and grading is shown. Lastly, the overview shows where to get information to answer the assessment question. As described in Section 4.2, this research considers the sources to gather information as drawings and desk research, visual inspection, inspection report and the project team.

(a) Stage 1 [1/2]

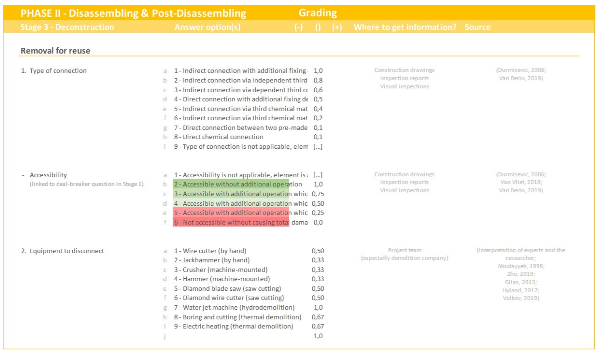


(b) Stage 1 [2/2]

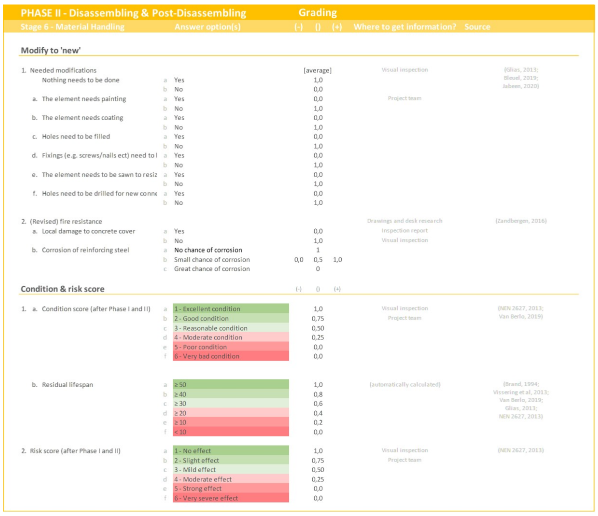


(c) Stage 2

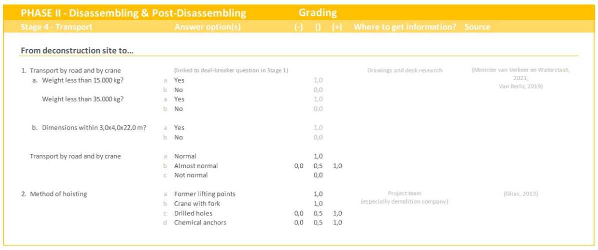
Figure G.1: Input of Phase I, with grading (own figure).



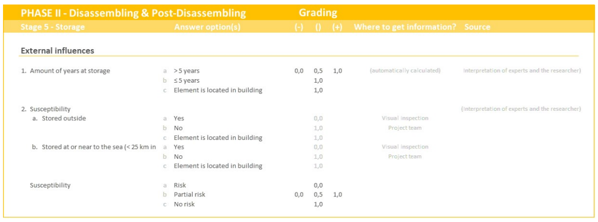
(a) Stage 3



(b) Stage 6



(c) Stage 4



(d) Stage 5

Figure G.2: Input of Phase II, with grading (own figure).

(a) Stage 7 [1/2]

(b) Stage 7 [2/2]

Figure G.3: Input of Phase III, with grading (own figure).

H | Validity of Decision Support Tool

Validity refers to the validation and verification of the Decision Support Tool, which is carried out with the preliminary versions and final version. Appendix H.1 analyses the received and processed feedback on the preliminary versions of the Decision Support Tool, resulting in the final version. Appendix H.2 shows the results of the test-case which is executed by the researcher and experts. This Chapter finalizes with an overview of the received feedback on Phase I, Phase II and Phase III in Appendix H.3 (A3 format).

H.1 Preliminary versions

This Chapter describes the interviews and feedback sessions which are conducted throughout the research. This is done with structural engineers of Pieters Bouwtechniek and with (external) parties of the case-study. All conversations considered (parts of) the process of 'Deconstruct & Reuse' and were based on open-ended questions. After each discussion, notes were written down regarding the given feedback. These notes (and thoughts) form the basis for the results in this Chapter.

The interviews and feedback sessions resulted in valuable information for the development of the Decision Support Tool for the structural engineer. All feedback of Phase I (Pre-Disassembling), Phase II (Disassembling and Post-Disassembling) and Phase III (Re-Assembling) can be found respectively in Appendix H.1.1, Appendix H.1.2 and Appendix H.1.3. An recapitulation of the most valuable improvements which make the Decision Support Tool useful in practice is given in Table 8.1. This is processed in the preliminary versions of the Decision Support Tool, resulting in the final version.

H.1.1 Phase I: Pre-Disassembling

Table H.1: Received and processed feedback of preliminary versions of the Decision Support Tool regarding Phase I [1/2].

Phase I: Pre-Disassembling		Feedback (processed in research)	Evaluation
Stage 1: Inventory		• Focussing on desk research • Clarifying difference with Stage 2 (on site research)	Feedback sessions at Pieters Bouwtechniek
Quick check if reuse is possible	General information about the (structural) element to be reused	Structural element • Formulating only one element can be tested at a time Standardisation • Formulating definitions and explaining grading Density • Adding remark with the density for normal and reinforced concrete Geometry • Implementing an answer option for additional comment(s) • Implementing answer option to overrule calculated weight by actual weight	Feedback sessions at Pieters Bouwtechniek
	General information about the (origin) building	Project name and location • Changing order (function not relevant for quick check and corresponds with design load(s)) Construction and deconstruction year • Adding check which indicates if element is located in building or already deconstructed	Feedback sessions at Pieters Bouwtechniek Interviews with (external) parties of case-study
	Deal-breaker questions	• Identifying the four deal-breakers (e.g. the amount of additional work is not considered, because this is included in the condition score) Condition (1) • Simplifying the condition score by changing the deal-breaker questions to yes-no answer options • Indicating the positive and negative effect on the reuse potential (by colouring the answer options and by adding a colour scale to the condition score) • Implementing 'unknown' answer options • Clarifying answer options with figures • Processing the need for further research (in another Stage) in case an answer has a negative effect on the reuse potential Residual lifespan (2) • Adding remark that most buildings are designed for 50 year (conservative lower limit) Accessibility (3) • Formulating only one connection of the element to be reused can be tested at a time • Formulating definitions • Indicating the positive and negative effect on the reuse potential (by colouring the answer options) Transport by road (4) • Including crane capacity (maximum of 15.000 kg) • Indicating the positive and negative effect on the reuse potential (by colouring the answer options)	Feedback sessions at Pieters Bouwtechniek

Table H.2: Received and processed feedback of preliminary versions of the Decision Support Tool regarding Phase I [2/2].

Stage 1: Inventory		Feedback (processed in research)	Evaluation
Properties of the (structural) element to be reused	Concrete and reinforcing steel	Cement • Simplifying to the types of cement to the most used in the Netherlands • Implementing 'unknown' answer option (CEM I) Fire resistance • Implementing 'unknown' answer option (30 min) • Adding foldout button for more information (whether the code for new or existing buildings should be used is up to the structural engineer) Strength class • Implementing 'unknown' answer options (C20/25 for in-situ and C35/45 for pre-cast) • Simplifying to 'normal' concrete • Adding foldout button for more information Environmental class • Implementing 'unknown' answer option (XD1) • Eliminating classes which do not correspond to superstructures • Adding foldout button for more information Yield strength • Open-ended question (instead of closed-ended) • Implementing 'unknown' answer option (220 N/mm² before 1960, 400 N/mm² before 1990, 500 N/mm² after 1990) • Adding foldout button for more information	Feedback sessions at Pieters Bouwtechniek
	Concrete cover	• Implementing 'unknown' answer option (based on Eurocode 2, 2013 with filled-in strength class and environmental class)	Feedback sessions at Pieters Bouwtechniek
	Function	• Changing order (function corresponds with design load(s))	Feedback sessions at Pieters Bouwtechniek
	Design load(s)	• Simplifying to design load(s) at midspan and at support which are compared with the design load(s) in the new design • Simplifying design load(s) to the elastic theory and stress distribution for statically determinate structures • Adding other materials than concrete in design value of total load (e.g. finishing) • Eliminating calculation with dimensions of reinforcing steel, because these are often not available • Implementing option if reinforcement drawings are available (e.g. to calculate maximum capacity)	Feedback sessions at Pieters Bouwtechniek
Stage 2: Performance Testing		• Focussing on on-site research • Clarifying difference with Stage 1 (desk research)	Feedback sessions at Pieters Bouwtechniek
Composition		• Implementing 'unknown' answer options • Indicating the positive and negative effect on the reuse potential (by colouring the answer options) • Displaying output / advice after answer is filled-in • Adding foldout button for more information • Adding and eliminating indicators by distinguishing the difference between bridges and buildings	Feedback sessions at Pieters Bouwtechniek
Certified or not?		• Displaying output / advice after answer is filled-in • Processing the need for further research in case an answer has a negative effect on the reuse potential	Feedback sessions at Pieters Bouwtechniek
Deterioration	Internal and external deterioration	• Implementing 'unknown' answer options • Indicating the positive and negative effect on the reuse potential (by colouring the answer options) • Displaying output / advice after answer is filled-in (limited to risk / partial risk / no risk) • Adding foldout button for more information • Adding and eliminating indicators by distinguishing the difference between bridges and buildings	Feedback sessions at Pieters Bouwtechniek

H.1.2 Phase II: Disassembling and Post-Disassembling

Table H.3: Received and processed feedback of preliminary versions of the Decision Support Tool regarding Phase II.

Phase II: Disassembling and Post-Disassembling		Feedback (processed in research)	Evaluation
Stage 3: Deconstruction		• Implementing option if element is located in building or already deconstructed and at storage site	Feedback sessions at Pieters Bouwtechniek
Removal for reuse	Type of connection	• Adding foldout button for more information • Clarifying answer options with figures • Formulating definitions	Feedback sessions at Pieters Bouwtechniek
	Equipment to disconnect	• Implementing suggestion for equipment to disconnect to limit damage to the connection • Implementing answer option to ensure the executor remains accountable (overruling the suggestion and selecting the preferred equipment to disconnect) • Adding foldout button for more information • Indicating the positive and negative effect on the reuse potential (by specifying the advantages and disadvantages) • Focussing the advantages and disadvantages on damage to the element, accurate removal and damage to (protruding) rebars • Identifying the equipment to disconnect from the point of view of the demolition company	Feedback sessions at Pieters Bouwtechniek Interviews with (external) parties of case-study
Stage 4: Transport		• Eliminating transport by air, rail and water	Feedback sessions at Pieters Bouwtechniek
Transport by crane	Method of hoisting	• Adding foldout button for more information about method of hoisting • Clarifying answer options with figures • Indicating the positive and negative effect on the reuse potential (by specifying the advantages and disadvantages)	Feedback sessions at Pieters Bouwtechniek
Transport by road		• Including crane capacity (maximum of 15.000 kg) • Displaying output / advice after answer is filled-in • Indicating the positive and negative effect on the reuse potential (by formulating questions)	Feedback sessions at Pieters Bouwtechniek
Stage 5: Storage		• Eliminating how the elements are stored or stacked	Feedback sessions at Pieters Bouwtechniek
External influences		• Displaying output / advice after answer is filled-in • Indicating the positive and negative effect on the reuse potential (by colouring the answer options) • Including 5 years at storage site can form a risk for reuse	Feedback sessions at Pieters Bouwtechniek
Stage 6: Material Handling		• Clarifying element can be added to the database	Feedback sessions at Pieters Bouwtechniek
Modify to 'new'	Modifications	• Identifying the (needed) modifications from the point of view of the structural engineer • Implementing an answer option for additional comment(s)	Feedback sessions at Pieters Bouwtechniek
	Fire resistance	• Adding this indicator from the point of view of the structural engineer • Indicating the positive and negative effect on the reuse potential (by colouring the answer options) • Displaying output / advice after answer is filled-in	Feedback sessions at Pieters Bouwtechniek
Condition and risk score		• Formulating questions • Indicating the positive and negative effect on the reuse potential (by colouring the answer options and by adding a colour scale to the condition and risk score) • Implementing an answer option for additional comment(s)	Feedback sessions at Pieters Bouwtechniek

H.1.3 Phase III: Re-Assembling

Table H.4: Received and processed feedback of preliminary versions of the Decision Support Tool regarding Phase III [1/2].

Phase III: Re-Assembling		Feedback (processed in research)	Evaluation
Stage 7: Construction		• Creating awareness by adding an option if the design of the (new) building is known	Feedback sessions at Pieters Bouwtechniek
Requirements of the (new) design	General information about the (new) design	• Implementing an answer option for additional comment(s) • Creating awareness by adding the distance to the second-hand element (as close as possible) • Adding remark that most buildings are designed for 50 year (conservative lower limit) • Indicating if the element is sufficient for the (new) design by comparing output / advice after answer is filled-in with origin • Processing the need for further research if in case an answer is not sufficient	Feedback sessions at Pieters Bouwtechniek Interviews with (external) parties of case-study
Properties of second-hand element	Concrete and reinforcing steel	Fire resistance • Adding foldout button for more information • Indicating if the element is sufficient for the (new) design by comparing output / advice after answer is filled-in with origin Environmental class • Adding foldout button for more information	Feedback sessions at Pieters Bouwtechniek
	Concrete cover	• Displaying output / advice after answer is filled-in, indicating the positive and negative effect on the reuse potential	Feedback sessions at Pieters Bouwtechniek
	Function	• Changing order (function corresponds with design load(s)) • Indicating if the element is sufficient for the (new) design by comparing output / advice after answer is filled-in with origin	Feedback sessions at Pieters Bouwtechniek
	Design load(s)	• Indicating if the element is sufficient for the (new) design by comparing output / advice after answer is filled-in with origin • Simplifying to design load(s) at midspan and at support which are compared with the design load(s) in the new design • Simplifying design load(s) to the elastic theory and stress distribution for statically determinate structures • Eliminating calculation with dimensions of reinforcing steel • Implementing option to show example calculation (beam)	Feedback sessions at Pieters Bouwtechniek
	Holes for services	• Adding this indicator from the point of view of the structural engineer (especially important for slabs and beams) • Creating awareness by adding the reuse of the holes for (new) services • Indicating the positive and negative effect on the reuse potential (by colouring the answer options) • Including diameter of 20 mm at midspan or at support(s) can form a risk for the strength of the element • Indicating if the element is sufficient for the (new) design by comparing output / advice after answer is filled-in with origin	Feedback sessions at Pieters Bouwtechniek

Table H.5: Received and processed feedback of preliminary versions of the Decision Support Tool regarding Phase III [2/2].

Stage 7: Construction		Feedback (processed in research)	Evaluation
Implementation of second-hand element	Re-element	Change of function • Creating awareness by adding this indicator Type of reconnection • Identifying the type of reconnections to the most common ones from the point of view of the structural engineer • Adding damage to the (protruding) rebars relating to the equipment to disconnect (Stage 3) • Implementing option if element will be reconnected to another second-hand element or to a newly-made element	Feedback sessions at Pieters Bouwtechniek
	Re-connect	Equipment to reconnect • Indicating the positive and negative effect on the reuse potential (by specifying the advantages and disadvantages) • Identifying the equipment to reconnect to the most common ones • Implementing answer option to ensure the executor remains accountable (selecting the preferred equipment to reconnect) General procedure • Creating awareness by adding this indicator regarding the (preferred) equipment to reconnect Adaptation of the second-hand element • Creating awareness by adding this indicator • Implementing an answer option for additional comment(s)	Feedback sessions at Pieters Bouwtechniek

H.2 Final version (results of the test-case)

H.2.1 Phase I: Pre-Disassembling

PHASE I - Pre-Disassembling										
Stage 1 - Inventory		Reference by researcher			Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Difference
		()	(+)	(-)	()	()	()	()	()	
General information about the (structural) el		0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,0%
1. Structural element		Concrete slab	[...]	[...]	Concrete slab	Concrete beam	Concrete slab	Concrete beam	Concrete slab	
2. Standardisation		0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	
3. Density	ρ	2400 kg/m³	[...]	[...]	2400	2500	2500	2500	2500	
4. Geometry										
a. Width	w	2814 mm	[...]	[...]	2000	180	1210	180	2800	
b. Height	h	400 mm	[...]	[...]	400	400	400	400	400	
c. Length	L	8021 mm	[...]	[...]	8000	8000	8000	8000	8000	
d. Weight	G	6000 kg	[...]	[...]	6000	6000	6000	6000	6000	
5. Image		[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	
General information about the (origin) building										
1. a. Project name		Satellietgebouw	[...]	[...]						
b. Location in the Netherlands		Amsterdam	[...]	[...]						
2. a. Construction year		1988	[...]	[...]						
Added later		No	[...]	[...]						
b. Deconstruction year		2021	[...]	[...]						
Deal-breaker questions		0,48	0,74	0,39	0,52	0,48	0,48	0,48	0,00	48,0%
1. Condition of the element		0,50	1,00	0,25	0,75	0,50	0,50	0,50	0,25	
a. (Constructive) cracks	Yes	1,00	1,00	1,00	1,00	0,50	0,50	0,50	0,50	
b. Expansion and/or deformation	Unknown	0,50	1,00	0,00	1,00	0,50	0,50	1,00	0,50	
c. Pop-outs of concrete pieces	Yes	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,50	
d. Efflorescence / alkali-silicic gels	Yes	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
e. Honeycomb	Unknown	0,50	1,00	0,00	1,00	0,50	0,50	0,50	0,50	
f. Reinforcement corrosion	Unknown	0,50	1,00	0,00	0,50	0,50	0,50	0,00	0,00	
Condition score (before deconstruction)	C_i	3	1	4	2	3	3	3	4	
2. Residual lifespan										
Based on condition score	13 years	0,20	1,00	0,00	0,40	0,20	0,20	0,20	0,00	
Based on design service life	17 years	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	
3. Accessibility	4	0,50	0,50	0,50	0,25	0,50	0,50	0,50	0,25	
4. Transport by road	Yes	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
5. Reuse		Reuse is possible								
Properties of the (structural) element to be r		1,00	1,00	1,00	1,00	0,92	1,00	0,83	0,92	16,7%
1. a. Type of cement	CEM I	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
b. Fire resistance	60 min	1,00	1,00	1,00	1,00	1,00	1,00	0,50	0,50	
c. Strength class	C30/37	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
d. Environmental class	X0	1,00	1,00	1,00	1,00	0,50	1,00	0,50	1,00	
e. Yield strength	500 N/mm²	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
2. Concrete cover	c_{nom}	20 mm	[...]	[...]						
3. Function		Office areas	[...]	[...]						
4. Design load(s)										
Design value of the tototal load	q_d	2,7 kN/m²	[...]	[...]						
a. Bending moment at midspan	M_{Ed}	10 kNm	[...]	[...]						
Shear force at midspan	V_{Ed}	0,0 kN								
Normal force at midspan	N_{Ed}	0,0 kN								
b. Bending moment at support	M_{Ed}	0 kNm	[...]	[...]						
Shear force at support	V_{Ed}	5,0 kN	[...]	[...]						
Normal force at support	N_{Ed}	0,0 kN	[...]	[...]						
c. Reinforcement drawings	Yes	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
5. First signature below EID	Yes	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,0%

Figure H.1: Comparison of filled-in answers of Phase I [1/2].

PHASE I - Pre-Disassembling										
Stage 2 - Performance Testing		**Reference by researcher**			**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Difference**
Composition		0,63	1,00	0,25	0,75	0,50	0,50	0,63	0,50	12,5%
1. a. Iron fibres	Unknown	0,50	1,00	0,00	0,50	0,50	0,50	0,50	0,50	
1. b. Composite fibres	Unknown	0,50	1,00	0,00	0,50	0,50	0,50	0,50	0,50	
1. c. Asbestos	Not presen	1,00	1,00	1,00	1,00	0,50	0,50	1,00	0,50	
1. d. Chlorides	Unknown	0,50	1,00	0,00	1,00	0,50	0,50	0,50	0,50	
Certified or not?		0,80	1,00	0,60	0,90	0,80	1,00	0,60	0,80	20,0%
2. a. Type of cement	Certified	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
b. Fire resistance	Not certified	0,50	1,00	0,00	1,00	1,00	1,00	0,00	0,00	
c. Strength class	Certified	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
d. Environmental class	Not certified	0,50	1,00	0,00	0,50	0,00	1,00	0,00	1,00	
e. Yield strength	Certified	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
Deterioration		0,85	0,90	0,80	0,85	0,62	0,80	0,65	0,80	23,5%
3. Internal deterioration		1,00	1,00	1,00	1,00	0,63	1,00	0,69	1,00	
a. Internal sulphate attack	No risk	1,00	1,00	1,00	1,00	0,50	1,00	0,50	1,00	
b. Alkali Silica Reaction (ASR)	No risk	1,00	1,00	1,00	1,00	0,75	1,00	0,88	1,00	
4. External deterioration		0,70	0,80	0,60	0,70	0,60	0,60	0,60	0,60	
a. Corrosion	Partial risk	0,50	1,00	0,00	0,50	0,50	0,50	0,50	0,50	
b. Cracks	No risk	1,00	1,00	1,00	1,00	0,50	0,50	0,50	0,50	
c. Penetration of sulphates	No risk	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
d. Penetration of chlorides	No risk	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
e. Penetration of carbonation	Risk	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
5. Second signature below EID	Yes	1,00	1,00	1,00	1,00	1,00	0,00	1,00	0,00	100,0%

Figure H.2: Comparison of filled-in answers of Phase I [2/2].

H.2.2 Phase II: Disassembling and Post-Disassembling

PHASE II - Disassembling & Post-Disassembling										
Stage 3 - Deconstruction		**Reference by researcher**			**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Difference**
Removal for reuse		0,53	0,59	0,48	0,45	0,47	0,53	0,53	0,38	15,0%
1. Type of connection	3	0,60	0,60	0,60	0,60	0,40	0,60	0,60	0,40	
- Accessibility	4	0,50	0,50	0,50	0,25	0,50	0,50	0,50	0,25	
2. Equipment to disconnect	5	0,50	0,67	0,33	0,50	0,50	0,50	0,50	0,50	
Stage 4 - Transport		**Reference by researcher**			**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Difference**
From deconstruction site to...		0,75	1,00	0,50	0,75	0,75	0,75	0,75	0,75	0,0%
1. Transport by road and by crane	Yes	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
2. Method of hoisting	Chemical anchors	0,50	1,00	0,00	0,50	0,50	0,50	0,50	0,50	
Stage 5 - Storage		**Reference by researcher**			**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Difference**
External influences		[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	
1. Amount of years at storage		[...]	[...]	[...]						
2. Susceptibility		[...]	[...]	[...]						
a. Stored outside										
b. Stored at or near to the sea (< 25 km inland)										
Stage 6 - Material Handling		**Reference by researcher**			**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Difference**
Modify to 'new'		0,78	0,94	0,61	0,78	0,78	0,72	0,78	0,72	5,6%
1. Needed modifications		0,83	0,83	0,83	0,83	0,83	0,67	0,83	0,67	
Nothing needs to be done	-									
a. The element needs painting	No	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
b. The element needs coating	No	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
c. Holes need to be filled	No	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,00	
d. Fixings (e.g. screws/nails ect) need to be	No	1,00	1,00	1,00	1,00	1,00	0,00	1,00	1,00	
e. The element needs to be sawn to resize	No	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
f. Holes need to be drilled for new connec	Yes	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
2. (Revised) fire resistance										
a. Local damage to concrete cover	No	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	
b. Corrosion of reinforcing steel	Small chance	0,50	1,00	0,00	0,50	0,50	0,50	0,50	0,50	
Condition & risk score		0,72	1,00	0,57	0,72	0,63	0,48	0,72	0,48	23,3%
1. a. Condition score (after Phase I and II)	2	0,75	1,00	0,50	0,75	0,75	0,50	0,75	0,50	
b. Residual lifespan	25 years	0,40	1,00	0,20	0,40	0,40	0,20	0,40	0,20	
2. Risk score (after Phase I and II)	1	1,00	1,00	1,00	1,00	0,75	0,75	1,00	0,75	

Figure H.3: Comparison of filled-in answers of Phase II.

H.3 Final version (feedback of the experts)

During the test-case executed by five experienced structural engineers, the process of 'Deconstruct & Reuse' is discussed based on the final version of the Decision Support Tool. An overview of the feedback on the test-case is shown on the next three pages (A3 format). The overview is ordered in Phase I, Phase II, Phase III, output and general. In order to draw a conclusion considering the feedback of the test-case, points of attention are addressed for remarks, opportunities, challenges and further research. A recapitulation for the points of attention is given in Table 9.1 and Table 9.2, which outline the most important remarks, opportunities, challenges and further research.

Phases	Stages	Indicators	Needed information	Remarks	Opportunities	Challenges	Further research
Phase I **Pre-Disassembling**	**Recap of received feedback on Phase I**			• Add assessment questions and answer options • Specific knowledge results in 'unknown' answer option(s), but creates awareness • Certification	• Automatically determine • Include codes	• Lacking information results in speculation	• Consider other elements • Consider residual lifespan and capacity
	Stage 1: Inventory	Quick check if reuse is possible	1. Structural element	• At the start of Stage 1, add a question if existing information by drawings and desk research is available.			• The research mainly focuses on 'solid' concrete (structural) elements. For further research, also consider other elements (e.g. a prefabricated hollow core slab with standard dimensions, or stairs/landings). Which indicators need to be assessed else?
			2. Standardisation				• Include pre-tensioned and post-tensioned concrete.
			3. Density				
			4. Dimensions				
			5. Image				
			1. Project name and location				
			2. Construction and deconstruction year		• Automatically determine the used standards corresponding to the construction year of the (origin) building.		
			1. Condition of the element *(deal-breaker question 1)*	• The condition is a transparent list and clearly shows what to think about corresponding to NEN 2627. • The technical questions are difficult to fill in because they require specific knowledge for this Stage.	• Include (inspection) policies/standards/regimes (e.g. the decomposition according to NEN 2627).		
			2. Residual lifespan *(deal-breaker question 2)*	• Except for the residual lifespan, almost all other deal-breaker questions can be dissolved in a later stage (e.g. with coating).	• Automatically determine the design service life of the existing building by including Consequence Classes (CC1 / CC2 / CC3).		• The residual lifespan is the most important deal-breaker question because it is the hardest to improve. However, it is hard to give an exact value to the residual lifespan which makes it difficult to interpret. Therefore, more research is needed.
			Accessibility *(deal-breaker question 3)*				
			Transport *(deal-breaker question 4)*				
		Properties of the (structural) element to be reused	1. Properties of concrete and reinforcing steel	• Add more type of cements, environmental classes and strength classes.	• Automatically determine the chance of deterioration based on e.g. type of cement..		
			2. Concrete cover				
			3. Function		• Include legally obtained level for the existing building (in Dutch: 'rechtensverkregen niveau') to automatically determine function		
			4. Design load(s)	• Consider an option to express the reinforcing steel in percentage.	• Automatically determine the design load(s) on the element by considering the used standards corresponding to the construction year and function of the (origin) building.	• Speculation occurs if existing information of the (origin) building is not available. • For the case-study, a lot of information is known (e.g. reinforcement drawings). Take in mind that this is not always the case for existing (to-be-demolished) buildings.	• The (calculated) capacity does not say anything about the residual capacity. Therefore, research which values of the reinforcement are relevant for each element or include reinforcement drawings
	Stage 2: Performance Testing	Composition	1. Toxic materials	• These specific questions will probably always be answered with 'unknown'. However, these indicators create awareness about the risks for reuse.	• Automatically determine the presence of toxic materials in the element by considering the environmental class and type of cement.		
		Certified or not?	1. Properties of concrete	• Is certification of the properties of a second-hand element necessary, or is existing information by drawings and desk research sufficient? For example, the fire resistance of concrete is good, which means it is not always needed to perform testing in practice. Additionally, the strength class of concrete can be determined by drawings due to safety margins in (older) codes.			• Which properties really need to be researched and certified? And which can be assumed with conservative lower limits?
		Deterioration	1. Internal deterioration				• Consider if the element has suffered extreme loading during its service life which can cause damage to the element (e.g. fire, earthquake, shock loading, etc).
			2. External deterioration				

Phases	Stages	Indicators	Needed information	Remarks	Opportunities	Challenges	Further research
Phase II Disassembling and Post-Disassembling	Recap of received feedback on Phase II			•	•	•	•
	Stage 3: Deconstruction	Removal for reuse	1. Type of connection	• Substantiate the suggested equipment to disconnect in the Decision Support Tool based on the advantages and disadvantages.			• It is only possible to assess one connection in the Decision Support Tool. In order to add multiple connections, consider a button to copy rows.
			2. Accessibility				
			3. Equipment to disconnect	• Depends on other parties (e.g. demolition company). • What if it is possible to use multiple equipments?			• Consider the bracing of elements during deconstruction.
	Stage 4: Transport	By crane	1. Method of hoisting				• Consider loading scheme of element (e.g. in situ is differently designed than pre-cast). What are ways to strengthen an element?
		By road	1. Geometry	• Substantiate result in Decision Support Tool if a combination of information is used (now only described in the report).		• Speculation occurs, because transport is a profession on its own.	• Consider the CO_2 emissions linked to transport by road and by crane.
	Stage 5: Storage	External influences	1. Amount of years	• Add question what the maximum allowed time is for the executor (instead of assuming 5 years).			• Consider how the element is stored/stacked (with image).
			2. Susceptibility	• These specific questions will probably always be answered with 'unknown'. However, these indicators create awareness about the risks for reuse. • Substantiate result in Decision Support Tool if a combination of information is used (now only described in the report).			
	Stage 6: Material Handling	Modify to 'new'	1. Modifications	• Is it necessary to modify a second-hand element to new? • Modifications depend on demolition and reconnection in (new) design, and thus on other parties.	• Do these modifications extend the design service life of a second-hand element?		• Consider if the (origin) gains of the second-hand element can be reused for reconnecting.
			2. Fire resistance	• Substantiate result in Decision Support Tool if a combination of information is used (now only described in the report).		• Speculation occurs, because with fire resistance there is no need to perform testing (see Stage 2).	
		Condition and risk score	1. Condition score				
			2. Risk score		• Automatically determine by linking to NEN 2627. Additionally, link the condition and risk score to a maintenance plan of existing buildings (in Dutch: Meerjaren Onderhoudsplan).		
Phase III Re-Assembling	Recap of received feedback on Phase III			• Phase III indicates what to think of in a (new) design and supports the decisions of a structural engineer. • Consider Phase III separately, because it comes years after Phase I and II.		• Include Consequence Classes (CC1 / CC2 / CC3) to determine requirements of the (new) building.	
	Stage 7: Construction	Requirements of the (new) design	1. Project name and location	• What happens if the new design is not (yet) known?		• Can the Decision Support Tool also form a design strategy to implement circularity?	• Consider if the element suits (current) Eurocode regulations and what needs to happen if not.
			2. Construction year				
			3. Design service life				• Consider if the element needs maintenance measures and periodical inspections.
		Properties of second-hand element	1. Properties of concrete and reinforcing steel		• Link to deterioration mechanisms (e.g. risk for ASR if element is used in humid environment or with XS1).		• Consider if the element suits (required) building physiscs (e.g. thermal resistance, oisture, acoustics, air, light, etc).
			2. Concrete cover		• Automatically determine construction class with standards (now only S4 is considered).		• Consider tolerances for construction and fabrication (e.g. lengthening for repairs).
			3. Function				• Include legally obtained level for the existing building (in Dutch: 'rechtensverkregen niveau').
			4. Design load(s)		• Automatically determine design load(s) on the element by considering the used standards corresponding to the construction year and function of the (origin) building.	• Speculation occurs if existing information of the (origin) building is not available.	• For further research, extend example calculation to check capacity for all elements (now only beam).
			5. Holes for services	• Option to express the holes for services in percentage (per zone).			

Phases	Stages	Indicators	Needed information	Remarks	Opportunities	Challenges	Further research
(continuation of Phase III)		Implementation of second-hand element	1. Change of function	• The capacity of a wall is different for a slab, depending on the reinforcement and quality.			
			2. Type of reconnection	• Limited amount of type of reconnections available • Add question if wet/dry joint is required, or easiness of putting in practice.			• Consider boundary conditions (rigid, semi-rigid or pinned).
			3. Equipment to reconnect	• Add sketches related to the type of reconnection to make it more feasible.			
			4. General procedure	• Add sketches.			
			5. Adaptation				• Consider adding all needed modification(s). • Next to general procedure and adaptation, consider costs, production rate, mechanics, applicability, …
Output of Decision Support Tool				• The output motivates towards a (more) circular economy. • The output is easy to understand for structural engineers. However, specific knowledge is required for some questions (e.g. for the equipment to disconnect). Add source(s).	• After Phase I and II, the reuse potential of an element is allocated a percentage. This makes it possible to compare different applications. • For further development of the tool, link the input of the tool to BIM of (existing) buildings to automatically generate the output (or to NL-SfB tables). If for all new and harvested (structural) elements the needed information of the indicators is documented, the reuse potential can be easily determined (also on the long term).	• After Phase I and II, the reuse potential of an element is allocated a percentage. From what percentage is reuse not recommended? What does it mean if the percentage is above, around or below this tipping point? How is this percentage interpreted by others? What can be done to improve the reuse potential? Make it a puzzle until the optimum is found.	• The output takes into account the labels to add a harvested (structural) element to a database. However, the database still needs to be developed! • A reuse potential close to 0% results in higher costs to enable reuse.
General				• Clear checks in the Graphic User Interface. • Add explanations at which moment an executor can fill in Phase I, II or III (now only described in the report). • Add explanations of what a filled-in answer is used for (now only described in the report). Or add links to report. • Add explanations of what happens if an answer is not filled in (or make clear which questions are mandatory and optional). • Add more answer options for additional comment(s) by the executor to the output (e.g. at the end of each Stage).	• The tool includes all aspects associated with reuse. Additionally, it is possible to influence every indicator of the process of Deconstruct & Reuse. The assessment summarizes all information needed to determine which elements in a building are reusable (in the initial phase). • All indicators are supported by theory. • Currently, the structural engineer has a pioneering role in making reuse possible, by testing the strength of second-hand elements and making the implementation of these feasible. With further development of the tool, structural engineers may no longer be needed in the future, because with the output the client can decide which elements are suitable in a (new) design. Due to the performance specification, it does not matter whether an element is new or reused. Some questions depend on (regular) inspection reports which mean it is convenient to execute the assessment next to regular inspections. Since both require desk research, this will not take extra time and information can be shared. Additionally, relevant aspects of the (regular) inspections might be overlooked and can be added to the assessment. Therefore, consider to integrate (regular) inspections into the Decision Support Tool.	• Phase I and II determine if reuse is possible according to the reuse potential. These phases should be applied at the start of a (demolition) project. Phase III supports the decisions of a structural engineer about the implementation in a (new) design. However, a structural engineer is (probably) already involved and gives his or her twist to the design of connections and calculations.	• Adding legal liability / warranties / responsibilities. • Adding economic value in practice. One of the executors suggested that if a building is designed and inspected in such a way that the elements can be reused at their end of life cycle, a party will retain or become the owner at retrieval. Due to these responsibilities of material flows (without intermediaries), disassembling is already taken into account in the design of a building. Additionally, the owner of the material flows can apply a revenue model and warranty to the elements which can make reuse beneficial. • The current added value in practice is in Phase I and II because every structural engineer gives his or her twist to the design of connections and calculations. For further research, the first draft of Phase III can be extended. • For further development of the tool, link to a database to combine the supply and demand of harvested (structural) elements with a Dynamic Final Design (in Dutch: Dynamisch Definitief Ontwerp (DDO)). • It is only possible to assess individual elements in the Decision Support Tool which means the execution takes a lot of time in case multiple elements of a building need to be tested and reused. For further research, consider the execution of the Decision Support Tool for a building as a whole (e.g. by making the tool self-learning with the executor by skipping irrelevant questions or copying information for multiple elements).