REUSE OF CONCRETE STRUCTURAL ELEMENTS IN PRACTICE

Design of a tool which stimulates structural engineers to reuse concrete structural elements by giving insight in structural safety, the environmental impact, and economic impact

Master Thesis

J.M. Beukers

Front page: Damaged concrete floor of the Merin Building in Breda (Heijmans Internal Document, 2021)

REUSE OF CONCRETE STRUCTURAL ELEMENTS IN PRACTICE

Design of a tool which stimulates structural engineers to reuse concrete structural elements by giving insight in structural safety, the environmental impact, and economic impact of reusing

by

J. (Janna) M. Beukers

To obtain the degree of Master of Science in Civil Engineering at the Delft University of Technology, to be defended publicly on Monday July 11, 2022 at 14:00 PM.

Project duration: December 2021 – July 2022

Graduation Committee:

Dr. ir. M. (Marc) Ottele	Delft University of Technology
Prof. dr. ir. H. (Henk) M. Jonkers	Delft University of Technology
Ir. H. (Hoessein) Alkisaei	Delft University of Technology
Ir. H.J. (John) Bossong	Heijmans Utiliteit B.V.

Contact Information

Author:

Name:	J. (Janna) M. Beukers
University:	Delft University of Technology
Student number:	4369432
Faculty:	Civil Engineering and Geosciences
Master track:	Building Engineering
Specialisation:	Structural Design

Graduation Committee:

Name (chair):	Dr. ir. M. (Marc) Ottele
University:	Delft University of Technology
Department:	Materials, Mechanics, Management & Design
Section:	(3Md) Materials and Environment

Name:	Prof. dr.ir. H. (Henk) M. Jonkers
University:	Delft University of Technology
Department:	Materials, Mechanics, Management & Design
Section:	(3Md) Materials and Environment

Name:	Ir. H. (Hoessein) Alkisaei
University:	Delft University of Technology
Department:	Materials, Mechanics, Management & Design
Section:	(3Md) Applied Mechanics

Name:	Ir. H.J. (John) Bossong
Company:	Heijmans Utiliteit B.V.
Profession:	Department coordinator / Sr. Advisor Method & Construction

Preface

This research presents the final chapter of the Master Civil Engineering at Delft University of Technology. Within this master I have followed the Master Track Building Engineering and a specialization in Structural Design. During my master studies, I experienced the upcoming need for a sustainable construction sector. Especially, due to the course Materials and Ecological Engineering, I became very enthusiastic about circularity and environmental impact calculations. After completing the course I knew I wanted to work on a research focusing on reducing the environmental impact of the construction sector. By diving into literature and master theses of my fellow Civil Engineering students, I found out that there is potential for reusing concrete structural elements. However, reusing concrete structural elements in practice, is the next step. Since I have a background in Systems Engineering, Policy Analysis and Management I wanted to integrate my knowledge about stakeholder management and decision making, with my knowledge about environmental- and structural engineering. Therefore, my research focusses on the stimulation of reuse of concrete structural elements in practice, by giving insight in structural safety, environmental impact, and economic impact of reusing concrete structural elements.

This research has been done in collaboration with Heijmans Utiliteit, where I was welcomed at the department of Method & Construction. During my graduation project I was supervised by John Bossong. I want to thank John for his encouragement to let me think in multiple directions within my research. Besides, I want to thank John for finding me the perfect case study and bringing me in contact with his colleagues. Moreover, a big thanks to Caroline Koks who gave me lots of insights for the development and applicability of the Reusability Tool. Although I started my graduation project from home due to the pandemic, I felt very welcome at the office after a couple of months, which is thanks to a bunch of kind and enthusiastic colleagues.

Next to the supervision from Heijmans Utiliteit, I would like to thank my graduation committee of Delft University of Technology. Thank you for your feedback and critical view throughout my research. Marc, I want to thank you for your guidance and helping me not to lose sight of the bigger picture and ultimate goal of my thesis. I want to thank Henk for his enthusiasm about sustainability, and his focus on the structure of the research and report. Hoessein, thank you for your questions making me reflect on my own work, your feedback on my structural analysis and visualizations of my process trees.

Besides, I would like to thank my fellow students for the fun study sessions and discussions. Thanks to my friends, family and roommate who supported me throughout the process, kept me motivated, and gave me confidence in my research project.

By writing this, my time as a student almost came to an end. I enjoyed my time at Delft University of Technology and I am looking forward to what the future has me to bring!

Janna Beukers
Delft, July 2022

Executive summary

Since the globe is warming and without action the planet will be ruined, the Paris Agreement states to keep the global warming below 2 degrees Celsius. The construction sector is liable for 40% of primary energy utilization. Therefore, constructing according to principles of the circular economy can strongly contribute to lowering the global warming. Almost 80% of the building material consists of concrete. The past years, around 42% of the demolished utility buildings were constructed in the 70s/80s and consisting of in-situ concrete. Demolition results in lots of released concrete rubble which is often down- or recycled. For new construction projects, new concrete elements will be produced. However, instead of new produced concrete elements, potentially also reused concrete elements can be used. Therefore, this research focusses on the reuse potential of in-situ concrete elements which can be dismantled from demolition projects of utility buildings. Nowadays, the main reason for reusing structural elements is the reduction of environmental emissions. The main reasons for not reusing structural elements are the high costs and structural feasibility. Since these aspects are often not properly analysed, this research presents the Reusability Tool in which the reuse potential of in-situ concrete structural elements can be assessed based on structural safety, environmental impact, and economic impact.

The Reusability Tool is developed for structural engineers to stimulate the reuse of concrete elements in practice in new buildings. The Reusability Tool analyses and compares the environmental- and economic impact of three circular strategies: reusing, upcycling, and downcycling. Therefore, the definitions of reuse, upcycling, and downcycling are of importance, whose are explained in Figure 1.

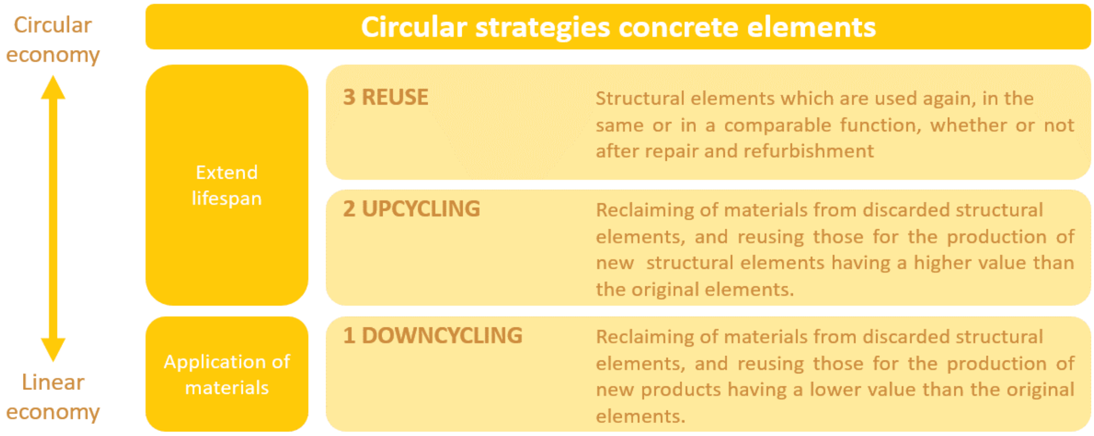


Figure 1: Circular strategies included in Reusability Tool

Moreover, the structural safety of reusing is assessed based on the current condition and the future applicability of an element. Regardless of the environmental- and economic impact, an element should be structurally safe in order to be reused.

Based on an extensive desk research, interviews with experts from the field, and a case study the process reuse, upcycling, and downcycling is analysed. This process is divided into five main steps: Preparation, Deconstruction/demolition, Transport, Post-processing, New element production. Each step results in an environmental impact expressed in an Environmental Cost Indicator (ECI) value, and an economic impact expressed in costs. For each circular strategy, this leads to an ECI value and total costs which can be compared.

In order to analyse the reuse potential, the Reusability Tool requires input information from six categories: Product choices, Applicability, Design choices, Element condition, Forms of collaboration, and Budget and planning. Based on the input information, the Reusability Tool presents on of the circular strategies: reusing, upcycling, or downcycling. This advice is the result of the structural safety analysis and a calculated element score. The element score varies between 0 and 100 and is calculated based on three aspects: the residual lifespan of a structural element, the environmental impact of reusing compared to downcycling, and the economic impact of reusing compared to downcycling. Since a building which is planned to be demolished, will be demolished or deconstructed, this will in any case leads to environmental- and economic impact. Therefore, the Reusability Tool analyses the benefits and loads of reusing compared to downcycling which is currently the most often applied strategy. When the element score results in a score above 60 and the structural assessment turns out to be sufficient, the Reusability Tool advises to reuse the analysed structural element. In case the element score is below 60 or the structural assessment is insufficient it is advised to upcycle the structural element.

The focus and returned output of the Reusability Tool is shown in Figure 2.

Figure 2: Focus and returned output of Reusability Tool (Own figure)

The Reusability Tool is developed in MS Excel and consists of several sheets being important for the end-user. The first sheet includes an explanation about the Reusability Tool and shortly explains the assessment system. The required input information for the analysis should be filled in on the *Input sheet*. In this sheet, the required information is shortly explained, and links and references are included to provide additional information. The advised circular strategy for the analysed concrete structural element is generated and stated on the *Output sheet*. Moreover, the element score, important structural properties, and the environmental- and economic impact of the three analysed circular strategies are presented. In case the user prefers more detailed information, the *Detailed Output sheet* presents the output of all included structural checks, detailed environmental information, and all included costs.

By testing the Reusability Tool with a case study from practice, and feedback sessions with structural engineers, the tool has been validated and verified. Several concrete beams, columns, and floor elements are analysed in a case study resulting in element scores and advised circular strategies. For the test case it turned out that in-situ concrete floor elements have the most reuse potential. Also the influence of some input variables on the output of the Reusability Tool are analysed like dimensions of an element, reinforcement detailing, and concrete strength classes.

In order to improve the applicability of the Reusability Tool, a broader user field could be analysed. The Reusability Tool focusses on in-situ concrete elements of utility buildings. It is recommended to analyse how the reuse potential of other building types and building materials can be assessed. Moreover, there is still lots of uncertainty in the process of collaboration between parties which are involved in the process of reusing elements. Therefore responsibilities and liabilities could be analysed and translated into a protocol describing the collaboration process. Furthermore, the scoring system of the elements requires further research. It is advised to involve the interpretation of different experts from the field.

The Reusability Tool is a user friendly tool which can be used to assess the reuse potential of in-situ concrete structural elements from utility buildings, and will prevent valuable elements to get lost. The tool can give insight in the reuse potential in an early design stage of a future project, and can form the basis for further investigations.

'Everything has a value until proven otherwise'.

Table of Contents

List of Figures

List of Tables

Acronyms

ECI	Environmental Cost Indicator
EPD	Environmental Product Declaration
EVR	Eco-cost Value Ratio
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCA	Life Cycle Analysis
MKI	Milieu Kosten Indicator
MPG	Milieu Prestatie Gebouwen
NMD	Nationale Milieudatabase
SLS	Serviceability Limit State
ULS	Ultimate Limit State

PART I | RESEARCH FRAMEWORK

1 Introduction

In this chapter the problem context is described in Section 1.1, even as the motive for this research. The next section, Section 1.2, provides information about the state of art of the subject. In Section 1.3 the definition of the problem is given.

1.1 Problem context

On November 13th 2021, after two weeks of discussions, the COP26 in Glasgow reached consensus on key actions to address climate change. The agreements strengthen the three pillars of the UNFCCC collective climate action: Adaptation, Mitigation and Finance. The climate actions and plans should be in accordance with the Paris Agreement of 2015 (UNFCCC, 2021). The primary goal of the Paris agreement is to keep the global warming below 2 degrees Celsius and close to 1.5 degrees Celsius (Rijksoverheid, 2019).

The construction sector is liable for almost 40% of the primary energy utilization and therefore majorly contributing to the global warming. Most of this energy is from unrenewable resources causing large emissions of greenhouse gasses (Huang, Krigsvoll, Johansen, Liu, & Zhang, 2018). The reasons for the high emissions in the construction sector are mainly caused by the linear economic model which is handled. This model is based on the principle of take, make and dispose of. Raw materials will be extracted from the environment, processed into construction materials, and assembled on site. At the end of life, the construction will be disposed in landfills since deconstruction is not possible. Therefore a circular model, the Circular Economy, is developed in which a better management of resources is obtained (Benachio, Freitas, & Tavares, 2020). The Ellen MacArthur Foundation stimulates the Circular Economy in which waste and pollutions will be eliminated, products and materials will circulate, and nature will be regenerated. The diagram of Figure 1.1 visualizes the Circular Economy and shows the continuous flow of materials and resources (Ellen MacArthur Foundation, 2019). According to Cramer the relation between the linear- and circular economy can be divided into 10 steps as shown in Figure 1.2. This model is often used in order to see the circular possibilities of a building or structure.

Reusing of construction elements and materials will contribute to the continuous flow of materials and resources and will contribute to achieve the primary goal of the Paris Agreement. In order to support the transition to a circular building economy in the Netherlands, Platform CB’23 created a guideline about circular designing. In this guideline, it is stated that the application of recycled materials can be promoted by expressing the quality of the object, doing pilots and sharing those information (Platform CB’23, 2021). Parties which are affiliated with CB’23 are for example producers, demolishers, clients, executors, from start-ups till large contractors. Teams are working on guidelines about future reuse, measuring of circularity, and passports for construction projects (Platform CB’23, 2022a).

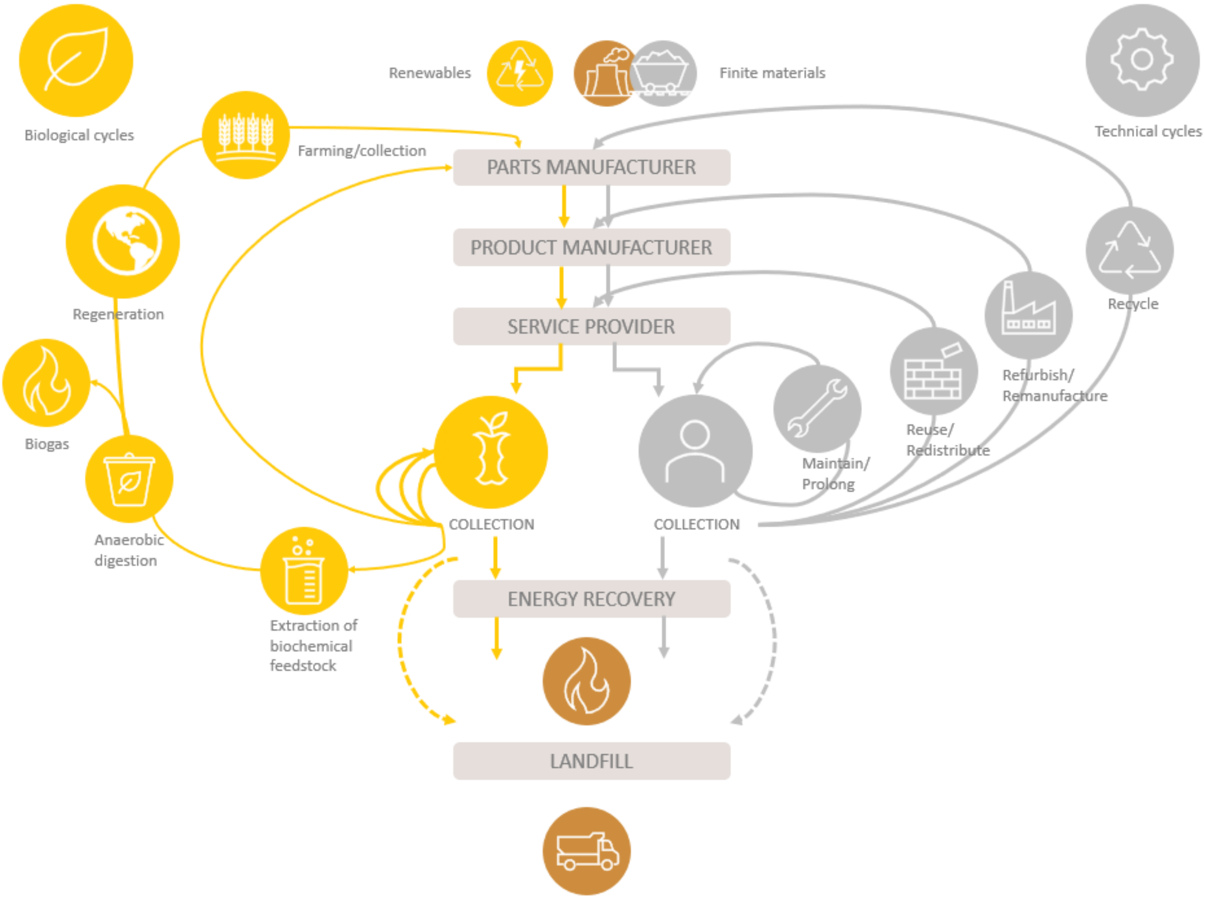


Figure 1.1: Circular Economy Systems Diagram (Adapted from Ellen MacArthur Foundation, 2019)

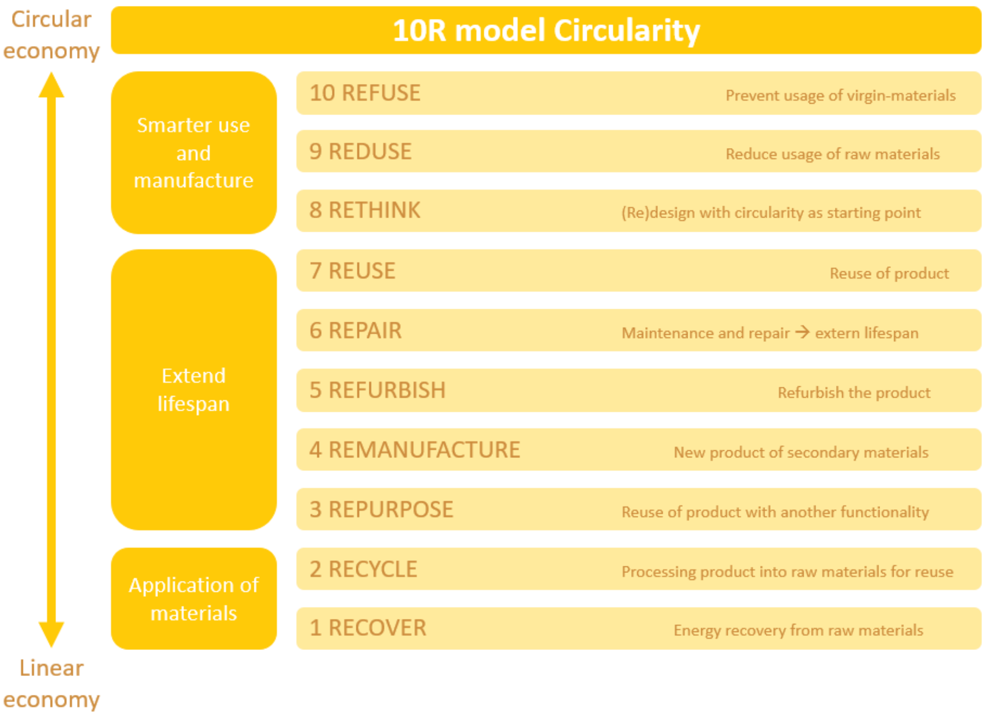


Figure 1.2: 10R Model of Circularity (Adapted from Archipunt, 2021)

According to Brand a building consists of six building layers: Stuff, Space plan, Services, Skin, Structure, and Site. As shown in Figure 1.3, each layer has its own lifespan. The technical service life of the structure of a building varies between 30 and 300 years while the functional service life is less (Brand, 2006). In other words; the construction loses its functionality after a certain period while the structural elements are still intact. This often results in demolition of structures and landfill with products which have potential to be reused in new constructions.

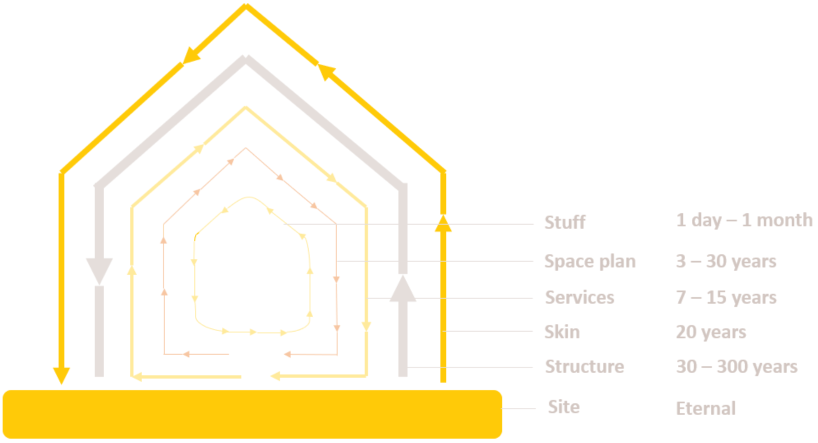


Figure 1.3 Building layers (Adapted from Brand, 2006)

From Figure 1.3, it can be concluded it is interesting to focus on circular strategies of the structure of a building.

In the Netherlands, around 80% of the building materials in utility and residential buildings consists of concrete and therefore concrete has the largest contribution to environmental footprint. In the production process of concrete, especially cement causes high emissions (Arnoldussen et al, 2020). These emissions can be prevented by reusing concrete elements. Therefore, reusing concrete structural elements should be stimulated in practice.

It is important to think of environmental and economic impacts of reusing structural elements. What is the total environmental and economic impact of reusing existing concrete elements compared to a new concrete element? And what about the safety requirements when reusing structural elements? In order to stimulate reusing structural elements, those impacts should be mapped to give insight in the costs and benefits of reusing.

1.2 State of the art

Circular Economy is upcoming in the building sector. However, there is no universal way of reusing structural elements. Therefore, demolition projects in the Netherlands are analysed to see what kind of concrete structures are demolished. Besides, structural safety, environmental impact, and economic impact of (circular) building projects are assessed. Moreover, existing tools assessing circularity are explored and compared based on structural safety, environmental impact, and economic impact.

1.2.1 Demolition in the Netherlands

In the Netherlands, structures are categorized in two groups: residential- and utility buildings (B&U), and ground-, roads, and water works (GWW). For each of the two categories, EIB analysed the flows of materials, environmental impact, and energy usage, together with Metabolic and SGS Search. In Appendix A.1 detailed information about these aspects is given.

1.2.1.1 B&U-sector

The demand for new construction has been increased over the years. Where in 2014 around 45.000 residential housing and 8.000 utility buildings were constructed, in 2019 this was increased to around 72.000 residential housing and 11.000 utility buildings. However, the amount of demolishment projects remained almost the same. In the residential building sector, especially serial housing constructed in 1945-1970 (the so called 'early after war housing') are demolished (around 61% of residential housing demolition in 2019), as shown in Figure 1.4. This is caused by the low quality of these buildings and the increased quality demands for buildings those days. Next to that, the building stock of building corporations mostly exists of these types of buildings. Building corporations have more demolition projects compared to private landlords. In the utility sector, mainly buildings constructed in the 70s/80s are demolished (around 42% of utility demolition in 2019), shown in Figure 1.5. This is caused by increasing demands for health, sustainability, and comfort.

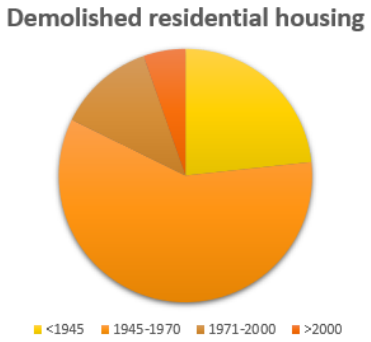


Figure 1.4 Demolished residential buildings in the Netherlands (Adapted from Arnoldussen et al, 2020)

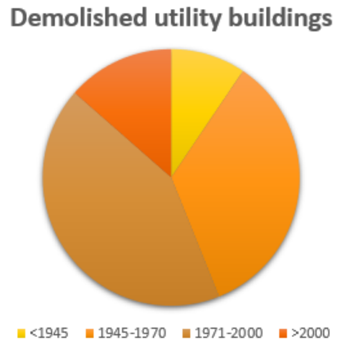


Figure 1.5 Demolished utility buildings in the Netherlands (Adapted from Arnoldussen et al, 2020)

By comparing the total required material flows for new construction with the released material flows from demolition projects, it can be concluded that the required flows are over 4.5 times bigger than the released ones. Moreover, it should be noted that in practice not all released materials will be reused, a material flow analysis (MFA) only shows the theoretical potential of the supply of secondary materials (Arnoldussen et al, 2020; Arnoldussen et al, 2022).

Focusing on the MFA of residential housing and utility buildings, the flow of concrete is dominant and is more than 70% of the total mass of building materials (Blok, 2020). From analysing the required and released concrete elements, hollow core slab floors, wide slab floors, and in-situ concrete elements with strength class C20/25 are the most required concrete products, where wide slab floors, and in-situ C20/25 are the most released elements after demolition (Arnoldussen et al, 2020). In the Netherlands, most in-situ structures are made of concrete strength classes C20/25, C25/30, and C30/37. More information about concrete properties is included in Appendix B.

1.2.1.2 GWW-sector

When focusing on civil construction works (bridges, viaducts, tunnels, and locks) in 2019, the area consists of 68.800 works of which almost 80% is managed by municipalities. The area of these works are dominated by concrete bridges (57.300). In 2019, 530 new concrete bridges and 15 viaducts are constructed and 315 bridges and 35 viaducts are replaced. Demolition of GWW works without replacement does not happen often because of the important function those works fulfil. Analysing the material flows in the GWW sector, also the flow of concrete is dominant (Arnoldussen et al, 2022). Nowadays, Rijkswaterstaat managed around 1800 viaducts. From analysis of the area of viaducts, around 90% (1632) of the viaducts consists out of girders and 10% consists out of plates. Currently, 7 viaducts are demolished per year with an average age of 40 years. Expected is this amount will increase significantly because of the so called V&R (Replace and Renovate) task of Rijkswaterstaat (Ministerie van Infrastructuur en Waterstaat, 2021b)

1.2.2 Structural safety

It is important to guarantee sufficient safety when reusing structural elements. To design a structural safe construction, the effect of the load should be lower than the resistance of the structure during its design life (De Vries et al, 2013). According to Bouwbesluit, the definition of structural safety is *'the chance of failure of a construction'*(Banga, 2012). Terwel and Jansen defined structural safety as *'inadequate performance of a structure that creates or might create an unsafe situation'* (Terwel, Jansen, 2015).

The effect of the load on a construction depends on the following basic variables: the load and effects from the environment, material- and product properties, and geometric information of the construction and its elements. The assessment of a structure is a deterministic process. In reality, the basic variables will not have the exact same value as the assumed values in calculations, because all basic variables are stochastic ones. Loads will differ during time, dimensions of elements are in between tolerance boundaries, and also material properties will show some scatter. It is task of the structural engineer to show that the chance of failure is sufficiently small (De Vries et al, 2013; Banga, 2012).

Failure of a construction will result in economic failure and can result in loss of life. Due to regulations, the chance of failure of a construction will be below a boundary which is socially acceptable. Failures of structures can be caused by higher applied loads than included in calculations, less material qualities than expected, design mistakes, or mistakes during execution. Besides, the robustness and ductility of the structure is of importance. The process of guaranteeing safety can be seen as a chain in which one weak link can result in disastrous consequences (Banga, 2012).

Figure 1.6 Critical factors structural safety (Adapted from Terwel & Jansen, 2015)

Terwel and Jansen analysed the critical factors for structural safety in the design- and construction phase in which three levels of factors are distinguished, as shown in Figure 1.6.

In this research, especially some company- and project factors are interesting to focus on. In order to guarantee sufficient structural safety when reusing structural elements, they should fulfil the requirements written in protocols like the Eurocode. Since reusing structural elements is new phenomenon, additional control mechanism could help improving structural safety. A realistic project planning and a proper budget for reusing elements will improve the structural safety as well. In Appendix A.2, all factors influencing structural safety are explained in more depth. Moreover, some examples of structural unsafety in the Netherlands are analysed in order to see what are the main causes for unsafety.

1.2.3 Environmental impact

In the Netherlands, the Bepalingsmethode Milieuprestatie Bouwwerken is developed to calculate the environmental performance of construction works during their life cycle, based on EN 15804. Together with the Nationale Milieudatabase (NMD), which includes environmental information of materials and elements, the Bepalingsmethode is managed by the Stichting Nationale Milieudatabase (Stichting NMD). Next to the EN 15804, the Bepalingsmethode describes values for specific processes in order to avoid unjustified mistakes in the calculation of environmental impact of different building products (Stichting Nationale Milieudatabase, 2020). The process of the Bepalingsmethode is shown in Figure 1.7. Each step of the Bepalingsmethode is shortly explained.

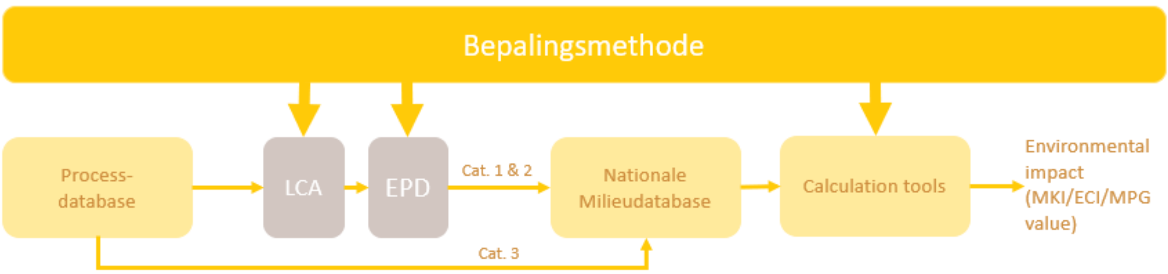


Figure 1.7 Bepalingsmethode (Adapted from Stichting Nationale Milieudatabase, 2020)

The calculation method of the environmental impact during the life cycle, which is described in the Bepalingsmethode, is based on a Life Cycle Analysis (LCA) explained in EN 15804:2012. This analysis includes the product stage (Module A1-A3), the construction process stage (Module A4-A5), the use stage (Module B1-B7), the end of life stage (Module C1-C4), and the benefits and loads (Module D). The complete building life cycle information is shown in Figure 1.8.

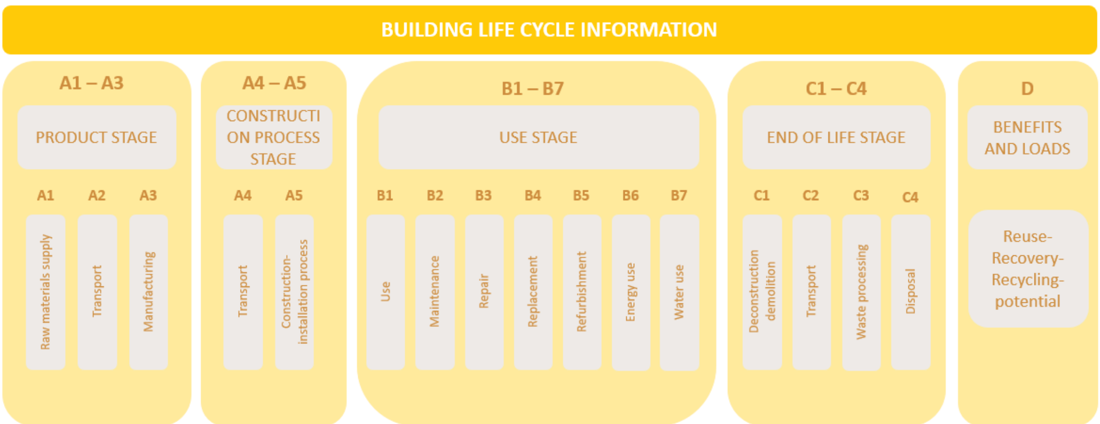


Figure 1.8 Building life cycle information (Adapted from EN 15804:2012+A9:2019)

The environmental impact of concrete structural elements can be analysed and measured in equivalent units for 19 impact categories for each module. The result of this analysis is an Environmental Product Declaration (EPD) on which the total environmental impact (emissions) are presented (Levels-Vermeer et al, 2015). NEN-EN 16757:2021 provides information about EPD's on concrete products.

The Nationale Milieudatabase includes product information about materials and elements. The environmental impact expressed in equivalent units is related to shadow costs (€). These costs The NMD contains distinguishes three categories of product information. Appendix A.3 explains the differences between these categories (Stichting Nationale Milieudatabase, 2020).

By making use of calculation tools, the total environmental impact expressed in a shadow price is called the Environmental Cost Indicator (ECI), or in Dutch: Milieu Kosten Indicator (MKI). It is also possible to express the total environmental performance of a building in €/MFA. This performance is called the Milieu Prestatie Gebouwen (MPG) (Rijksdienst voor Ondernemend Nederland, 2021).

The Bepalingsmethode is used to calculate the environmental impact of structural elements, or complete buildings. In order to analyse the environmental impact of a reused structural element and compare this to the environmental impact of other circular strategies, as explained by Mac Arthur and Cramer, the Bepalingsmethode is a suitable method. More detailed information about the calculation of environmental impact is given in Appendix A.3.

1.2.4 Economic impact

The circular economy is associated with other costs than the linear economy. In order to analyse the economic viability of investing in circular strategies and compare alternatives, Life Cycle Costing (LCC) can be used (Van den Boomen et al, 2016). According to NEN-EN-IEC 60300-3-3, the objective of life cycle costing is to assist in making a decision about the most convenient alternative options during the life cycle of an element. In LCC, all costs expressed in €, of an element are included during its complete life cycle. In a new design of buildings, revenues are leading in the determination of what buildings may cost (Royal HaskoningDHV, 2021b). Therefore LCC can be used in order to see the economic effects of circular strategies.

1.2.5 Reusability tools

Several tools assessing circularity are developed, each focussing on different circular aspects. In order to see a gap for which a new tool could be developed, the existing tools are analysed and compared based on structural safety, environmental impact, and economic impact. This is shown in Figure 1.9. Besides, the tools are analysed and compared based on some other important focus points which is shown in Table 1.1. Detailed information about the analysed tools can be found in Appendix A.4.

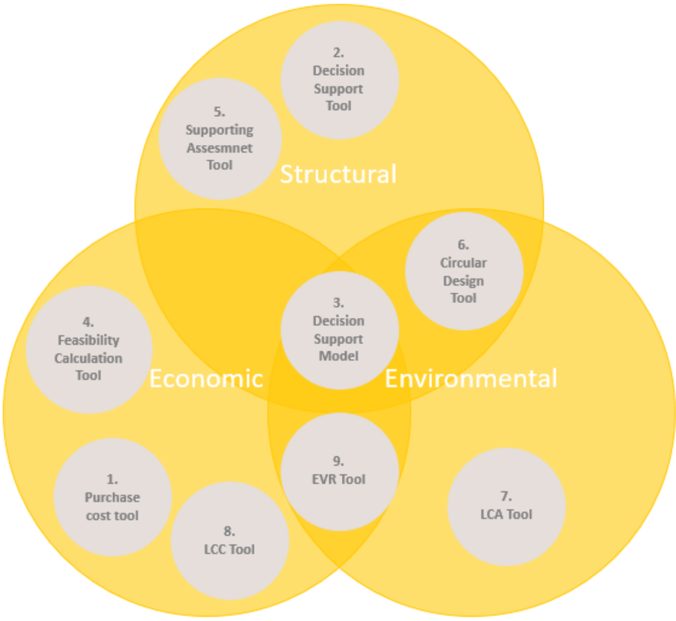


Figure 1.9 Analysed reusability tools (Own figure)

Table 1.1 Focus analysed reusability tools

Tool	(Non)structural element	Material	Element type	Circular strategy	Included in structural analysis
1. Purchase Cost Tool	Non-structural	-	-	Reuse Recycling Recover	-
2. Decision Support Tool	Structural Non-structural	Concrete (prefab + in-situ)	Floors + Beams + Columns + Walls	Reuse	Condition Detailing
3. Decision Support Model	Structural	Concrete (prefab)	Hollow core slab floor	Reuse	Condition
4. Feasibility Calculation Tool	Structural	Concrete (prefab)	Floors	Reuse	-
5. Supporting Assessment Tool	Structural	Concrete + Steel (prefab)	Floors + Beams + Columns	Reuse	Condition Detailing
6. Circular Design Tool	Structural	Concrete + Steel + Timber	Floors + Beams + Columns + Walls	Reuse	Structural calculations
7. LCA Tool	Structural Non-structural	Concrete + Steel + Timber	Floors + Beams + Columns + Walls	Recycling Recover	-
8. LCC Tool	Structural Non-structural	Concrete + Steel + Timber	Floors + Beams + Columns + Walls	Recycling Recover	-
9. EVR Tool	Structural Non-structural	Concrete + Steel + Timber	Floors + Beams + Columns + Walls	Recycling Recover	-

1.3 Problem definition

From analysing the current state of the art, some conclusions and recommendations for further research can be made. From the analysis of demolition projects in the Netherlands it can be concluded that in the B&U-sector especially housing constructed during 1945-1970 is demolished the past few years and utility buildings constructed in the 70s/80s. The main reason of demolishment of the housing is low quality where the main reason of demolishment of utility buildings is the increased demand for health, sustainability, and comfort. This shows concrete elements from utility buildings can still have technical potential.

Structural safety, environment, and economics are important aspects in a new design. In case of analysing the reuse potential of concrete structural elements, sufficient structural safety should be guaranteed. Moreover environmental- and economic loads and benefits are important aspects in the decision about reusing or other circular strategies.

By analysing existing tools and comparing those based on their focus it can be seen each tool is focussing on structural safety, environmental impact, or economic impact in its own way. The Decision Support Model is focussing on all three aspects. However, the tool is only focussing on the reuse potential of hollow core slabs. No other circular strategies are included for comparison of the impacts. Besides, the structural safety and therefore applicability of reused hollow core slabs is not assessed based on structural calculations. Therefore, a tool should be developed focussing on structural safety in which either the condition and structural applicability is assessed based on calculations, on environmental impact based on the LCA-method, and on economic impact by calculating the costs over the life cycle of an element.

This research focusses on these three main aspects in the development of a new tool. The three focus points are visualized in Figure 1.10. The underlying idea of the research can be expressed as:

'Everything has a value until proven otherwise'

Figure 1.10 Focus of the research (Own figure)

2 Research Approach

In this chapter the research objective is explained in Section 2.1 followed by the research questions in Section 2.2. Furthermore, the scope and strategy provided in Section 2.3 and Section 2.4 subsequently. Section 2.5 describes the research outline.

2.1 Research Objectives

The main goal of the research is to stimulate the reuse of structural concrete elements in practice. Although structural elements show potential for reusing in terms of residual lifespan, in practice reuse is still not often applied. Since reusing concrete structural elements is relatively new, there is still little known about the structural safety, environmental impact, and economic impact of reusing concrete elements. Therefore, the research should contribute to the objective…:

'…to stimulate structural engineers to reuse structural concrete elements in practice by deconstructing and reusing concrete structural elements in new buildings.'

In order to contribute to the stimulation of the reuse of structural concrete elements, the objective of the research is:

'…to develop a tool which stimulates structural engineers to reuse concrete structural elements by giving insight in structural safety, environmental impact, and economic impact of reusing concrete structural elements.'

The to be developed tool will help structural engineers and contractors in the decision of implementing reused structural elements in a new design by assessing the structural safety, costs, and environmental benefit. Using this tool in an early stage of the design process, a global insight can be given about the reuse potential of structural elements in a new design.

2.2 Research Questions

In this Section the objective of Section 2.1 is translated into a main research question. Besides, sub-research questions are formulated.

2.2.1 Main Research Question

In order to meet the research objective, the following main research question is formulated:

'How to assess the reuse potential of concrete structural elements in an early design stage focussing on structural safety, and environmental impact, and economic impact?'

2.2.2 Sub-Research Questions

This research focuses on three main aspects influencing the reuse potential: structural safety, economic impacts, and environmental impacts. The main research question can be split in three parts. The first part analyses the current existing knowledge about the process- and impact of reuse. The second part includes reusability factors which are required for the assessment of the reuse potential of a structural element, and the assessment system itself. The third and last part focusses on the tool and implementation of it in practice. Therefore, the main research question is split into three sub-questions:

1. ***What processes influence circular strategies in terms of structural safety, environmental impact, and economic impact?***

1.1 What are the differences in the process of demolition and deconstruction?
1.2 How should a structural element be post-processed?
1.3 How can the economic value of structural elements be analysed?
1.4 What methods can be used to analyse and quantify the environmental impact of structural elements?

2. ***How to assess the structural safety, environmental impact, and economic impact for concrete structural elements?***

2.1 How can safety measures for reusing structural elements be quantified in a tool?
2.2 How can the environmental impact be assessed and included in a tool?
2.3 How can the economic value be related to the environmental value in a tool?
2.4 What assumptions are necessary in order to make it possible to assess the environmental, economic, and safety impact for concrete structural elements?
2.5 What is the most relevant information for contractors in order to decide to reuse an element or not?
2.6 What is the desired output of the tool?

3. ***How can the Reusability Tool be used to stimulate the reuse of concrete structural elements in practice?***

    3.1 Does the outcome of the tool lead to realistic results?

    3.2 How should the outcome of the tool be interpreted by the contractor?

    3.3 How can the tool be improved?

2.3 Research Scope

In order to answer the main research question in sufficient depth, the research boundaries are formulated in Table 2.1. These boundaries are important to formulate and to be reminded of during the research. The boundaries are followed from the initial literature review to the state of the art as illustrated in the introduction, Chapter 1.

Table 2.1 System boundaries of the research

Subject	Description
Building type	This research focusses on existing concrete utility buildings whose functional lifespan is finished but consists of concrete structural elements whose still have a residual technical service life. From research of EIB, Metabolic, and SGS Search it became clear often utility buildings, constructed during the 70s/80s are demolished. Therefore, the research focusses on utility buildings constructed in the period 1970-1980.
Structural elements	In this research only load-bearing concrete structural elements of structure of utility buildings are analysed. Non-structural elements and building products are out of the scope of this research. Besides, structural elements of foundations are not included. Therefore, this research focusses on the following concrete load-bearing structural elements: columns, beams, floors, and walls.
Structural materials	Since the objective of this research is to develop a tool which stimulates the reuse of concrete structural elements, the research focusses on concrete and its reinforcement. From the analysis of existing tools it followed that often there is only focussed on prefab elements or in-situ elements are depreciated because they are difficult to demount. Moreover, from demolition lots of in-situ concrete is released. Therefore this research focusses on in-situ concrete. Since in-situ concrete is project-specific, deconstructing and reusing these elements is challenging.
Environmental impact	The environmental impact of a reused element will be calculated in the tool and compared to a new produced element. Also other circular strategies will be included and compared. In this way the tool gives insight in the environmental benefits or burdens of reusing a structural element. The environmental impact is calculated according to the LCA method, as explained in Section 1.2.3. For these calculations data from the Nationale Milieudatabase (NMD) are the main source. The environmental impact is expressed in shadow costs and can therefore be compared to economic costs.
Economic value	The economic costs of reusing structural elements will be compared to the production costs of new structural elements. Also other circular strategies are included. In this way, the economic feasibility will be clear. Next to that, the economic value can be weighed against the environmental impact and give insight in the practical potential of reusing the structural element.
Structural safety	Structural safety is quite a broad aspect which cannot be fully assessed in this research due to time limits. Important aspects which are researched in order to guarantee sufficient structural safety are technical factors and human factors. Important technical factors are the processes from deconstruction to re-implementation, and the current codes. Next to that human factors which are included are product- and design choices, and forms of collaboration.

The research scope explained in Table 2.1 is visualised in Figure 2.1.

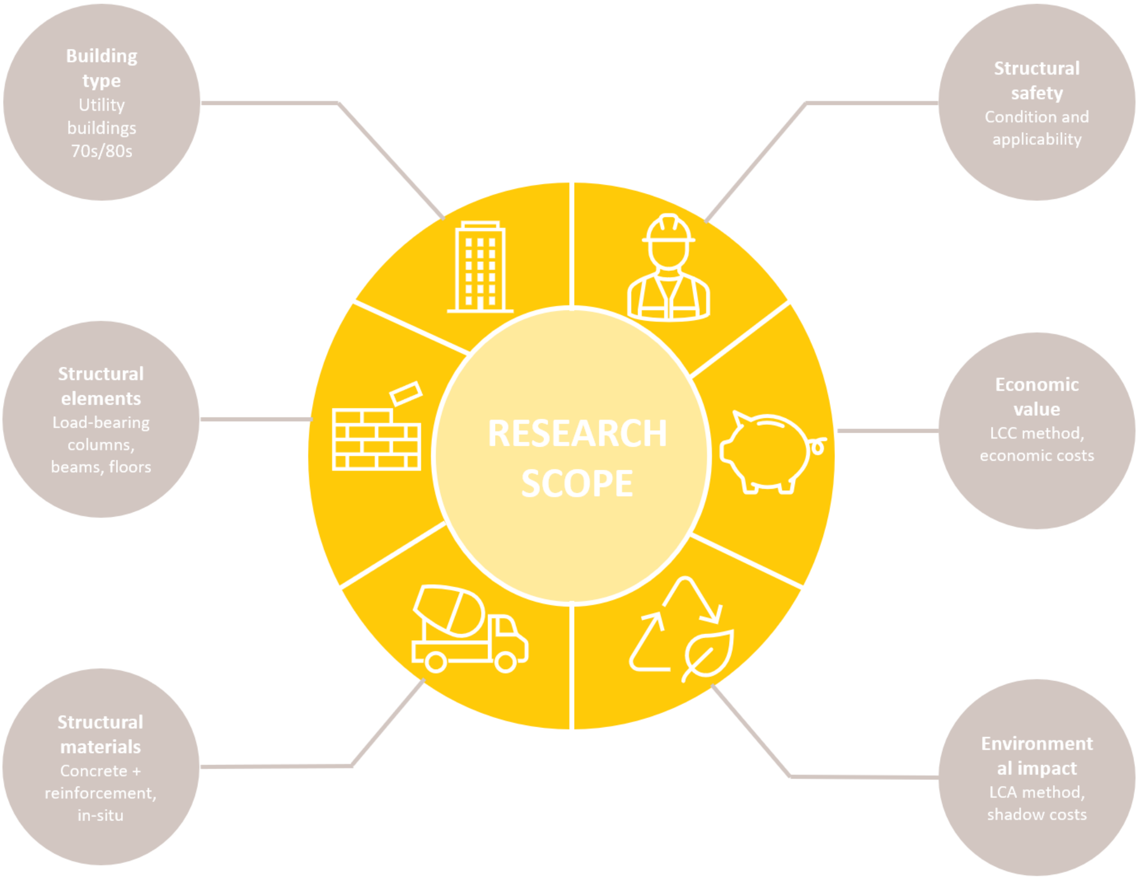


Figure 2.1 Research Scope (Own figure)

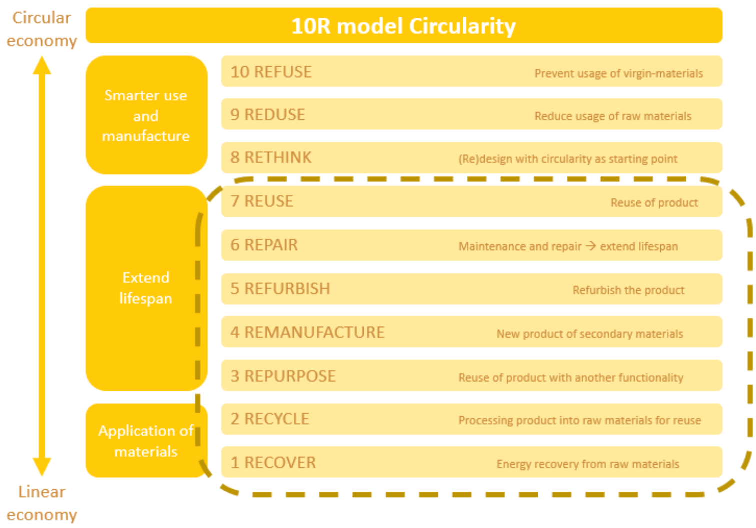


Figure 2.2 10R Model of Circularity (Adapted from Archipunt, 2021)

In order to assess the reuse potential of concrete structural elements there is focussed on the (combined) lower 7 steps of the 10R model of circularity (boxed part in Figure 2.2). The upper three steps belong to smarter use and manufacture of a building and are out of the scope of this research. Three examples from practice linked to each of these three upper steps are explained in Appendix C.

Next to the boundaries of the research, the reusability tool has some boundaries as well. These boundaries are expressed in Table 2.2.

Table 2.2 Boundaries of the reusability tool

Subject	Description
User field	The reusability tool will assess the reuse potential of concrete structural elements in utility buildings by assessing structural safety, environmental impact, and economic value from the deconstruction process up to the re-implementation of the element. The condition and structural applicability of an element is assessed and benefits or burdens of reusing structural elements are expressed in shadow costs and economic costs by comparing the to be reused structural element with other (circular) strategies.
End-users	The reusability tool is developed for (structural) engineers. Prior structural knowledge is necessary in order to use the tool.
Software	The reusability tool is developed in Excel which is a commonly used software. Results can easily be extracted from the program and used in reports or other documentation.
Output	The output of the tool is an advice about reusability of an element combined with a value of the element. This value is based on structural safety assessment, environmental impact expressed in shadow costs, and economic impact expressed in costs. If the structural safety of the structural element is not sufficient but extra processing of the element can make it sufficient, advise about the processing and extra costs are given as well. Since the tool only globally checked the reuse potential of structural element, structural properties will be given which can be used for further detailed calculations.

2.4 Research strategy

In order to answer the research questions, a research strategy is created. The development of the reusability tool is divided into three parts: the criteria development, the reuse criteria, and reusability tool. An overview of the research strategy is visualized in the research framework in Figure 2.3. Each part of the research will be explained in more depth in the following sub-sections.

Criteria development

This part of the research is divided into two sub-parts. First the process of reuse is analysed and compared to the processes of other circular strategies. These processes are analysed by an extensive desk research, and interviews with demolition contractors- and managers, and structural engineers in which the processes of reuse are discussed with the help of a case study. Besides, the environmental impact and economic impact are analysed based on desk research and interviews with demolition contractors and environmental experts. Based on the process- and impact of reuse, the criteria can be analysed which are necessary for the assessment of the reuse potential.

Assessment reuse criteria

In this part of the research the required criteria for assessing the reuse potential of concrete structural elements are analysed and explained. Moreover, an assessment system is developed based on the reuse factors. In interviews involved parties can be asked about preferred assessment systems. The assessment system forms the basis of the reusability tool.

Reusability tool

In the last stage of the research the assessment of the criteria is translated into a reusability tool. The scope of this tool is already explained in Section 2.3. The tool assesses the reuse potential of a concrete structural element focussing on structural safety, environmental impact, and economic value. The tool will compare those impacts to the other circular strategies and the implementation of a new structural element. Therefore, the environmental benefit and economic burden can show the differences between reusing a structural element and using a new structural element. Based on these outputs, the engineer and contractor can decide about reusing a structural element. Based on a test case study, the tool is validated. Moreover, the influence of some factors on the final output of the tool is assessed.

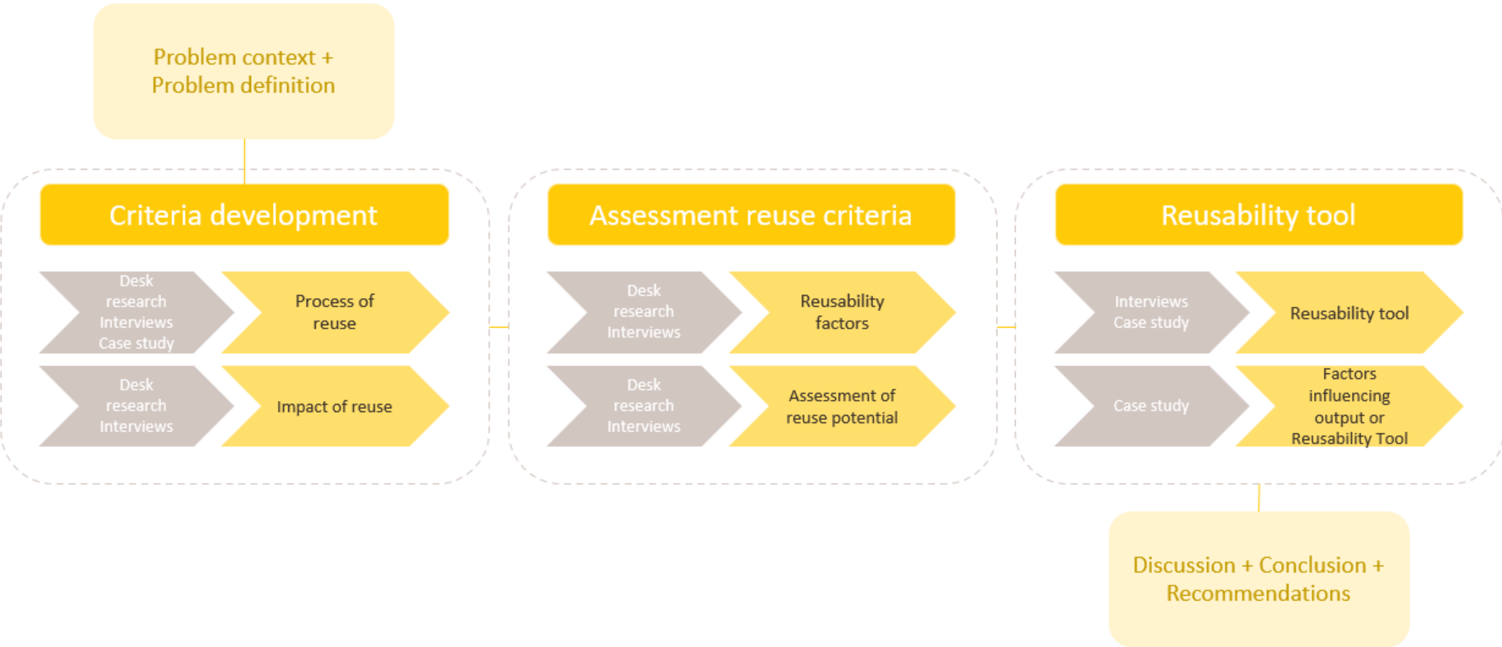


Figure 2.3 Research Framework (Own figure)

2.5 Research outline

The research is outlined in three main research parts:

- Part I | Research Framework
- Part II | Research to reusability factors and assessment
- Part III | Reusability tool
- Part IV | Discussion, conclusion, recommendations

In the first part the research is introduced by giving the problem context, state of the art, and problem definition. The introduction is given in Chapter 1. The Research Framework also covers the approach of the research including the objectives, research questions, scope, strategy, and outline. The research approach is described in Chapter 2.

Part II | Research to reusability factors and assessment includes research to the criteria for the development of the tool. Therefore, Chapter 3 explains the process of reuse, in which processes of deconstruction, and post-processing of an element are explained in depth. The impact of reuse is explained in Chapter 4. Economic costs and environmental impact are related to the processes described in Chapter 3. Based on these two chapters, the first sub-research question can be answered. From the analyses of Chapter 3 and 4 the required information for the assessment of the reuse potential follow, which is explained in Chapter 5. In Chapter 6, the assessment system is explained. Chapter 5 and 6 give the answer to the second sub-research question.

Part III | Reusability tool explains the developed Reusability Tool and validates the tool by tests using a case study, and feedback sessions with experts (Chapter 7). In Chapter 8, factors influencing the output of the tool are discussed. These two chapters answer the third sub-research question.

In the final part, Part IV | Discussion, conclusion, recommendations, the research and developed tool is discussed (Chapter 9) and concluded (Chapter 10) followed by recommendations for further research (Chapter 11).

PART II | RESEARCH TO REUSABILITY FACTORS AND ASSESSMENT

3 Process of reuse

In this chapter the process of reuse is explained in more depth. First the circular strategies are explained (Section 3.1) on which this research focusses on. Besides, the definition of deconstruction is explained in more depth in Section 3.2, followed by information about the case study which is used in interviews with demolishers to gather information about the process of reuse (Section 3.3). In Section 3.4, the processes of the circular strategies are explained in more depth which can all be linked to the main steps shown in Figure 3.1.

Figure 3.1: Process of circular strategies (Own figure)

3.1 Circular strategies

In order to see if a structural element has potential to be reused, first the definition of reuse and other circular strategies should be clear. In Section 1.1, the Butterfly model of Ellen MacArthur and the 10R model of circularity of Jacqueline Cramer are explained. Both models interpretate circularity in their own way. This research focusses on the reuse potential of a concrete structural element in a new situation, analysing the element in terms of structural safety, environmental impact, and economic impact. However, in order to see if reusing actually is the 'best' way to deal with the element, also other circular strategies should be analysed and should be compared to reuse. Therefore, based on the circular strategies of MacArthur and Cramer, and the scope of this research focusing on the process from deconstruction/demolition to (re)construction, the following main three circular strategies are included in this research and are shortly explained, shown in Figure 3.2:

- Reuse;
- Upcycling;
- Downcycling.

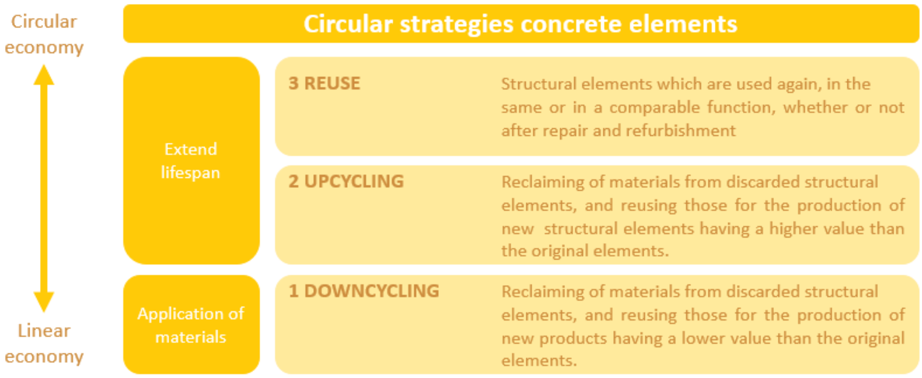


Figure 3.2 Circular strategies (Based on Archipunt, 2021)

3.1.1 Reuse

According to Platform CB'23, the definition of *reuse* is the following: *''building products or building elements which are used again, in the same function, whether or not after processing.''* Next to reuse, also *''high-quality reuse''* is often used. With this term the reused element should be of better quality or have a functionality of a higher value than where it was used before. Platform CB'23 (2022) uses this term for reusage of the same quality or higher quality.

Where Platform CB'23 uses the definition of reuse also for element which are processed, MacArthur and Cramer distinguished Reuse, Repair (or Maintain), and Refurbish. In these models, only directly one-to-one use of the element is included in the definition of reuse. If processes are required in order to prepare the element for future usage, they speak of Repair (Maintain) and Refurbish. From interviews with deconstruction/demolition contractors it turned out that directly one-to-one reuse is almost impossible in practice and therefore almost always repair or refurbishment is necessary. Therefore, in this research the definition of *reuse* is the following: *''Structural elements which are used again, in the same or in a comparable function, whether or not after repair and refurbishment.''*

3.1.1.1 Reusage in the Netherlands

In the Netherlands, reusing concrete structural elements is quite new and therefore it is in its infancy. Though, there are a few interesting examples from the GWW- and B&U-sector of reusing concrete structural elements in practice.

Rijkswaterstaat (executive organization of the ministry of Infrastructure and Water management) started the SBIR-method (Strategic Business Innovation Research). Three ideas were selected the development of a prototype. Vergoossen from Royal HaskoningDHV concludes from calculations that prefab viaducts girders from to be demolished viaducts still have a technical residual lifespan of 100 years. One of the difficulties of reusage of viaduct girders are the current norms about civil construction works. Circularity is not yet included in those norms (Royal HaskoningDHV, 2021a). Due to the SBIR-method, already some viaduct girders are saved from demolishment by harvesting the elements. According to Vergoossen around 100 girders will be released the coming 4/5 years (Structural engineer, Personal Communication, 2022).

An office building in Arnhem: Prinsenhof A will be fully deconstructed and used as a donor building for a new construction project. In April 2022, demolisher Lagemaat BV has officially started the deconstruction process. 7.400 m^2 of prefab concrete hollow core slab elements will be dismantled, hoisted out of the building (Figure 3.3), post-processed, and reused in new construction projects, of which one project is a sports hall. Besides, concrete hollow core slabs, also other building elements will be reused like window frames (Tektoniek, 2022; Municipality of Arnhem Personal Communication, 2022).

Figure 3.3 : Reuse of floor elements Prinsenof A (Retrieved from: Perree, 2022)

Also, the Mining Group started reusing hollow core slab elements from a roof construction as ground floor in a new bungalow construction (Demolition contractor 1 Personal Communication, 2022). Moreover, demolisher M. Heezen has sawn in-situ concrete floor elements from an apartment building in Brunssum which were reused in a pond. According to Lamber (2022), reusing concrete floor elements as ground for a pond is a low-grade way of reusing (Demolition contractor 2 Personal Communication, 2022).

3.1.2 Upcycling

In order to analyse if reusage of a structural concrete element is advised in terms of structural safety, environmental impact, and economic impact, also the impact of those aspects for upcycling is analysed. In case of upcycling, reclaimed materials of discarded structural elements will be used for the production of new structural elements having a higher value than the discarded structural elements. Based on the guidelines about future reusage and circular design of Platform CB'23 (2022), and the definitions used in the circular strategies of MacArthur (2019) and Cramer (2021), this research uses the following definition of *upcycling*: *''reclaiming of materials from discarded structural elements, and reusing those for the production of new structural elements having a higher value than the original elements.''*

3.1.2.1 Upcycling in the Netherlands

Next to reusing, lots of research is done into new concrete technologies in which old concrete is used as a component for new concrete production. Granulate old concrete and using it as a substitute for gravel does not influence environment that much, since the usage of gravel has a small impact on the environment (Demolition contractor 3 Personal Communication, 2022). CE Delft has researched a mechanical way of recycling in which stony material and old cement are separated from each other resulting in cement which can be reused. In the production of cement lots of CO_2 is released and therefore this mechanical recycling method can greatly lower the environmental impact (Nusselder et al, 2021). Also in practice, there is experimented with circular concrete. For example, in 2020 Heijmans used a concrete mixture of which 60% of the ingredients consists of secondary material and in 2021 even a mixture of which 75% of the ingredients consists of secondary materials (Heijmans 2020; Heijmans, 2021).

3.1.3 Downcycling

Next to comparing reuse to upcycling, also the process of downcycling should be analysed. In the Butterfly model of MacArthur landfill is included which is the result of linear economy. However, nowadays concrete material is no longer be deposit, but lots of materials are downcycled which means that materials of discarded structural elements are reused for the production of new products having a lower value than the original elements. For example, when materials of a discarded concrete beam are reused for the production of a concrete bench, the new product has a lower value than the original product (Demolition contractors, Personal Communication, 2022). Based on the models of MacArthur and Cramer, and the United States Environmental Protection Agency, the definition *downcycling* used in this research, is the following: *"Reclaiming of materials from discarded structural elements, and reusing those for the production of new products having a lower value than the original elements.''*

3.2 Deconstruction vs. Demolition

Deconstruction is often described as: '*construction in reverse*'. However, most important is to disassembly a concrete structural element without causing (irreparable) damage. Damage will affect the residual value of a structural element and therefore deconstruction can be defined as: *''dismantling of a structure in structural elements of which the residual value is guaranteed.''* (Glias, 2013; Kamp, 2021; Platform CB'23, 2021).

As described in Section 2.3, this research focusses on in-situ concrete elements originated from utility buildings constructed in the 70s/80s. In-situ concrete is associated with lots of wet/chemical connections which result in difficulties for dismantling according to the research of Durmisevic (2006) and Van Vliet et al (2019).

In order to decide about deconstruction or demolition, the circular strategy (explained in Section 3.1) and accessory process should be clear. Therefore, deconstruction- and demolition processes for in-situ concrete elements are analysed by interviewing deconstruction-/demolition-contractors using a case study which lays within the scope of this research. First the case study is shortly explained. Besides, the deconstruction- or demolition processes are explained related to the circular strategies which are within the scope of this research.

3.3 Case study

The processes of deconstruction and demolition related to circular strategies are based on interviews in which is elabourated on the case study of the Merin Building, located at Chasséveld 3-13 in Breda. This building, with an GFA of 5713 m^2, previously housed a banking- and police office, and was established in 1984 and revised in 1997. In Figure 3.4, the front view of the building, and in Figure 3.5 a revision-drawing of architect Haverman van den Meiracker Vermeulen bv is shown. The structure of the building consists of a concrete main load bearing structure including in-situ columns, floors, and walls. The structure was engineered by BV Bouwtechnisch Adviesburo Ir W.A. van Boxsel c.i. The 3-layer Merin Building functioned as an office building and is constructed with consequence class 2 (CC2) (Heijmans Utiliteit B.V. Internal Documentation, 2021). From archive documentation and a site visit, it followed that the in-situ flooring system works as a flat slab floor supported by columns including drop-panels. Developer Synchroon and Heijmans Vastgoed are the owners of the building.

Figure 3.4 Merin Building (Own photograph)

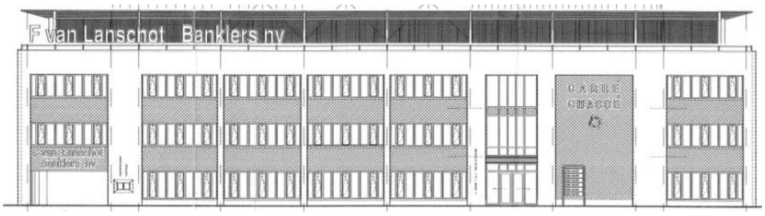


Figure 3.5 Architectural drawing of Merin Building (Heijmans Internal Document)

The area of the Chasséveld will be redeveloped in the future. One goal of the redevelopment is to create more connection between the Chasséveld and the city centre of Breda. In the area, apartment buildings will be realized in which Merin Building does not fit. The building is a perfect example of a project of which the functional service life has passed, but the technical service life has not, as explained by Brand (2006). Therefore, it is planned to demolish this building in about 5 years (Heijmans Utiliteit B.V., Personal Communication, 2022).

In contrast to the ground floor, the first- and second floor are stripped until the concrete casco. Some installations are still present and function, but the complete finishings, partition walls and interior has been removed, as shown in Figure 3.6. At the moment, only some start-ups are housed on the ground floor (anti-squat). Because parts of the building are totally stripped, it is not possible to easily create temporary officing. However, Heijmans is analysing options for temporary use of the building (Peeters, 2022).

Figure 3.6 Interior of Merin Building: Ground floor - First floor - Second floor (Own photographs)

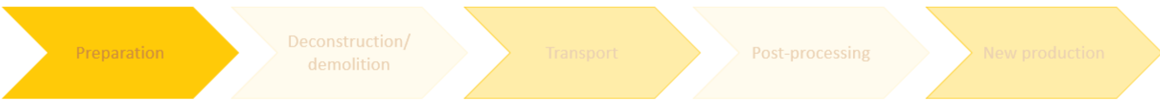
Since this building is planned to be demolished but consists of a concrete casco which is still functioning in a technical way, the reuse potential of the concrete structural elements can be assessed. In order to analyse the environmental impact, the processes of deconstruction and demolition should be clear. Therefore, these processes are analysed based on the case study and interviews with demolition contractors.

3.4 Process of Downcycling, Upcycling, and Reuse

In this section, the process of downcycling, upcycling, and reuse are explained. The steps shown in Figure 3.1 are explained in more depth. In case of reusage, a structural element is deconstructed after preparation, will be transported for post-processing, can be temporarily stored, and will be reused in a new construction. When a structural element is discarded, the element can be demolished, after which the material can be processed into raw materials for the new production of a structural element. In case of downcycling, the raw materials will not be used for the production of a structural element, but for the production of other products, having a lower value. In this research, it assumed these future other products are not known when analysing the structural element.

3.4.1 Preparation of deconstruction and demolition

Before the deconstruction or demolition of a project can start it should be well prepared. Therefore, the preparation of demolition for downcycling and upcycling are explained, followed by the preparation of the deconstruction process for reuse.



3.4.1.1 Preparation of (traditional) demolition – Downcycling and Upcycling

The preparation phase of a (traditional) demolition process can be divided into three main steps, shown in Figure 3.7. First, the building will be inventoried by the demolisher and costs calculator. Inventory for asbestos is mandatory. Besides, the potential for reusing or recycling building products and materials is analysed, like isolation material, window frames, and doors. If the building contains lots of valuable building products which can be reused or recycled, the demolisher can offer a lower price for the total demolition of the building, since the building products or materials result in extra revenue for the demolisher. During inventory the costs for demolishment will be calculated by the cost calculator. After inventory, the demolisher has a general impression of the demolition project and therefore the process of demolition can be planned. Before actually starting the demolition, the building should be stripped; the interior of the building needs to be removed until the concrete casco, like sanitary, window frames, and doors.

Figure 3.7 Process of Preparation – Downcycling and Upcycling (Own figure)

3.4.1.2 Preparation of deconstruction – Reuse

Figure 3.8, shows the steps of preparation for deconstruction. In case of deconstruction it is important to gather all possible information from documentary which are important for reusing a structural element. Important reusability factors of which information should be gathered, are explained in Chapter 5. The planning and stripping of the project are comparable to those in the process for demolition for down- and upcycling.

When the building is fully stripped, inspections are required in order to check the condition. The condition of the to be reused elements should be analysed visually. This inspection is explained in Chapter 5. In case the visual degradation is visible, extra tests are required in order to guarantee an element is structurally safe. Additional testing can be either non-destructive and destructive. Examples of non-destructive tests are rebound hammer tests, pull-out tests, and ultrasonic pulse velocity (Glias, 2013). For destructive tests often cores are drilled out which can be analysed for carbonation, the presence of chlorides, analysis of reinforcement steel and strength tests. Residual lifespan calculations based on carbonation and the presence of chlorides are explained in Appendix D.1.

Structural elements which are dependent of each other should be temporarily supported by scaffolding. For example, when deconstructing a column which is supporting a floor element, the floor element needed to be temporarily supported in order to prevent a collapse. All demolishers indicated that (traditional) demolition is way more safe since no workers needed to be inside the building during demolition. In case of deconstruction, workers will work inside the building and therefore temporarily scaffolding is important (Demolition contractors, Personal Communication, 2022).

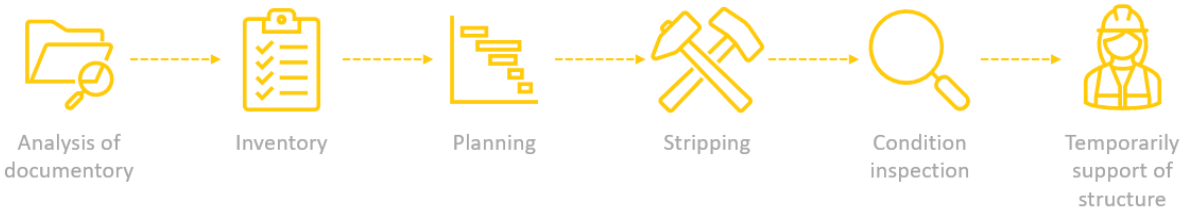
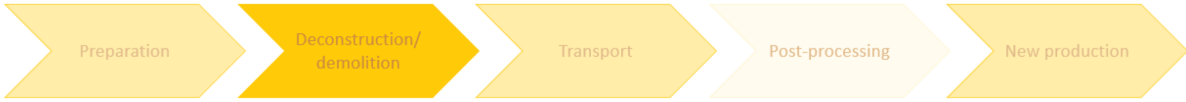


Figure 3.8 Process of Preparation - Reuse (Own figure)

3.4.2 Processes of deconstruction and demolition

As explained in Section 3.1, the processes of reuse, upcycling, and downcycling are analysed. This section elabourates on the process of deconstruction or demolition related to these circular strategies. First the traditional demolition process is analysed related to downcycling. Besides, demolition for upcycling is explained, followed by the deconstruction process for reuse.



3.4.2.1 (Traditional) demolition – Downcycling

The process of demolition of utility buildings can be divided into two main steps, shown in Figure 3.9. First, the structure will be cut by a concrete cutter for which a 40-ton crane is used. When the complete building is cut into large debris, a smaller crane will crush the debris into smaller rubble which can be transported to a material processor. The average demolition rate is 250-350 m^2/day, making use of two workers; one worker operating the 40-ton crane for cutting the concrete, and one worker operating the smaller crane for crushing the concrete (Jabeen, 2020; Demolition contractor 2,4 Personal Communication, 2022).

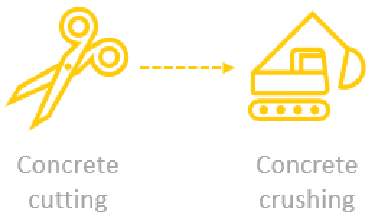


Figure 3.9 Process of Demolition - Downcycling (Own figure)

3.4.2.2 Demolition - Upcycling

The process of demolition for upcycling is comparable to traditional demolition as shown in Figure 3.10.

In case of upcycling, materials of the discarded element will be used for the production of a new structural element having higher value. Therefore, concrete rubble can already be sorted on site. For example, the concrete rubble and reinforcement can be gathered in different containers which eases the recycling process resulting in additional revenue for the demolisher. Since in case of downcycling the future products are not known yet, the concrete rubble is often directly transported to a material processor (Demolition contractors, Personal communication, 2022).

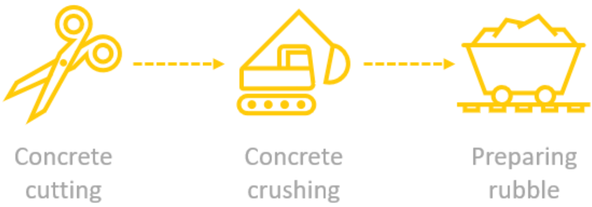


Figure 3.10 Process of Demolition - Upcycling (Own figure)

3.4.2.3 Deconstruction for Reuse

Where in a demolition project the concrete casco of a building will be fully cut into debris, in case of deconstruction, different techniques are involved in order to harvest structural elements. The way of deconstruction strongly depends on the element type to be deconstructed. In Appendix D.2, the processes of deconstruction of in-situ concrete beams, columns, monolith linearly supported floors, and monolith flat slab floors are explained in more detail. For all elements, the deconstruction method is based on the process shown in Figure 3.11.

When the elements are temporarily supported, the concrete around the element can be cut by a 40-ton concrete cutter, and close to the element with a hammer by hand. It is important to generously cut around the element in order to release the reinforcement. Subsequently, the element can be cut by using a concrete saw with diamond blade. Also in case of sawing it is important to not directly cut off the reinforcement since then it is difficult to (re)connect the element in the future situation. If it is only possible to directly cut the concrete element without protruding bars, the possibilities for drilling additional rebars should be analysed. When the element is sawn, it should be hoisted using a large crane, depending on the weight of the concrete element. For some elements, like floor elements, it is necessary to drill some anchors in order to hoist the element in a safe way. Before the element can be transported, the element should be cleaned in order to prevent, dirt or debris damaging the element during transport. Compared to (traditional) demolition, deconstruction is more time consuming. The deconstruction rate is 50-100 m^2/day. Moreover, more labour is required. Where 1-2 workers are required for (traditional) demolition, for deconstruction 4-5 workers are required (Jabeen, 2020).

Figure 3.11 Process of Deconstruction - Reuse (Own figure)

3.4.2.4 Deconstruction contractors

There are lots of demolition contractors in the Netherlands. Almost 100 demolition contractors are associated with VERAS which represents the interests of demolition contractors and focusses on the circular economy (Veras, 2021). Moreover Stichting Veilig en Milieukundig Slopen (SVMS) is an organization which offers a project verification for circular demolition projects. SVMS consists of representatives of employers, buyers of demolition materials, research institutions, the government and demolition contractors. With the verification demolition contractors can indicate their circular way of demolition (Circulairsloopproject, 2022). Therefore, demolition contractors which have a verification declaration of circular demolition projects can also be called deconstruction contractor. According to SVMS a demolition project is circular if the demolition contractor fulfil the aspects explained in Table 3.1.

Table 3.1 Aspects of a circular demolition project (Adapted from SVMS, 2020)

Circular demolition project aspects	Description
Material inventory	Demolition contractors should indicate which demolition materials will be released categorized in building products, building elements, and material flows. For each of the released demolition materials the level of reusing should be indicated (product reusing, material reusing, recycling, thermically recycling, or burning).
Demolition plan / sorting plan	A demolition- and sorting plan should be proposed in which the following aspects should be described: - way of deconstruction; - work instructions; - way of checking the material; - internal rejecting criteria; - responsible parties for checking; - way of registration. In the plan, all demolition elements and materials should be included.
Accountability of materials	The demolition products and materials should be designated, the amount of products or materials should be given in numbers or volume, and the qualitative disposal destination should be indicated.

3.4.3 Transport

When a concrete structural element is harvested and hoisted out of the structure, it should be transported. Transport of a concrete structural element for reuse differs from transporting rubble for down- and upcycling. Besides, the amount of transport movements differ for each of the three circular strategies. In the Netherlands, a truck can be maximally loaded by 50.000 kg, can have a maximum length of 22 meters, a maximum width of 3 meters, and a maximum height of 4 meters (Ministerie van Infrastructuur en Waterstaat, 2021a). When a load above 50.000 kg should be transported, like the transport of a telescopic crane, there can be applied for a permit at the Department of Road Transport (Ministerie van Infrastructuur en Waterstaat, 2021e). It should be noted that exceptional transport drastically increase the costs of a project.

This section explains the transport methods and movements for downcycling, upcycling, and reuse.

3.4.3.1 Transport for Downcycling

As explained in Section 3.4.2.1, the structure of the building is cut and crushed into rubble which can be transported to a material processor where the rubble can be processed into materials for the production of other products. Usually, container trucks are used for this transport. Since the maximum allowed load of trucks is 50.000 kg, multiple trucks are used to transport the rubble (Ministerie van Infrastructuur en Waterstaat, 2021a). Since the material is downcycled, it will not be used for the production of a new concrete structural element.

From a concrete producer, in-situ concrete should be transported to the new building site by a concrete truck mixer. In case of a prefab element, it should be transported with or without exceptional transport depending on the dimensions and weight of the element.

As shown in Figure 3.12, two transport movements are included which can take place in parallel.

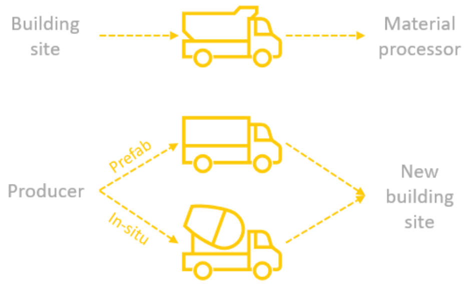


Figure 3.12 Process of Transport - Downcycling (Own figure)

3.4.3.2 Transport for Upcycling

In case of upcycling, the concrete rubble and reinforcement can be transported to the material processor using container trucks. The material processor will prepare the concrete rubble and reinforcement into raw materials for new production. These materials should be transported to the producer for the production of concrete which can be poured in-situ or to a prefab producer which prefabricates the new concrete element. From the producer, the in-situ concrete should be transported by a concrete truck mixer or the prefab element should be transported with or without exceptional transport depending on the dimensions and weight of the element. This result in multiple transport movements which are shown in Figure 3.13.

Figure 3.13 Process of Transport - Upcycling (Own figure)

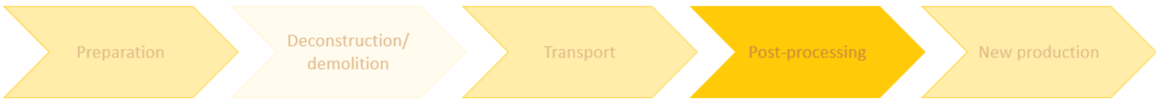
3.4.3.3 Transport for Reuse

When a structural concrete element is reused an element should be transported by truck to the element processor. Only elements with dimensions within 3X4X22 meters and a weight below 50.000 kg can be 'normally' transported by road, otherwise exceptional transport is required. When the structural element is processed at the element processor it can be directly transported to the new building site or it can be temporarily stored. Often the planning of a deconstruction project are not completely in line with the planning of the new construction project, resulting in temporarily storage. This results in the transport movements shown in Figure 3.14. It is important to carefully transport the structural elements. In case damage occur which is irreparable or too expensive to repair, the element cannot be reused anymore resulting in high lost costs.

Figure 3.14 Process of Transport - Reuse (Own figure)

3.4.4 Post-processing

After material or an element is transported to the material- or element processor, it should be processed. The post-processing of the three circular strategies are shortly explained.



3.4.4.1 Post-processing for Downcycling

Landfill is only accepted in The Netherlands when debris contains less than 12% material which can be recycled. Therefore landfill is less applied nowadays than during the 70s/80s when the utility buildings this research focusses on were constructed. In case of downcycling, the concrete rubble will be processed into raw materials which can be used for the production of products having a lower value than concrete structural elements, as shown in Figure 3.15.

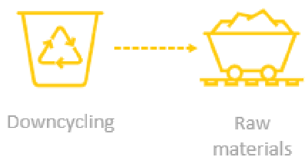


Figure 3.15 Process of Post-processing - Downcycling (Own figure)

3.4.4.2 Post-processing for Upcycling

When the concrete debris and reinforcement is already separated on site it can be processed into raw materials for the production of new concrete elements. Nowadays, about 95% of the granulate is used in the road industry instead of for the production of new concrete elements. In this research, there is focused on upcycling in which the debris is processed into raw materials which will be used for the production of new concrete elements, as explained in Section 3.1.2. Therefore, it is assumed 95% of the concrete rubble and reinforcement will be recycled into raw materials for the production of new concrete elements having a higher value than the discarded structural elements (Upcycling). 5% will be downcycled, as shown in Figure 3.16.

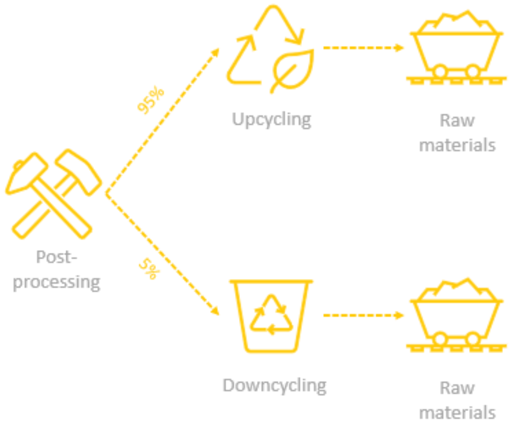


Figure 3.16 Process of Post-processing – Upcycling (Own figure)

3.4.4.3 Post-processing for Reuse

The way of post-processing a structural element strongly depends on the element type and the future situation in which the element will be implemented. Less required modifications result in less environmental- and economic impact (Bleuel, 2019). In case damage occurred (during hoisting or transport), it should be decided if this is reparable and affordable. If this is not the case, it can be decided to upcycle the element instead of reusing it.

The most important modification is to create a new connection in order to implement the element in the future structure. During deconstruction, the concrete can be cut and sawn in order to have protruding bars. These bars are important for the continuation of the reinforcement in the future situation. Though, these bars should be cleaned and all concrete debris should be removed. This is rather time consuming influencing the costs for modification. If it was not possible to saw the element with protruding bars, the element can be sawn to a smaller size in order to have protruding bars or additional rebars should be drilled into the element (Volkov, 2019; Kamp, 2021). This is only possible if there is sufficient space; no other rebars should make it impossible to drill additional rebars.

If holes of previous fixings or anchors for hoisting are present, they needed to be filled (Jabeen 2020). When the concrete cover of the element is not in accordance with the required thickness of the cover in fire circumstances, the thickness of the concrete cover can be increased by casting an additional layer of concrete cover (Glias, 2013). Therefore, it is important to check the rules of detailing under fire conditions which are explained in Appendix B.6.

Moreover, some additional holes could be drilled in order to reconnect the element in the future situation. (Jabeen, 2020). Next to modifying the element for future connection, the element could need some painting or coating for protection (Bleuel, 2019).

The process of post-processing for reuse is visualized in Figure 3.17.

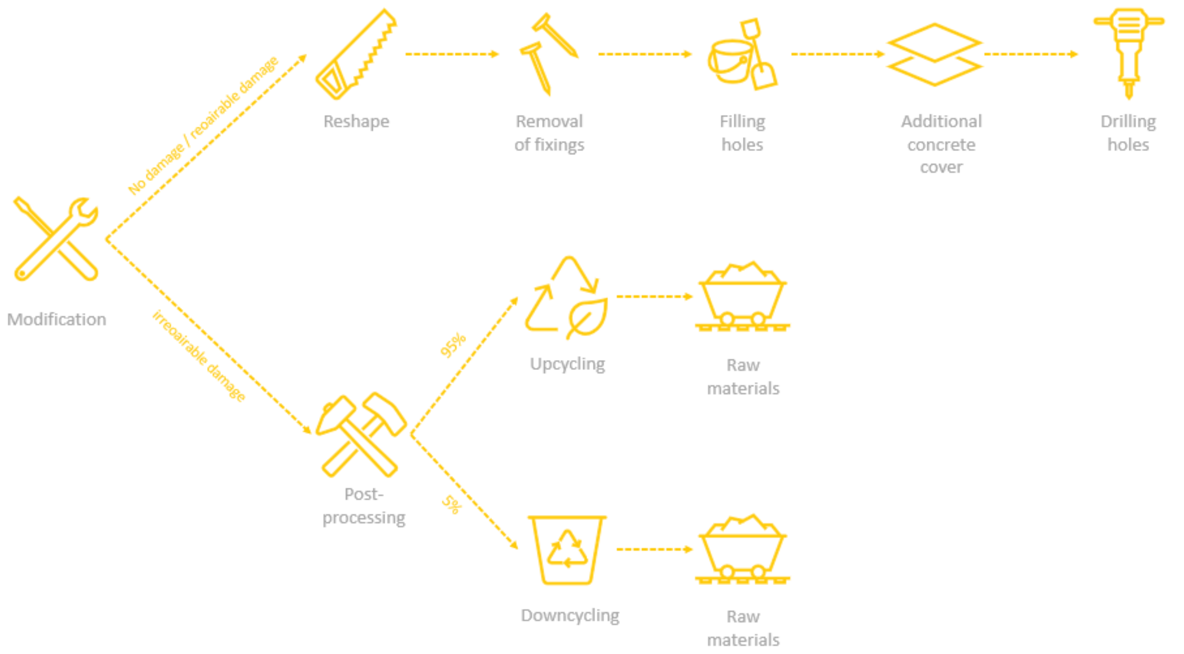
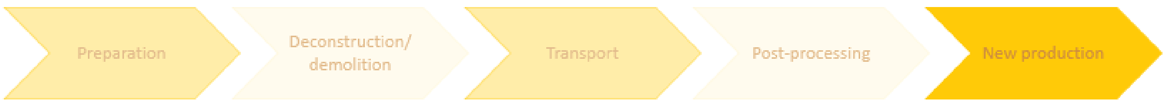


Figure 3.17 Process of Post-processing - Reuse (Own figure)

3.4.5 Production of new element

In case of down- and upcycling, a new structural element should be produced for the future situation, where in case of reusage this is prevented. Therefore, in this section the (prevented) production of a new element for downcycling, upcycling, and reuse are explained. In this research two ways of new production are distinguished:

- New production of concrete which can be poured in-situ;
- New production of a prefab concrete element.



3.4.5.1 Production of new element - Downcycling

As explained in Section 3.4.4.1, the demolition rubble will be processed into raw materials for the production of other products having a lower value than concrete structural elements. For the production of a new concrete structural element, raw materials should be supplied and transported to the producer. In case of the production of concrete which will be poured in-situ, raw materials will be supplied to the producer. Concrete will be produced after which it will be transported by a truck mixer, as explained in Section 3.4.3.1. When a prefab element is produced, it should be transported by heavy road transport.

3.4.5.2 Production of new element – Upcycling

In the process of upcycling, concrete rubble and reinforcement will be processed into raw materials which will be transported and used for the production of new in-situ concrete or a new prefab element. The supply of raw materials can be prevented, reducing the environmental impact. Besides, upcycling affects the costs since the supply of raw materials is reduced. Details about these impacts are explained in Chapter 4.

3.4.5.3 Production of new element – Reuse

When reusing a concrete structural element, the complete production process of a new element can be prevented. In this way, the environmental impact of producing and structural element can be prevented even as the costs for production. However, as explained in Section 3.4.4.3, the reusage of a structural elements required modification which can increase the environmental- and economic impact. In Chapter 4, more details are explained about these impacts.

4 Impact of reuse

This chapter describes the impact of reuse, compared to up- and downcycling, in terms of environment and economics. Section 4.1 describes the economic impact of reusing, upcycling, and downcycling. Costs and income are explained and related to the processes described in Chapter 3. Moreover, the calculation of the environmental impact is explained in Section 4.2.

4.1 Economic impact

Hastings (2015, p. 93) *"The hardest part of financial analysis is not the calculations, but deciding what factors should be taken into account and estimating the cost, revenues and risks."*

In this section, the economic impact of downcycling, upcycling, and reusing is described. Based on the LCC method described in NEN-EN-IEC 60300-3-3, the economic impact of each strategy is calculated. To the process described in Chapter 3, economic impact is linked. Economic data which is used for the impact calculations, is retrieved by literature research. Since costs are changing over the years, it is important to be aware of inflation. Compared with the past four years, costs are increased drastically. In April, prices increased with 9.6% compared to April last year (Centraal Bureau voor de Statistiek, 2022).

Economic data and formulas used for the calculation of the economic impact are included in Appendix E.3.

This section shortly addresses the economic impact of the circular building strategies.

4.1.1 Economic impact of Downcycling

As explained in Chapter 3, the process of downcycling consists of five steps: Preparation, Deconstruction/demolition, Transport, Post-processing, and New production. The economic impact of the preparation phase is calculated as a percentage of the total demolition costs. The impact of demolition consisting of concrete cutting and concrete crushing, is calculated based on the element surface (in case of floor elements) or element length (in case of beams and columns). Moreover, costs for transport are included based on the transport type. Therefore, costs for container transport are included for materials transport. For transport of concrete mix, costs for a concrete mixer are used, and for prefab element transport, costs for element transport are included. The economic impact of post-processing concrete rubble is calculated depending on the rubble weight. In case of downcycling, materials will be used in new products having a lower value than the original structural element. Therefore, a new concrete element should be produced of which the costs are dependent on the required amount of concrete and reinforcement.

The total economic impact of the process of downcycling is visualized in Figure 4.1. The costs factors are explained in Appendix E.3.1. Since two different transport movements are included in the process of downcycling, two cost factors are shown. Besides, costs for risks are included. These costs are based on the research of Glias (2013) and Jabeen (2020) and are expressed as an percentage of the total demolition costs.

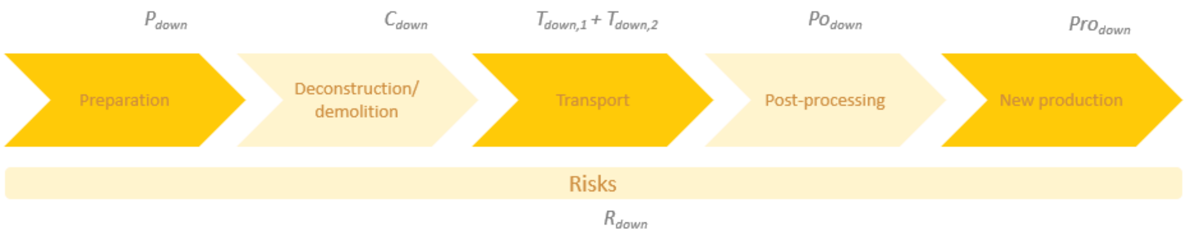


Figure 4.1 Economic impact - Downcycling (Own figure)

4.1.2 Economic impact of Upcycling

Even as for downcycling, the economic impact of the process of upcycling is calculated based on the steps described in Chapter 3. The economic impact of the preparation phase is calculated as a percentage of the total demolition costs. Compared to the process of downcycling this percentage is higher because of the preparation of the rubble for the new structural element production. Next to the economic impact of demolition, costs for sorting concrete rubble are included depending on the weight of the rubble. Costs for transport are included based on the transport type. Therefore, costs for container transport are included for materials transport. For transport of concrete mix, costs for a concrete mixer are used, and for prefab element transport, costs for element transport are included. Since in case of upcycling materials will be used in new element production, the material costs for new production are reduced.

The total economic impact of the process of upcycling is visualized in Figure 4.2. The costs factors are explained in Appendix E.3.2. Compared to downcycling an additional costs factor is included for the demolition phase due to the sorting of rubble on site. Moreover, three different transport movements are included in the process of upcycling. Therefore, three cost factors are shown. The risks are assumed to be equal to the process of downcycling (Glias, 2013; Jabeen, 2020).

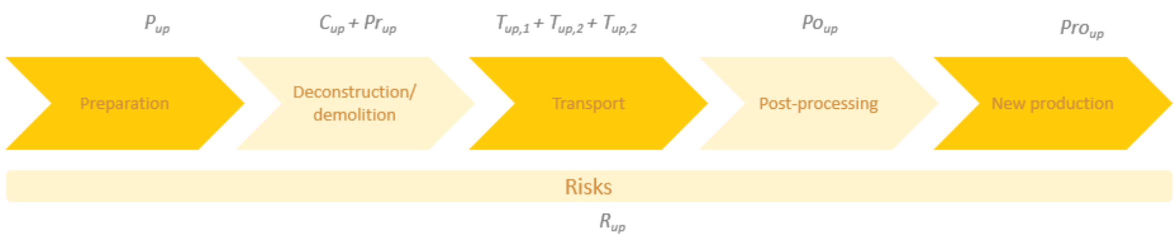


Figure 4.2 Economic impact - Upcycling (Own figure)

4.1.3 Economic impact of Reuse

The economic impact of the process of upcycling is calculated based on the steps described in Chapter 3. Compared to the process of down- and upcycling, additional processes are included in the preparation phase resulting in economic impact. An important factor is the analysis of documentary for which a structural engineer is required. Moreover, the inspection of the condition of the element, and the temporarily supports of the structure results in additional costs. For deconstruction of an element, the economic impact is based on cutting of the concrete around the element, sawing of the element, hoisting, and cleaning. The economic impact is the deconstruction phase is dependent on the element type and element dimensions. Costs for transport are included based on the transport type. Therefore, costs for container transport are included for materials transport. For transport of concrete mix, costs for a concrete mixer are used, and for prefab element transport, costs for element transport are included.

Before a deconstructed element can be reused, it should be post-processed. The costs for the modification of the element are dependent of the element type and element dimensions. A post-processed element can be directly transported to a new building site, or it can be temporarily stored. When an element is temporarily stored, this results in additional costs.

In case of reuse of the structural element, the material- and labour costs of the production of a new element can be prevented. Therefore, the costs for new production equals 0. Since reusing concrete in-situ elements is new, a higher risk-percentage is included compared to down- and upcycling.

The total economic impact of the process of reuse is visualized in Figure 4.3. The costs factors are explained in Appendix E.3.3. Compared to down- and upcycling an additional costs factors are included. Since an harvested element can be directly transported to a new building site after post-processing, or can be temporarily stored, two options are shown for the calculation of the economic impact of transport.

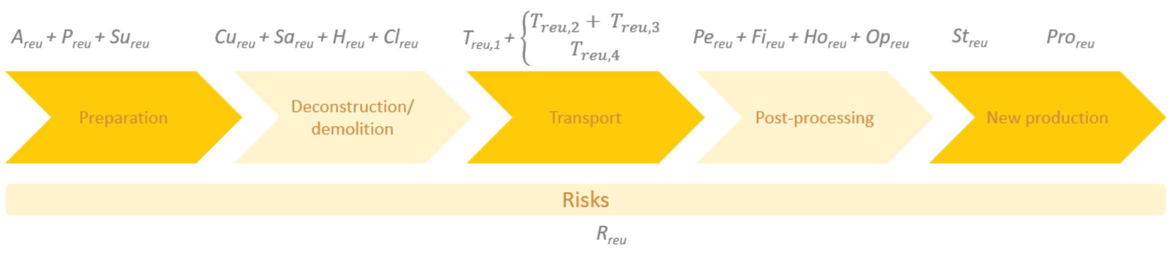


Figure 4.3 Economic impact - Reuse (Own figure)

4.1.4 Uncertainties costs

In 2021 the material prices have been raised drastically. These increases are firstly caused by the Covid pandemic in which the production capacity was reduced. Secondly, based on increased import duties, steel prices are increased. Transport costs are increased due to closure of Chinese ports and dislocation of containers (e.g. the blockage in the Suez-channel) (Bouwend Nederland, 2021).

Besides, the war between Ukraine and Russia results in increases of material- and energy prices, and logistic problems. For example. at Heijmans it is not possible anymore to make closed price agreements, but indexations should be used (BNR, 2022).

Based on these factors, the uncertainty about the supply of raw materials is increased. This should function as an extra incentive to seriously consider reuse.

4.2 Environmental impact

As described in Section 3.1, this research distinguishes 3 circular strategies. Each strategy has its own additional- and prevented environmental impact compared to the linear strategy. In the NEN-EN 15804 the assessment of construction works is explained based on the LCA method as explained in Section 1.2.3. For the calculation of the environmental impact of each of the strategies, data of the Nationale Milieudatabase is used. This database contains product cards including general information about the product like name, lifespan, and functional unit. Besides, it includes environmental information retrieved from a life cycle analysis The database includes information about products like materials or structural elements, but it contains also information about processes like hoisting with a crane (Stichting Nationale Milieudatabase, 2022).

The data of the Nationale Milieudatabase is used and related to the processes described in Chapter 3. All used data in this research is included in Appendix D.3.

This section shortly addresses the additional- and prevented environmental impact of the circular building strategies.

4.2.1 Downcycling

In Chapter 3, the complete process of downcycling is explained to which environmental data can be linked. The environmental impact of the preparation phase of downcycling is assumed to be equal to the preparation phases of upcycling and reuse. Only the impact of installing scaffolding will be included in the process of reuse. The impact of the preparation phase for downcycling is not included in the total impact calculations.

As explained in Section 3.4.2.1, the traditional demolition process consists of concrete cutting and concrete crushing. For calculating the environmental impact of the demolition process data of a demolition crane including cutters is used for concrete cutting and data of a smaller crane is used for concrete crushing. For transport of the rubble data of a diesel truck is used. The total impact is based on the load of the rubble and the distance the rubble should be transported. Dependent of the concrete type which is used, data of module C3 – waste processing and module C4 – disposal is used for calculating the impact of waste processing and disposal of the rubble. More information about the concrete types included in this research are explained in Chapter 5.

The new concrete element can be produced in-situ of can be prefabricated. For the production of a new in-situ concrete element, the amount of concrete and reinforcement is assumed to be the same as the analysed element for reusage. Depending on the concrete type, environmental data for in-situ concrete and reinforcement is used for the production phase (A1-A3) of the element. For the production of a prefab element the environmental data depends on the element to be produced. In Appendix D.3, all used data are included and explained. For transport of in-situ concrete, data of a concrete mixer is used. For transport of a prefab element, data of a diesel truck is used.

In Figure 4.4, the building life cycle information of the downcycling process is shown. It is shown that the life cycle of the future structure has no benefits from the downcycled element. However, downcycling results in less disposal in the current life cycle.

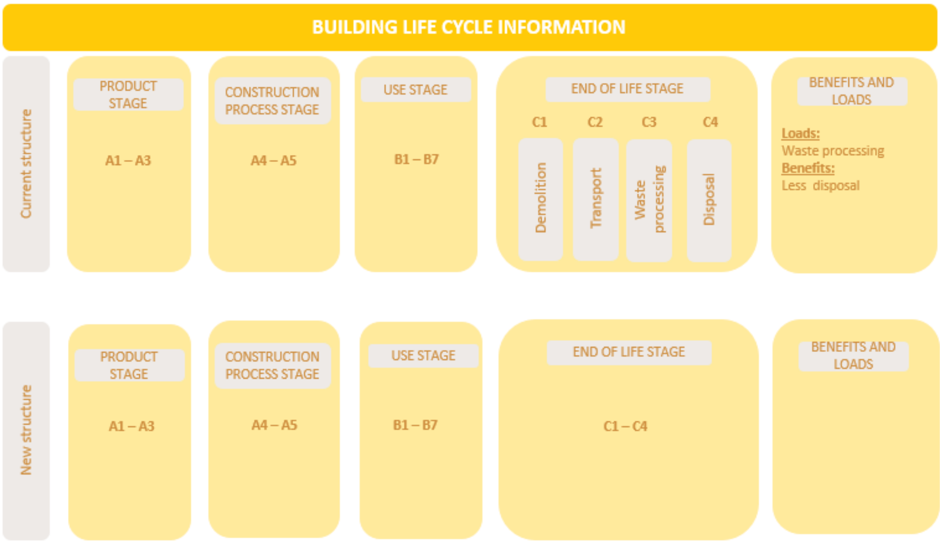


Figure 4.4 Building life cycle information - Downcycling (Own figure)

4.2.2 Upcycling

The calculation of the environmental impact of upcycling is based on the processes described in Chapter 3. Even as for downcycling, the environmental impact of the preparation is not included in the calculation of the environmental impact.

The demolition phase of the upcycling strategy consists of three steps in which the first two steps are equal to the (traditional) demolition process. Therefore, also data of the demolition crane and smaller crane are used for these two steps. For the preparing of concrete rubble for upcycling also data of a smaller crane is used. This crane is used for separating the concrete rubble and reinforcement before transporting to the element processor. Moreover, the impact of transport of concrete- and reinforcement rubble is based on data of a diesel truck. A difference with the process of downcycling is that additional transport movements are included affecting the environmental impact of upcycling.

The biggest environmental benefit of the process of upcycling can be found in the production phase of a new concrete element. The raw materials retrieved from the concrete rubble and reinforcement can be supplied for the production of the new element. In this way the impact of material supply can be reduced. As explained in Section 4.1.2, it is assumed 20% of the material of the new element consists of recycled cement. Therefore 20% less material should be supplied for production, reducing the environmental impact. More information about the reduced impact is given in Appendix D.3.

In Figure 4.5, the building life cycle information of the upcycling process is shown. It is shown that the supply of raw materials can be partly prevented reducing the environmental impact. Besides, the extra environmental loads are shown, following from material processing and additional transport.

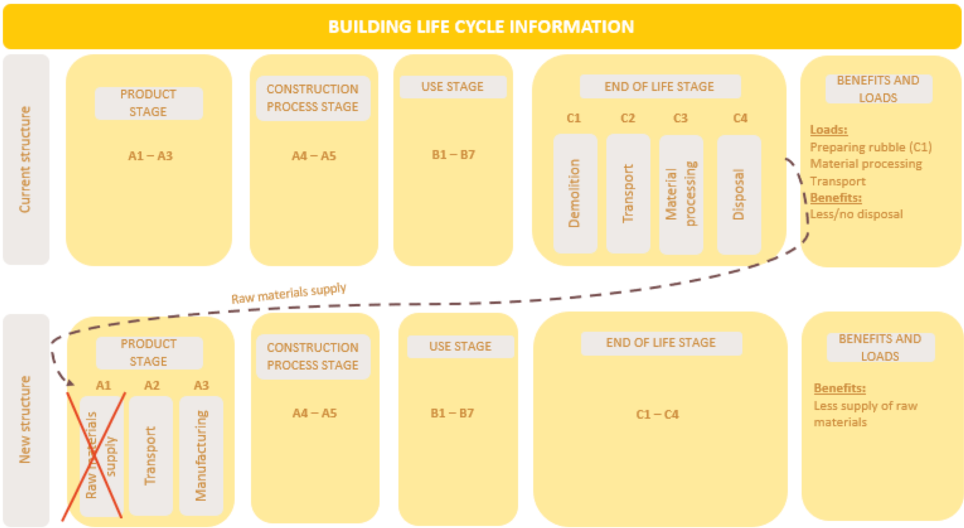


Figure 4.5 Building life cycle information - Upcycling (Own figure)

4.2.3 Reuse

Compared to the processes of down- and upcycling multiple additional steps are included in the process of reuse. Where the impact of the preparation phase is not included in the calculation of the environmental impact of down- or upcycling, the impact of the temporarily scaffolding is included in the calculation of the impact of reuse. The amount of required scaffolding is calculated based on the weight of the element to be supported. The Nationale Milieudatabase provides information about the environmental impact of scaffolding (including installation).

As explained in Section 3.4.2.3, the process of deconstruction consists of four steps: concrete cutting, concrete sawing, element hoisting, and element cleaning. Just as in the processes of down- and upcycling data of a demolition crane with cutters is used for concrete cutting. For sawing of the element, data of an asphalt-concrete saw is used. Using this data, the environmental impact of sawing can be calculated based on the sawing time. The sawing time of an element depends on the element type, number of supports, and support system. More detailed information about sawing time related to element type and supports, is given in Appendix D.2. For hoisting the element out of the structure, a Tower crane or Telescopic crane is used based on the weight of the element. The Nationale Milieudatabase contains data of the usage of those cranes. The impact of cleaning of the element before transport is left out of the impact calculations. For transport of the element, data of a diesel truck is used.

The post-processing phase in which the concrete element will be modified includes four steps: reshaping of the element, removal of fixings, filing holes with concrete mortar, drilling holes in order to reconnect the element in the new situation. For reshaping the element data of the asphalt-concrete saw is used. The environmental impact of the removal of fixings is left out of the environmental calculation. For filling holes with concrete mortar, environmental data of the concrete type of the element is used, and for drilling additional holes the data of the asphalt-concrete saw is used again. More detailed information about the usage of environmental data is given in Appendix D.3.

As shown in Figure 4.6, reusing a structural element result in additional environmental loads for deconstruction, transport, and element processing. However, a huge environmental benefit can be gained since the complete production phase of the element is prevented.

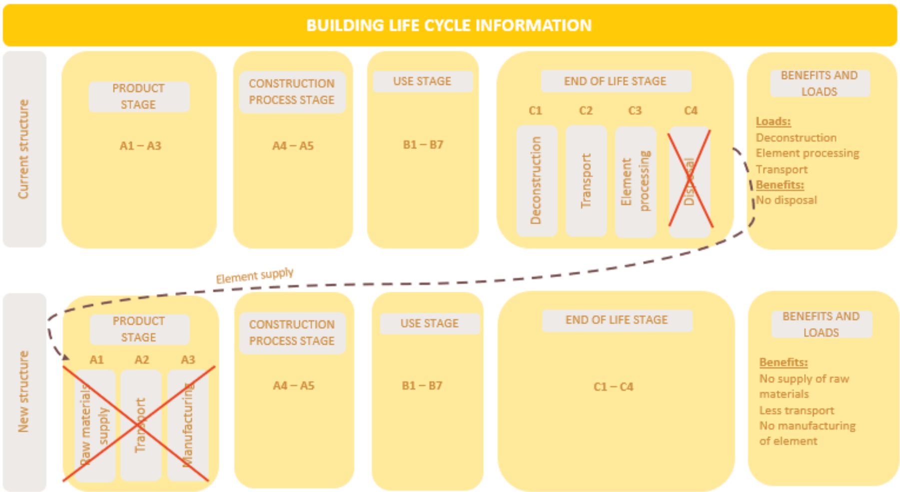


Figure 4.6 Building life cycle information - Reuse (Own figure)

4.2.4 Environmental loads and benefits of circular strategies

As explained in the previous sections, up- or downcycling an element, or reusing an element results in additional environmental loads compared to the traditional linear process, but also in environmental benefits. Therefore, the environmental loads and benefits or each circular strategy are shown in Table 4.1.

Table 4.1 Environmental benefits and loads compared to linear process (Based on 10R model of circularity and NEN-EN 15804)

Circular building strategy	Environmental benefit	Environmental load
DOWNCYCLING	Current structure: C4: less disposal	Current structure: C3: Waste processing
UPCYCLING	Current structure: C3: Waste processing C4: Disposal New structure: A1: Raw materials supply	Current structure: C1: Preparing rubble C3: Material processing
REUSE	Current structure: C3: Waste processing C4: Disposal New structure: A1: Raw materials supply A2: Transport A3: Manufacturing	C1: Deconstruction C2: Transport C3: Element processing

5 Reusability factors

In this chapter factors influencing the reuse potential are explained focusing on structural safety, environmental impact, and economic impact. To analyse the reuse potential of a structural element, information about the current structure is important. However, to analyse the future application of a structural element also information about the future structure is required. The discussed reusability factors are visualized in Figure 5.1.

First of all, product choices are important. Think of element information like dimensions of the reused element and material properties like the strength class. The product choices are explained in Section 5.1. Next to the project choices, the future applicability of the element should be analysed. Therefore, the future function of the element is explained in Section 5.2. Moreover, the design choices should be analysed. Therefore the loading capacity of the element should be analysed, the reinforcement detailing of the element should be checked, and it should be analysed if the element is demountable. These aspects are explained in Section 5.3. The factors important for assessing the condition of the element are discussed in Section 5.4. Furthermore, forms of collaboration are important factors in terms of reusing. The current (linear) system of contracting and responsibilities are analysed and explained (Section 5.5). Besides, the available budget and planning is of major importance. Some aspects about planning and economics are explained in more depth in Section 5.6.

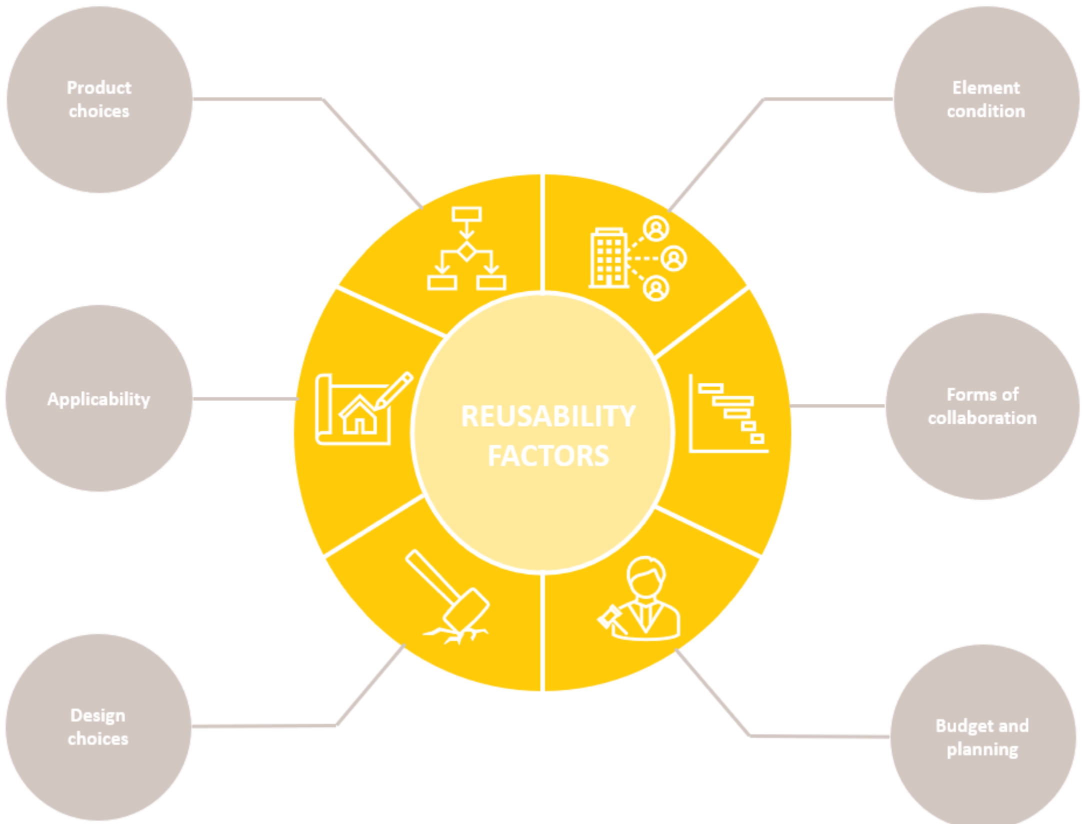


Figure 5.1 Reusability factors (own figure)

5.1 Product choices

In order to investigate if reusing of concrete elements is possible, first the product choices of the concrete element should be analysed. In order to reuse a structural element in a new situation, material properties should have been known. Therefore all available information about the structural element should be gathered. Important documentation for analysing the structural element are shortly explained in Table 5.1 (Glias, 2013)

Table 5.1 Important documentation for analysing the structural element

Available information	Description
Architectural and technical drawings	Structural drawings, plans, details
Element calculations	Structural calculations for ULS and SLS
Codes	Used codes are important since rules and codes have been changed over the years. Therefore some concrete properties and their reinforcement steel properties are explained and compared in Appendix B.

From this information, the product choices should be clear. If the information is not available, site analyses should result in the required information (Glias, 2013). First it is important to gather some general information about the element and material properties of the concrete and reinforcement. The required information is explained in Section 5.1.1 and Section 5.1.2. In case it is not possible to retrieve all required information from the available information, default options could be used whose are explained in Appendix G.3.

5.1.1 Element information

Before analysing the reuse-potential in depth, the general information about the element should be clear. The following information is necessary which is further explained in Table 5.2:

- Element type;
- Element dimensions;
- Concrete density;
- Residual lifespan.

Table 5.2 Required element information for analysing reusability

Element information	Description
Element type	Concrete columns, beams, monolith linearly supported floors, and monolith flat slab floors are the most common used in-situ concrete structural elements in utility buildings constructed in the 70s/80s. Therefore those structural elements can be analysed. A monolith linearly supported floor is supported by line supports (beams). A monolith two-sided linearly supported floor functions as a one-way slab, and a three- or four-sided linear supported floor distributed load in two ways and therefore function as a two-way slab. A monolith flat slab floor is a point supported floor without beams which distributes load in two ways and therefore function as a two-way slab (Braam, Lagendijk, 2011).
Element dimensions	The element dimensions are important in order to design a new structure with the reused element. Moreover, possibilities for transport depends on the dimensions and shape of the concrete element. Smaller elements are easier and therefore cheaper to transport (Structural engineer Personal Communication, 2022).

Element information	Description
Concrete density	According to EN 206, concrete has a density between 2000 and 2600 kg/m^3. Concrete with a density lower than 2000 kg/m^3 is called light concrete and a density above 2600 kg/m^3 heavy concrete. Those concrete types are out of scope of this research.
Technical lifespan	According to NEN 2767-1+C1:2019 the definition of technical service life is: *''period in which a building or installation component is assumed to be able to maintain a certain technical level''* According to NEN-EN 1990:2002, for buildings and normal structures, a technical lifespan of 50 years should be used. Together with the year of construction, year of deconstruction, and the condition of the element, the residual lifespan can be calculated. Calculation methods for the residual lifespan are explained in Appendix D.1.

5.1.2 Element properties

Besides the element information, some properties of the element should be known in order to analyse the structural reusability of the element. If it is not possible to get this information, reusing is not advised. Recycling of the concrete material can still be an option.

The following properties are important and are explained in Table 5.3.

- Cement type;
- Concrete strength class;
- Environmental class;
- Reinforcement strength.

Table 5.3 Required element properties for analysing reusability

Element properties	Description
Cement type	According to NEN-EN 197-1 there are 27 cement types which satisfy the defined European norms. For 90% of the works in the Netherlands, CEM I (Portland Cement), CEM III/A, CEM III/B, and CEM II/B-V are used (Betonvereniging, 2020). Therefore, only those cement types are included in the assessment of the reuse potential of a structural element.
Concrete strength class	The compression strength of concrete determines the strength class. In the Netherlands, most in-situ structures are made of concrete with strength class C20/25, C25/30, or C30/37 (Braam, Lagendijk, 2011). Appendix B.1 gives additional information about concrete strength classes. Since the naming of strength classes were different before 2012, Appendix D.4 explains the naming of previous used strength classes and compared those to the strength classes of the current Eurocode 2. In the assessment of the reusability potential it is possible to select concrete strength classes C20/25, C25/30, and C30/37 according to the current Eurocode. It is also possible to select concrete strength classes according to previous Eurocodes. In further calculations, the comparable concrete strength class according to the current Eurocode will be used.
Environmental class	NEN-EN 206-1 describes environmental classes which are based on the chance of deterioration of the reinforcement, and deterioration of concrete by frost or chemicals. Requirements for the concrete composition depends on the environmental class. For utility buildings the following environmental classes are distinguished: X0, XC1, XC3, XC4, XD1, XS1, XF1 (NEN-EN 206-1, 2005). Appendix B.5 gives additional information about environmental classes.

Element properties	Description
Reinforcement strength	In the Netherlands, according to NEN-EN 1992-1-1 only reinforcement steel FeB 500 is used. Structures designed according to previous codes can contain other types of reinforcement steel like FeB 400 or FeB 220. Therefore, it is possible to select the reinforcement strength according to the current Eurocode and previous ones. Appendix D.4 gives additional information about the steel reinforcement strengths of previous codes.

5.2 Applicability

In order to analyse the reuse potential, the (proposed) future application should be known. If an element does not fit in any new situation, there is no need to deconstruct the element. For example, compared to the 70s/80s, internal heights of buildings are increased. A column could therefore be too small to function or lots of modifications are required in order to fit in a new situation. In that case, up- or downcycling could be a better option. It is therefore important to think of the future situation and function of the structural element. In Figure 5.2, the options of element type related to their future function are shown, whose are included in this research.

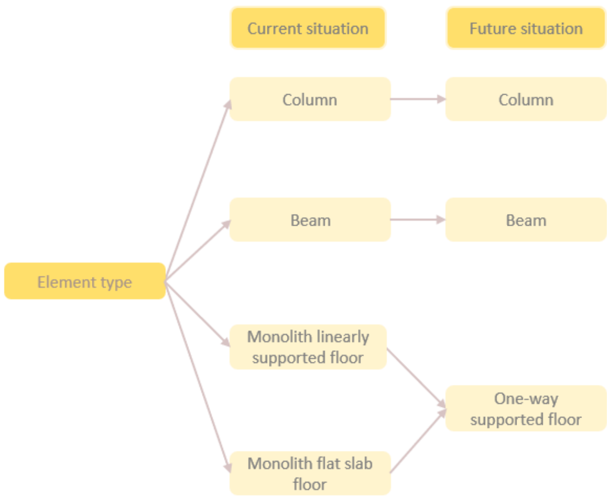


Figure 5.2 Applicability of structural elements (Own figure)

As described in Section 5.1.1, in-situ monolith linearly supported floors and monolith flat slab floors were often used in utility buildings during the 70s/80s. Therefore, this research focusses on these two floor types. For these floors, the reuse potential can be analysed for future implementation as one-way (hinged) supported floor.

5.3 Design choices

Concrete structures of utility buildings from the 70s/80s are designed with other intentions than structures nowadays. For example, reusing structural elements in a later stage is not a factor where is thought of in the design of utility buildings. Moreover, structures can be designed in a flexible way. The design allows the buildings to change their function over the years by making use of demountable connections and moveable walls. All those design choices were not made during the 70s/80s. Therefore it is important to analyse the design choices of the current structure in order to investigate the reusability of the structural elements. When the future loads on the structural element are known, the loading capacity of the element can be compared to these loads. If future loads are not known (yet), they can be estimated, or just the loading capacity of the element can be analysed.

Moreover, the reinforcement detailing should be analysed and checked with the current codes. The detailing rules for reinforcement differ per element type. Therefore, the assessment of the reinforcement depends on the chosen element type. Also, the connections of the element should be analysed and criticized. Think of the location and amount of connections and the demountability of the element.

5.3.1 Loading capacity

To reuse a structural element in a new structure, the loading capacity of the to be reused element can be calculated. If the future loads on the element in the new situation are already known, these can be compared to the loading capacity of the element. In order to compare future loads to the loading capacity of the element, the following information is required, explained in Table 5.4:

- Permanent loading;
- Variable loading;
- Consequence class;
- Function.

Table 5.4 Required information about loading capacity for analysing reusability

Loading capacity	Description
Permanent loading	Loading which is permanent present. Examples of permanent loading are own weight, toppings, or finishings (Glias, 2013; Braam, Lagendijk 2011).
Variable loading	Variable loading is the consequence of usage of a building. Examples of variable loading are persons, furniture, machinery, cars, etcetera. Variable loading can be characteristic (small chance of exceeding the value), frequent (loading with a short duration), or quasi-lasting (big chance of presence at random time) (Braam, Lagendijk 2011).
Consequence class	NEN-EN 1990+A1+A1/C2:2019 distinguishes three consequence classes. Consequence class 1 (CC1) stands for minor consequences and if often used for farms, standardized family homes and industry building with maximum two floors. Consequence class 2 (CC2) stands for average consequences and is used for housing, apartment buildings, offices, public buildings, and industry buildings. In case of big consequences, consequence class 3 is used (CC3). CC3 is often seen in high rise structures, tribunes, and large public buildings.
Function	The future building in which the structural element will be used can have another function than the building of which the element originates from. Since the future function of the building affects the load combinations by a Ψ-factor, it is important to state this future function (Sagel et al, 2013).

5.3.2 Detailing of reinforcement

The reinforcement of the element should be investigated since also rules for reinforcement design has been changed over the years. Appendix D.4 explains more about the changes for reinforcement.

The following design details of the reinforcement are important and are explained in Table 5.5:

- Diameter of bars;
- Number of bars;
- Spacing of bars;
- Concrete cover;
- Fire resistance.

Table 5.5 Required reinforcement information for analysing reusability

Reinforcement details	Description
Diameter of bars	In NEN-EN-1992-1-1 the minimum required diameters of rebars and stirrups are given. Those diameters differ per structural element. The diameters of the rebars of reused elements can be compared with the NEN-EN-1992-1-1. The minimum required diameters of rebars per structural element are given in Appendix D.5.
Number of bars	The minimum and maximum required area of the rebars and stirrups is important to check for reused elements. In order to calculate the total area of rebars and stirrups, the number of bars in the element should be known. Additional requirements for the area of rebars/stirrups for reused elements are described in NEN-EN-1992-1-1. Appendix D.5 contains detailed information about the required area of rebars and stirrups for the structural elements included in this research.
Spacing of bars	The spacing of the rebars and stirrups depends on the used diameter of reinforcement steel, but also the grain size of the largest concrete substant (Braam, Lagendijk, 2011). The minimum- and maximum spacing of the rebars and stirrups are described in Appendix D.5.
Concrete cover	The thickness of the concrete cover is an important factor to analyse, since the reinforcement steel needs sufficient protection. In the NEN-EN-1992-1-1 minimum requirements for the thickness of the concrete cover are explained based on annexation requirements, environmental classes, and construction classes. Also execution tolerances are included. Appendix D.5 explains the calculation of the minimum required thickness of the concrete cover.
Fire resistance	The required fire resistance depends on the height of a building, the function of the building, and the permanent fire loading (Boot-Dijkhuis, 2014). For utility buildings, the requirements for fire resistance depends on whether the utility building has a sleeping function not. The following fire resistances can be used for utility buildings: 30 minutes, 60 minutes, 90 minutes. Additional information about fire resistance is given in Appendix B.6.

5.3.3 Demountability of the element

In order to execute a structure, different structural elements are connected with each other. The extent to which connections can be broken and the elements can keep their initial function, determines the demountability. According to the report 'Circular Buildings', the definition of demountability is the following (Van Vliet et al, 2019):

'*Demountability is the extent to which objects can be demounted on all scale levels within buildings while keeping their function resulting in high-quality reuse*'

The design of a building has the biggest influence on the demountability. Since demountability was not a design criteria in utility buildings of the 70s/80s, the connections of those elements are not designed to be demounted. Verberne analysed demountability factors and divided those factors into three groups: technical factors, process factors, and financial factors (Verberne, 2016). Alba Concepts proposed a method to measure the demountability of an element. Based on those researches and methods, the factors which are important for the demountability of concrete structural elements are shown in Figure 5.3.

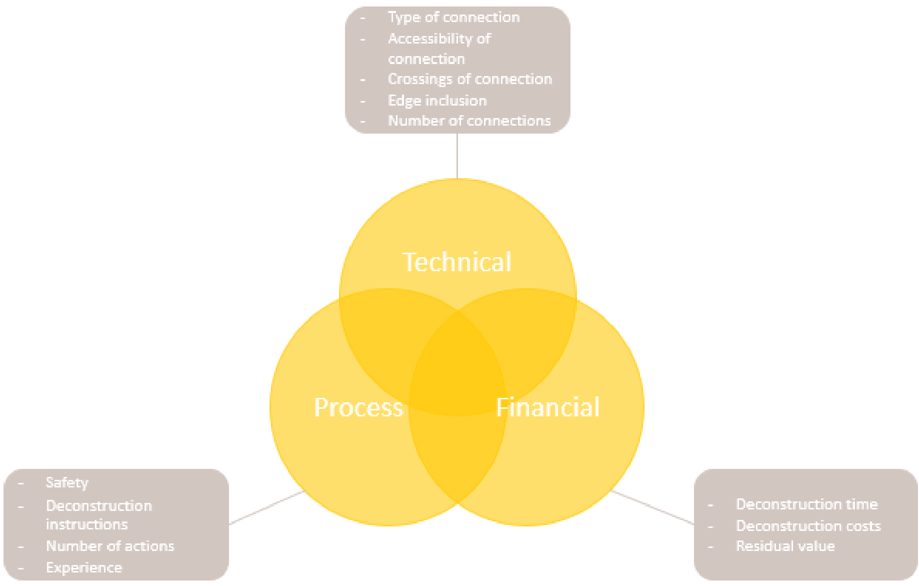


Figure 5.3 Demountability aspects (Adapted from Van Vliet et al, 2019)

In this section, the technical factors of the demountability of concrete elements are explained in more depth influencing the risk of causing damage, environmental- and economic impact. The process of deconstruction is explained in Chapter 3. Financial aspects of reusing structural elements are described in Section 4.1.

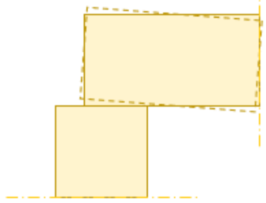
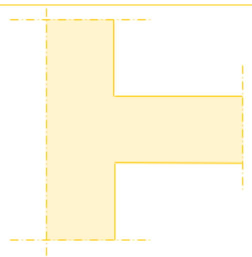
Number of connections

An important aspect influencing the demountability of a structural element is the amount of connections. The amount of connections will increase the risk of causing damage (Van Vliet et al, 2019; Bouwens, 2022). The amount of connections will differ per element type. Concrete flooring systems require more connections than a single concrete column. In case of beams, columns, and point supported floor elements, the number of point connections should be chosen. In this research, there is a maximum of six point supports. In case of linearly supported floor elements, the number of line supports can differ per analysed floor element. The maximum amount of line support is four, since a floor element has four sides.

Type of connection

In her doctoral thesis, Durmisevic defined three main types of connections: direct (integral) connections, indirect (accessory) connections, and filled connections. Integral connections are connections which are overlapping of interlocking. Indirect connections are connections in which third elements are used in the connection. This can be an internal or external connection. Filled connections are connections which are filled with a chemical material. To design demountable connections it is important to keep the elements separated, so to avoid penetration. Besides, chemical connections should be replaced by dry joints. (Durmisevic, 2006). In the design of future buildings, demountability of connections will be an important criterium. In utility buildings constructed during the 70s/80s this was not the case and therefore mostly chemical/wet joints are used. Therefore, in this research only two connection types are included which are shown in Table 5.6.

Table 5.6 Type of connection (Adapted from Van Vliet et al, 2019; Braam, Lagendijk, 2011)

Schematized connection	Type of connection	Description
	Dry connection – hinged (potentially pinned/nailed)	Hinged connection, rotation possible. Could be connected by an additional pin.
	Wet connection – rigid (casted)	Rigid connection, no rotation possible. Elements are integrated with each other.

In case of linearly supported floors, the amount of line supports can differ, even as the type of connection. For example, a floor element can be two-sided supported on the width of the element. However, it also possible a floor element is three-sided supported on the length and two times the width. Appendix D.6, includes detailed information about the support options for linearly supported floors.

Accessibility of connection

To demount a connection it is important to access the connection without causing damage to the adjacent elements (Van Vliet et al, 2019). Therefore it is important to analyse the accessibility of the connection. Finishings complicates the accessibility of connections. In practice, often perfectly designed demountable connections are used but there was not thought of the finishing (Terneuzen, 2022). Based on the research of Durmisevic, Verberne and Alba Concepts, the categories which are distinguished are explained in Table 5.7.

Table 5.7 Accessibility of connection (Adapted from Durmisevic, 2006; Van Vliet et al, 2019; Verberne, 2016)

Accessibility of connection	Description
Free accessible	Visible and reachable
Accessible with additional action without causing damage	Not visible, not immediately reachable
Accessible with additional action causing repairable damage	Not visible, not immediately reachable, removal causing damage
Not accessible, irreparable damage	Not visible, removal causing irreparable damage

Crossings of connection

Elements can cross other elements which complicates the deconstruction process of the element. An element can be (structurally) dependent of other elements (Van Vliet et al,2019). This result in temporary support of the structure before deconstructing the element. Therefore the crossings of the element and their dependencies should be analysed. Table 5.8 shows the distinguished categories. In this research, floor elements without crossings of connections are assumed.

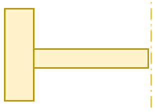
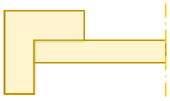
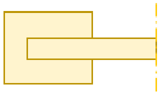
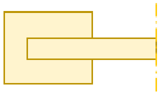
Table 5.8 Crossings of connection (Adapted from Durmisevic, 2006; Van Vliet et al, 2019; Verberne, 2016)

Crossings of connection	Description
No crossing	Modular zoning of elements
Crossing of one or multiple elements (functional dependencies)	Crossing elements which are functional dependent of each other (voids for services or installations)
Crossing of one or multiple elements (structural dependencies)	Crossing elements which are structural dependent of each other (load transfer dependencies)
Full integration of elements	

Edge inclusion

The edge inclusion of an element influences the deconstruction process. Durmisevic distinguished open and interpenetrating geometries. Interpenetrating geometries can only be disassembled in one direction and are therefore complicated to deconstruct. Based on the edge geometries, the categories which are distinguished for concrete elements are shown in Table 5.9.

Table 5.9 Edge inclusion (Adapted from Van Vliet et al, 2019; Verberne, 2016)

Schematized	Edge inclusion	Description
	Open, no enclosements	No enclosement of connection by other elements
	Overlap at one edge	Partly enclosement of connection at one side by other element
	Closed at one edge	Completely enclosement of connection at one side by other element
	Closed at multiple edges	Completely enclosement of connection at multiple sides by other elements

Next to the design choices explained above, some element specific design choices are required. Therefore, the required information about design choices of columns, beams, and floor elements are included in Appendix G.1.

5.4 Element condition

In order to reuse a concrete element the condition of the element should be checked on site. When a concrete element is suitable for reuse based on the product- and design choices, it does not mean the condition of the concrete element is sufficient. The residual lifespan of a concrete structural element can be influenced by toxic substances or deterioration which is explained in Table 5.10 and Table 5.11 (Bouwens, 2022). Therefore it is important to analyse these aspects in order to estimate the residual lifespan. Based on NEN 2767 concrete elements can be visually inspected. The element condition can be scored based on a six-point scale. This score is used to calculate the residual life span of the structural element. More details about the calculation of the residual lifespan based on the condition score are given in Appendix D.1.

Table 5.10 Toxic substances (Adapted from Bouwens, 2022; Van Berlo, 2019)

Toxic substances	Description
Chlorides	Chlorides can influence the residual lifespan of the concrete element. Especially building which could have been in contact with sea water should be checked for chlorides penetration (Van Berlo, 2019). Therefore concrete elements originating from buildings in a coastal are should be analysed for chlorides. According to methods described in CUR recommendations, the residual lifespan can be calculated. More detailed information about chlorides, and coastal area is given in Appendix D.1.
Asbestos free	Asbestos is a cancer causing substance and therefore is forbidden since 1994. Since this research focusses on utility buildings from the 70s/80s, asbestos can potentially be present in structural elements (Ministerie van Infrastructuur en Waterstaat, 2021f). It Is therefore important to check if certificates are available guaranteeing that the building is free of asbestos. If that's not that case, additional checks are required for the presence of asbestos.

Table 5.11 Condition of the element (Adapted from Bouwens, 2022)

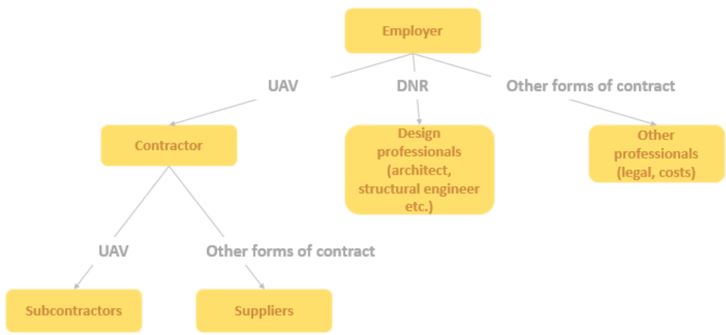
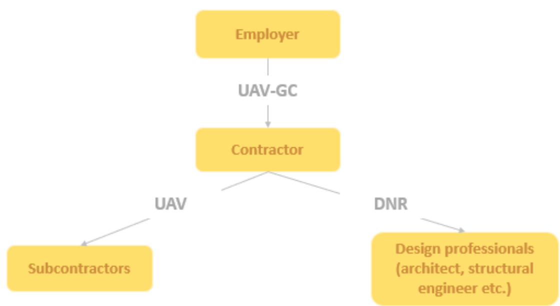
Deterioration	Description
Visibility of aging	In NEN 2767-1+C1:2019, it is described how aging influences the condition score of a structural element and therefore the residual lifespan. It should be analysed if defects as result of aging are visible, and when it is visible, if it is only locally or regularly visible. In Appendix D.1 more details about the visibility of aging related to condition scores are explained.
Visibility of defect	Defects could be visible in different forms, like symptoms of weathering, affection by dirt, or only aesthetical defects. Besides, it should be analysed if these defects occur only locally, regularly, or even to a considerable extent. Appendix D.1 explains more details about visibility of defects.
Visibility of (external) corrosion	Due to corrosion, parts of the surface can pit, the surface can delaminate or even spall, and brown/red colouring can occur indicating corrosion. Therefore, it should be checked if one of those aspects is visible. In Appendix D.1 it is explained how the visibility of external corrosion affects the condition score of the structural element.
Cracks	Internal deteriorations like Alkali-Silica reaction or sulphate attack should be checked. Alkali-Silica reaction (ASR) has been a known issue since 1989. When blast furnace cement is used (CEM III/B), Alkali-Silica reaction cannot occur. Therefore, a check for Alkali-Silica is only necessary if other cement types than CEM III/B are used. The reaction can be recognized by inhomogeneous anisotropic cracks in a map pattern. Sulphate can penetrate inside concrete structural elements when these are located in coastal areas. Moreover, structural elements with environmental classes X0 or XC1 have no chance of sulphate attack. Therefore, it is only necessary to check the element for potential sulphate attack when it is originated from a coastal area having an environmental class unequal to X0 and XC1. Sulphate attack can be recognized by a inhomogeneous anisotropic cracks in a tree-shape pattern (Bouwens, 2022).
Crackwidth	NEN-EN 1992-1-1 states the maximum allowable crackwidth depending on the environmental class and if the element is prestressed or not. According to this Eurocode the maximum crackwidth which is present in the to be reused structural element can be compared to the maximum allowable crackwidth based on the environmental class. In this research only in-situ concrete elements are analysed without prestress.

5.5 Forms of collaboration

Next to product- and design choices, forms of collaboration are of major importance. In the linear building process there are already difficulties in understanding forms of collaboration and the corresponding responsibilities. Due to bottlenecks in the current system, the circular building system is not stimulated (Boot et al, 2015). It is important to be aware of the responsibilities of involved parties when reusing structural elements, the collaboration model, and to be reminded of the law system before reusing concrete structural elements. The most often used forms of collaboration in the Netherlands are explained in this section. In Appendix A.2, more detailed information is given about responsibilities of parties involved in the building process, used contracting forms, and the law system used in the building sector.

In the Netherlands there are multiple forms of collaboration in which responsibilities are distributed. The amount and complexity of contracts also contributes to difficulties in understanding regulations and the application in practice. The most often used forms of collaboration are the design-bid-build method, and the design-build method. Where design-bid-build methods are mostly used for residential, commercial, and industrial construction, the design-build contracts are more often used in civil engineering projects like bridges and tunnels (Boot et al, 2015). The two forms of collaboration are shortly explained in Table 5.12.

Table 5.12 Forms of collaboration in the Netherlands

Form of collaboration	Description	Relations visualized
Design – bid - build	In this traditional model the design and construction are fully separated. The design will be prepared by a client or an advisor according to a DNR (De Nieuwe Regeling) contract. The contractor is liable for executional risks and has a UAV (Uniforme Administratieve Voorwaarden) contract with the employer (Boot et al, 2015).	 **(Adapted from Boot et al, 2015)**
Design – build	The design-build method is a form of collaboration in which design and construction are integrated. The contractor is involved in the design, technology and systems integration. Because of that, there are larger risks for the contractor, compared to a design-bid-build form of collaboration (Hombergen, 2021b, Boot et al, 2015).	 **(Adapted from Boot et al, 2015)**

A major drawback of the traditional model, which is often used for utility buildings, is that the contractor is not involved in the design of the structure. Contractors and their sub-contractors potentially have lots of insight in available reusable structural elements or are the owner of them. By involving (sub-)contractors in an early stage of the design process, reusable elements can be integrated in the design. By involving the contractor after the design is finished, there is a risk of used concrete profiles or dimensions in the design which are not available. By involving the contractor in an earlier stage, the design could have been adapted in order to implement more reusable concrete elements resulting in a reduced environmental impact of the project.

5.6 Budget and planning

Budget and planning are important factors in the assessment of the reusability of concrete structural elements retrieved from utility buildings. Reusing should fit within the budget- and planning boundaries or (extra) time should be scheduled for the necessary processes in order to reuse structural elements. This section describes important factors influencing the budget and planning of a project.

The work environment can drastically influences the planning and required budget of a project. Therefore it is important to analyse the site before planning the deconstruction. Important aspects are shortly explained in Table 5.13.

Table 5.13 Factors budget and planning

Influencing factors	Description
Site area	It is important to check if the site area is large enough for the usage of cranes and large trucks. When the site area is too small for the usage of those machinery, deconstruction can be an issue.
Accessibility	The accessibility influences the logistics and time of the deconstruction process. In the process of reuse, upcycling, and downcycling multiple transport movements are included, explained in Section 3.4.3. The distances of all included transport movements influences the budget and planning and therefore affects the costs of the project. Moreover, transport affects the environment.
Storage	In case a structural element is harvested but cannot be immediately reused in a new structure, it can be temporarily stored. The duration of the storage influences the budget and planning of a project.

6 Assessment of reuse potential

This chapter explains the assessment of the reuse potential. Based on the process of reuse, the impact of reuse, and the reusability factors, the reuse potential is assessed focusing on structural safety, environmental impact, and economic impact, as explained in Section 1.3. Figure 6.1 visualizes the assessment of the reuse potential. First, the assessment of the reuse potential based on structural safety is explained in Section 6.1. Second, the assessment of the environmental impact is described in Section 6.2, followed by the assessment of the economic impact in Section 6.3. Finally, Section 6.4 explains the output and how the final advice is generated based on the three main focus points.

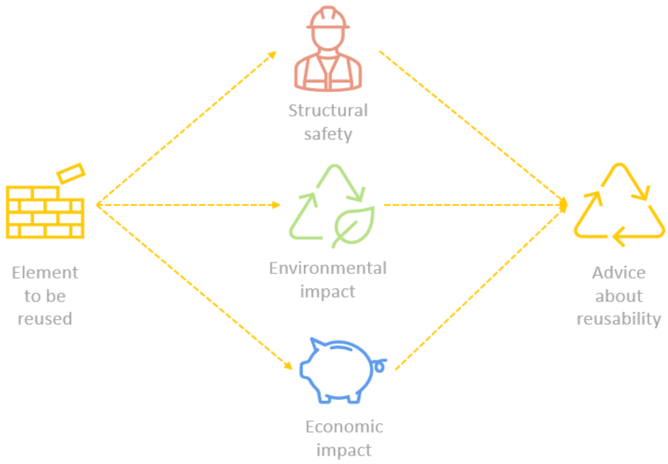


Figure 6.1 Assessment of reuse potential (Own figure)

6.1 Structural safety

To guarantee the to be reused structural element is safe in a new situation, the structural safety of the element should be assessed. In order to indicate if the element is structurally safe, it will be assessed based on criteria for condition and structural applicability.

The aim of the reusability tool is to give a first indication about the reusability potential of a structural element. Therefore, the structural potential of the element is only checked in a global way. When the element turns out to have potential in the new situation, detailed structural calculations are required.

Based on the checks for condition and structural applicability, an advice about the reusability will follow. This process is visualized in Figure 6.2. If the condition and structural applicability turns out to be sufficient, this will result in the advice to reuse the structural element (based structural safety), and further analyse the element by detailed calculations. In Appendix E.1 the detailed structural assessment is included and explained.

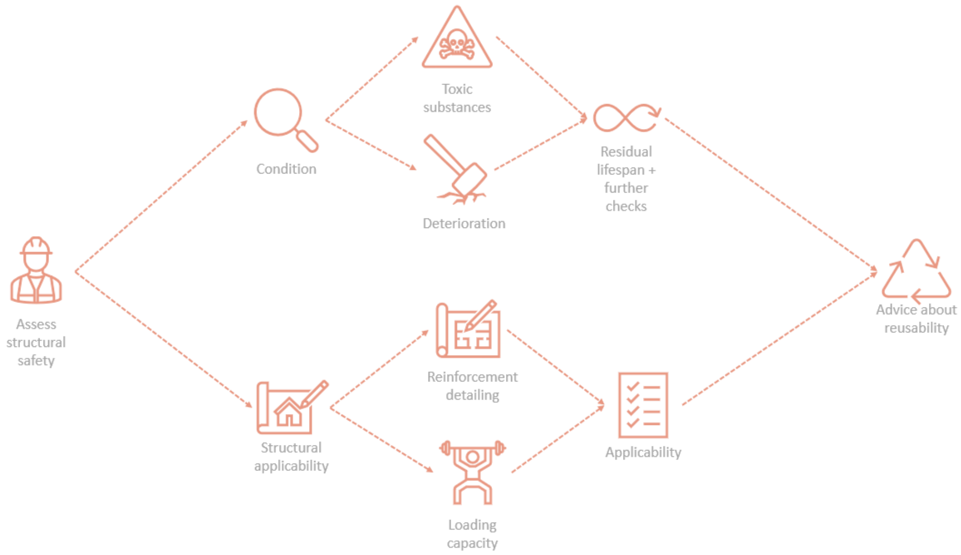


Figure 6.2 Assessment of structural safety (Own figure)

6.1.1 Condition

The condition of the structural element is checked based on the potential presence of toxic substances and deterioration, which is explained in Section 5.4. Based on the method described in NEN 2767, scores are linked to condition properties which are used for the calculation of the residual lifespan. The calculation of the residual lifespan is explained in Appendix D.1. Moreover, it is analysed if additional research or checks are required. In Appendix E.1.1, the full process of analysing the condition of a structural element is explained.

6.1.2 Structural applicability

The applicability of the element in the new situation is analysed by checking if the detailing of the reinforcement is according to the current Eurocode (NEN-EN 1992-1-1), and by global structural checks. The rules for reinforcement detailing are element specific and explained in Appendix D.5. Besides, the loading capacity of the reused elements are analysed. This is done by structural checks for the ultimate limit state (ULS) and serviceability limit state (SLS). In case of beams and floor elements, the maximum allowed bending stress is calculated for the ultimate limit state, using the reinforcement which is present in the element. For the serviceability limit state, the maximum deflection is analysed. For columns, the compression stress is analysed in ultimate limit state, including the slenderness of the column. Moreover, it is checked if second order calculations are required for bending (Braam, Lagendijk, 2011). More detailed information about the structural calculations are included in Appendix E.1.2.

In Appendix E.1, the assessment processes of the condition and structural applicability are explained in depth.

6.2 Environmental impact

Next to the structural safety, the impact of reusing a structural element is assessed and compared to the impact of upcycling and downcycling. The environmental impact is expressed in an ECI value which makes it possible to easily compare the impact of reusing, upcycling, and downcycling. The advice about reusability in terms of environmental impact is based on the lowest ECI value. For example, when the ECI value of reusing a structural element is the lowest compared to up- and downcycling, it will be advised to reuse the structural element.

The impact of the processes related to reuse, upcycling, and downcycling which are described in Chapter 4 are calculated and expressed in an ECI value. The final ECI values of reuse, upcycling, and downcycling are compared resulting in an advise about reusability. When only focusing on environmental impact, the circular strategy with the lowest ECI value is advised. The assessment of the environmental impact is based on some assumptions. Therefore, these assumptions are included in Appendix G.2.

The process of assessing the environmental impact is shown in Figure 6.3. Appendix E.3 explains the calculation of the ECI value for reuse, upcycling, and downcycling in depth.

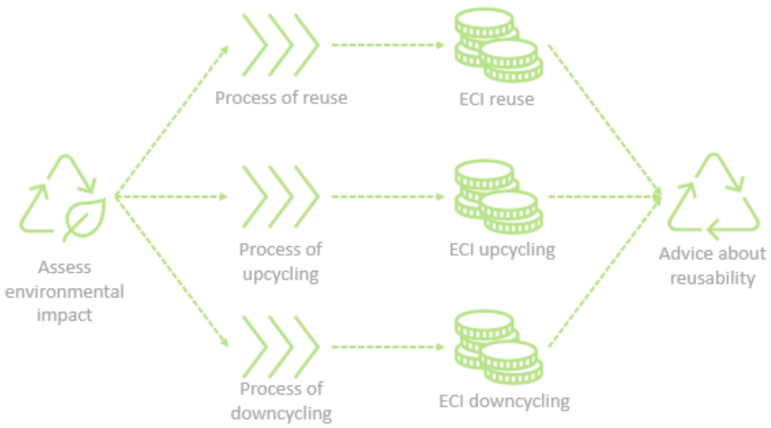


Figure 6.3 Assessment of Environmental impact (Own figure)

6.3 Economic impact

An important factor in terms of feasibility is the economic impact, expressed in economic costs (€). In this way, the economic impact of reusing, upcycling, and downcycling can be easily compared. The circular strategy with the lowest costs will be advised in terms of economic impact.

The processes of reuse, upcycling, and downcycling are explained in Chapter 3 and the corresponding costs are explained in Chapter 4. The total costs of each circular strategy will be calculated on which the advice about reusability is based. The circular strategy with the lowest corresponding costs will be advised (in terms of economic impact).

The process of assessing the economic impact is shown in Figure 6.4. In Appendix E.3 the economic assessment is explained in depth. Also for the assessment of the economic impact, some assumptions have been made whose are included in Appendix G.2.

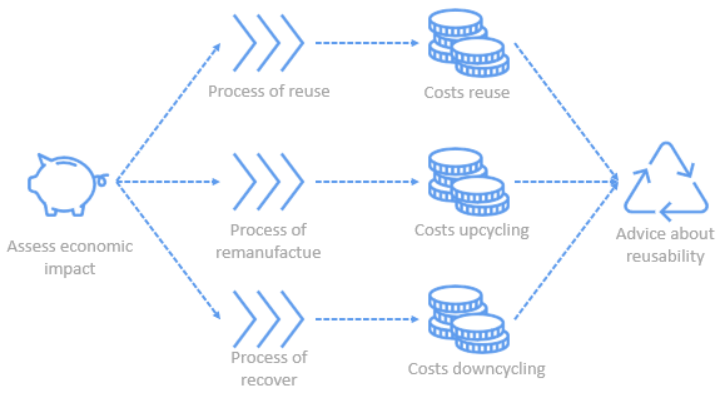


Figure 6.4 Assessment of Economic impact (Own figure)

6.4 Output of assessment

The output of the assessment of the reuse potential is divided into three parts:

- Score of structural element which Is explained in Section 6.4.1;
- Final advice about reusability which is explained in Section 6.4.2;
- Element properties for detailed structural calculations when the final advise is 'Reuse', explained in Section 6.4.3.

6.4.1 Score of element

According to researches of Bradley (2004) and Jabeen (2020), when salvage costs are taken into account, the costs of the process of reuse can be lower than the costs of up- or downcycling. However, these salvage costs are hard to determine. The salvage costs can be estimated as a percentage of the retail price of new produced elements (Bradley, 2004). However, in that case the environmental benefit and residual lifespan of a reused element are not included. Therefore, in this research a reused element is scored based on three aspects, as shown in Figure 6.5:

- Economic load of reuse compared to downcycling;
- Environmental benefit of reuse compared to downcycling;
- Residual lifespan of the element.

Figure 6.5 Scoring of an element (Own figure)

The economic load is calculated by subtracting the costs of downcycling from the costs of reuse. This value shows the economic impact of reuse, since it should be noted the costs of downcycling will be there anyway. When the economic load turns out to be a negative value, even economic benefit is resulted when reusing an element. The difference of economic impact between reuse and downcycling is expressed in a percentage for the calculation of the score of the element.
Besides, the environmental benefit is calculated. This is calculated by subtracting the environmental shadow costs of reuse from the environmental costs of downcycling. Also the difference in environmental impact is expressed in a percentage, used for the calculation of the final score of the element.
Next to the impact of the element, the residual lifespan is an important factor. When the residual lifespan is low, reusing the element is not useful since it cannot be used over the complete functional service life of the new structure. Therefore the residual service life influencing the final score. In Table 6.1, it is shown how the element is scored based on the explained aspects.

Table 6.1 Scoring of an element - Scores

Economic load (%)	Scoring	Environmental benefit (%)	Scoring	Residual lifespan	Scoring
<10	100	>100	100	>100	100
10-20	95	100-90	95	90-100	95
20-30	90	90-80	90	80-90	90
30-40	85	80-70	85	70-80	85
40-50	80	70-60	80	60-70	80
50-60	70	60-50	70	50-60	70
60-70	60	50-40	60	40-50	60
70-80	50	40-30	50	30-40	50
80-90	40	30-20	40	20-30	40
90-100	30	20-10	30	10-20	30
>100	20	<10	20	<10	20

For the calculation of the final score, weight factors can be used. The weight, and therefore the importance of the factors could be adapted by the end-user. Since environmental impact is of increasing importance, for this research a factor 2 is used, where for economic impact and residual lifespan a factor 1 is used. The weight factors are shown in Table 6.2.

Table 6.2 Scoring of an element - Weighting

Aspect	Weight factor
Economic load	1
Environmental benefit	2
Residual lifespan	1

The final score of the element can be determined by calculating the weighted average of the scores of the described aspects.

6.4.2 Final advice

Based on the advice of structural safety and the calculated score of the element, a final advice should be given. In the final advice, the advice of structural safety is quite leading, When the element is structurally not reusable but is advised to reuse based on the score, the element still will not be reused. An element can only be reused when it is structurally safe.

The options for the final advice are shown in Figure 6.6. Following the lines of the same colour from the advice based on structural safety and the element score, results in the final advice.

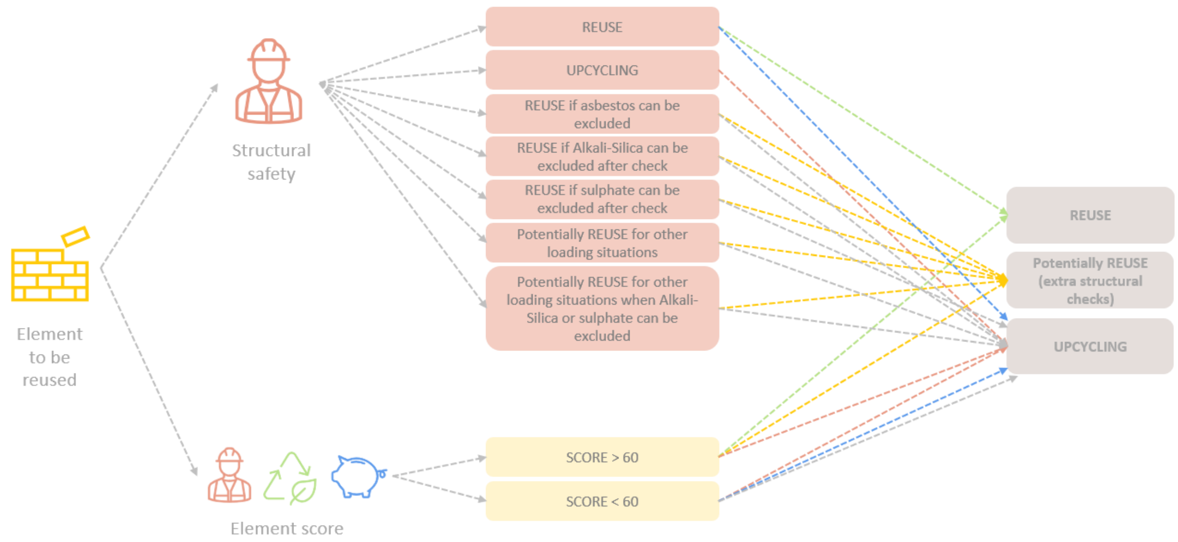


Figure 6.6 Decision tree final advice

6.4.3 Properties for detailed structural calculations

When the final advice of the assessment of the reuse potential results in 'Reuse', further detailed structural calculations are required. As explained in Section 2,3, the analysis of the reuse potential is a global assessment in which a first indication about reusability of a structural element can be given. Therefore, the structural engineer should further analyse the structural element. When the final advice about the element is to reuse it, the following structural properties will be given which can be used in further calculations:

- Own weight of the structural element;
- Concrete strength class according to the current Eurocode;
- Suitable environmental classes to implement the structural element (without extra modification);
- Reinforcement strength according to the current Eurocode;
- Maximum applicable design stress and design forces.

PART III | REUSABILITY TOOL

7 Reusability tool

In this chapter the Reusability Tool is presented. In Section 7.1, the development of the tool is addressed. By using the test case of the Merin Building and feedback sessions with experts, the Reusability Tool is validated (Section 7.2).

7.1 The developed Reusability Tool

The Reusability Tool is developed to assess the reuse potential of concrete structural elements and therefore stimulates reusing in practice. The assessment system, which is explained in Chapter 6, is translated into the Reusability Tool using the software MS Excel. The tool is developed by an extensive desk research into the assessment of the structural safety of an element, assessing environmental impact, and the assessment of economic impact. Besides, interviews with demolition contractors- and managers, structural engineers and researchers, resulted in information about deconstruction processes necessary for the detailed assessment of the environmental- and economic impact. Moreover, especially demolition managers and structural engineers indicated their preferred output of the tool. A residual value/score of an element combined with the environmental impact- and economic impact will help the construction sector thinking about circular design options. The tool can help prevent buildings from (traditional) demolishment and reduce the environmental impact of future structures. Moreover, from the interviewed parties it is followed that a well-known program, like MS Excel, is preferred for the development of the tool. A well-known program eases the willing to use and finally the usage of a tool (Demolition contractors, Personal Communication, 2022).

7.1.1 Set-up of the tool

The Reusability Tool is developed in MS Excel and consists of different tabs indicated by a colour. The red tabs include the structural assessment, the green tabs include the environmental assessment, and the blue tabs include the economic assessment. The yellow tabs are created for the end-user, and are of major importance. The following yellow tabs are included in the Reusability Tool and are shortly explained:

- *Explanation Reusability Tool;*
- *Input sheet;*
- *Info Input sheet;*
- *Output sheet;*
- *Detailed Output sheet;*
- *Process trees.*

Explanation Reusability Tool

In this sheet, the aim, the (proposed) users, and scope of the Reusability Tool is shortly explained. Moreover, the other 'yellow tabs' are shortly explained and references to process trees and formulas are included.

Input sheet

This sheet needed to be fill in by the user of the Reusability Tool. All required information about the current situation and (potential) future situation of the structural element is asked. This information is explained in

Chapter 5: Reusability Factors. By clicking on the input boxes, additional information or default options about the input variable appears. Moreover, references to the report are shown in case the user prefers additional detailed information about the variable.

Info Input sheet

Some input variables include visualizations for clarification. The support options for linearly supported floors (visualized in Appendix D.6), and options for edge inclusion (Section 5.3.3) are included in this sheet.

Output sheet

As explained in Chapter 6, the assessment of the reuse potential results in a final advice and element score which is the main important output of the Reusability Tool. Therefore, these aspects are stated on top of the *Output sheet*. Besides, the O*utput sheet* includes the main important output regarding structural safety, environmental impact, and economic impact. Also, the additional costs, environmental benefit, and residual lifespan of reusing is shown, resulting in the element score.

Detailed Output sheet

In the *Detailed Output sheet*, additional output information is included compared to the *Output sheet*. Information about the (proposed) future form of collaboration is given, followed by the results of all structural checks. In case, the *Output sheet* shows an insufficient structural assessment, the *Detailed Output sheet* can be used in order to see which structural checks are insufficient. Moreover, the *Detailed Output sheet* includes ECI values of all life cycle stages included in the environmental calculations and costs of stages included in the economic calculations.

Process trees

This sheet includes process trees showing the calculation process of the structural- and environmental assessment, and formulas for calculating the economic impact whose are included in Appendix E. The user will be directed to these trees and formulas by the links in the sheet *Explanation Reusability Tool*.

In Figure 7.1, the requested input and delivered output of the tool are visualized.

The *Explanation Reusability Tool*, *Input sheet,* and *Output sheet* can be found on page 62 till page 69.

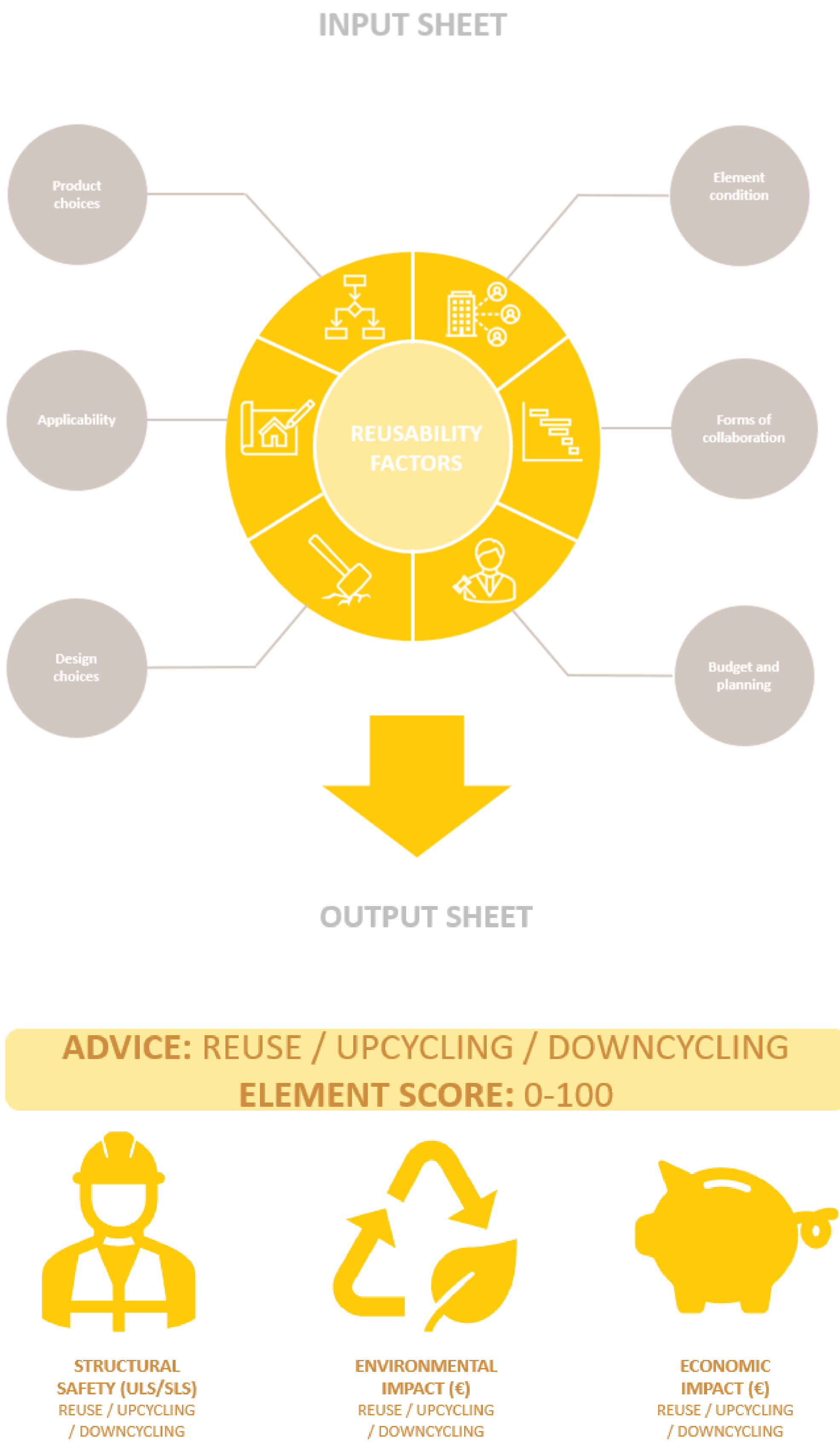


Figure 7.1 Input & Output of Reusability Tool (Own figure)

REUSABILITY TOOL

jul-22

Aim of the Reusability Tool

This Reusability Tool is developed to analyse the reuse potential of an in-situ structural concrete element of utility buildings constructed in the 70s/80s. The reuse potential is analysed based on three main aspects: Structural safety, Environmental impact, and Economic impact. The Reusability Tool compares those aspects for three circular strategies: Reuse, Upcycling, and Downcycling. Using the Reusability Tool results in an advised circular strategy and element score, in which is aimed for the most circular strategy.

The circular strategies can be understood as the following:

Circular strategies concrete elements

Circular economy ↕ Linear economy			
Circular economy	Extend lifespan	3 REUSE	Structural elements which are used again, in the same or in a comparable function, whether or not after repair and refurbishment
	Extend lifespan	2 UPCYCLING	Reclaiming of materials from discarded structural elements, and reusing those for the production of new structural elements having a higher value than the original elements.
Linear economy	Application of materials	1 DOWNCYCLING	Reclaiming of materials from discarded structural elements, and reusing those for the production of new products having a lower value than the original elements.

Users of the Reusability Tool

The Reusability Tool is developed for structural engineers. Prior structural knowledge is necessary in order to use the tool.

Scope of the Reusability Tool

The Reusability Tool can be used to assess the reuse potential of in-situ concrete structural elements in utility buildings. The Reusability Tool analyses the process from the preparation of deconstruction/demolition up to re-implementation of an element in a new future situation. The tool is developed to be used in a preliminary design stage. The Reusability Tool only globally assess the reuse potential of an element. It is advised to use this tool as a first indication.

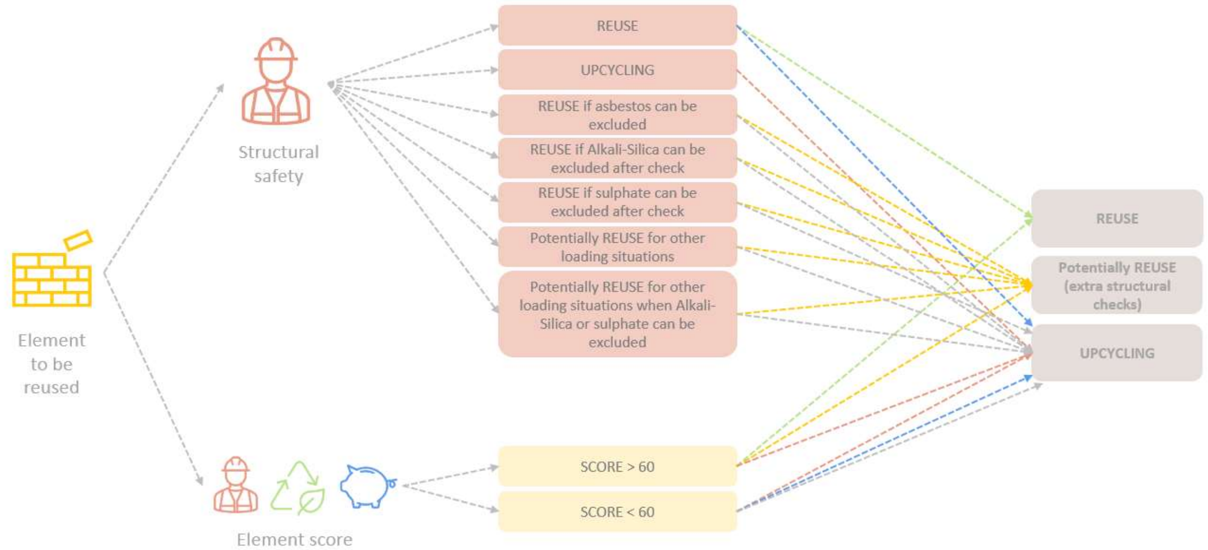
Set-up of the Reusability Tool

The reuse potential is assessed based on three main aspects: Structural safety, Environmental impact, Economic impact. The Reusability Tool outputs an advised circular strategy and a score of the analysed element.

REUSABILITY TOOL

ADVICE: REUSE / UPCYCLING / DOWNCYCLING
ELEMENT SCORE: 0-100

For the generation of the final advice, structural safety is leading. When an element is not structurally safe, it will never be advised to reuse the element. Moreover, an element should have a minimum score of 60 in order to result in the advice of reuse. Detailed information about the assessment system is included in Chapter 6 of the report: *Reuse of concrete structural elements in practice* . In the decision tree, it is shown how the final advice is generated.



User manual of the Reusability Tool

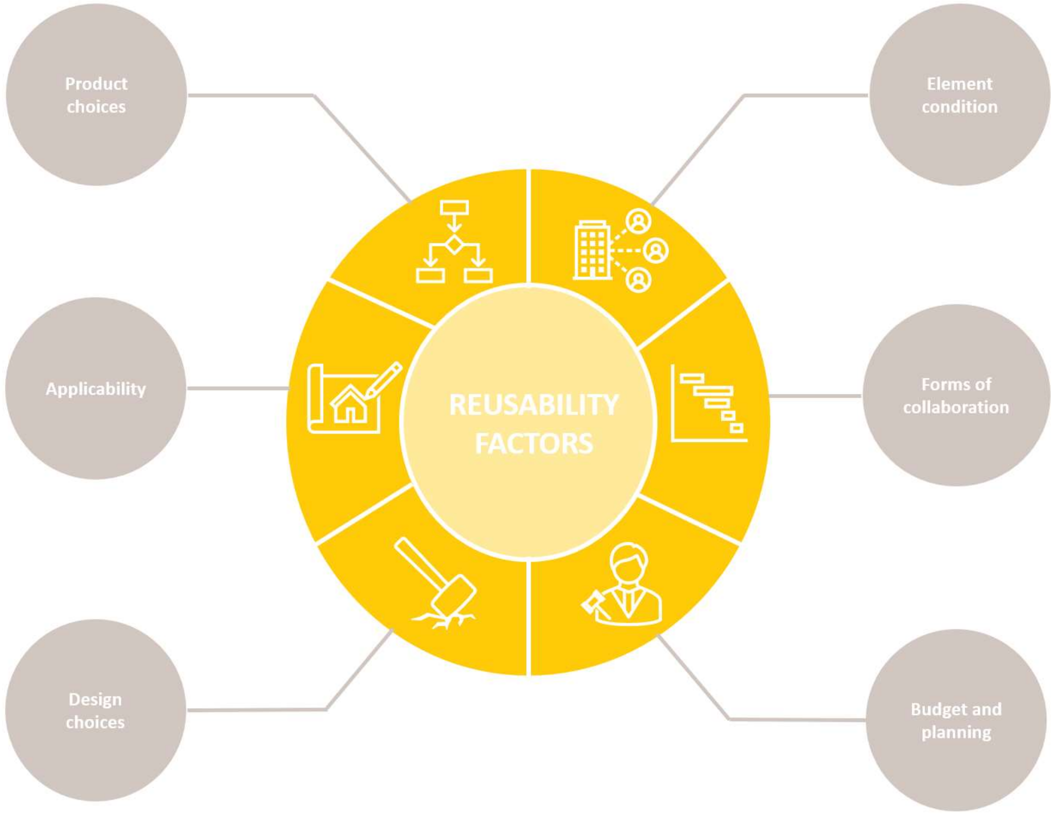
For the user of the Reusability Tool, four sheets are of importance:

>Input sheet
>Info Input sheet
>Output sheet
>Detailed Output sheet

Input sheet

This sheet should be filled in by the user of the Reusability Tool. All required information about the current situation and (potential) future situation of the structural element is asked. By clicking on the yellow input-boxes, some additional information appears about the input variable. Besides, some input variables show links to the sheet: *Info Input sheet* on which additional information is given about the input variable. Moreover, references towards the report *Reuse of concrete structural elements in practice* are shown in which detailed information is given.

The Input sheet asks information about the analysed element for six categories.



Info Input sheet

In this sheet, some additional information is given about input variables. Via links on the *Input sheet* , the user will be directly leaded to the aditional information.

Output sheet

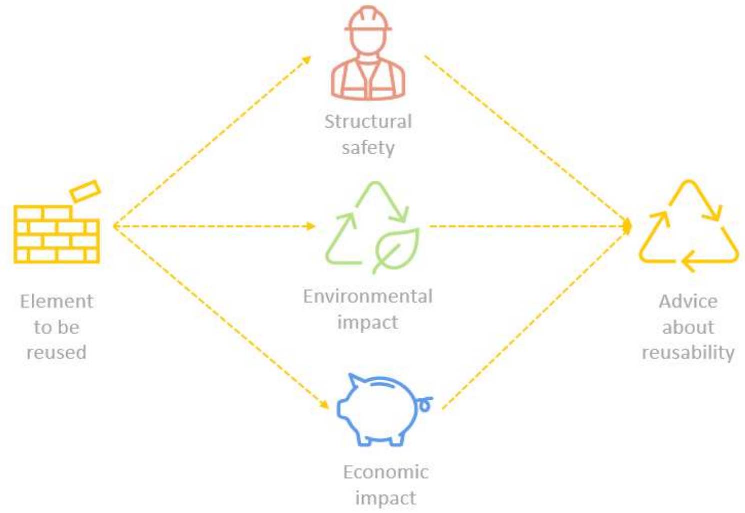
The Output sheet shows the generated final advice and element score of the analysed element. Moreover, details of the structural-, environmental-, and economic analyses are shown. Furthermore, it is shown how the final element score is generated.

Detailed Output sheet

The *Detailed Output sheet* shows additional, more detailed structural, environmental, and economic information about the generated final advice.

Assessment system of the Reusability Tool

A concrete structural element is assessed based on three main aspects: Structural safety, Environmental impact, and Economic impact.



Structural safety

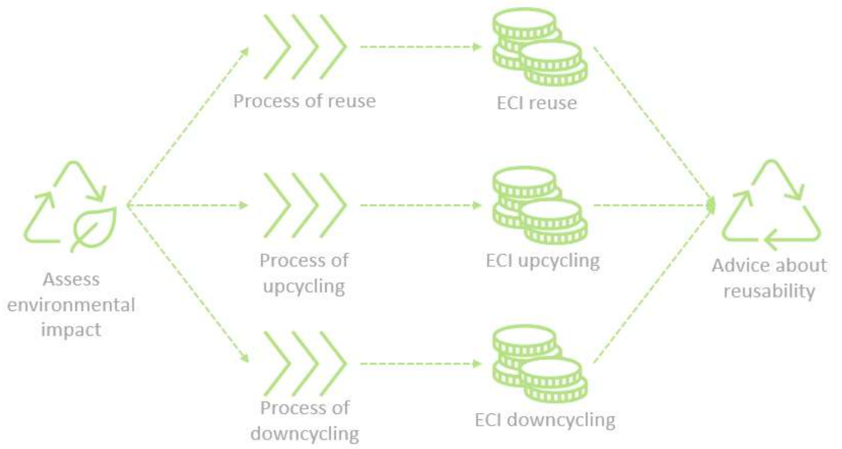
In order to indicate if an element is structurally safe, it will be assessed for condition and structural applicability. The condition is checked based on the potential presence of toxic substances and deterioration. The structural applicability is assessed based on reinforcement detailing and the loading capacity of the element.

The assessment of structural safety is visualized in the following process trees:

Assessment of condition	Condition
Assessment of reinforcement detailing	Reinforcement detailing
Assessment of loading capacity	Loading capacity

Environmental impact

The environmental impact is analysed for the three included circular strategies: reuse, upcycling, and downcycling. Based on a Life Cycle Assessment (LCA) for each circular strategy, Economic Cost Indicators (ECI) are generated whose can be compared.

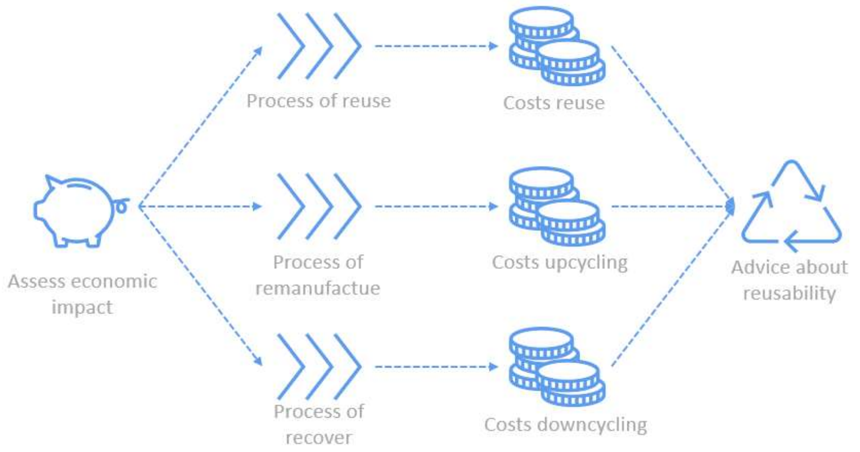


The calculation of environmental impact is visualized in the following process trees:

ECI REUSE	ECI REUSE
ECI UPCYCLING	ECI UPCYCLING
ECI DOWNCYCLING	ECI DOWNCYCLING

Economic impact

The economic impact is analysed for the three included circular strategies: reuse, upcycling, and downcycling. Based on Life Cycle Costing (LCC) for each circular strategy, the life cycle costs are generated whose can be compard.



The calculation of the economic impact is expressed in the following formulas:

Costs REUSE	Costs REUSE
Costs UPCYCLING	Costs UPCYCLING
Costs DOWNCYCLING	Costs DOWNCYCLING

INPUT SHEET REUSABILITY TOOL

This sheet should be filled in by the user of the Reusability Tool. All required information about the current situation and (potential) future situation of the structural element is asked. By clicking on the yellow input-boxes, some additional information appears about the input variable. Moreover, some input variables show links to the sheet: *Info Input sheet* on which additional information is given about the input variable. Furthermore, references towards the report *Reuse of concrete structural elements in practice* are shown in which detailed information is given.

The Input sheet asks information about the analysed element for six categories.

Product choices
Includes element information and properties of the analysed element. Therefore, information is required about the current situation (before deconstruction)

Applicability
In this section, the future applicability should be selected for which an analysis is prefered.

Design choices
Information is asked about the future loading situation, the current reinforcement detailing, and the current supporting situation in order to analyse the demountability of the element.

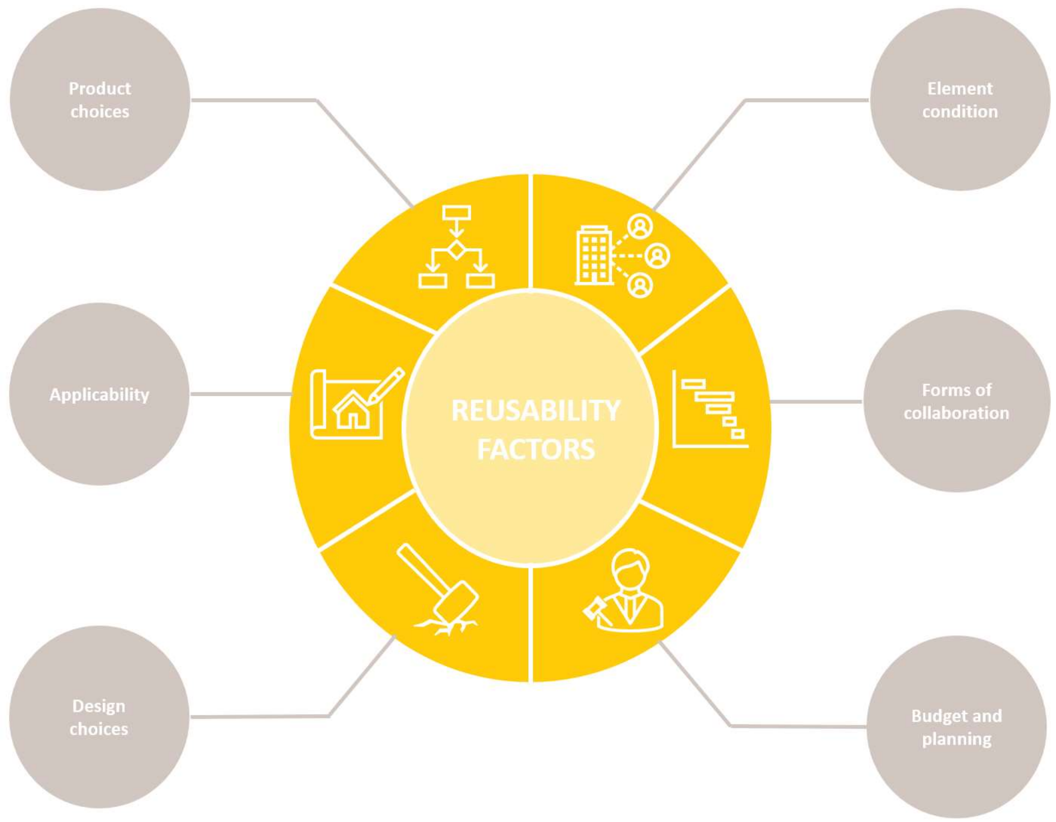
Element condition
The condition of the element should be visually analysed on site. Additional checks can be proposed.

Forms of collaboration
In a design project in which a structural element will be potentially reused, the form of collaboration is of major importance since this can influence collaboration of the reuse process. To keep the engineer aware of the collaboration process, the (potential future) form of collaboration is asked.

Budget and planning
Information about some logistics and the included transport movements are required.

User information Input sheet Reusability Tool
The input sheet includes two types of input boxes, indicated in two different colors:

- (dark yellow box) Information about the element in the current situation (before deconstruction).
- (light yellow box) Information about the (potential) future situation (new structure in which an element will be reused).



Product choices				**Additional information**	
Element information					**§ 5.1.1**
Element type	Choose option	Monolith_linearly_supported_floor		Additional Information	§ 5.1.1
Element dimensions	Length (ly)	6000	mm	Normal road transport possible	§ 3.4.3 + § 5.1.1
	Width (lx)	2500	mm	Normal road transport possible	§ 3.4.3 + § 5.1.1
	Height	220	mm	Normal road transport possible	§ 3.4.3 + § 5.1.1
Concrete density	Choose option	2400	kg/m3		§ 5.1.1
Technical lifespan		50	years		§ 5.1.1

Element properties				§ 5.1.2
Cement type	Choose option	CEM III/A		§ 5.1.2
Concrete strength class	Choose option	C20/25		§ 5.1.1 + Appendix B.1 + Appendix D.4
Environmental class	Choose option	XC1		§ 5.1.1 + Appendix B.5
Reinforcement strength	Choose option	FeB 500		§ 5.1.1 + Appendix B.1 + Appendix D.4

Applicability				§ 5.2
Element to be reused as	Choose option	One-way supported floor		§ 5.2

Design choices			**Additional information**	
Loading capacity reused element				§ 5.3.1
Permanent loading	Finishing	1,3	kN/m2	§ 5.3.1
	Walls	0,8	kN/m2	§ 5.3.1
Variable loading	Variable loading	4,0	kN/m2	§ 5.3.1
Consequence class	Choose option	CC2		§ 5.3.1
Function	Choose option	Housing		§ 5.3.1
Detailing of reinforcement				§ 5.3.2
Diameter of bars	Diamter of bars			
	Main reinforcement	12	mm	§ 5.3.2 + Appendix D.5
	Main reinforcement - meshes	8	mm	§ 5.3.2 + Appendix D.5
	Dividing reinforcement	10	mm	§ 5.3.2 + Appendix D.5
	Dividing reinforcement - meshes	8	mm	§ 5.3.2 + Appendix D.5
Number of bars	Number of bars			
	Main reinforcement	10		§ 5.3.2 + Appendix D.5
	Main reinforcement - meshes	18		§ 5.3.2 + Appendix D.5
	Dividing reinforcement	20		§ 5.3.2 + Appendix D.5
	Dividing reinforcement - meshes	40		§ 5.3.2 + Appendix D.5
Spacing of bars	Spacing of bars			
	Main reinforcement	300	mm	§ 5.3.2 + Appendix D.5
	Main reinforcement - meshes	150	mm	§ 5.3.2 + Appendix D.5
	Dividing reinforcement	300	mm	§ 5.3.2 + Appendix D.5
	Dividing reinforcement - meshes	150	mm	§ 5.3.2 + Appendix D.5
	Main reinforcement (maximum moments/loads)	40	mm	§ 5.3.2 + Appendix D.5
	Dividing reinforcement (maximum moments/loa	60	mm	§ 5.3.2 + Appendix D.5
Concrete cover	Thickness	30	mm	§ 5.3.2 + Appendix D.5
Fire resistance	Choose option	60	minutes	§ 5.3.2 + Appendix B.6
Demountability of element				§ 5.3.3
Number of connections (Supported at ... sides)	Choose option	Four		§ 5.3.3 + Appendix D.6
Type of connection	Choose option	4 line supports, all rigid	Additional information	§ 5.3.3 + Appendix D.6
Accessibility of connection	Choose option	Accessible with additional action causing repairable damage		§ 5.3.3
Edge inclusion	Choose option	Closed at multiple edges	Additional information	§ 5.3.3

Floor specific design choices				Additional information
Support system new situation				
Length between supports (*ln*)		5800	mm	Appendix G.1
Length of support (*t*)		400	mm	

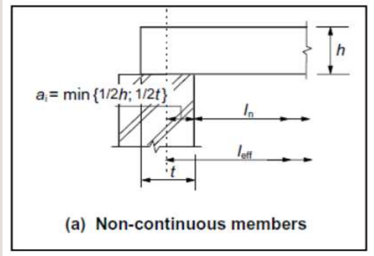


Figure 1: Floor specific design choices

Condition of the element				Additional information
Toxic substances				§ 5.4
Structural element in coastal area?	Choose option	No		Appendix D.1
Chlorides	No chance for chlorides penetration, no additional checks necessary			
Asbestos free (certificate)?	Choose option	Yes		§ 5.4
Deterioration				§ 5.4
Visibility of aging	Choose option	No defects as result of aging		§ 5.4 + Appendix D.1
Visibility of defect	Choose option	Slight damage/ defects of aesthetic nature		§ 5.4 + Appendix D.1
Visibility of (external) corrosion	Choose option	No visible corrosion		§ 5.4 + Appendix D.1
Cracks	Alkali-Silica reaction?	Chance for corrosion, check crackpattern		
	Suplhate attack?	No chance for sulphate attack		
	Check crackpattern of concrete element	None of the options		§ 5.4
Crackwidth	Maximal crackwidth	0,2	mm	§ 5.4

Forms of collaboration				§ 5.5
Form of collaboration future project	Choose option	Design - bid - build		§ 5.5

Budget and planning				§ 5.6
Site area	Site area large enough?	Yes		§ 5.6
Accessibility	Distance building site - element processor	50	km	§ 5.6 + § 3.4.3
	Distance building site - material processor	20	km	§ 5.6 + § 3.4.3
	Distance element processor - building site	30	km	§ 5.6 + § 3.4.3
	Distance material processor - producer	20	km	§ 5.6 + § 3.4.3
	Distance producer - building site	40	km	§ 5.6 + § 3.4.3
	Distance element processor - storage	10	km	§ 5.6 + § 3.4.3
	Distance storage - building site	40	km	§ 5.6 + § 3.4.3
Storage	Storage duration	8	months	§ 5.6 + § 3.4.3

Additional information				
Internal floor height	Height	2880	mm	

OUTPUT SHEET REUSABILITY TOOL

TU Delft heijmans

REUSABILITY TOOL

ADVICE: REUSE / UPCYCLING / DOWNCYCLING
ELEMENT SCORE: 0-100

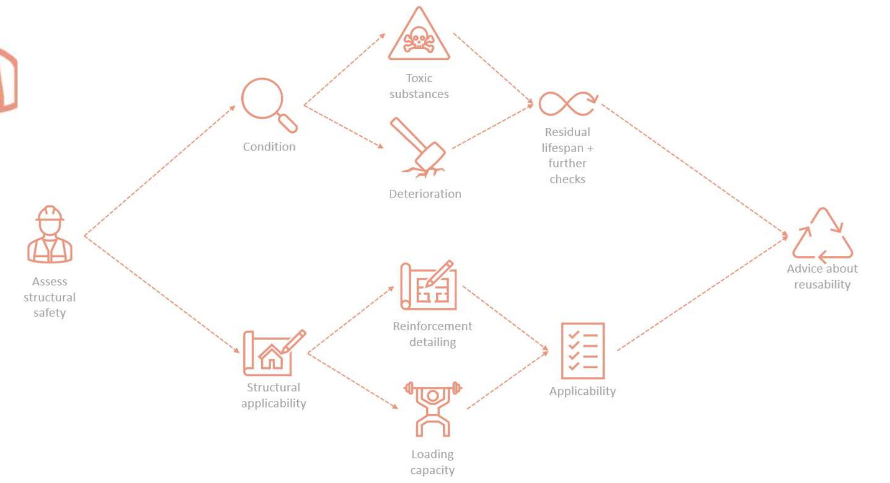
STRUCTURAL SAFETY | ENVIRONMENTAL IMPACT | ECONOMIC IMPACT

FINAL ADVICE	**REUSE**
ELEMENT SCORE	**80**
analyseD FOR APPLICABILITY	**One-way supported floor**

ADVICE STRUCTURAL SAFETY	REUSE
ADVICE ENVIRONMENTAL IMPACT	REUSE
ADVICE ECONOMIC IMPACT	UPCYCLING

FORM OF COLLABORATION	Design - bid - build

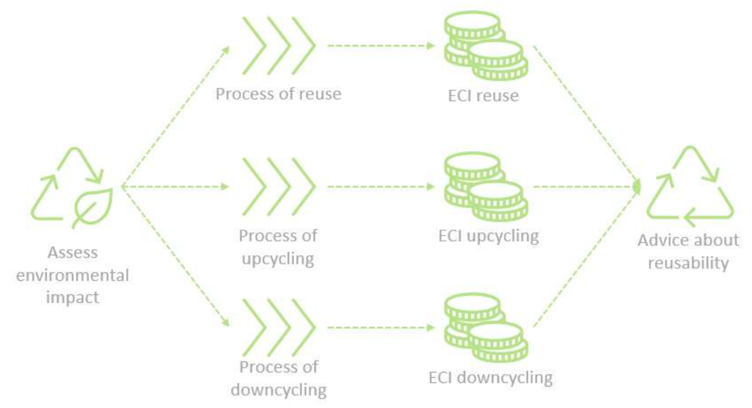
STRUCTURAL SAFETY



ADVICE CONDITION	REUSE
Condition	Excellent condition
Residual lifespan (years)	50
Crackwidth	Sufficient
Asbestos	Asbestos free
ADVICE APPLICABILITY	REUSE
Reinforcement detailling	Sufficient
Reinforcement ratio	Sufficient
ULS check	OK
SLS check	OK

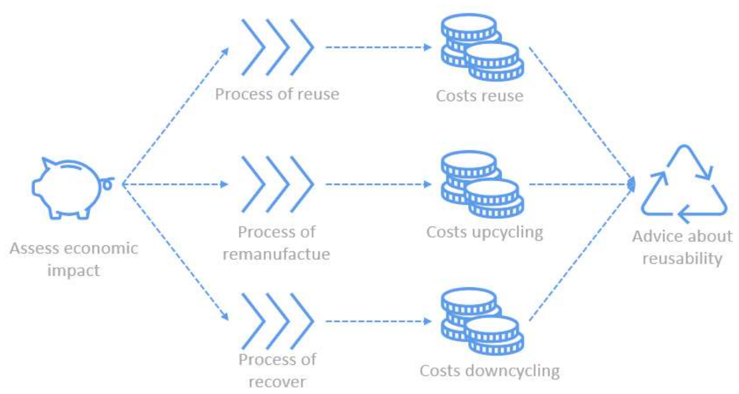
CALCULATION PROPERTIES	
Length [mm]	6000
Width [mm]	2500
Height [mm]	220
Effective length [mm]	6020
Own weight [kg]	7920
Own weight [kN/m2]	5,17968
Concrete strength class	C20/25
Suitable environmental classes	X0, XC1
Reinforcement strength	FeB 500
Maximum applicable design stress [N/mm2]	9,52
Maximum applicable shear force [kN]	25,85

ENVIRONMENTAL IMPACT



ADVICE IN-SITU		REUSE
ADVICE PREFAB		REUSE
ECI REUSE	€	73,80
ECI UPCYCLING		
In-situ	€	234,15
Prefab	€	185,89
ECI DOWNCYCLING		
In-situ	€	252,44
Prefab	€	204,18

ECONOMIC IMPACT



ADVICE IN-SITU		UPCYCLING
ADVICE PREFAB		UPCYCLING
COSTS REUSE	€	3.315,95
COSTS UPCYCLING		
In-situ	€	2.196,92
Prefab	€	2.090,56
COSTS DOWNCYCLING		
In-situ	€	2.487,14
Prefab	€	2.382,67

ELEMENT SCORE

ELEMENT SCORE IN-SITU	81,3
ELEMENT SCORE PREFAB	78,8
WEIGHT FACTOR ADDITIONAL COSTS	1
WEIGHT FACTOR ENVIRONMENTAL BENEFIT	2
WEIGHT FACTOR REISUDAL LIFESPAN	1
SCORE ADDITIONAL COSTS	
In-situ	85
Prefab	85
SCORE ENVIRONMENTAL BENEFIT	
In-situ	85
Prefab	80

SCORE RESIDUAL LIFESPAN	70
Additional costs REUSE	
In-situ (€)	828,82
In-situ (%)	33
Prefab (€)	933,28
Prefab (%)	39
Environmental benefit REUSE	
In-situ (€)	178,65
In-situ (%)	71
Prefab (€)	130,38
Prefab (%)	64
Residual lifespan REUSE (years)	50

7.2 Validation of the Reusability Tool

7.2.1 Validation by test case

Using a test case: the Merin Building, which is shortly introduced in Section 3.3, the reuse potential of several concrete structural elements is assessed using the Reusability Tool. Since it is possible to assess in-situ floor elements, beams, and columns, the reuse potential of these elements is assessed with test-elements from the Merin Building. For each element typology, two test elements are used. In Appendix F, all detailed information and drawings of the analysed elements are included. Of the Merin Building, either architectural and structural drawings were available since these documentary was stored in the city archive of Breda. Besides, structural calculations could be analysed. Since the year of construction is known, it is possible to check the properties and calculations with the Eurocode used for the design of the structure.

7.2.1.1 Assessment of columns

In this research the Reusability Tool is tested for two columns of the Merin Building which will be used as column in a future project. Based on the analysis of archive documentary and a site visit, the *Input sheet* of the Reusability Tool could be filled in. By comparing the input of the analysed columns, the reinforcement detailing is different even as the accessibility of the connection. Besides, one columns includes drop panels where the other column does not. Since the analysed columns are from the same building. The design choices, form of collaboration, budget and planning, and applicability are (assumed to be) the same.

The Reusability Tools delivered an advice about the reuse potential based on a structural-, environmental-, and economic analysis. In Table 7.1, the returned output on the *Output sheet* of the analysed elements is shown. Figure 7.2 shows the environmental benefit of reusing the columns compared to downcycling the columns in which a new in-situ or prefab column is produced. Moreover, the economic loads of reusing the columns is shown in Figure 7.3.

Table 7.1 Output analysed columns

Advice about element	Column 1	Column 2
	UPCYCLING	UPCYCLING
Score of element	**Column 1**	**Column 2**
Score of element	54	33
Structural safety	**Column 1**	**Column 2**
Condition	Excellent condition	Good condition
Residual lifespan	50 years	25 years
Crackwidth	Sufficient	Sufficient
Asbestos	Asbestos free	Asbestos free
Reinforcement detailing according to Eurocode	Not sufficient	Not sufficient
ULS check	OK	OK
Second order calculation required?	NO	NO
Environmental impact	**Column 1**	**Column 2**
Environmental benefit REUSE	In-situ: €15,98 (35%) Prefab: €19,48 (40%)	In-situ: €-4,06 (-14,6%) Prefab: €17,25 (35,1%)
Economic impact	**Column 1**	**Column 2**
Economic burden REUSE	In-situ: €909,44 (126%) Prefab: €841,61 (109%)	In-situ: €1.019,87 (161%) Prefab: €873,61 (112%)

From Table 7.1, it becomes clear both columns are advised to upcycle. The main deciding factor in this advice is that the structural safety is not sufficient. In both situations the reinforcement detailing is not sufficient according to the current code. When looking at the details in the *Detailed output sheet*, it follows that in both situations the spacing of the stirrups is not in accordance with the maximum allowed spacing according to NEN-EN 1992-1-1.

Besides, Table 7.1 shows the environmental benefits and economic burdens of reusing a column. Especially the situation of reusing the second column compared to a new produced in-situ one is quite remarkable. Reusing leads to a costs increase of 161% compared to the circular strategy of downcycling and an environmental benefit of -4,06%. The final scores of the analysed columns are therefore quite low which also had leaded to the advice of remanufacturing, even if the elements were reusable based on structural safety.

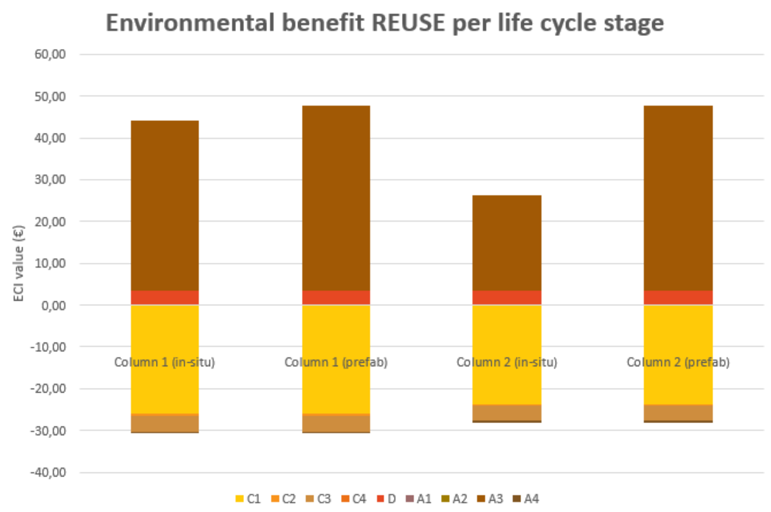


Figure 7.2 Environmental benefit - Reusing columns

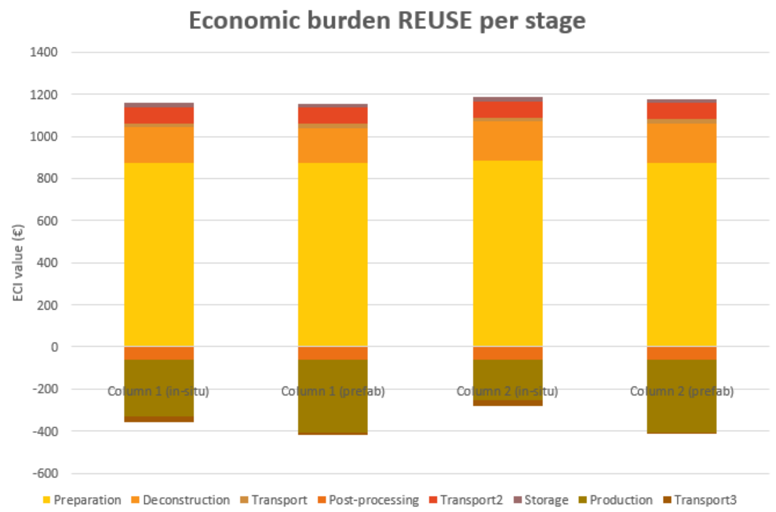


Figure 7.3 Economic load - Reusing columns

7.2.1.2 Assessment of beams

Next to columns, two reuse potential of two beams of the Merin Building are assessed. Based on the analysis of archive documentary and a site visit, the *Input sheet* of the Reusability Tool could be filled in. By comparing the input of the analysed beams, the dimensions of the beams are different even as the reinforcement detailing. By analysing the demountability of both beams, one beam is connected to three elements where the other beam is only connected to two elements.

The Reusability Tools delivered an advice about the reuse potential based on a structural-, environmental-, and economic analysis. In Table 7.2, the returned output on the *Output sheet* of the analysed elements is shown. Figure 7.4 shows the environmental benefit of reusing the beams compared to downcycling the beams in which a new in-situ or prefab beam is produced. Moreover, the economic loads of reusing the beams is shown in Figure 7.5.

Table 7.2 Output analysed beams

Advice about element	Beam 1	Beam 2
	UPCYCLING	In-situ: UPCYCLING Prefab: REUSE
Score of element	**Beam 1**	**Beam 2**
Score of element	71	51
Structural safety	**Beam 1**	**Beam 2**
Condition	Excellent condition	Excellent condition
Residual lifespan	50 years	25 years
Crackwidth	Sufficient	Sufficient
Asbestos	Asbestos free	Asbestos free
Reinforcement detailing according to Eurocode	Not sufficient	Sufficient
Reinforcement ratio according to Eurocode	Sufficient	Sufficient
ULS check	OK	OK
SLS check	OK	OK
Environmental impact	**Beam 1**	**Beam 2**
Environmental benefit REUSE	In-situ: €44,39 (51%) Prefab: €39,75 (48%)	In-situ: €5,17 (10%) Prefab: €94,85 (67%)
Economic impact	**Beam 1**	**Beam 2**
Additional costs REUSE	In-situ: €674,52 (55%) Prefab: €414,56 (28%)	In-situ: €789,78 (68%) Prefab: €571,98 (41%)

The analysis of the reuse potential of two beams of the Merin Building leads to different final advices. The first beam is advised to upcycling since the reinforcement detailing is not sufficient. However, the score of the element is 71 showing the element had great potential if it was structurally safe and allowed to reuse. In case of the second beam it is advised to upcycling the beam for the production of in-situ concrete or reuse the element instead of the production of a prefab element. Reusing the beam compared to downcycling the beam and producing a new prefab element leads to an environmental benefit of 67% and 41% additional costs.

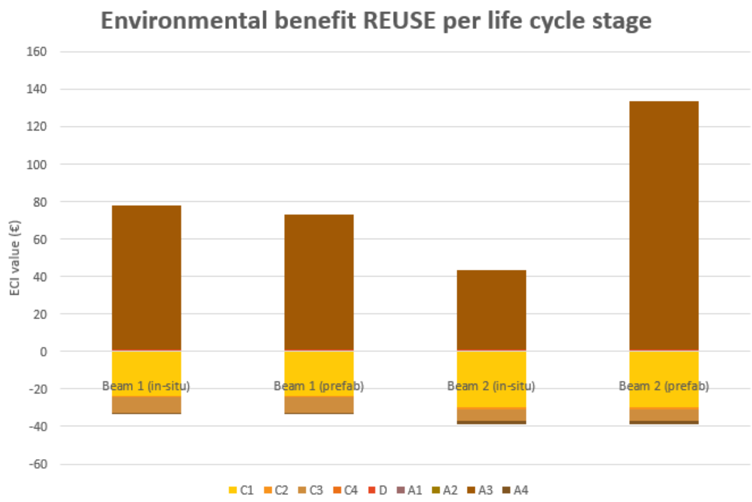


Figure 7.4 Environmental benefit - Reusing beams

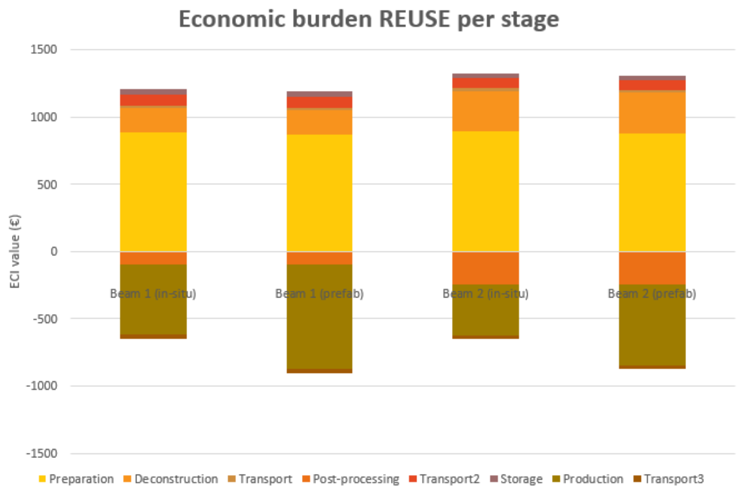


Figure 7.5 Economic load - Reusing beams

7.2.1.3 Assessment of floor elements

In the Merin Building, monolith flat slab floor elements are used. By analysing archive documentary and a site visit, the *Input sheet* of the tool could be filled in. Detailed information of the floor elements is included in Appendix F.3.

Most floor parts consist of reinforcement meshes of Ø8-150 with dimensions 5950 mm x 2500 mm. To keep this meshes intact, it is advised to saw floor elements with dimensions of at least 6000 x 2500 mm.

By comparing the input of the analysed floor elements, the dimensions are the same, but the location of the floor element in the building differs, and therefore the number of connections and crossing elements are different. Moreover, the reinforcement detailing of the floor elements differ due to the different location of the floor in the building.

The Reusability Tools delivered an advice about the reuse potential based on a structural-, environmental-, and economic analysis. In Table 7.3, the returned output from the *Output sheet* of the analysed elements is shown. Figure 7.6 shows the environmental benefit of reusing the floor elements compared to downcycling the floor elements in which a new in-situ or prefab floor element is produced. Moreover, the economic burdens of reusing the floor elements is shown in Figure 7.7.

Table 7.3 Output analysed floor elements

Final advice about element	Floor 1	Floor 2
	REUSE	Potentially REUSE (extra structural checks)
Score of element	**Floor 1**	**Floor 2**
Score of element	82	80
Structural safety	**Floor 1**	**Floor 2**
Condition	Excellent condition	Excellent condition
Residual lifespan	50 years	50 years
Crackwidth	Sufficient	Sufficient
Asbestos	Asbestos free	Asbestos free
Reinforcement detailing according to Eurocode	Sufficient	Sufficient
Reinforcement ratio according to Eurocode	Sufficient	Sufficient
ULS check	OK	NOT OK
SLS check	OK	OK
Environmental impact	**Floor 1**	**Floor 2**
Environmental benefit REUSE	In-situ: €246,94 (83%) Prefab: €153,21 (75%)	In-situ: €169,01 (77%) Prefab: €153,57 (75%)
Economic impact	**Floor 1**	**Floor 2**
Additional costs REUSE	In-situ: €870,58 (34%) Prefab: €1.019,82 (43%)	In-situ: €1.058,37 (45%) Prefab: €1.019,82 (43%)

The analysis of the reuse potential of the two floor elements leads to the advice of reuse. Even if the second floor element does not fulfil the ULS requirements due to the future loading, the floor still have potential for other load cases. Therefore the final advice of this floor element is that it is potentially reusable and additional structural checks are required. The first floor element scored 82 points since around 40% additional costs leads to an environmental benefit of around 80%, having a residual service life of 50 years.

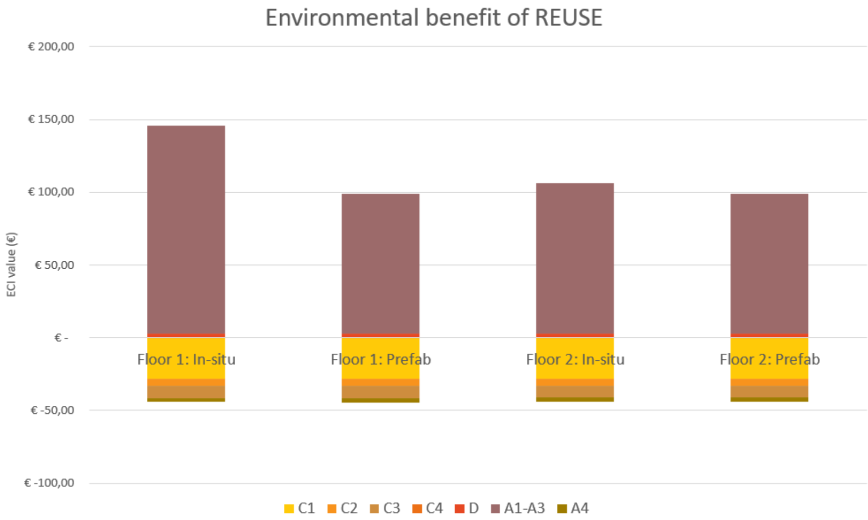


Figure 7.6 Environmental benefit - Reusing floor elements

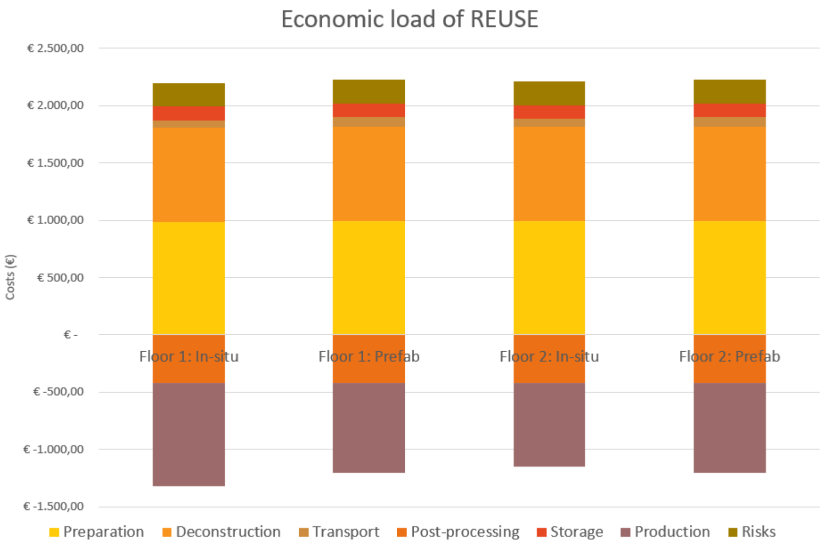


Figure 7.7 Economic load - Reusing floor elements

7.2.1.4 Conclusion of tests of Reusability Tool

From testing the Reusability Tool with in-situ elements from the Merin Building, some conclusions could be drawn.

First, the tests showed that due to insufficient reinforcement detailing, the analysed columns of the Merin Building are not reusable. Moreover, reusing columns leading to costs more than twice the costs of downcycling columns and producing new ones. Besides, the environmental benefit is quite low and therefore does not outweigh the additional costs.

The beams show more potential compared to columns. However, also in case of the beams the reinforcement detailing is an important factor. In terms of environmental benefit and economic burden, it can be concluded that around 50% of additional costs can lead to an environmental benefit of 50%. Furthermore, the analysed floor elements results in the most potential. Both floor elements seems to be reusable. Although, the second floor element does not fulfil the ULS requirements and is therefore advised to reuse in another loading situation. For the floor elements around 40% of additional costs can lead to 80% of environmental benefit and is therefore the most promising element to reuse.

7.2.2 Validation by experts

Next to testing the Reusability Tool by the case of the Merin Building, the tool is validated by experts. In feedback sessions, feedback is gathered from structural engineers, whose are the future users of the Reusability Tool.

First, earlier versions of the Reusability Tool are discussed with- and tested by structural engineers. In Table 7.4, suggested improvements are shown. Besides, it is explained how these suggestions are implemented in the final version of the Reusability Tool.

Table 7.4 Validation preliminary version of Reusability Tool

Category	Suggested improvements based on earlier versions of Reusability Tool	Improvements implemented in final version of Reusability Tool
Explanation Reusability Tool	Without reading the Report, the aim of the Reusability Tool is not clear. Adding an Explanation Sheet can help.	The final version of the Reusability Tool includes an Explanation sheet including information about the aim, the users, and the scope of the tool. Moreover, a user manual of the Reusability Tool is included.
	Explain the scoring system of the element. In this way, the end-user can interpretate the results.	In the *Output sheet* a box is added including information about the scoring system. Moreover it is explained that the end-user can adjust the weight factors according to importance.
	In Report, process trees and formulas are included explaining the assessments of the Reusability Tool. Include these process trees and formulas in the Reusability Tool as well.	In the Explanation sheet the assessment system of the Reusability Tool is addressed for structural safety, environmental impact, and economic impact. Links to process trees and formulas are included in order to get insight in the calculations behind the assessments.
	The *Input sheet* requires information of six categories whose are visualized in a figure. Explanation of the categories could help understand the *Input sheet*.	The *Input sheet* includes a short description about the sheet. Moreover, each category of input information is shortly explained.
	Suggested improvements based on earlier versions of Reusability Tool	**Improvements implemented in final version of Reusability Tool**
Additional information	Adding a column in the *Input sheet* including references to chapters in the Report or Eurocodes could help, in case additional information is required.	An additional column is added in which references are stated towards chapters and appendices of the report. It should be noted that the end-user should understand the *Input sheet* without the stated additional information.
	In the *Input sheet*, lots of transport distances are asked, but information about all these distances is lacking. Add some additional information.	Additional notes are added to the input boxes in which the transport distances are explained.
	In case of the analysis of floor elements, two types of floor elements can be chosen. Explain the differences between these elements.	In the *Input sheet* a note is included shortly explaining the support system and support direction of the two included two floor types.

	In case of monolith linear supported floor elements, multiple options are given for the connection type which is difficult to imagine. Additional information is required.	For monolith linear supported floor elements, all the support options are visualized in drawings included in an additional sheet: *Info input sheet*. Using the link in the *Input sheet*, the user will be directly leaded to the drawings of the support options.
	It is difficult to imagine what is meant with edge inclusion. Additional information is required.	The different options for edge inclusion are visualized in drawings which are included in the additional sheet: *Info input sheet*. Using the link in the *Input sheet*, the user will be directly leaded to the drawings of options for edge inclusion.
	Suggested improvements based on earlier versions of Reusability Tool	**Improvements implemented in final version of Reusability Tool**
Structure	Due to the usage of colours, it is not directly clear where the input boxes of the *Input sheet* can be find. Use colours in a way to focus on the right boxes.	The colouring of the Input- and Output sheets has been adapted. For the Input/Output boxes, colours are used, where descriptions and additional information is shown in grey. In this way the end-user will be directly leaded to the Input/Output boxes.
	For the end-user, it is useful to export and/or print the *Output sheet*. Create sheets which are printable.	The Input- and Output sheets are transformed into printable sheets.
	In the *Output sheet*, the end-user needs to search for the final advice, since it is stated on the bottom of the sheet. Start with the final advice, and subsequently show more detail.	In the *Output sheet*, first the final advice and element score are presented. The *Output sheet* continues with the most important output of the structural-, environmental-, and economic assessment.
	To have the overview, it is better to structure al information vertically instead of horizontally. Use different font sizes and colouring to put the focus on the interesting parts.	The information is vertically structured. The is made use of different fonts and colours to focus on the most important parts of the sheets.
	It is not directly clear which required information about the current situation (element before deconstruction) and which information is about the future situation (situation in which the element is reused). Distinguish input information about the current- and future situation.	In order to make clear which required information is about the current structure, and which information is about the future structure, two different colours are used for the input boxes. The *Input sheet* includes a legend in which the two types of information are explained.

The final version of the Reusability Tool is discussed with- and tested by structural engineers. In Table 7.5, the most useful features and suggestions for further improvement are shown.

Table 7.5 Usefull features and suggestions for improvements Reusability Tool

Useful features
A major benefit of the Reusability Tool compared to other tools assessing the reuse potential of (structural) elements is that the output can directly be checked when changing one or multiple input variables. In lots of other tools the user is automatically leaded through questions after which the output is generated. In that case it is not possible to quickly adapt the input.
The short notes supporting the input boxes are helpful. It gives enough information to the user in order to fill in the required input.
Since sometimes it is not possible to fill in all the required input information, the given default options (indicating a lower limit) a useful.
Some users are more interested in the calculations behind the assessment than others. Therefore, it is good that the *Explanation sheet* includes links towards process trees and formulas, but not directly show them.
Suggestions for further improvement
When clicking on the input boxes, some additional information appears in notes. This is very useful. However, the notes are still present when scrolling through the document. It is better to only show the notes when moving above the boxes.
By including multiple options for further application (for example the option to analyse a beam as future column), the applicability of the Reusability Tool can be increased.
It could be interesting to also include assessments of the reuse potential for structural elements of other materials, like timber and steel.

8 Factors influencing output of the Reusability Tool

In this chapter it is analysed how specific input choices influencing the output of the Reusability Tool. Since from testing it turns out floor elements are the most promising elements to reuse, the influence of several aspects is analysed for floor elements. The environmental benefits and economic loads of reuse compared to downcycling and new in-situ production are analysed and discussed. In Section 8.1, the environmental- and economic impact are compared for different floor lengths and widths. Moreover, the impact of the concrete class is analysed in Section 8.2. Reinforcement detailing can influence the impact of the floor element. The amount of reinforcement influences the environmental impact and economic costs and is therefore discussed in Section 8.3. Finally, the number of connections, and connection types can influence the impact. Therefore, the demountability of a floor element is analysed in Section 8.4. A conclusion of the analysis followed in Section 8.5.

8.1 Dimensions

The behaviour of the environmental benefits and economic loads is analysed for different element lengths and widths. It should be noted that when the element length increases in practice, also the amount of reinforcement will increase. The graphs in Figure 8.1 and Figure 8.2 only show the influence of the increased volume of the element, and therefore the amount of concrete.

In Figure 8.1, it is shown that the economic load equals around 170% for an element length of 1000 mm, where the load turns into benefit when the element length equals 15000 mm. The environmental benefit is stable over the length of the element. Since the Reusability Tool compares the environmental impact of reuse with the environmental impact of downcycling, and new production of an element having the same dimensions as the analysed element, the environmental benefit is stable. Also in Figure 8.2 it is shown that the environmental benefit is stable. The maximum transportable width of an element is 3000 mm, therefore the impact of the width is analysed till the maximum transportable width.

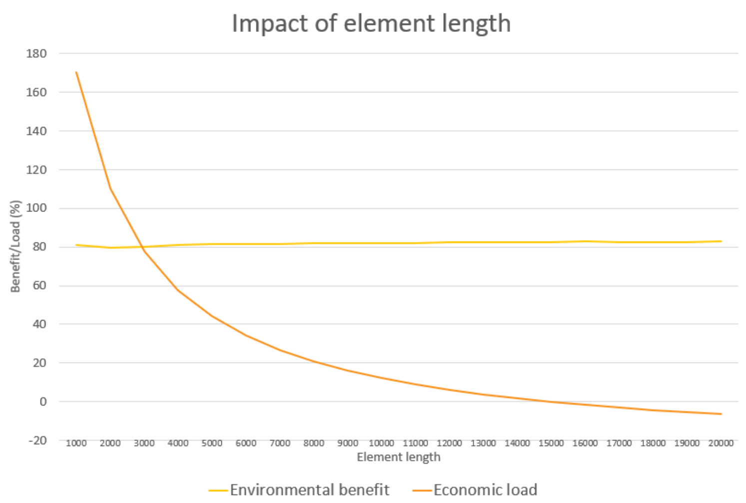


Figure 8.1 Influence element length on Environmental benefit & Economic load

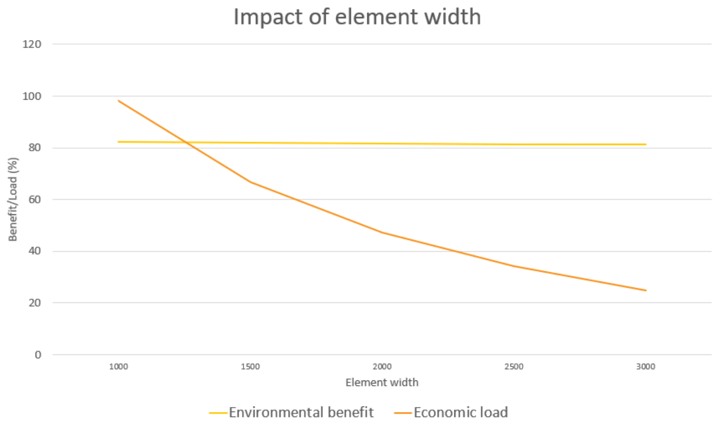


Figure 8.2 Influence element width on Environmental benefit & Economic load

8.2 Concrete strength class

The concrete strength class influences the environment. An increased strength class results in increased impact. In Appendix D.3, the used data of the Nationale Milieudatabase is included which show the different equivalent for the concrete strength classes C20/25 and C30/37. Moreover, the costs per m^3 concrete increase for increasing concrete strength class. In Appendix E.3 the materials costs are shown. In Figure 8.3, the impact of the concrete strength class of the analysed element is shown. As explained, the impact of reuse is compared to the impact of downcycling and new production with the same concrete strength class as the analysed element. In the figure is shown that using C20/25 concrete results in an environmental benefit of 81% and an economic load of 34%. C30/37 concrete results in an environmental benefit of 83% and an economic load of 32%.

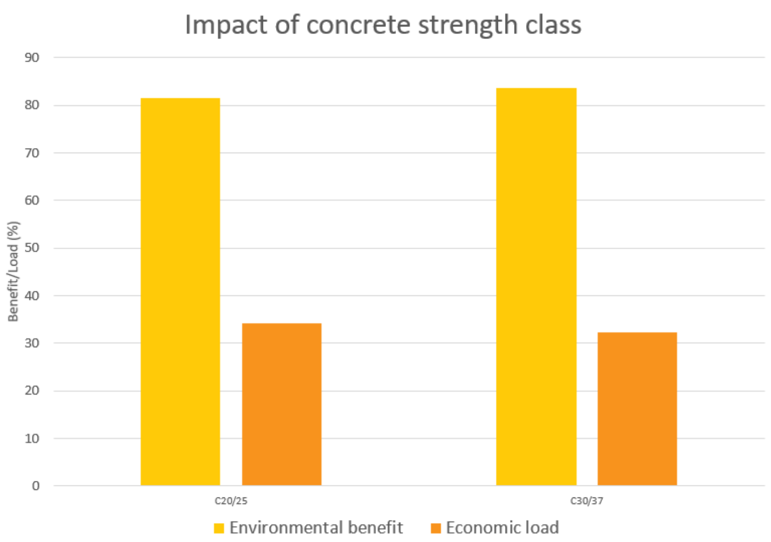


Figure 8.3 Influence concrete strength class on Environmental benefit & Economic load

8.3 Reinforcement detailing

In terms of reinforcement detailing, multiple aspects are analysed. The more reinforcement included in the analysed element, the more impact can be prevented, resulting in the most environmental benefit and the least economic load. This is shown in Figure 8.4, Figure 8.5, and Figure 8.6 which are shortly explained.

First, the impact of four types of reinforcement meshes are analysed. These four types have dimensions 5950 x 2350 (Holterman Staal, 2021) and therefore fit within the dimensions of the elements used as default. Mesh B-754 results in the greatest environmental benefit and lowest economic load since this mesh includes the most reinforcement.

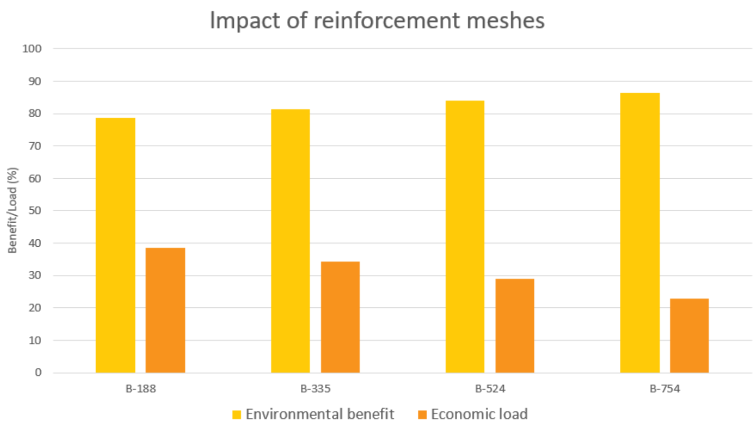


Figure 8.4 Influence reinforcement mesh on Environmental benefit & Economic load

Besides, the impact of the diameter and the spacing of the main reinforcement is analysed. An increasing diameter leads to a greater amount of reinforcement and therefore to a greater prevented environmental impact and reduced economic load, in case of reusing. On the other hand, an increased spacing of reinforcement bars leads to a decreased amount of bars and therefore less reinforcement.

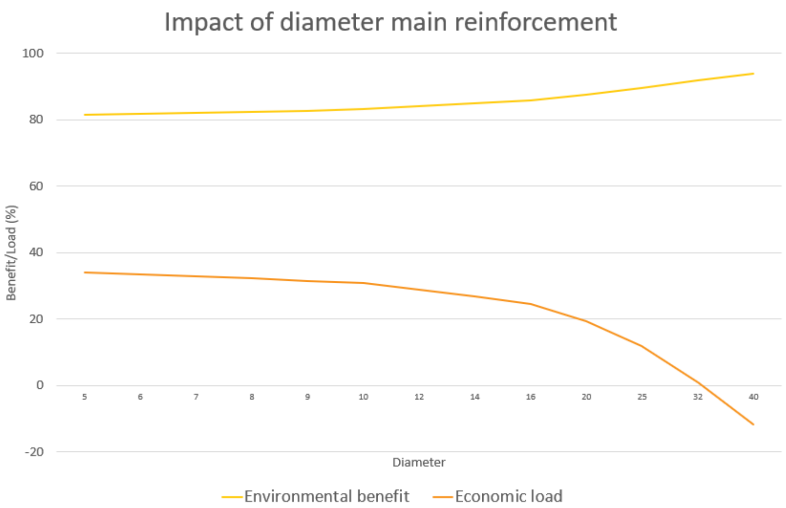


Figure 8.5 Influence reinforcement diameter on Environmental benefit & Economic load

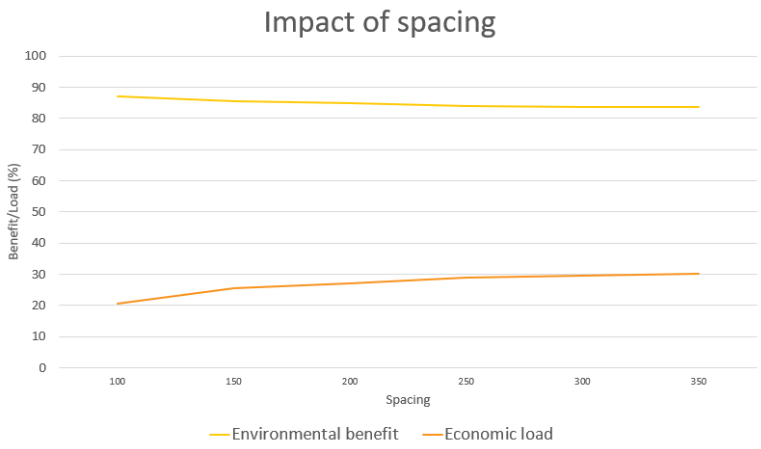


Figure 8.6 Influence reinforcement spacing on Environmental benefit & Economic load

8.4 Demountability

As explained in Section 5.3.3, the demountability of an element depends on different factors. The influence of the number of connections and support type on the environmental- and economic impact is analysed. Since the Reusability Tool can be used for analysing the reuse potential of monolith flat slab floors and monolith linear supported floors, for both floor types the influence of the number of connections and support type is analysed.

8.4.1 Monolith flat slab floors

In case of monolith flat slab floors, floor elements are supported by point supports. In the Reusability Tool, the impact is calculated per point support and multiplied with the amount of supports resulting in a linear graph as shown in Figure 8.7. For monolith flat slab floors, the influence of the connection type on the environmental benefit and economic load is almost negligible, as shown in Figure 8.8.

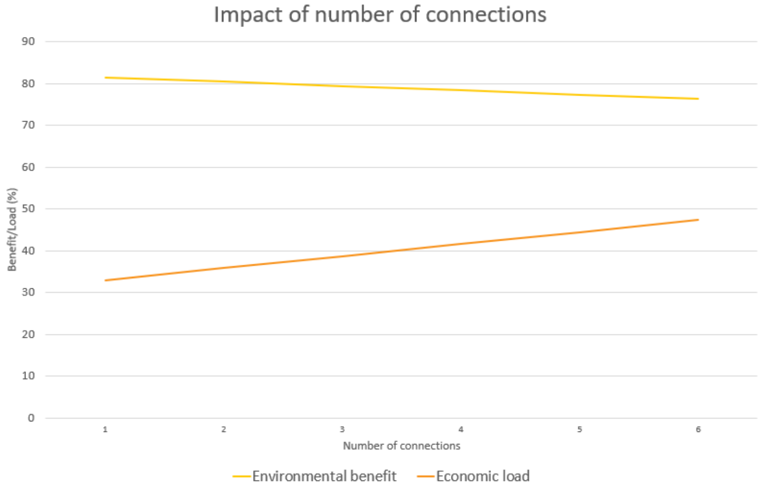


Figure 8.7 Influence number of connections on Environmental benefit & Economic load

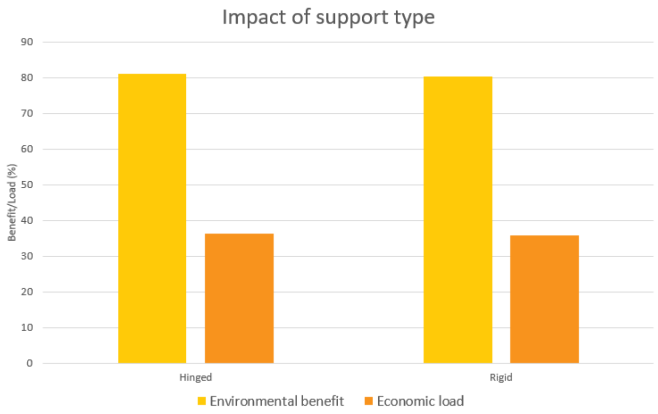


Figure 8.8 Influence support type on Environmental benefit & Economic load

8.4.2 Monolith linear supported floors

The impact of the demountability of linear supported floor is analysed differently compared to flat slab floors. Where for flat slab floors the impact is analysed per connected point, the impact of linear supported floors is analysed per m support of a supported side.

In Figure 8.9, it is shown that the environmental benefit is less compared to flat slab floors. This is caused by the fact that the sawing time of line supports is greater than the sawing time of point supports. The changes in environmental benefit and economic load are less compared to flat slab floors. Also in case of linearly supported floors, the impact of the support type is small, as shown in Figure 8.10. However, the differences between hinged and rigid supports are greater for linear supported floors than for flat slab floors.

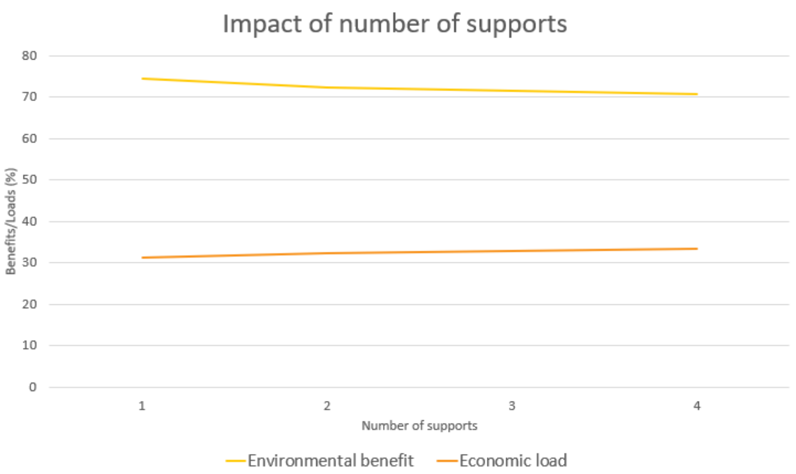


Figure 8.9 Influence number of line supports on Environmental benefit & Economic burden

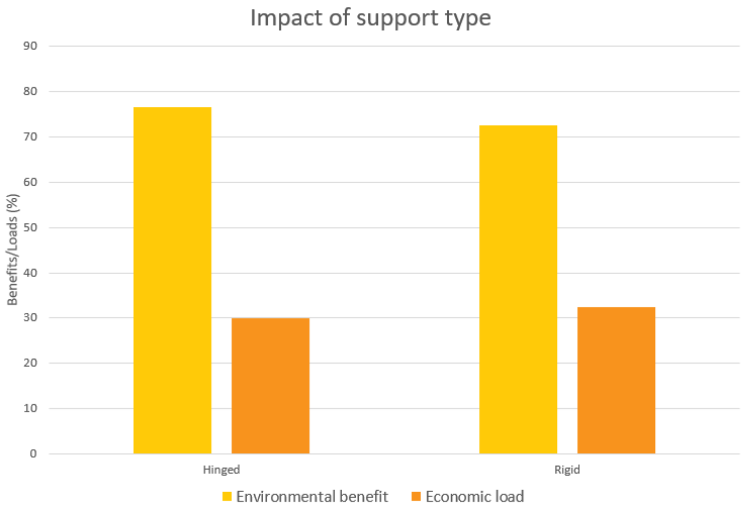


Figure 8.10 Influence support type on Environmental benefit & Economic load

8.5 Conclusion of influencing factors

From the analyses of impact of some aspects, it can be concluded that increased element dimensions do not influence the environmental benefit of an element in case of reusing. This can be explained by the fact an element is compared to downcycling and new production of an element with the same dimensions. However, the economic load will decrease when element dimensions increase. In case of concrete strength: the greater the concrete strength class of the to be reused element, the greater is the environmental benefit and the less is the economic load.

When a floor element can be reused with a great amount of reinforcement (if it is also required in the future situation), this results in greater environmental benefits and less economic loads. Where the number of supports affects the impact of the element, the support type does not affect the impact that much.

PART IV | DISCUSSION, CONCLUSION, RECOMMENDATIONS

9 Discussion

This chapter discusses the limitations and promising aspects of the Reusability Tool and the relevance of the research. In Section 9.1, the circular strategies are discussed which are included in the Reusability Tool. Besides, Section 9.2 includes a discussion of the assessment system used in the Reusability Tool. Since the tool includes some assumptions, the research methods and assumptions included in the Reusability Tool are discussed in Section 9.3. Furthermore, the validity of the tool is discussed in Section 9.4.

9.1 Circular strategies

The Reusability Tool analyses the environmental- and economic impact of three circular strategies and compares those with each other leading to an advised circular strategy: reuse, upcycling, or downcycling. The analysed existing tools assessing circularity often only focusses on reusing. However, it should be noted that when a project is planned to be demolished, it will result in an environmental- and economic impact anyway. In case of concrete demolition projects, the most common used strategy is downcycling. An advice about a circular strategy based on structural safety, environmental impact, and economic impact, should be based on the benefits and loads of a circular strategy compared to the common used strategy. Therefore, the Reusability Tool makes a decision based on the differences in impact between the included circular strategies and distinguishes itself from the other analysed tools.

9.2 Assessment system

The final advice of the Reusability Tool is based on the structural safety of an element and the generated element score. The element score is based on the residual lifespan of the structural element, the environmental benefit of reuse compared to downcycling, and the economic load of reuse compared to downcycling. The scores related to those aspects are based on the interpretation of the researcher. Since the scores and weights of the scores strongly influence the final advice of the Reusability Tool the assessment system requires more research in order to verify the tool.

Besides, the Reusability Tool addresses the two most common used forms of collaboration in the Netherlands. The output of the Reusability Tool includes some information about the consequences of the form of collaboration on the process of reuse. The form of collaboration which is used as an input does not influence the final advice of the Reusability Tool. Since reusing structural elements is quite new, there are no protocols about the process of collaboration. Therefore, research to the working process of involved parties resulting in a ‘reuse-protocol’ can considerably strengthen the process of reuse. This could be implemented in the Reusability Tool and influencing the advice.

9.3 Research method and assumptions in Reusability Tool

The Reusability Tool focusses on three important aspects: structural safety, environmental impact, and economic impact. The research methods and assumptions which have been made are shortly discussed for those three aspects.

9.3.1 Structural safety

In order to assess if a structural element can be reused, the structural safety of an element is analysed by focusing on the current condition of the element and the future applicability. For the assessment of the condition, the chance for the presence of toxic substances and deteriorations are analysed based on product choices and the location of the structure. Based on NEN 2767, the residual lifespan is calculated. The structural applicability is assessed based on reinforcement detailing and the loading capacity of the analysed element. This assessment is based on detailing rules stated in NEN-EN 1992-1-1. The loading capacity of the analysed element is globally assessed. Therefore, it is important for the end-user of the Reusability Tool to realize that if the tool generates the advice of reuse, and therefore indicates the element is structurally safe, always additional detailed structural calculations are required in order to guarantee structural safety. For these detailed structural calculation, additional information is required about the future (proposed) application of the element.

9.3.2 Environmental impact

For each of the three included circular strategies, the environmental impact is calculated by a Life Cycle Analysis (LCA). The Reusability Tool assesses the environmental impact from the end-of-life stage of the element in the current structure, till re-implementation in the future structure. In this research the impact of re-implementation of a reused element is assumed to be equal to the implementation of a new produced structural element. Therefore, the current life cycle includes the stages C (end-of-life stage), and D (benefits and loads). The future life cycle includes the stages A1-A3 (Product stage), and A4 (Transport).

In order to calculate the impact of the deconstruction/demolition stage, some assumptions have been made. Based on interviews with demolition contractors, rates for concrete cutting, crushing, sawing, and drilling are estimated depending on element- and connection type. Since reusing concrete structural elements is still in its infancy, no data is available about these aspects. Besides, the demountability of a structural element is assessed and expressed in (additional) environmental impact, based on assumptions. In order to improve the environmental impact calculations these assumptions should be verified.

For the environmental impact calculations, environmental data of the Nationale Milieudatabase (NMD) is used. Therefore, the Reusability Tool strongly depends on the availability and publicity of environmental data. Some examples of limitations of the Reusability Tool due to the lack of available data:

- It is only possible to analyse the environmental impact of reusing in-situ concrete elements having strength class C20/25 or C30/37. The NMD does not include data of C25/30 concrete;
- The NMD often only includes combined environmental data of life cycle stages A1:A3, which makes it impossible to analyse the environmental effects of the stages A1, A2, A3 separately.
- All used data is of category 3, which is brand-unrelated data and property of Stichting NMD. This data is not tested according to the NMD protocol, resulting in some uncertainties. However, due to the fact this data is brand-unrelated, it is the only data which is public.
- From January 2021, 19 impact categories should be used for the calculation of the environmental impact. Before January 2021, only 11 impact categories were included. Nowadays, the NMD only provides data containing 11 impact categories and therefore it is only possible to calculate the environmental impact based on 11 impact categories. However, when data including 19 impact categories is available, it can be easily implemented in the Reusability Tool to improve the model.

9.3.3 Economic impact

Next to the environmental impact, the economic impact is calculated for the three included circular strategies according to the principle of Life Cycle Costing (LCC). The costs included in the Reusability Tool are based on literature in which current material- and labour costs are described. From interviews with demolition contractors it turned out they could not give (detailed) information about costs of a demolition or deconstruction project. Moreover, from 2021 material prices have been raised drastically caused by the Covid pandemic. The prices further increased in 2022 due to the war in Ukraine. This results in lots of uncertainty about material prices and economic impact. In the Reusability Tool, current costs are included together with a risk percentage. Since the costs are still increasing and the future is difficult to predict the future situation. Therefore, it is advised to be aware of changes of costs when using the Reusability Tool. Since the economic values used in the Reusability Tool are based on estimations, the feasibility of the economic values should be further analysed.

9.4 Validity of Reusability Tool

The Reusability Tool has been validated based on a test-case and feedback sessions with structural engineers in which especially the usability is discussed. From this validation it followed that the Reusability Tool is a useful tool which can be easily used in practice. On the other hand, there are some limitations in the validation of the Reusability Tool. First of all, only one test case is used for the validation of the Reusability Tool. However, multiple structural elements of this case are analysed. The validity of the Reusability Tool can be improved by including more test cases. Moreover, the used test case is a utility building which is not demolished/deconstructed yet. Therefore, it was not possible to compare the output of the Reusability Tool with reality.

Besides, the Reusability Tool is validated by feedback sessions with three structural engineers of different organizations. Including more structural engineers in the validation process, the usability and applicability of the Reusability Tool could be further improved.

10 Conclusion

In this chapter the conclusion is given. In order to answer the main research question, first the sub-research questions are answered (Section 10.1). In Section 10.2 an answer is given to the main question of this research.

As stated in Section 2.1, the aim of this research is:

'…to develop a tool which stimulates structural engineers to reuse concrete structural elements by giving insight in structural safety, environmental impact, and economic impact of reusing concrete structural elements.'

This research aim has been translated in the following main research question:

'How to assess the reuse potential of concrete structural elements in an early design stage focussing on structural safety, environmental impact, and economic impact?'

In order to answer this main research question, first the sub-research questions are answered.

10.1 Sub-research questions

In this section, the sub-research questions are answered, stated in Section 2.2.

1. *What processes influence circular strategies in terms of structural safety, environmental impact, and economic impact?*

This research distinguishes three circular strategies: reuse, upcycling, and downcycling. Reuse can be understood as structural elements which are used again, in the same or in a comparable function, whether or not after repair and refurbishment. One can speak of upcycling when materials from discarded structural elements are reclaimed and reused for the production of new structural elements, having a higher value than the original elements. In case of downcycling materials from discarded structural elements are reclaimed and reused for the production of new products, having a lower value than the original elements.

The processes influencing the circular strategies in terms of structural safety, environmental impact, and economic can be divided into five main steps: Preparation, Deconstruction/demolition, Transport, Post-processing, and New production, as shown in Figure 10.1. Deconstruction can be understood as the dismantling of a structure in structural elements of which the residual value is guaranteed.

Figure 10.1 Process of circular strategies

The five main steps are divided into sub-processes which differ per circular strategy. Each process step results in environmental- and economic impact.

In case of down- and upcycling, the preparation phase consists of inventory, planning, and stripping of the building. In case of reusage, first documentary of the current structure should be analysed. Moreover, the condition of the to be reused element should be inspected. Before deconstruction can start, the structure should be temporarily supported. Besides, there are differences in the process of deconstruction for reuse and demolition for up- and downcycling. The traditional demolition method consists of concrete cutting with a concrete cutter, resulting into large debris which can be crushed into rubble by a concrete crusher. When the material will be upcycled, the rubble can be prepared on site before transporting to a material processor. In case of deconstruction for reuse, first the concrete should be cut around the element which will be reused. Thereafter, the element can be sawn by a concrete saw with diamond blade. Consequently, the element should be hoisted by a crane and should be cleaned after which it can be transported to the element processor. In this research, five steps are distinguished for the post-processing of a structural element in order to prepare it for reuse: reshape, removal of fixings, filling of holes, applying additional concrete cover, and drilling holes for reconnection. Where the process of downcycling results in complete new element production, in the process of upcycling materials from the discarded structural element are used for the new element production. In case of reuse of the element, the complete new production of a concrete structural element is prevented. All those processes influence the circular strategies in terms of structural safety, environmental impact, and economic impact.

The detailed answer to this question is given in Chapter 3 and Chapter 4.

2. *How to assess the structural safety, environmental impact, and economic impact for concrete structural elements?*

In order to assess the reuse potential of in-situ concrete structural elements, the Reusability Tool is developed focusing on structural safety, environmental impact, and economic impact. Since none of the existing tools assess the reuse potential based on those three aspects, the Reusability Tool is a comprehensive tool.

In the Reusability Tool, the structural safety of an element can be assessed for condition and applicability. In case of condition, the element will be checked for the potential presence of toxic substances and (visible) deterioration. Based on these checks, a residual lifespan is calculated. Besides, the applicability of the element is analysed by checking if the reinforcement detailing of the element is sufficient according to the current detailing rules. The Reusability Tool calculates the design stress of the analysed element and checks the element for the ultimate limit state (ULS) and serviceability limit state (SLS). Using the LCA method, the environmental impact of each process step indicated in Figure 10.1 can be expressed in an Environmental Cost Indicator (ECI) value. Besides, the Life Cycle Costing (LCC) method is used to express the economic impact of the process in costs. For each circular strategy, this leads to an ECI value and total costs which can be compared.

In order to assess the structural safety, environmental impact, and economic impact, the Reusability Tool requires input information. This input information is divided into six categories: Product choices, Applicability, Design choices, Element condition, Forms of collaboration, and Budget and planning. The input information of the Reusability Tool results in an advised circular strategy: reuse, upcycling, or downcycling. This advice is generated based on the structural analysis and an element score. The element score varies between 0 and 100 and is calculated based on three aspects: the residual lifespan of a structural element, the environmental impact of reusing compared to the environmental impact of downcycling, and the economic impact of reusing compared to the economic impact of downcycling. Since a building which is planned to be demolished, will be demolished or deconstructed anyway, this will in any case leads to environmental- and economic impact. Therefore, the Reusability Tool analyses the benefits and loads of reusing compared to downcycling, which is currently the most often applied strategy.

When the element score results in a score above 60 and the structural assessment turns out to be sufficient, the Reusability Tool advises to reuse the analysed structural element. In case the element score is below 60 and/or the structural assessment is insufficient it is advised to upcycle the structural element.

The detailed answer to this question is given in Chapter 5 and Chapter 6.

3. *How can the Reusability Tool be used to stimulate the reuse of concrete structural elements in practice?*

The Reusability Tool is developed in order to stimulate the reuse of in-situ concrete structural elements in practice. The tool can be used for analysing the potential of structural elements of a utility building which is planned to be demolished. In this way the Reusability Tool can prevent valuable elements to get lost. The Reusability Tool is developed in MS Excel and can be used in an early design stage to analyse if a structural element can be reused in a new situation. It includes several sheets whose are important for the end-user of the tool. On the *Input sheet*, the required input information, divided into six categories, should be filled in. Each input variable is shortly explained. In case the user required additional information, references and links are included. Based on the information on the *Input sheet*, the Reusability Tool generates an final advice and element score which is expressed on the *Output sheet*. Besides, this sheet includes important structural properties, and the environmental- and economic impact of the three analysed circular strategies are presented. In case the user prefers more detailed output-information, the *Detailed Output sheet* can be used on which the output of all included structural checks, detailed environmental information, and all included costs are presented.

The Reusability Tool is validated by a test-case and feedback sessions with structural engineers. Therefore, the usability of the tool is optimized. Concrete beams, columns, and floor elements are analysed in a case study resulting in element scores and advised circular strategies. For the test case it turned out that in-situ concrete floor elements have the most reuse potential.

The detailed answer to this question is given in Chapter 7 and Chapter 8.

10.2 Main research question

'How to assess the reuse potential of concrete structural elements in an early design stage focussing on structural safety, environmental impact, and economic impact?'

This research presents the Reusability Tool which is developed for structural engineers to assess the reuse potential of in-situ concrete elements from utility buildings of the 70s/80s, in an early design stage. From analyses of existing tools it followed that there is need for a tool assessing the reuse potential based on structural safety, environmental impact, and economic impact. This need has been translated into the Reusability Tool which assesses the reuse potential and results in an element score an advised circular strategy: reuse, upcycling, or downcycling.

From interviews with demolition contractors it turned out that re- and downcycling of materials is common practice but reusing concrete structural elements is quite new. The mentioned reasons for not reusing concrete structural elements are too high costs and too little environmental benefit. However, they see possibilities for dismantling in-situ elements.

In order to fulfil the goal stated in the Paris Agreement to keep the global warming below 2, and close to 1.5 degrees Celsius, action is needed. Since the construction sector is liable for almost 40% of the energy utilization which contributes to global warming, this sector can contribute a lot to the reduce global warming. Since particularly utility buildings constructed in the 70s/80s are demolished last year and around 80% of the building materials consists of in-situ concrete, harvesting in-situ concrete structural elements from demolition projects and reuse them in new construction projects can largely contribute to the goal of the Paris Agreement. Therefore, the Reusability Tool stimulates structural engineers to prevent valuable concrete structural elements to get lost due to demolishment, by assessing the reuse potential of those elements. The Reusability Tool can be used to prove this value, or otherwise…

‘Everything has a value until proven otherwise’.

11. Recommendations

Since the Reusability Tool is the only developed tool assessing the reuse potential of in-situ concrete structural elements based on structural safety, environmental impact, and economic impact, there is room for improvements. In this chapter recommendations for improvements of the Reusability Tool are explained.

From the scope of this research explained in Section 2.3, and the limitations discussed in Chapter 9, some recommendations followed for improvement of the Reusability Tool

- *Analyse other building types and building materials*
  The Reusability Tool is developed for the assessment of the reuse potential of in-situ concrete elements of utility buildings. From the analysis of the state of the art it follows that most utility buildings constructed in the 70s/80s are demolished containing in-situ concrete. Moreover, around 80% of the building material consists of concrete. However, the Reusability Tool could be broader applied when it is made possible to also analyse the reuse potential of other building types and other building materials. Therefore, it is recommended to analyse the reusability factors for other building types and the assessment system for structural elements consisting of other materials. This analysis can be used to expand the applicability of the Reusability Tool.

- *Investigate other deconstruction techniques*
  In this research, the deconstruction technique of sawing with diamond blade is used for the assessment of the reuse potential. However, other (new) deconstruction techniques could be promising to investigate since these techniques could affect the reuse potential of structural elements in a different, and possibly more promising, way. For example, the influence of deconstruction by water jetting could be further investigated.

- *Analyse collaboration and liabilities between involved parties*
  The two most common used forms of collaboration are shortly discussed in this research, but not explicitly affecting the final advice about the reuse potential of the structural element in the Reusability Tool. In contracts there is still nothing stated about responsibilities and liabilities in case of reusing structural elements. It is recommended to investigate the processes of collaboration and create protocols (or an additional contract form) for collaboration in case of reusage.

- *Analyse future applicability options*
  In the Reusability Tool it is possible to analyse the reuse potential of beams used as beams in a future project, and columns used as columns. However, it could be interesting to analyse the reuse potential of beams used as columns, and columns used as beams in future projects. Moreover, in the Reusability Tool the reuse potential of monolith linearly supported floors and monolith flat slab floors can be analysed for the future application as one-way hinged supported slab. For further research, other support options should be analysed even as the possibilities for reusing floor elements as wall and vice versa.

- *Validate with other test-cases*
  The Reusability Tool is tested for several columns, beams, and floor elements from a test-case. However, testing the tool by more cases can improve the validity of the Reusability Tool. In case there is a project in which in-situ concrete elements are reused in practice, it can be checked if the actual impact is in accordance with the output of the Reusability Tool.

- *Further analyse the scoring system of the Reusability Tool*
  The score of an analysed element is calculated based on the economic load of reuse compared to downcycling, the environmental benefit of reuse compared to downcycling, and the residual lifespan. The final score is calculated based on a weighted average in which weighting factors are used for the three aspects. The end-user can change this weighting factors and therefore the importance of the aspects in the calculation of the total score. Further research to scoring systems can improve the scoring system of elements and therefore improve the validity of the Reusability Tool.

Bibliography

Archipunt. (2021, February). Het 10R model voor circulariteit. Hoe? Retrieved on February 2022, from https://www.archipunt.nl/het-10r-model-voor-circulariteit-hoe/

Arnoldussen, J., Errami, S., Semenov, R., Roemers, G., Blok, M., Kamps, M., & Faes, K. (2020, January). Materiaalstromen, milieu-impact en energieverbruik in de woning- en utiliteitsbouw. Economisch Instituut voor de Bouw | Metabolic | SGS Search. https://circulairebouweconomie.nl/wp-content/uploads/2020/02/Rapport-Materiaalstromen-in-de-woning-en-utiliteitsbouw-klein.pdf

Arnoldussen, J., Endhoven, T., Kok, J., Groot, P., Blok., M., & Kamps, M. (2022, April). Materiaalstromen in de bouw en infra. Instituut voor de Bouw | Metabolic | SGS Search. https://www.eib.nl/pdf/EIB%20Metabolic%20materiaalstromen%20bouw.pdf

Banga, J. (2012). Bouwbesluit Constructieve Veiligheid. Nederlands Normalisatie-instituut. https://connect.nen.nl

Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *260*, 121046. https://doi.org/10.1016/j.jclepro.2020.121046

Betonstation. (2021). *Betonstation Nijmegen*. Retrieved on May 2022, from https://betonstation-nijmegen.nl/prijzen/

Betonvereniging. (2020). Basiskennis Beton Algemeen. https://www.betonvereniging.nl/media/16636/dictaat-basiskennis-beton-algemeen-bba-2020.pdf

Betonvereniging. (2022, March). Studio Beton 17–02-2022 | Hergebruik betonnen viaductliggers [Video]. YouTube. https://www.youtube.com/watch?v=NPSgjOopJoA

Blok, M. (2020, February). Assessing all materials consumed for building in the Netherlands. Metabolic. Retrieved on December 2021, from https://www.metabolic.nl/projects/assessing-materials-consumed-for-building-in-the-netherlands/

BNA & NLingenieurs. (2013, July). Rechtsverhouding opdrachtgever – architect, ingenieur en adviseur DNR 2011.

BNR. (2022, April). *Heijmans kampt met grotere onzekerheid door oorlog in Oekraïne*. bnr.nl. Retrieved on May 2022, from https://www.bnr.nl/nieuws/financieel/10474610/heijmans-kampt-met-grotere-onzekerheid-door-oorlog-in-oekraine

Boot-Dijkhuis, C., Eggink-Eilander, S., Ruytenbeek, D., & Van den Berg, M. (2014). Bouwbesluit Brandveiligheid. Nederlands Normalisatie-instituut. https://connect.nen.nl

Boot, W., Terwel, K., & Strang, H. (2015). Legal matters related to structural damage in the Netherlands. Proceedings of the Institution of Civil Engineers - Forensic Engineering, 168(3), 117–126. https://doi.org/10.1680/feng.14.00017

Bouwdelen. (2021). *Bouwdelen.nl*. Retrieved on May 2022, from https://www.bouwdelen.nl/

Bouwend Nederland. (2021). *Materiaalkostenstijgingen Update 2021 & verwachting 2022*. https://www.bouwendnederland.nl/media/13595/onderzoek-prijsstijgingen.pdf

Bouwens, N. M. A. (2022). Reclaim and reuse potential of load-bearing components of se school buildings: Research into the criteria to define the reclaim and reuse potential of load-bearing components of SE school buildings in the Netherlands at an early stage. Delft University of Technology. http://resolver.tudelft.nl/uuid:28fa630d-2212-48df-9fc4-8a162ab24620

Bouwkundig bureau Vuyk. (2013). *Voorbeeld Elementenbegroting DO*. http://www.bbvuyk.nl/wp-content/uploads/2013/11/Elementenbegroting-voorbeeld.pdf

BouwTotaal. (2019, December). *Wat kost storten van geïsoleerde betonvloer?* Retrieved on May 2022, from https://www.bouwtotaal.nl/2019/12/wat-kost-storten-van-geisoleerde-betonvloer/

Bradley, G. (2004). Reuse and recycling of building materials. *Conference on Use of the Recycled Materials in Building and Structures, 31*(1), 316-321.

Brand, S. (2006). Urban Design Reader (1ste editie) [E-book]. Routledge.

Braam, C. R. (2010). Ontwerpen in Gewapend Beton (Second edition). Aeneas, uitgeverij van vakinformatie bv.

Braam, C. R., & Lagendijk, P. (2011). Constructieleer Gewapend Beton (7de editie). Aeneas, uitgeverij van vakinformatie bv.

Braam, C.R., Ensink, L.T.H., Meester, J.J., De Vos, W.A.P., Wijte, S.N.M. (2017). Bezwijken Parkeergarage Eindhoven Airport (Adviesbureau ir. J.G. Hageman B.V. report 9663-1-0). Adviesbureau ir. J.G. Hageman B.V.. https://d21buns5ku92am.cloudfront.net

Breunese, A. J., & Maljaars, J. (2015). Fire Safety Design (Version November 2015). Delft, The Netherlands: Delft University of Technology.

BUKO Transport. (2021). *Wagenpark*. Retrieved on 2022, from https://transport.buko.nl/wagenpark/

Circulairsloopproject. (2022). veiligslopen.nl. Retrieved on March 2022, from https://www.veiligslopen.nl/nl/circulairsloopproject/

Centraal Bureau voor de Statistiek. (2022, May). *Inflatie 9,6 procent in april*. Retrieved on May 2022, from https://www.cbs.nl/nl-nl/nieuws/2022/19/inflatie-9-6-procent-in-april

Clahsen, A. (2021, July). Hoe oud beton nieuw leven krijgt. *FD.nl*. Retrieved on 2022, from https://fd.nl/futures/1390219/circulair-beton-tse2caHYnHhf

Cobouw. (2021, 21 July). *2020 opnieuw meer ongevallen in de bouw; 19 doden*. Retrieved on November 25, 2021 from https://www.cobouw.nl/bouwkwaliteit/nieuws/2021/07/2020-opnieuw-meer-ongevallen-in-de-bouw-19-doden-101297766.

De Lepper, R. (2022, April). *Kosten constructeur | Wat kost een constructieberekening?* ConstructieShop B.V. Retrieved on May 2022, from https://constructieshop.nl/kosten-constructeur-verbouwing.

De Vries, P. A., Fennis, S. A. A. M., & Pasterkamp, S. (2013). Veiligheid. Bouwen met staal.

De Vries, P. A., Fennis, S. A. A. M., & Pasterkamp, S. (2014). Reader Veiligheid (2de editie). TU Delft Faculteit CITG.

Durmisevic, E. (2006). *Transformable Building Structures - Design for disassembly as a way to introduce sustainable engineering to building design & construction*. Delft University of Technology. http://resolver.tudelft.nl/uuid:9d2406e5-0cce-4788-8ee0-c19cbf38ea9a

Dutch Safety Board. (2018). Bouwen aan constructieve veiligheid (DSB-report). DSB.

Ellen MacArthur Foundation. (2019). *New to circular economy overview*. Retrieved on November 2021, from https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Endicott, B., Fiato, A., Huang, T., Totev, P., & Foster, S. (2005, May). *Research on building deconstruction.* University of California, Berkeley Department of Civil and Environmental Engineering Engineering and Project Management. https://community-wealth.org/sites/clone.community-wealth.org/files/downloads/paper-endicott-et-al.pdf

European Commission. (2021). Life cycle costing - GPP - Environment - European Commission. Ec.Europa.Eu. Retrieved on June 2022, from https://ec.europa.eu/environment/gpp/lcc.htm

Glias, A. (2013, December). *The "Donor Skelet": Designing with reused structural concrete elements*. Delft University of Technology. http://resolver.tudelft.nl/uuid:20002372–1d7d-4824-8217-bdff4b60ecb5

Grondverzet. (2021, January). Grondverzet.nu. Retrieved on May 2022, from https://grondverzet.nu/mobiele-kraan-huren-met-machinist-prijs/

Hastings, N. A. J. (2015). *Physical Asset Management* (Second Edition). Springer. https://doi.org/10.1007/978-3-319-14777-2

Heijl, B. (2021, 3 september). Circulair hergebruikt betonnen casco van warenhuis Amstelveen. Tektoniek. Retrieved on February 2022, from https://www.tektoniek.nl/circulair/projecten/circulair-hergebruikt-betonnen-casco-warenhuis-amstelveen

Heijmans. (2020, December). *Fietspad van circulair beton*. Retrieved on March 2022, from https://www.heijmans.nl/nl/nieuws/fietspad-van-circulair-beton/

Heijmans. (2021, September). *primeur-met-hoogwaardig-circulair-beton-aan-contactweg-amsterdam*. Retrieved on March 2022, from https://www.heijmans.nl/nl/nieuws/primeur-met-hoogwaardig-circulair-beton-aan-contactweg-amsterdam/

Heijmans Utiliteit B.V. (2021). Het Donorskelet | Kansen & Risico's [Poster].

Hendriks, C. F., Vogtländer, J. G., & Janssen, G. M. T. (2006). The eco-costs/value ratio: A tool to determine the long-term strategy for delinking economy and environmental ecology. International Journal of Ecodynamics, 1(2), 136–148. https://doi.org/10.2495/ECO-V1-N2-136-148

Holterman Staal. (2021). *Wapeningsnetten standaard*. Holterman Staal. Retrieved on June 2022, from https://www.holtermanstaal.nl/3/producten/wapeningsnetten-standaard

Hombergen, P. I. M. (2021a, 8 September). CIE5981 Design & Construct | Forms of Collaboration in Civil Engineering [Lecture]. Brightspace. https://brightspace.tudelft.nl

Hombergen, P. I. M. (2021b, 21 September). CIE5981 Design & Construct | Forms of Collaboration in Civil Engineering [Lecture]. Brightspace. https://brightspace.tudelft.nl

Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., & Zhang, X. (2018). Carbon emission of global construction sector. *Renewable and Sustainable Energy Reviews*, *81*, 1906–1916. https://doi.org/10.1016/j.rser.2017.06.001

Icibaci, L. (2019). *Re-use of Building Products in the Netherlands he development of a metabolism based assessment approach*. Delft University of Technology. https://doi.org/10.7480/abe.2019.2

IsoBouw. (2021). *Circulariteitsladder | IsoBouw: innovatie in isolatie*. isobouw.nl. Retrieved on February 2022, from https://www.isobouw.nl/nl/wij-zijn-circulair/de-10r-circulariteitsladder/

Jabeen, I. (2020, August). *Economic Feasibility of Reusing Structural Components*. Delft University of Technology. http://resolver.tudelft.nl/uuid:e17e92e0-9b3e-4e70-8b93-5f77ccbe1154

Jonkers, H. (2018). Reader CIE4100: Materials and Ecological Engineering. Delft University of Technology

Kamp, B. (2021, July). *Assessment of the reuse potential of existing concrete: Enhancing circularity in the Dutch building sector by harvesting structural elements from demolition projects*. Delft University of Technology. http://resolver.tudelft.nl/uuid:252f00c3-17c7-4491-9e21-f8b0dac2c67e

Kempenaar, F. (2022). Betonconstructie historische loods hergebruikt. Tektoniek. Retrieved on February 2022, from https://www.tektoniek.nl/circulair/projecten/betonconstructie-historische-loods-hergebruikt

Koks, C. (2022, februari). Working with Environmental Impact [Presentation]. Week of Circularity - Heijmans, Online, Netherlands.

Koper, A. (2020, september). *Research partial collapse AFAS Stadium Alkmaar* [Presentatieslides]. brightspace.tudelft.nl. https://brightspace.tudelft.nl

Levels-Vermeer, J., Van Ewijk, H., Scheepmaker, J., & De Vries, S. (2015, maart). Milieuprestatiebepaling van recycling en hergebruik van bouwmaterialen. https://usi.nl

Meester, J. J. (2020, oktober). *Investigation into the cause of the failure of parking garage Eindhoven Airport* [Lecture slides]. brightspace.tudelft.nl. https://brightspace.tudelft.nl

Ministerie van Infrastructuur en Waterstaat. (2021a, January). *Regeling voertuigen*. Wettenbank. Retrieved on May 2022, from https://wetten.overheid.nl/BWBR0025798/2021-01-21/0/Hoofdstuk5/Afdeling2/Paragraaf13/Artikel5.2.77/informatie

Ministerie van Infrastructuur en Waterstaat. (2021b, March). V&R-projecten op de markt in 2021. Rijkswaterstaat. Retrieved on February 2022, from https://www.rijkswaterstaat.nl/nieuws/archief/2021/03/vervangings-en-renovatieprojecten-op-de-markt-in-2021

Ministerie van Infrastructuur en Waterstaat. (2021c, April). Circulaire viaducten en bruggen. Rijkswaterstaat. Retrieved on February 2022, from https://www.rijkswaterstaat.nl/zakelijk/duurzame-leefomgeving/circulaire-economie/strategic-business-innovation-research-circulaire-viaducten

Ministerie van Infrastructuur en Waterstaat. (2021d, May). SBIR Circulaire Viaducten naar fase prototypes. Rijkswaterstaat. Retrieved on February 2022, from https://www.rijkswaterstaat.nl/nieuws/archief/2021/04/sbir-circulaire-viaducten-naar-fase-van-prototypes-met-3-veelbelovende-oplossingen

Ministerie van Infrastructuur en Waterstaat. (2021e, September). *'Convoi Exceptionnel': wat is dat nou eigenlijk?* Rijkswaterstaat Verkeersinformatie. Retrieved on May 2022, from https://www.rwsverkeersinfo.nl/nieuws/wat-is-convoi-exceptionnel/

Ministerie van Infrastructuur en Waterstaat. (2021f, oktober 1). *De belangrijkste asbestregels*. Asbest | Rijksoverheid.nl. Retrieved on May 2022, from https://www.rijksoverheid.nl/onderwerpen/asbest/asbestregels

Ministerie van Infrastructuur en Waterstaat. (2021g, December). Rijkswaterstaat - Onze organisatie. Rijkswaterstaat. Retrieved on February 2022, from https://www.rijkswaterstaat.nl/over-ons/onze-organisatie

Nebest. (2022a). *Studio Beton 17–02-2022 | Hergebruik betonnen viaductliggers* [Video]. YouTube. https://www.youtube.com/watch?v=NPSgjOopJoA

Nebest. (2022b). Wapeningsconfiguratie. nebest.nl. Retrieved on June 2022, from https://www.nebest.nl/diensten/wapeningsconfiguratie

NEN 2767–1+C1:2019 - Condition assessment built environment - Part 1: Methodology. (2019).

NEN-EN 197–1 Cement - Part 1: Composition, specifications and conformity criteria for common cements. (2011).

NEN-EN 206–1 Concrete - Part 1: Specification, performance, production and conformity. (2005).

NEN-EN 1992–1-1+C2 Eurocode 2: Design of concrete structures – Part 1–1: General rules and rules for buildings. (2011).

NEN-EN 1990+A1+A1/C2: Eurocode: Basis of structural design. (2011).

NEN-EN 13501–2:2021 - Fire classification of construction products and building elements - Part 2: Classification using data from fire resistance tests, excluding ventilation services. (2021).

NEN-EN 15804+A2 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. (2019).

NEN-EN 16757:2021 Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements. (2021).

Nusselder, S., Nieuwenhuijse, I., Bruinsma, M. (2021). Kostencurves beton 2020. CE Delft. https://ce.nl/publicaties/kostencurves-en-circulariteit-beton/

Panteia. (2018, July). *Kostencalculaties in het beroepsgoederenvervoer over de weg*. https://panteia.nl/index.cfm/_api/render/file/?method=inline&fileID=5B52D01F-D3BA-4170-9179D3CC1C0706B5

Panteia. (2019a). *Panteia brengt nieuwe rapportage uit: "Kostenontwikkelingen in het wegvervoer 2019–2020" - Panteia.nl*. Archief Panteia. Retrieved on May 2022, from https://archief.panteia.nl/nieuws/panteia-brengt-nieuwe-rapportage-uit-kostenontwikkelingen-in-het-wegvervoer-2019-2020/

Panteia. (2019b). *Rapporten kostenontwikkeling wegvervoer openbaar - Panteia.nl*. Archief Panteia. Retrieved on May 2022, from https://archief.panteia.nl/nieuws/rapporten-kostenontwikkeling-wegvervoer-openbaar/

Peeters, P. (2022, February). *Miljoenenaankoop Bowling en oud-politiekantoor in Breda is aanzet tot 'Koepelkwartier'*. bndestem.nl. Retrieved on May 2022, from https://www.bndestem.nl/breda/miljoenenaankoop-bowling-en-oud-politiekantoor-in-breda-is-aanzet-tot-koepelkwartier

Perree, H. (2022, May). *Gelders kantoorgebouw circulair gesloopt* [Photograph]. Binnenlandsbestuur. https://www.binnenlandsbestuur.nl/

Platform CB'23. (2021, July). *Circulair ontwerpen Werkafspraken voor een circulaire bouw*. https://platformcb23.nl/images/leidraden/PlatformCB23_Leidraad_Circulair-Ontwerpen_versie1.pdf

Platform CB'23. (2022a). *CB'23*. Retrieved on May 2022, from https://platformcb23.nl/over-platform-cb-23

Platform CB'23. (2022b, April). *Leidraad Toekomstig hergebruik* (80% version). https://platformcb23.nl/images/consultatie/2022/conceptleidraad-toekomstig_hergebruik-1-2022-03-16.pdf

RDW. (2022). *LZV-ontheffing*. Retrieved on May 2022, from https://www.rdw.nl/zakelijk/branches/transporteurs/lzv-ontheffing

Rijksdienst voor Ondernemend Nederland. (2021). *MilieuPrestatie Gebouwen - MPG*. Wetten en regels gebouwen. Retrieved on May 2022, from https://www.rvo.nl/onderwerpen/wetten-regels/milieuprestatie-gebouwen-mpg

Rijksdienst voor Ondernemend Nederland. (2022, March). *Duurzaam beton(product) met ten minste 30% gerecyclede content | RVO.nl | Rijksdienst*. Data RVO. Retrieved on May 2022, from https://data.rvo.nl/subsidies-regelingen/milieulijst-en-energielijst/miavamil/duurzaam-betonproduct-met-ten-minste-30-gerecyclede-content

Rijksoverheid. (2019, June). *Klimaatakkoord*. https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord

Rijksvastgoedbedrijf. (2021, March). *Veilig bouwen*. Veiligheid | Rijksvastgoedbedrijf. Retrieved on November 2021, from https://www.rijksvastgoedbedrijf.nl/expertise-en-diensten/veiligheid/veilige-bouwplaatsen-en-bouwconstructies

Royal Haskoning DHV. (2021a, April). *SBIR circulaire viaducten: tweede leven voor liggers maakt viaducten circulair*. RHDHV | Nederland. Retrieved on February 2022, from https://global.royalhaskoningdhv.com/nederland/nieuws/nieuwsberichten/sbir-circulaire-viaducten-tweede-leven-voor-liggers-maakt-viaducten-circulair

Royal HaskoningDHV. (2021b). *Life Cycle Costing (LCC) voor gebouwen*. Life Cycle Costing (LCC) voor gebouwen. Retrieved on May 2022, from https://www.royalhaskoningdhv.com/nl-nl/nederland/diensten/diensten-van-a-tot-z/life-cycle-costing-lcc-gebouwen/105

Royal Haskoning DHV. (2022, March). Studio Beton 17–02-2022 | Hergebruik betonnen viaductliggers [Video]. YouTube. https://www.youtube.com/watch?v=NPSgjOopJoA

Sagel, R., Braam, C. R., & Lagendijk, P. (2013, September). *GTB 2010*. Betonvereniging.

SGS Search. (2021, March). *Beslisboom Hergebruik (ge)bouwelementen.* http://cirkelstad.nl

Sloop concurrent. (2021, December). *Betonvloer slopen kosten | Sloop Concurrent | Alle kosten op een rijtje*. Retrieved on April 2022, from https://sloop-concurrent.nl/sloopwerk/betonvloer-slopen-kosten/

Stichting Koninklijk Nederlands Normalisatie Instituut. (2020). Nationale bijlage bij NEN-EN 1992–1-1+C2 Eurocode 2: Ontwerp en berekening van betonconstructies - Deel 1- 1: Algemene regels en regels voor gebouwen (ICS 91.010.30; 91.080.40). https://connect.nen.nl

Stichting Nationale Milieudatabase. (2020, July). Bepalingsmethode Milieuprestatie Bouwwerken (Nr. 1). https://Milieudatabase.nl

Stichting Nationale Milieudatabase. (2022). *Nationale Milieudatabase*. Nationale Milieudatabase. Retrieved on May 2022, from https://milieudatabase.nl/database/nationalemilieudatabase/

SVMS. (2020). *Verificatieregeling Circulair Sloopproject*. veiligslopen.nl. https://www.veiligslopen.nl/site/media/upload/files/verificatie-circulair-sloopproject-versie-4-juni-2020-vastgesteld-bestuur.pdf

Tektoniek. (2022, April). *Seminar Circulair Delven Prinsenhof A Arnhem*. Retrieved on April 2022, from https://www.tektoniek.nl/circulair/tektoniek-university/seminar-circulair-delven-prinsenhof-a-arnhem

Terneuzen, J. (2022, februari). Demountability [Interactive presentation]. Week of Circularity - Heijmans & Alba Concepts, Online, Netherlands.

Terwel, K. C., & Jansen, S. J. T. (2015). Critical Factors for Structural Safety in the Design and Construction Phase. Journal of Performance of Constructed Facilities, 29(3), 04014068. https://doi.org/10.1061/(asce)cf.1943-5509.0000560

UNFCCC. (2021, November). *COP26 Reaches Consensus on Key Actions to Address Climate Change*. United Nations Climate Change. Retrieved on November 18, 2021 from https://unfccc.int/news/cop26-reaches-consensus-on-key-actions-to-address-climate-change

Van Berlo, S. (2019). *Assessing the circularity potential of infrastructure assets: A methodology to assess and inspect 1 on 1 reuse of concrete components*. University of Twente. https://essay.utwente.nl/78103/1/Final%20Thesis%20Sammie%20van%20Berlo%202.1.pdf

Van den Boomen, M., Schoenmaker, R., Verlaan, J., & Wolfert, A. (2016). Common misunderstandings in life cycle costing analyses and how to avoid them. *Life-Cycle of Engineering Systems*, 315. https://doi.org/10.1201/9781315375175-251

Van de Minkelis, H. (2020, May). *Assessing the Market Potential of Second-hand Building Products*. Delft University of Technology. http://resolver.tudelft.nl/uuid:a9737eff-ea0b-4732-9b27-9ed000010b05

Van Uffelen, K. (2012). *Herbestemming van een monument in beton een protocol voor het constructief beoordelen van een betonconstructie uit 1910–1940*. Eindhoven University of Technology. https://research.tue.nl/nl/studentTheses/herbestemming-van-een-monument-in-beton

Van Vliet, M., Van Grinsven, J., & Teunizen, J. (2019). *Circular Buildings - Meetmethodiek losmaakbaarheid* (1.1). https://albaconcepts.nl/circulairbouwen/

Veras. (2021). *Over Veras*. Sloopaannemers.nl. Retrieved on March 2022, from https://www.sloopaannemers.nl/over-veras/

Verberne, J. J. H. (2016). *Building Circularity Indicators - An approach for measuring circularity of a building*. Eindhoven University of Technology. https://pure.tue.nl/ws/portalfiles/portal/46934924/846733-1.pdf

Verbouwkosten B.V. (2022, May). *Verbouwkosten*. Verbouwkosten. Retrieved on May 2022, from https://www.verbouwkosten.com/beton-laten-storten/

Volkov, M. (2019). *Structural connections in circular concrete.* Delft University of Technology. http://resolver.tudelft.nl/uuid:41bd0462-cac9-4314-9682-06962df42e52

PART V | APPENDICES

Appendices

A. Literature research
   - A.1 Demolition in the Netherlands
   - A.2 Structural safety
   - A.3 Environmental impact
   - A.4 Existing tools

B. Material- and design properties concrete
   - B.1 Concrete strength classes
   - B.2 Modulus of elasticity
   - B.3 Stress-strain diagram
   - B.4 Stiffness
   - B.5 Environmental classes
   - B.6 Fire resistance of concrete structures

C. 10R Model of circularity and examples from practice
   - C.1 REFUSE
   - C.2 REDUCE
   - C.3 RETHINK

D. Background information Reusability Tool
   - D.1 Residual lifespan
   - D.2 Deconstruction techniques
   - D.3 Environmental data
   - D.4 Evolution of building codes
   - D.5 Reinforcement detailing
   - D.6 Monolith floors

E. Assessment system of Reusability Tool
   - E.1 Assessment of structural safety
   - E.2 Assessment of environmental impact
   - E.3 Assessment of economic impact

F. Case study
   - F.1 Columns
   - F.2 Beams
   - F.3 Floor elements

G. Properties of Reusability Tool
   - G.1 Additional input information
   - G.2 Assumptions of the Reusability Tool
   - G.3 Default settings Reusability Tool

A. Literature research

A.1 Demolition in the Netherlands

In the Netherlands in both the B&U (residential and utility) and GWW (ground, roads and water) sector lots of concrete structures will be demolished. In order to get insight in the elements to be released, the current area is analysed together with the demolishing plans. First, the structures in the B&U sector are analysed and explained, followed by the structures of the GWW sector.

B&U sector

Together with Metabolic, and SGS Search, EIB (Economisch Instituut voor de Bouw) analysed the flows of materials, environmental impact, and energy usage in the housing- and utility building sector. For the year of 2014, those aspects are analysed and based on these outcomes, a prediction for the year of 2030 has been prepared.

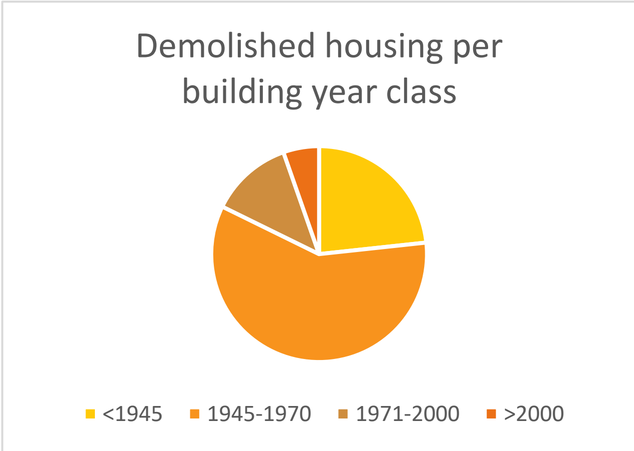


Figure A.0.1 Demolished housing categorized by building year class (Adapted from: Arnoldussen et al, 2020)

In 2014, 45.000 residential houses are constructed. Almost half of this number are apartments and 30% are serial houses. The buildings which are demolished in 2014 are categorized in 'building year classes'. Especially serial housing and apartments which are constructed in 1945-1970 (the so called 'early after war housing') are deconstructed in 2014. This is caused by the low quality of these buildings and the increased quality demands for buildings, those days. Next to that, the building stock of building corporations mostly exists of these types of buildings. Building corporations have more demolition projects compared to private landlords. The diagram in Figure A.0.1 shows the demolished housing categorized by building year class.

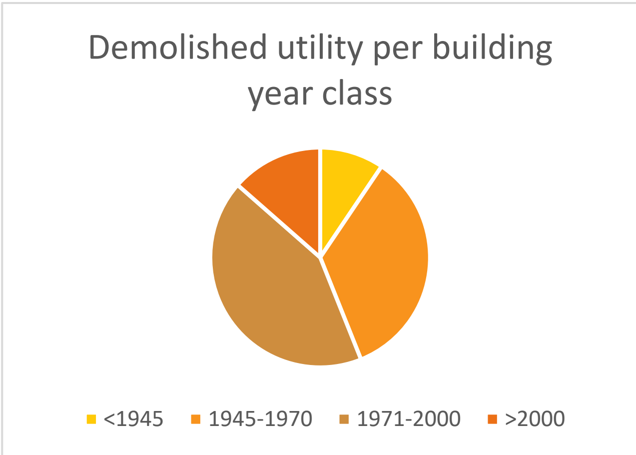


Figure A.0.2 Demolished utility categorized by building year class (Adapted from: Arnoldussen et al, 2020)

Next to housing, around 8000 utility buildings have been constructed in 2014. A division of the demolished utility building per building year class is shown in Figure A.0.2. Compared to the demolishing housing projects, more buildings which are constructed during the 70s/80s are demolished. This is caused by the increasing demands for health, sustainability, and comfort.

Based on the production- and demolition processes, the material flows and building elements are linked to those activities according to the Urban Mining Model. Figure A.0.3, shows the balance between materials and elements of housing and utility buildings in 2014. It should be noted that this diagram only shows the theoretical potential of reusing material or elements in which the offer of secondary material can supply the demand. Technical aspects, logistics, and economic value is not included in this analysis.

Expected is that the differences in input and output of material flows will be smaller in 2030 compared to 2014. This is especially caused by the relative growth of demolish projects of residential buildings. The input flows of materials were 2.4 times larger than the output flows in 2014, in 2030 this factor will only be 1.7.

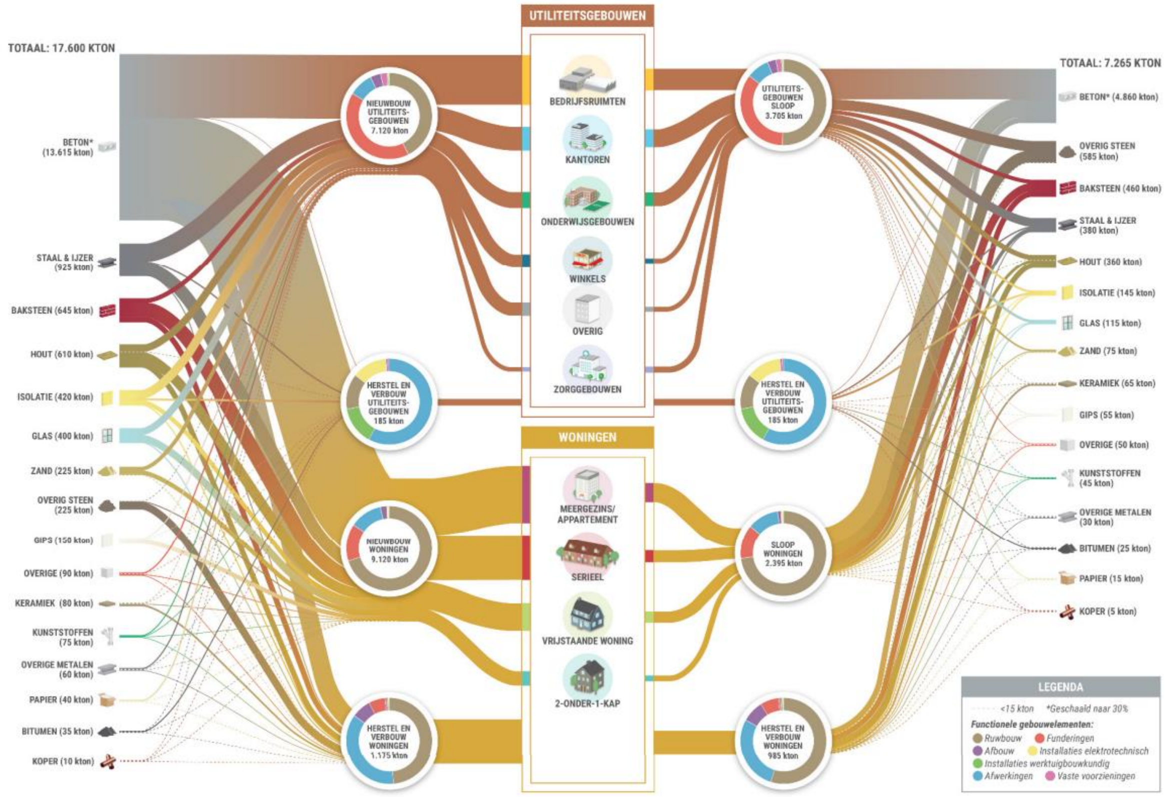


Figure A.0.3 Mass balance between materials and elements of housing and utility buildings in 2014 (Reprinted from: Blok, 2020)

Furthermore, the material demand is analysed. Apartments have the highest material demand compared to other housing types. Focusing on the material flows, concrete is dominant within the housing sector. More than 80% of the total mass of building material consists of concrete. In single-family homes, concrete has a contribution of 75-80% to the total building mass and in apartments, concrete even has a contribution of 85%. Materials from serial housing with building year class 1945-1970 have the biggest share in the total material flow. Compared to new housing construction projects, the contribution of concrete is more.

In the utility building sector the largest demand for materials follows from new construction projects of offices. Also in this sector, concrete has the largest material flow. In 2014 almost 79% of the total mass of building material consists of concrete. Demolition of office buildings is responsible for 42% of the total mass of building material within the utility sector. Next to that, offices (20%) and school buildings (13%) are an important source for materials. Wood, masonry bricks and glass have a larger contribution in the demolition of utility buildings than new construction projects, and concrete a smaller contribution. This can be explained by the demolition of school buildings from the 70s/80s. In these type of buildings, the contribution of wood and glass are relatively high (Arnoldussen et al, 2020; Blok, 2020)

The report about material flows, environmental impact and energy usage of housing- and utility buildings also includes an overview of the ratio between input and output of product types. In Table A.0.1 information about the ratios of concrete products is included. From this overview it can be concluded that hollow core slabs, wide slab floors, and in-situ concrete elements of C20/25 are the largest required materials for new construction projects. On the other hand, wide slab floors, and in-situ concrete elements of C20/25 are the most released concrete elements after demolishing (Arnoldussen et al, 2020). In the Netherlands, most in-situ structures are made of concrete strength classes C20/25, C25/30, and C30/37. The minimum required strength class for prefab concrete elements is C35/45 (Braam, Lagendijk, 2011).

GWW sector

In the Netherlands, Rijkswaterstaat is the executive organization of the ministry of Infrastructure and Water Management. Rijkswaterstaat manages most civil construction works in the Netherlands and has the ambition to work climate neutral and circular in 2030 (Ministerie van Infrastructuur en Waterstaat, 2021d). In order to develop circular viaducts, Rijkswaterstaat started the SBIR-method, standing for Strategic Business Innovation Research. All interested parties (or consortia) could submit a quotation with possible solutions and options for circular viaducts and bridges. This resulted in 32 consortia of which 10 were selected to do a feasibility study (Ministerie van Infrastructuur en Waterstaat, 2021b) . After this study, 3 consortia were selected in February 2021 to create a tested prototype. Those three consortia are the following (Ministerie van Infrastructuur en Waterstaat, 2021c):

- ViCi - designs renewable and modular arch structures;
- Nebest – with its ‘Closing the Loop’ project;
- Royal HaskoningDHV – investigates the reusability of prefab concrete beams.

Rijkswaterstaat currently manages around 1800 viaducts. From analysis of the area of viaducts, around 90% (1632) of the viaducts consists out of girders and 10% consists out of plates which is also shown in Figure A.0.4.

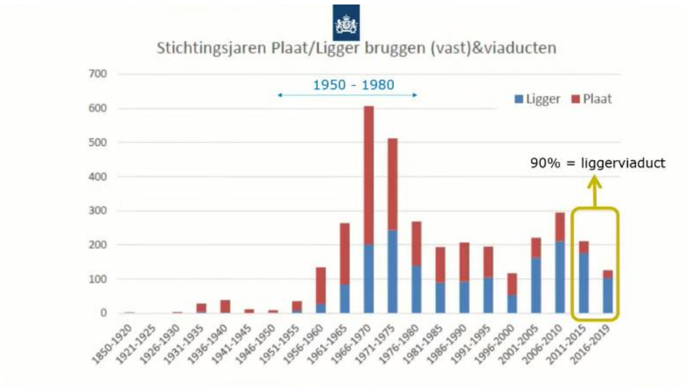


Figure A.0.4 Construction year of girder- and plate viaducts (Retrieved from Betonvereniging, 2022)

More than 500 girder-viaducts are older than the technical service life of 50 years for which they were designed those days. Currently, 7 viaducts are demolished per year with an average age of 40 years. Expected is this amount will increase significantly because of the so called V&R (Replace and Renovate) task of Rijkswaterstaat (Ministerie van Infrastructuur en Waterstaat, 2021a)

Moreover, Royal HaskoningDHV analysed the type of girders in viaducts. Most girders, 55%, are (reversed) T-beams including a compressions layer. Those girders spanned form 17.5 meters till 37.5 meters. Next to that, box girders are used with are prestressed transversely. Those girders have a span form 25 till 50 meters and have a 25% share of the total girders. With a share of 15%, also fully casted girders are used with a span of 8 till 16 meters. The remaining 5% are T-contact girders and T-girders including full casted concrete in between (Royal Haskoning DHV, 2022)

Therefore, next to the B&U-sector, concrete elements will be released in the GWW-sector which is a hot-topic at the moment.

This table (Table A.0.1) showing the ratio between the released and required concrete elements in 2014.

Table A.0.1 Ratio released and required concrete elements 2014 (Adapted from Arnoldussen et al, 2020)

Product	Input (ton)	Output (ton)	Input/output
Hollow core slabs, prefab concrete; AB-FAB_27.01.011	337.561	187.124	1,80
Concrete tiles	160.479	76.225	2,11
Concrete, prefab, housing; AB-FAB	109.400	49.960	2,19
Concrete, prefab, AB-FAB	110.130	49.619	2,22
Concrete, prefab; utility buildings	93.381	41.409	2,26
Compression layer wide slab floor; concrete mortar C20/25; including reinforcement	369.228	163.065	2,26
Wide slab floor excluding compression layer, 60 mm; prefab; AB-FAB_27.01.012	409.711	180.944	2,26
'Sand cement'	750.695	309.442	2,43
Dycore hollow core slabs 260 mm (iso)	1.006.697	396.431	2,54
Concrete blocks (glued)	12.572	4.810	2,61
Concrete, in-situ, C20/25; including reinforcement	2.265.512	830.333	2,73
Hollow core slabs, prefab concrete; AB-FAB_23.01.023	1.066.556	387.811	2,75
Concrete cells (Xella-Ytong)	207.124	71.144	2,91
Sand	222.727	76.322	2,92
Concrete, in-situ, C20/25; including reinforcement + eps (insulation)	971.004	331.883	2,93
Wide slab floor excluding compression layer, 60 mm, prefab, AB-FAB_23.01.024	2.334.045	761.827	3,06
Compression layer wide slab floor; concrete mortar C30/37, including reinforcement	2.103.419	686.551	3,06
Concrete, prefab; reinforcement: 120kg/m3	203.070	59.957	3,39
Concrete screw pile, in-situ, C20/25; including reinforcement	861.628	229.300	3,76
Ribfloor / rib cassette, including insulation	310.982	81.261	3,83
Concrete	24.965	6.299	3,96
Concrete, prefab, slender shaft, 400x400mm	378.522	90.583	4,18
BB&S concrete masonry brick + masonry mortar + grout	19.153	4.585	4,18
Prefab concrete; h;2.7.b:1.1m; including 'bordes'	93.558	10.454	8,95
Concrete, in-situ, C30/37; including reinforcement	7.104	420	16,91

A.2 Structural safety

There lots of factors influencing structural safety. Therefore, Terwel and Jansen analysed the critical factors for structural safety in the design- and construction phase in which three levels of factors are distinguished:

- On *macro* level, external factors are given related to the project situation;
- On *meso* level, company and project factors are included;
- On *micro* level, possible human factors are distinguished.

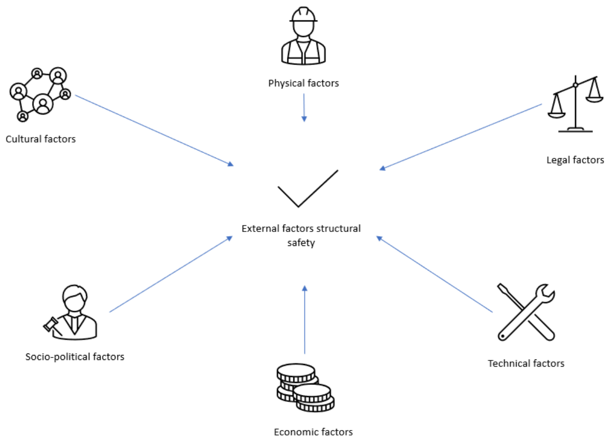


Figure A.0.5 External factors influencing structural safety (Adapted from Terwel, Jansen, 2014)

Factors on macro level cannot easily be influenced by a company within a building process. Although, these external factors can be of huge influence on the structural safety. Typical factors on macro level are cultural-, physical-, and legal factors. Also, socio-political factors and economic- and technical factors will influence the structural safety of a project. These factors are shown in Figure A.0.5. Some more in depth information about legal frameworks is described in the next paragraph about responsibilities.

Figure A.0.6 Company- and project related factors influencing structural safety (Adapted from Terwel, Jansen, 2014)

Figure A.0.6 shows the company- and project related factors influencing structural safety. All factors are shortly explained.

Safety goals are the objectives for structural safety. When the safety goals within a company or project are not clear it can result in incompatible goals between productivity and safety. The commitment of the management is important. If the management focusses on improving safety, the company is more willing to invest in it. Besides, the safety culture is an important factor influencing structural safety. For example, explicitly stating the safety goals within a company, influences the safety culture. Making people aware of safety by giving suggestions or compliments can highly contribute to improving safety.

It should be clear who is responsible for what task within a process. A clear assignment of responsibilities is important. The type of organization influences the project complexity and is therefore of major importance. By doing risks analyses and allocations the risks of the structure and building process can be identified. In order to improve safety, first the risks should be known.

Furthermore, by checking and controlling work of others, mistakes can be recovered. Therefore, it is important to have control mechanism within companies and projects. In protocols it is described how specific tasks should be performed. The chance of accidents and failures will be reduced when companies work according to protocols.

Another very important factor is communication. When information about the structure is not shared among others, it will influence the structural safety. Good collaboration between parties improve the quality of a project. Trust and atmosphere contribute to the sense of harmonious working relationships. If a planning of a project is too tight, it can result in tasks which will be finished in a rush leading to mistakes.

Therefore, a realistic planning and budget is necessary in order to deliver a structure with sufficient performance.

It is also important to think about the knowledge infrastructure within the project. One should think about years of education, experience, trainings. It is important to only use workers with the right certificates for the job. Moreover, the workspace and environment are important factors regarding performance. If the right tools and equipment are not available, it can result in problems and unsafe situations. Therefore, the availability of instruments is of importance and influence the structural safety of a project (Terwel, Jansen, 2015).

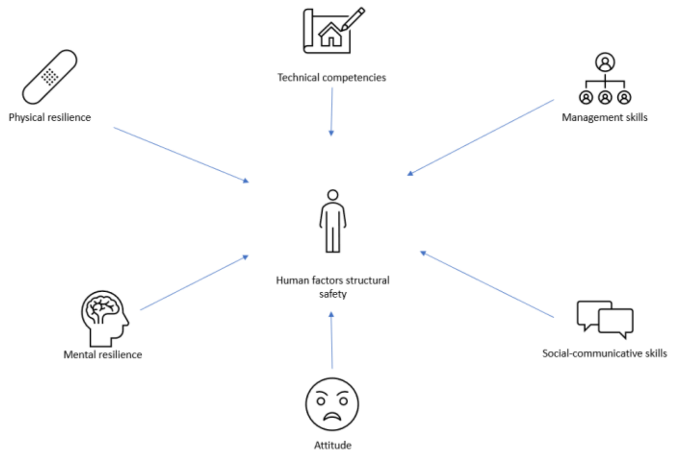


Figure A.0.7 Human factors influencing structural safety (Adapted from Terwel, Jansen, 2014)

Below the meso level, some human factors can influence structural safety. These factors, on micro level, are shown in Figure A.0.7 and are shortly explained.

First of all, if someone is able to apply knowledge and skills for designing and executing a construction, he has the right technical competencies. The technical skills of team leaders are of high importance. Besides, managers should have the right skills in order to manage a team. Think of management skills like capable of making decisions, plan, and organize. People should be recognized and appreciated for their work. This will motivate them to deliver high quality work. It is important to stimulate workers and properly communicate. Having a positive attitude will lead to less failures and more safe projects. Showing commitment to safety to involved parties contribute to an improved safety culture. Sometimes it is difficult for people to deal with stress. This can affect the work results. It is therefore important to deal with it in the right way and have a sufficient mental resilience. Next to mental resilience, physical resilience can affect the safety of a project. Health problems of workers should be prevented (Terwel, Jansen, 2015).

Lots of parties from the building industry indicates that the regulations are too complex. This is caused by the amount of and the uncertainties of the regulations. It is important to increase knowledge about laws and regulations among involved parties. Moreover involved parties indicates there is often unclearness about the responsibilities within a project.

In the following sub-sections, some macro- and meso factors are explained in more detail. In Section A.2.1 some additional information is given about responsibilities in the process of reuse followed by information about contracts/protocols which are often used (Section A.2.2). Besides, the juridical process used in the Netherlands is explained in more depth in Section Section A.2.3. In Section A.2.4 some examples of structural unsafety in the Netherlands are given.

A.2.1 Responsibilities

Reusing structural elements is still quite new and therefore it is often unclear how to allocate responsibilities among involved parties. For each of the involved parties there are some chances and risks.

In Table 3.11, responsibilities of the main parties involved in the (linear) building process are explained.

Table 3.1: Responsibilities of parties involved in building process (Adapted from Heijmans Utiliteit B.V. Internal Document, 2021; Banga, 2012)

Responsibilities	Description
Client	The employer can have a major impact on the structural safety of a project. The employer chooses the involved parties. He can decide about supervising the project and the preferred consequence class. For an employer reusing structural elements can be interesting. The employer can focus on reusing structural elements from the beginning and because of the circular aspect of the project it is often allowed to invest more money. The planning of the project can be an issue because of testing of the quality of reused elements, potential procedures with municipalities and adaptions in the design. Also here the question about responsibilities, guarantees, and liabilities arises.
Architects	Architects are challenged to think and design differently and should take into account future changes of functions. On the other hand, more research to available materials are necessary and the integration of installations can be an issue.
Structural engineer	During the design phase, the structural engineer is responsible for the structural safety of the project. Before calculating a structure using computer software, one should think about the expected results. The structural engineer should always understand the structure. He should think of the manufacturability during the design phase which should be known by the contractor. By implementing checklists at the end of every design phase, one can check whether points of attention are identified. By reusing overqualified elements some other structural savings can be possible. Issues for the structural engineers are the unknown material qualities, residual capacity after loading, and modifications before the structural element can be reused. The responsibility for structural engineers rise drastically.
Contractor	The contractor should check if there are sufficient measures to guarantee the strength and stability of the structure. The contractor should be aware of the manufacturability intended by the leading structural engineer. The contractor is responsible for the sub-contractors.
Sub-contractors (detailing)	It is often unclear where the responsibility of the main contractor stops and where the responsibility of the sub-contractors start. For example a question that can be raised is: Who is responsible for the connection details between structural elements of different suppliers and who calculates those connections?
Advisor	In order to coordinate the different elements of the construction it is important to have one advisor who is aware of all the details of the plan and who can assure the elements will be tested and integrated in the right way.
Purchaser	The one responsible for purchasing the project can buy reused elements which potentially are cheaper than new ones. On the other hand, testing and modifying the elements will increase the costs. Moreover, durable designs will result in higher tender scores which can be an advantage in the tender procedure.

A.2.2 Contracting

In this section, the DNR contract and UAV are shortly explained.

DNR contract

In the DNR it is stated that the employer must behave to the consultant (structural engineer) as a good and careful client. The right information should be provided in time and the consultant should be warned when the employer is missing some advice. The consultant should only advise the employer, warn over shortcomings, and should have the necessary knowledge for the assignment (Boot et al, 2015). The consultant has a duty to warn the employer if decisions which are made by or on behalf of the employer includes mistakes. Next to that, rules about the liability of the consultant for culpable shortcomings and faults are described. According to the DNR-contract, the definition of a culpable fault is the following (BNA, NLingenieurs, 2013):

“a shortcoming accountable to guilt, or by virtue of the law, legal action or according to generally accepted opinions comes at the expense of the debtor. Under generally accepted opinions is to be understood: a shortcoming which a well and conscientiously operating consultant or client under the relevant circumstances and with regard to a normal attentiveness – and with respect to the consultant: equipped with the professional knowledge and means required for the commission – should have been able and ought to have avoided.”

In the Netherlands the liability test is according to the DNR including well and conscientiously operation, normal attentiveness, and equipped with professional knowledge. In England it is about reasonable skill and care. About the interpretation of the criteria described in the DNR, the court need to decide. So the court decide if an error is an culpable fault or not (Boot et al, 2015).

Furthermore, structural engineers have the duty to warn. In the DNR it is stated that:

‘’The consultant has an obligation to warn the client if information and/or data provided by or on behalf of the client or decisions taken by or on behalf of the client manifestly contain such shortcomings or show such deficiencies that he would act in defiance of standards of reasonableness and fairness should he proceed thereupon with the fulfilment of the commission.’’

UAV contract

In the UAV it is stated that contractors remain liable after delivery for hidden defects. There lots of questions in cases about whether a defect was hidden or not. A change of the Dutch Civil Code is proposed in which is stated that the contractor will be discharged from liability for defects that have been discovered at the time of delivery.

In England the contractor has some extra protection. The employer or his agent will be held liable since they failed to discover the defects during the execution. When the proposed change is included in the Dutch Civil Code, the systems in the Netherlands and England are more comparable.

In the UAV it is stated that the contractor is liable if structures, methods, tools or materials show such errors and the contractor started the construction without warning the employer about it. In the Netherlands there are lots of cases available on which the scope and extent of the duty to warn. In England only limited cases are available (Boot et al. 2015).

A.2.3 Juridical process

When damage occurs, there are three types of insurances in the Netherlands. The insurances types are shortly explained in Table I.1.

Table 0.2: Types of insurances for structural damage in the Netherlands (Adapted from Boot et al, 2015)

Insurance	Description
Construction all risk (CAR) insurance	The CAR insurance will cover material damage and rebuilding costs. This insurance is often arranged by the client or contractor.
Professional indemnity insurance	The professional indemnity insurance is more of importance for the structural engineer. The losses due to professional errors are covered. For example when no damage is visible but extra reinforcement is necessary, this insurance will cover those costs, where the CAR insurance does not.

Liability insurance	To cover costs for physical injuries, or material properties of third parties, the liability insurance is required.

In the Netherlands there is a civil law legal system, based on a written code. Courts need to work according to the written code. It contains information about contract law and liability rules. Only some rules of those are especially for relationships between employers, contractors, and designers. Some extra general terms and conditions are made for the construction industry by a collaboration of building organizations. When all parties agree, it is possible to deviate from the rules stated in the Dutch Civil Code.

When there is only material damage, parties can decide to settle, use alternative dispute resolution, or litigate. In case of loss of life, permanent injuries or hospitalization during construction, the employer is obliged to let the Inspectorate SZW investigate the accident. If necessary, the Public Prosecution Service will be notified which can decide if criminal law is required or not. Also the Dutch Safety Board can decide to do an investigation. The board focuses on causes, consequences, safety issues and recommendations about the incident. It does not investigate liabilities (Boot et al, 2015).

The juridical process after structural damage occurred is visualized in Figure A.0.8.

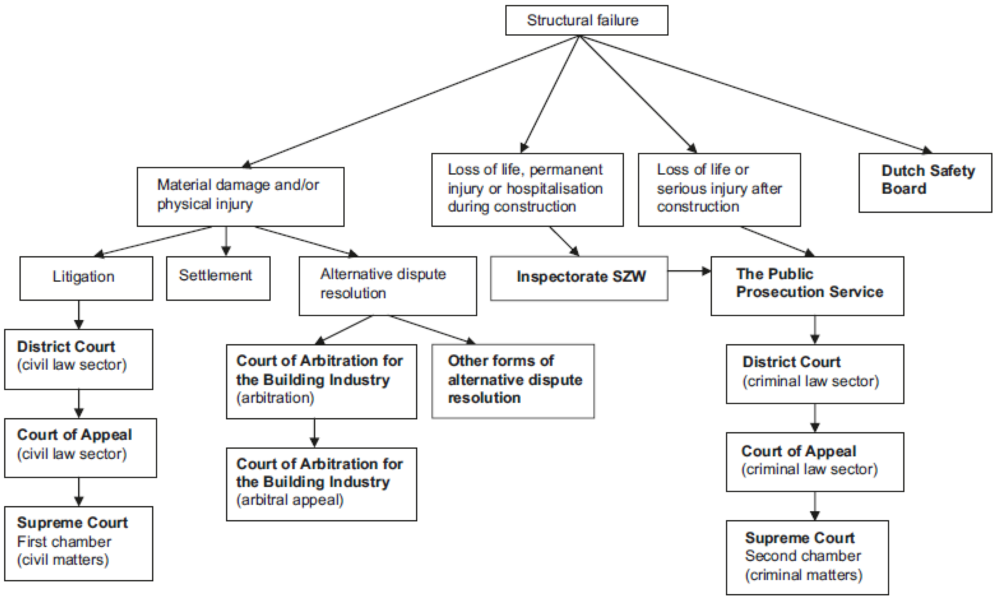


Figure A.0.8 Juridical process in the Netherlands after structural damage occurred (Reprinted from Boot et al, 2015)

After structural failure first it should be determined if there is only material damage and/or injuries, loss of life, permanent injuries during construction, or after construction.

When there is only material damage, parties can decide to settle, use alternative dispute resolution, or litigate. When there is loss of life, permanent injuries or hospitalization during construction, the employer is obliged to let the Inspectorate SZW investigate the accident. If necessary, the Public Prosecution Service will be notified which can decide if criminal law is required or not. Also the Dutch Safety Board can decide to do an investigation. The board focuses on causes, consequences, safety issues and recommendations about the incident. It does not investigate liabilities.

Litigation

In the DNR it is stated that in case of structural damage, it will be solved by litigation unless parties decide to choose for arbitration. In case of litigation a district court will have a look at the case. After the decision is made, parties can use the Court of Appeal and again use the Supreme Court. The Supreme Court will only have a look at the application of the law and will not focus on facts of the case. After decision of the Supreme Court, no appeal is possible.

In England, there is a special court for construction projects: the Technology and Construction Court (TCC). The judge needs to make use of an expert witness since the judge usually lacks technical knowledge. In the Netherlands the expert witness is appointed by the judge, in England the expert is appointed by the parties.

A disadvantage of an expert witness appointed by a judge is that the judge will often follow the expert's opinion since the judge lacks technical knowledge. The current litigation framework in the Netherlands is therefore not that suitable for technical construction disputes. The English party-appointed system can therefore be an solution. But also the English version has some disadvantages. The expert sometimes needs to deal with conflicting interests, duty to help the court and duty to help the party who chose the expert.

Arbitration

In this case an expert is often not necessary since the arbitrators are engineers themselves. They can assess technical facts, only in some cases and extra expert is required. Arbitrators are chosen by organization representing different sides of the building industry. The chairman of the court will assign an arbitrator to a specific case in order to reduce the chance of partiality (Boot et al, 2015).

A.2.4 Structural unsafety in the Netherlands

In the Netherlands there are databases including information about structural failures. Terwel et al, compares those databases resulting in some unsafe situations.

Some examples of major failures in the Netherlands, the past 10 years, are the collapse of the balconies in Maastricht in 2003, the collapse of the roof of the FC Twente stadium in 2011, the collapse of the parking garage in Eindhoven in 2017, and the collapse of the roof of the AFAS stadium in 2019.

The collapse of the balconies in Maastricht were caused by design changes which were made for aesthetic and financial reasons. There were many parties involved in the process. An engineer of record was responsible for the design, a main contractor for the execution, also hiring sub-contractors. After the collapse, the engineer of record received a fine of €22.500 from the criminal court because of insufficient controlling. After discovery of some cracks, there was no further action. The contractor and other engineers were not convicted. After this collapse, a confidential reporting system is initialized in order to improve structural safety.

In 2011, part of the roof of the FC Twente stadium collapsed during construction. The collapse had two fatalities and nine injuries as a result. For creating the extension of the roof of the stadium, the same contractor and sub-contractors were involved as for the earlier constructed roof. Therefore, there was trust between the involved parties. From an investigation of the Dutch Safety Board, it could be concluded the failure was caused by an insufficient stability system when the finishing of the structure was applied. Besides, the dimensions of the structure did not match the intended dimensions. From the research it became clear that the tight planning resulted in an sequence of construction which was not optimal. Next to that, more attention on the method of construction was necessary. Due to the trust between the parties, the control mechanism was insufficient, and the responsibilities during execution were not clear.

On May 27, 2017 part of the parking garage collapsed located at the airport of Eindhoven. For the garage the Bubbledeck flooring system was used. It was a warm and sunny day resulting the top floor tried to bend up causing an imposed deformation. The columns restrained this resulting in extra positive bending moments in the floor. This was the trigger for the collapse. Due to lack of moment resistance in the floor, part of the garage collapsed. After the collapse, other buildings including the Bubbledeck flooring system needed to be checked as well (Meester, 2020). Research from the Dutch Safety Board showed that cracks were discovered before the collapse of the garage, especially near the columns (Dutch Safety Board, 2018). The crack width was over 0.4 mm which is the maximum allowable crack width according to EN 1992-1-1 (EN 1999-1-1, 20XX). During a site visit the cracks were noticed by engineering firm Opzeeland. They contacted the firm Bubbledeck and contractor BAM about their concerns. BAM advised to cosmetically recover the cracks. The cause of the cracks was not further investigated (Braam et al, 2017). Also in this example, the allocation of responsibilities was not clear.

During a storm on August 10th 2019, the roof structure of the AFAS stadium partly collapsed. The investigation to the technical causes of failure is based on The Delft Approach and carried out by Royal HaskoningDHV. In total there were 34 hypotheses formulated for the technical cause of failure. From the research it could be concluded that the roof partly collapsed due to the failure of the top chord connection of a specific truss. The downward wind during a storm was the trigger for the failure. The connection failed because the welds of the connection were too thin which was the main cause of the failure. Moreover, the design of the welds was not good and some welds have failed earlier in the lifetime resulting in weak connections (Koper, 2020).

In the Netherlands there are several databases including information about structural failure. The Cobouw database is set up by TNO and included 401 incidents from the period between 1993 and 2009. Next to the Cobouw database, the ABC registration is a confidential and anonymized reporting system of mistakes in structural design, execution, maintenance, and demolition. The arbitration database contained 151 structural failures from 1992 till 2009. Each database has its own way of categorizing failures.

From analysing the databases containing information about structural failures, conclusions can be made. From the annual numbers of fatalities, it can be seen that the number is still within the limits of the safety philosophy behind the Eurocode. In almost 85% of the reported structural failures, buildings were involved. The databases show that concrete structures are less prone to errors compared to steel buildings. Around 35% of the failures are caused in the design phase and 30% during execution. Only 10% of the structural failures are caused during maintenance. Besides, some failures are a combination of errors during different phases. Since the amount of failures caused in design phase and execution phase are almost equal, designers and contractors cannot claim design errors are not in the phase they are involved in.

Some factors highly contributing to the occurrence of failure are changes in the design and construction, and given warnings by people or the structure. Therefore, better procedures including how to deal with changes and warnings are advised. Next to that, a European database containing information about structural failures would be helpful.

Most of the errors are human errors (around 90%), but the human behaviour is not included in the probabilistic theory in the Eurocode. It is advised to integrate a quantification of human errors in the calculation model of the Eurocode. More research is necessary for this (Terwel et al, 2015).

A.3 Environmental impact

In the Netherlands the Bepalingsmethode Milieuprestatie Bouwwerken is developed to calculate the environmental performance of construction works during their life cycle and is based on EN 15804. Together with the Nationale Milieudatabase (NMD), which includes environmental information of materials and elements, the Bepalingsmethode is managed by the Stichting Nationale Milieudatabase (Stichting NMD). Next to the EN 15804, the Bepalingsmethode describes values for specific processes in order to avoid unjustified mistakes in the calculation of environmental impact of different building products (Stichting Nationale Milieudatabase, 2020).

According to EN 15804:2012, 11 impact categories are used to calculate the environmental impact of a concrete structure. Since January 2021, impact categories are added for calculating the environmental impact resulting in a total of 19 impact categories. The impact categories used in EN 15804:2012 and the categories used in EN 15804:2012+A2:2019 are shown in Appendix D.3. Therefore it is important to make use of updated versions of EN 15804 in order to calculate the environmental impact in the right way.

The NEN-EN 16757:2021 provides information about Environmental Product Declarations (EPD) on concrete products. This Eurocode defines allocation procedures for reuse and recycling, and includes rules about the calculation of Life Cycle Inventory (LCI) underlying the EPD.

The life cycle stages from cradle to grave and modules D, used in a Life Cycle Analysis (LCA) are shown in Figure A.0.9 and are all mandatory to include in the environmental impact calculation.

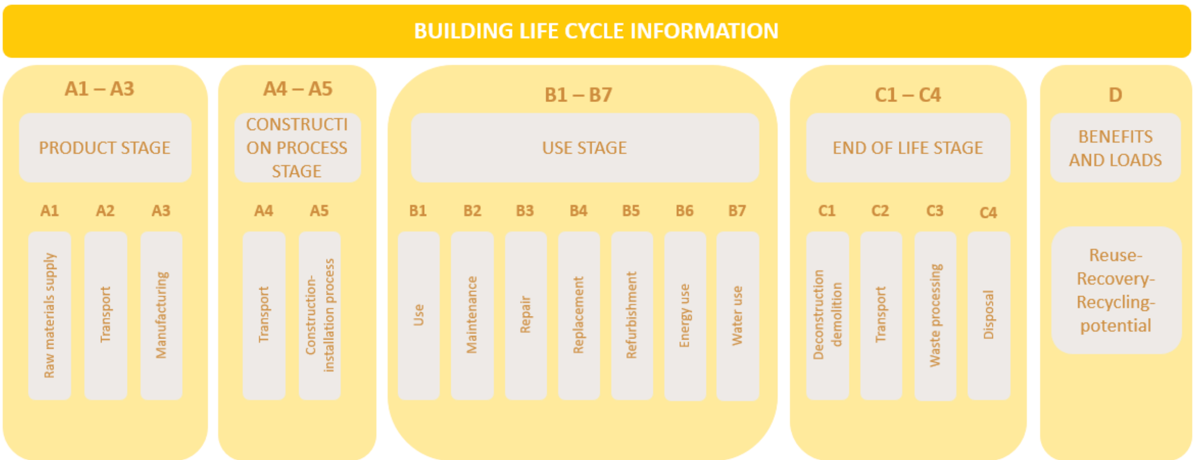


Figure A.0.9 Building life cycle information (Adapted from EN 15804:2012+A9:2019)

Compared to EN 15804:2012, Module D is not mandatory to include in an LCA. In the newest version of the EN 15804:2012, this Module is mandatory which stimulates thinking about the reuse potential of structural elements (Levels-Vermeer et al, 2015).

When no LCI of the constituents of a concrete element is available, aspects from the EPDs of EN 15804:2012+A2:2019 for constituents or ready-mixed concrete can be used which cover the stages A1 to A3. This assessment can be included in stage A1 of the EPD of the concrete element. Transport of the constituents can be included as well in the EPD of the concrete element. The transport of stage A4 of the EPD of the constituents, can be included in stage A2 of the EPD of the concrete element. This method is shown in Figure A.0.10.

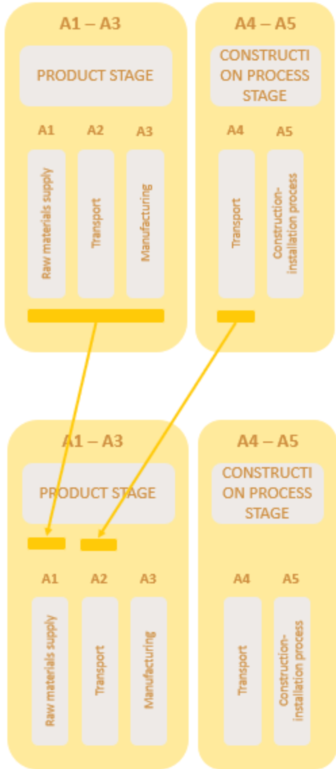


Figure A.0.10 Including EPd of constituents in EPD of concrete elements (Adapted from NEN-EN 16757:2021

Also the Bepalingsmethode explained how to calculate the costs and benefits in Module D. The equivalent of raw materials (grondstoffenequivalent) should be determined. This equivalent indicates how many and which production processes can be saved by reusing materials. The equivalent should be determined for (Stichting Nationale Milieudatabase, 2020):

- Secondary materials as input for the production phase (Module A);
- Secondary fuel as input for the production phase (Module A);
- Products for reusing as output of the processing phase (Module C);
- Materials for recycling as output of the processing phase (Module C);
- Materials for recovering energy as output of the processing phase (Module C).

The Nationale Milieudatabase (NMD) contains information about products in the format of a 'product card' referring to environmental profiles. These cards and profiles can be implemented in different calculation methods. The NMD distinguishes three categories of product information:

- Category 1: brand-related data, tested by third party according to NMD protocol. This category can be used by producers and suppliers;
- Category 2: brand-unrelated data, tested by third party according to NMD protocol, including mention of representativity and mentioning participating companies. This category can be used by producers, suppliers, branches, governmental institutions, etc.;
- Category 3: brand-unrelated data, property of Stichting NMD, not tested according to the NMD protocol.

The information in category 1 and 2 are delivered by producers and suppliers of building products whose still be the owners of the environmental profiles. The Bepalingsmethode provides information about how to create an EPD (Environmental Product Declarations), which deliver information for the 'product cards'. Since the environmental profiles of category 3 are not tested, an extra factor is included in the calculations. From practice it could be concluded the environmental impacts were too low and therefore should increase by a factor. Next to the product cards, NMD also has a data base for processes of materials.

The coherence of the databases and calculations are visualized in Figure A.0.11:

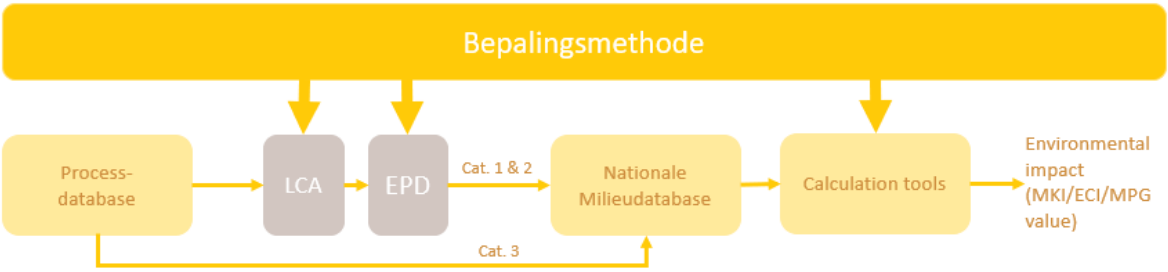


Figure A.0.11 Bepalingsmethode (Adapted from: Stichting Nationale Milieudatabase, 2020)

The Bepalingsmethode makes use of some lump sum values for transport. If there are specific data available about transport distances, one can deviate from the lump sum values.

In order to declare Module D in the right way, the following aspects are of importance:

1 A mass balance should be generated, derived from the Life Cycle Inventory (LCI) in which all secondary input and output flows of the product system should be included;
   a. Secondary input flows are of importance since these flows enter the product system without having any environmental impact. This is the case because the environmental impact is already declared in another product system;
   b. Secondary output flows can be available in a next product system. Therefore, the environmental impact of these output flows can be declared in Module D;
2 The equivalent of raw materials (grondstoffenequivalent) should be determined in a quantitative and qualitative way. Using this equivalent, the costs and benefits of Module D can be calculated;
3 Potential waste flows following from the recycling process (as result of degradation of efficiency) should also be included;
4 Module D can be calculated as a sum of the net input of the individual flows of secondary materials;
   a. When the net output has a negative value, it will result in an increase of environmental impact in Module D;
   b. When the net output has a positive value, it will result in a decrease of environmental impact in Module D.

When creating an environmental profile of reusing a complete structural element instead of materials, the same application of the Bepalingsmethode can be used (Stichting Nationale Milieudatabase, 2020).

A collaboration of LBP | Sight, IVAM, Ecofys, and USI proposed an operationalization of Module D in the Netherlands. By comparing EN 15804 and the Bepalingsmethode, the following recommendations for improvement of the Bepalingsmethode are proposed (Levels-Vermeer et al, 2015):

- Separate declaration of Module D conform EN 15804;
- Use the end-of-waste approach of EN 15804 in the NL Bepalingsmethode;
- Implement a control mechanism to check double counting between Module D and Module A;
- Create a National Annex of the EN 15804 (linked to the NL Bepalingsmethode);
- Structure the way of including principles for allocation and system boundaries.

A.4 Existing tools

In order to give insight in the potential of reusing structural elements, several researches focussed on different aspects of reusing. In terms of the market potential of reusing, the main reason not to reuse elements is the potential higher costs due to inventory, quality checks, the labour intensive deconstruction process, modification, storage, and transport (Van de Minkelis, 2020; Glias, 2013). Research of University California, Berkley showed a 21% difference in cost when comparing costs of demolition with costs of deconstruction of the same building. These high costs are because of cost of labour which are due to extensive time requirements of the process. The planning of the project is very important since cost of labour can affect the financial feasibility of the project. This can influence future projects (Endicott, Fiato, Huang, Totev, & Foster, 2015). Hermen van de Minkelis developed a Purchase Cost Tool in which a tree-shaped flow chart is used representing decisions, operations, and events, contractors have to deal with during disassembly. By adding up the costs of all operations and events, the total costs of the disassembly process can be computed. Based on these costs and the 'normal' costs of demolition, the purchase costs can be determined. The limitation of the Purchase Cost Tool is that no additional costs are included for making the building product applicable in a new situation. The model only focusses on the disassembly process of building products like stairs, insulation material, heating systems and window frames (Van de Minkelis, 2020). To get insight in the costs of deconstruction of structural concrete elements and the extra costs of reusing an element, further research is necessary.

For reusing structural elements, several actions are required. First the existing construction should be examined. If possible, as-built drawings should be analysed in order to see if the construction is suitable for deconstruction. Furthermore, the quality of the elements should be checked. Inspections and testing of the elements together with analysing drawings can result in the Element Identity (EID) of an element which shows that an element is suitable for reuse. The next step is to deconstruct the element. This demands a detailed planning and attention. Before an element can be reused it should be modified. Until reusage, the element will be stored after which it can be transported to the site for deconstruction (Glias, 2013).

Kamp (2021) assessed the reuse potential of existing concrete elements in depth resulting in the Decision Support Tool. In her research she analysed the three phases of *Deconstruct & Reuse*: Pre-Disassembling, Disassembling & Post-Disassembling, and Re-assembling.

During the first phase, Pre-Disassembling, the concrete element is reviewed by existing drawings and extra research. Based on the condition, residual lifespan, accessibility of the connection and transportation of the element, it can be decided if reusing of the element is possible. After analysing the element properties based on drawings and desk research, the performance of the element is tested on site. The first phase results in the Element Identity, based on the research of Glias (Glias, 2013).
The second phase, Disassembling & Post-Disassembling, covers the deconstruction and storage of the element. The material is handled and modifications are considered. From this phase, the reuse potential per stage will follow.
During the Re-assembling phase, the opportunities of the element in a new construction are indicated. The design of the new construction is analysed and the required properties are checked. Furthermore, the required equipment for deconstruction should be analysed.
All indicators of the phases and stages are written into assessment questions. According to a fuzzy calculation, the reuse potential and advice will be generated at the end of each phase. This information can

be used for discussion with the client or other parties. Recommended further research is to investigate the environmental and economic value of reusing elements (Kamp, 2021).

Bleuel (2019) created the Decision Support Model for analysing the reuse potential of hollow core slabs. In her research the environmental and economic impacts are analysed based on the Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) tool. An LCA identifies the environmental contribution to different life cycle stages of a structural element. The LCA is used to define the Environmental Product Declaration (EPD) which can compare the environmental performance of products based on similar functionalities (Jonkers, 2018). In an LCC the life cycle of a product is analysed in an economic way. This tool will help making decisions on exploitation, rehabilitation and disposal of assets. In order to analyse the reuse potential of a building component based on environmental and economic impact, the LCA and LCC analyses should be combined. The Eco-cost Value Ratio (EVR) is an existing model which analyses the environmental impact compared to the value of a product. For each life cycle stage the costs of the product can be calculated and the environmental impact can be expressed in an Environmental Cost Indicator (ECI). Bleuel used this EVR model for calculating the total costs of a reused element and compared this to the total costs of a new element. The total costs are the sum of the environmental costs and economic costs. Since the tool of Bleuel is only applicable to hollow core slab floor elements, it has to be modified and improved in order to determine the reuse potential of other structural elements. Moreover, improved databases, including up to date information about environmental impacts, are necessary to improve the tool. The tool of Bleuel is based on assumed situations instead of practical ones. Therefore the tool should be verified and tested in practice (Bleuel, 2019).

Next to the decision support model of Bleuel, Jabeen (2020) creates the Feasibility Calculation Tool for structural floor elements. This model predicts the future costs, taking into account variables influencing the costs. Based on random sampling, different combinations of variable costs are generated and the highest value of variable costs are calculated for which reuse is still economic. According to Jabeen, the variables affecting the reuse costs are:

- the method of construction (prefabrication/in-situ which affects way of deconstruction);
- type of connection (dry + demountable, dry or wet which affects way of deconstruction);
- accessibility to the site (influences the way of deconstruction);
- time constraint (due to market to find a new buyer for reuse);
- quantity (number of elements recovered from deconstruction);
- age of building (resulting in residual service life);
- presence of documents (insight in material properties and way of (de)construction);

The Feasibility Calculation Tool only gives information about the reuse feasibility of structural floor elements. Moreover, the environmental impact cost is not included in the model but a fixed percentage is used. In order to improve the tool it should also be possible to validate other structural elements. To give insight in the environmental impact of reusing structural elements next to the economic feasibility, the tool should be improved (Jabeen, 2020).

In her research, Bouwens (2022) focussed on outdated school buildings in the Netherlands. In the Supporting Assessment Tool the reclaim- and reuse potential of existing load-bearing components is assessed. This potential is based on three main indicators: breadth of application, demountability, and physical quality. Each indicator, including sub-indicators receives a score between 0 and 1 resulting in a final score. The tool is developed in the web-based program Figma. In the tool, no weighting factors are used for the indicators. Moreover, the environmental- and economic impact of reusing load-bearing elements from school buildings is not analysed. It is advised to validate the tool by feedback sessions with the end-users.

In order to support the usage of strategies which reduce the environmental impact, Kuijpers (2021) focussed on three circular design strategies, translated into the Circular Design tool making the practitioners in the building sector aware of the environmental impact of design choices. The circular design strategies Kuijpers focussed on are: Design for Adaptability, Design for Disassembly, and Design for Material Efficiency. The tool is validated by two case studies but is not tested in practice.

Moreover, there lots of LCA tools which are used in practice. For example, Heijmans Utiliteit is experimenting with the One Click LCA tool. In this tool, BIM models can directly be inputted of which data can be automatically used for ECI calculations. Next to the One Click LCA tool, comparable tools are developed like IMPACT, OpenLCA, and SimaPro.

LCC tools can be used for the calculation of all costs incurred during the lifetime of an element. It therefore included purchase prices and associated costs, operating costs, and end-of-life costs. LCC is often used by public authorities (European Commission, 2021).

The Eco-cost value ratio (EVR) analyses environmental issues compared to the value of a product. Products should have a high value/cost ratio combine with low burden on the environment. The EVR model links value chain to ecological product chain and can therefore be used for strategic design (Hendriks et al, 2006).

B. Material- and design properties concrete

In this appendix, material- and design properties are explained. First, information is given about concrete strength classes (Section B.1). Moreover, the modulus of elasticity, the stress-strain diagram of concrete, and the stiffness are explained in Section B.2, Section B.3, and Section B.4. Moreover, information about environmental classes and fire resistance are included in Section B.5 and Section B.6.

B.1 Concrete strength classes

The strength of concrete is expressed in strength classes. The compression strength of concrete determines the strength class. According to NEN-EN 1992-1-1 'Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings', the following concrete strength classes are distinguished:

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 (Stichting Koninklijk Nederlands Normalisatie Instituut, 2020).

All strength classes up to and including C50/60 are called 'normal' concrete, and the strength classes C55/67 till C90/105 are called 'high-strength' concrete.

In these strength classes, the letter 'C' stands for 'Concrete'. The first number shows the characteristic value of the cylindrical compression strength, and the second number the characteristic value of the cubic compression strength. Previously, in the Netherlands the letter 'B' (Beton) was often used instead of the letter 'C'. When analysing old drawings of constructions, people should aware of this.

In the Netherlands, most in-situ structures are made of concrete of strength classes C20/25, C25/30, and C30/37. When using prefab concrete elements, the minimum required strength class is C35/45, but often strength classes C45/55, and C50/60 are used. There are two main reasons for the higher strength classes for prefab concrete. First, prefab elements are often produced having better working conditions compared to in-situ concrete (production inside). Second, producers strive for the production of concrete elements as quickly as possible in order to reuse the mold for the production of a new element. Concrete mixtures with a high strength in an early stage, will also have a high final strength.

After casting the concrete, the development of the concrete properties will continue for years. 3 days after casting, 40-60% of the final strength of the concrete is already developed. For cylindrical compression strength of concrete, a strength of 70-90% is reached after 28 days. After that, there still will be an increase in compression strength of 10-30%.

Design value of compression strength of concrete:

The calculation value of the concrete compression strength is a characteristic value including safety in terms of a material factor $\gamma_c = 1.5$.

Since the strength of concrete is still developing after 28 days, the National Annex of the NEN-EN 1992-1-1 includes a coefficient for the long term effects of the compression strength: $\alpha_{cc} = 1.0$.

Including those factors, the design value of the compression strength of concrete equals (Equation B.1):

$$f_{cd} = \frac{\alpha_{cc} f_{ck}}{\gamma_c} = \frac{f_{ck}}{1.5} \tag{B.1}$$

Design value of tensions strength of concrete:

The tension strength of concrete is significantly lower than the compression strength (approximately 1/10 – 1/15). From tests a relation between the splitting tension strength $f_{ct,sp}$ and the tension strength f_{ct} follows (Equation B.2):

$$f_{ct} = 0.9\, f_{ct,sp} \quad \text{(B.2)}$$

The average tensions strength f_{ctm} follows from the characteristic cylindrical compression strength for strength classes up to and including C50/60 (Equation B.3), and from the average cylindrical compression strength for strength classes above (Equation B.4):

$$f_{ctm} = 0.30\, f_{ck}^{(\frac{2}{3})} \quad \text{for strength classes} \leq \text{C50/60} \quad \text{(B.3)}$$

$$f_{ctm} = 2.12 \ln(\, 1 + \frac{f_{ctm}}{10}) \quad \text{for strength classes} > \text{C50/60} \quad \text{(B.4)}$$

The relation between the average and characteristic cylindrical compression strength is expressed in Equation B.5:

$$f_{cm} = \ f_{ck} + 8 \text{ N/mm}^2 \quad \text{(B.5)}$$

The characteristic lower limit of the tensions strength equals (Equation B.6):

$$f_{ctk,0.05} = 0.7\, f_{ctm} \quad \text{(B.6)}$$

The tension strength of concrete depends on the speed of loading. When loading the concrete with a very low speed, the strength of the concrete will be approximately 30% lower.

In order to calculate the design value of the tension strength of concrete, the lower limit of the tension strength should be divided by the material factor γ_c (=1.5) and should be multiplied by factor α_{ct} (=1.0). This result in a design value for the tension strength of concrete, expressed in Equation B.7:

$$f_{ctd} = \frac{\alpha_{ct} f_{ctk,0.05}}{\gamma_c} = \frac{f_{ctk,0.05}}{1.5} \quad \text{(B.7)}$$

B.2 Modulus of elasticity

According to NEN-EN 1992-1-1, the modulus of elasticity can be calculated according to Equation B.8:

$$E_{cm} = 22000 * \left[\frac{f_{cm}}{10}\right]^{0.3} \quad \text{(B.8)}$$

B.3 Stress-strain diagram

For all strength classes up C50/60, the stress-strain diagram is shown in Figure B.1:

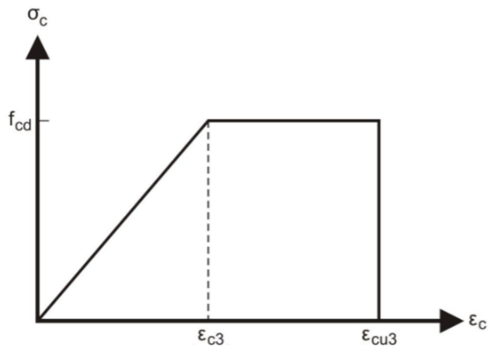


Figure B.1 Stress-strain diagram of concrete (Reprinted from: Braam, Lukovic, 2019)

Until strength class C50/60, the following values are determined:

ε_{c3} = 1.75‰ (beginning of plastic deformation)

ε_{cu3} = 3.50‰ (limit of concrete 'stuik')

B.4 Stiffness

Stiffness is the resistance against deformations. The stiffness of concrete depends on the strength class which is not the case for the stiffness of steel. The stiffness is expressed in the modulus of elasticity (Braam, Lagendijk, 2011).

B.5 Environmental classes

NEN-EN 206-1 distinguishes 18 different environmental classes which are based on the chance of deterioration of the reinforcement, and deterioration of the concrete by frost or chemicals. The 18 environmental classes are divided in 6 main groups:

- No chance of corrosion or deterioration;
- Corrosion initiated by carbonation;
- Corrosion initiated by chlorides, no seawater;
- Corrosion initiated by chlorides from seawater;
- Deterioration by frost and thaw cycles;
- Chemical deterioration.

Table B.1 shows the environmental classes as described in NEN-EN 206-1.

Table B.1 Environmental classes (Adapted from NEN-EN 206-1)

Environmental class	Description environment	Examples environment
1. No chance of corrosion or deterioration		
X0	Concrete without reinforcement, all environmental influences except frost/thaw, and chemical deterioration Concrete with reinforcement in very dry environment	Concrete inside buildings with low humidity
2. Corrosion initiated by carbonation		
Concrete with reinforcement faced to air and moisture		
XC1	Dry or continuously wet environment	Concrete inside buildings with low humidity Concrete continuously under water
XC2	Wet, rarely dry	Concrete surfaces with long-term water contact Foundations

XC3	Moderate humidity	Concrete inside buildings with moderate or high humidity Concrete outside sheltered from rain
XC4	Varying dry and wet	Concrete surfaces with water contact, not belonging to XC2
3. Corrosion initiated by chlorides, no seawater		
Concrete reinforcement faced to water including chlorides originating from seawater		
XD1	Moderate humidity	Concrete surfaces faced to chlorides originating from air
XD2	Wet, rarely dry	Swimming pools, Concrete faced to chloride-containing water from industry
XD3	Varying dry and wet	Bridge elements faced to chloride-containing water Hardenings Floors of parking places for vehicles
4. Corrosion initiated by chlorides from seawater		
Concrete reinforcement faced to chlorides from seawater or air containing salts from seawater		
XS1	Faced to salts from air, not directly in contact with seawater	Structures in coastal areas
XS2	Continuously in seawater	Parts of structures in seawater
XS3	Tide-, splash-, drift zones	Parts of structures in seawater
5. Deterioration by frost- and thaw cycles		
Concrete reinforcement faced to significant frost- and thaw cycles while being wet		
XF1	Not fully saturated with water, without de-icing salts	Vertical concrete surfaces faced to rain and frost
XF2	Not fully saturated with water, with de-icing salts	Vertical concrete surfaces of road constructions faced to frost and de-icing salts carried by air
XF3	Saturated with water, without de-icing salts	Horizontal concrete surfaces faced to rain and frost
XF4	Saturated with water, with de-icing salts or seawater	Roads and bridge decks faced to de-icing salts Concrete surfaces faced to directly spayed de-icing salts and frost Splash zones of structures in sea faced to frost
6. Chemical deterioration		
Concrete faced to chemical deterioration by ground and groundwater		
XA1	Weakly aggressive chemical environment	Concrete faced to natural ground and groundwater
XA2	Moderate aggressive chemical environment	Concrete faced to natural ground and groundwater
XA3	Strongly aggressive chemical environment	Concrete faced to natural ground and groundwater

B.6 Fire resistance of concrete structures

Fire is an extraordinary load which a concrete structure should withstand. The check for fire protection is always in the ultimate limit state (ULS), in which deflection are not relevant (Sagel et al, 2013).

The behaviour of a structure during fire depends on the thermal load, fire scenario. Often the standard fire curve is used which describes the fire from moment of flashover, shown in Figure B.2 (Breunese, Maljaars, 2015). This fire curve is described by the relationship (NEN-EN 13501-2) expressed in Equation B.9:

$$T = 345\, log_{10}\,(8t + 1) + 20 \quad \text{(B.9)}$$

In which: t time from start of the test in minutes (min);
T mean furnace temperature in degrees Celsius (^{o}C).

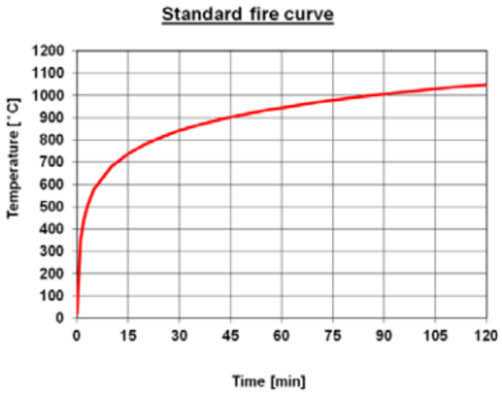


Figure B.2 Standard Fire Curve (Reprinted from Breunese, Maljaars, 2015)

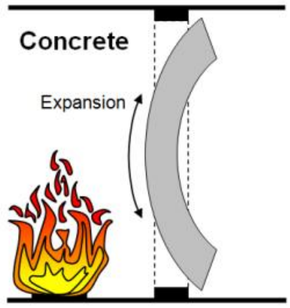


Figure B.3 Expansion of concrete towards the fire (Reprinted from Breunese, Maljaars, 2015)

Fire resistance of a structure is the ability of a construction to maintain its function during fire. The resistance to fire is expressed in minutes. At the side of the concrete element which is exposed to fire, moisture will evaporate. Concrete will expand during fire conditions and deforms towards the fire as shown in Figure B.3 (Breunese, Maljaars, 2015). In order to have sufficient resistance to maintain its function, NEN-EN 1992-1-2:2021 requires minimum dimensions of concrete structural elements in order to have sufficient resistance against fire. For example, the NEN-EN 1992-1-2:2021 distinguishes minimum dimensions for concrete columns when exposed to fire on four sides and exposed to fire on one side. NEN-EN 13501-2:2021 classifies fire scenarios for concrete structural elements and their performance characteristics. The most important performance characteristics of structural concrete elements exposed to fire are the load-bearing capacity (R), the integrity (E), and the thermal insulation (I). For loadbearing elements, three classes are distinguished in NEN-EN 13501-2:2021:

REI *tt* — *tt* is the classification period during which all criteria loadbearing capacity integrity and thermal insulation are satisfied;

RE *tt* — *tt* is the classification period during which the criteria loadbearing capacity and integrity are satisfied;

R *tt* — *tt* is the classification period during which the criterion loadbearing capacity is satisfied.

The Dutch Bouwbesluit Brandveiligheid describes the design rules about fire safety according to norms. The fire resistance depends on the required time to flee the building which is determined by the height of a building, the function of the building, and the permanent fire loading (Sagel et al, 2013; Boot-Dijkuis et al, 2014). For utility buildings, the requirements for fire resistance depends on whether the utility building has a sleeping function not. Therefore the requirements which are given in the Dutch Bouwbesluit Brandveiligheid are shown in Table B.2 and Table B.3:

Table B.2 Requirements fire resistance of utility buildings with sleeping function (Adapted from Boot-Dijkhuis et al, 2014)

Height of highest floor relative to the entrance of the building	Fire resistance regarding collapsing of the structure in minutes	Reduced fire resistance regarding collapsing of the structure due to a permanent fire loading (≤ 500 MJ/m²)
≤ 5 m	60	30
5 – 13 m	90	60
>13 m	120	90

Table B.3 Requirements fire resistance of utility buildings without sleeping function (Adapted from Boot-Dijkhuis et al, 2014)

Height of highest floor relative to the entrance of the building	Fire resistance regarding collapsing of the structure in minutes	Reduced fire resistance regarding collapsing of the structure due to a permanent fire loading (≤ 500 MJ/m²)
≤ 5 m	0	0
>5 m	90	60

A building is divided in multiple fire compartments based on the maximum allowed area of a fire compartment, possibility of taking care of people in another building compartment, and the presence of rooms with an increased risk for fire (Boot-Dijkuis et al, 2014). Table B.4 shows the maximum area of a fire compartment for utility buildings with several functions.

Table B.4 Requirements fire resistance of utility buildings without sleeping function (Adapted from Boot-Dijkhuis et al, 2014)

User function	Maximum area of a fire compartment	Description
Lodging function	500 m²	
Cell function: fire compartment with cells	500 m² + maximum of 77% of the user area of the building	77% because of evacuating people from the compartment with fire
Health function: fire compartment with area for beds	1000 m² + maximum of 77% of the user area of the building	77% because of horizontal evacuation of people from the compartment with fire
Other functionality	1000 m²	

Fire safety requirements NEN-EN 1992-1-2

In NEN-EN 1992-1-2 requirements for minimum dimensions of elements and reinforcement distance are given depending on the required fire resistance. Based on the required fire resistance for utility buildings, the required dimensions and detailing can be checked with the element analysed for reusage. Since the required fire resistance regarding collapsing of the structure due to a permanent fire loading has a maximum of 90 minutes for utility buildings, only requirements for concrete elements for resistances of 30 minutes, 60 minutes, and 90 minutes are shown in the following tables. Since the elements with a future function as one-way supported floor elements, beams, and columns are included in this research, the detailing rules regarding fire protection are given for those elements.

In Table B.5, the minimum dimensions and reinforcement distance for free, one-way supported monolith floor elements are given.

Table B.5: Fire safety requirements one-way supported monolith floor elements (Adapted from Braam, 2010)

Fire resistance regarding collapsing of the structure due to a permanent fire loading (≤ 500 MJ/m²)	Minimum height/thickness of floor element *h* (mm)	Minimum reinforcement distance *a* (mm)
REI 30	60	10
REI 60	80	20
REI 90	100	30

Table B.6, shows the minimum dimensions and reinforcement distance for rectangular and circular beams which are statically determined.

Table B.6: Fire safety requirements beams (Adapted from Braam, 2010)

Fire resistance regarding collapsing of the structure due to a permanent fire loading (≤ 500 MJ/m²)	Possible combinations of width of beam *w* (mm) and reinforcement distance *a* (mm)			
R 30	*w* = 80 *a* = 25	120 20	160 15	200 15
R 60	*w* = 120 *a* = 40	160 35	200 30	300 25
R 90	*w* = 150 *a* = 55	200 45	300 40	400 35

In order to check columns in fire situations, the buckling length is an important factor. Table B.7, showing the dimensions and reinforcement distance for braced columns related to the fire resistance, can be used if:

1. The buckling length under fire conditions $l_{buc,fi}$ ≤ 3.0 m. When the required fire resistance is higher than 30 minutes, a buckling length of half the length of the column can be used.
2. The first-order eccentricity under fire conditions $e = \frac{M_{0Ed,fi}}{N0Ed,fi} \leq e_{max}$

   Column width < 300 mm: e_{max} = 0,15 *h*

   Column width ≥ 300 mm: e_{max} = 0,4 *h*

   It can be assumed that the first order eccentricity during fire is the same as in normal temperature conditions.
3. The reinforcement ratio is smaller than 4%

It is assumed columns are exposed to fire at multiple sides of the column.

Table B.7: Fire safety requirements columns (Adapted from Braam, 2010)

Fire resistance regarding collapsing of the structure due to a permanent fire loading (≤ 500 MJ/m²)	Possible combinations of width of column *w* (mm) / reinforcement distance *a* (mm) based on loading ratio μ_{fi}		
	μ_{fi} = 0.2	μ_{fi} = 0.5	μ_{fi} = 0.7
REI 30	200/25	200/25	200/32 300/27
REI 60	200/25	200/36 300/31	250/46 350/40
REI 90	200/31 300/25	300/45 400/38	350/53 450/40

The loading ratio $\mu_{fi} = \frac{N_{ed,fi}}{N_{Rd}}$ (for calculation of the normal force under fire conditions, loading factors equals 1 and factor Ψ_2 should be used).

C. 10R Model of circularity and examples from practice

The 10R Circular Model is developed by Prof. Dr. Jacqueline Cramer. She is professor in durable entrepreneurship and former minister of VROM (public housing and spatial planning). The model consists of ten steps in which the top step is the most circular option and the bottom step the least circular (linear) option (IsoBouw, 2021). In practice the 10R Circular Model is often used in order to see the circular possibilities of a building or structure. The 10R model is visualised in Figure C.1.

In this section some circular projects are explained and linked to the top three circular strategies of the 10R Circular Model.

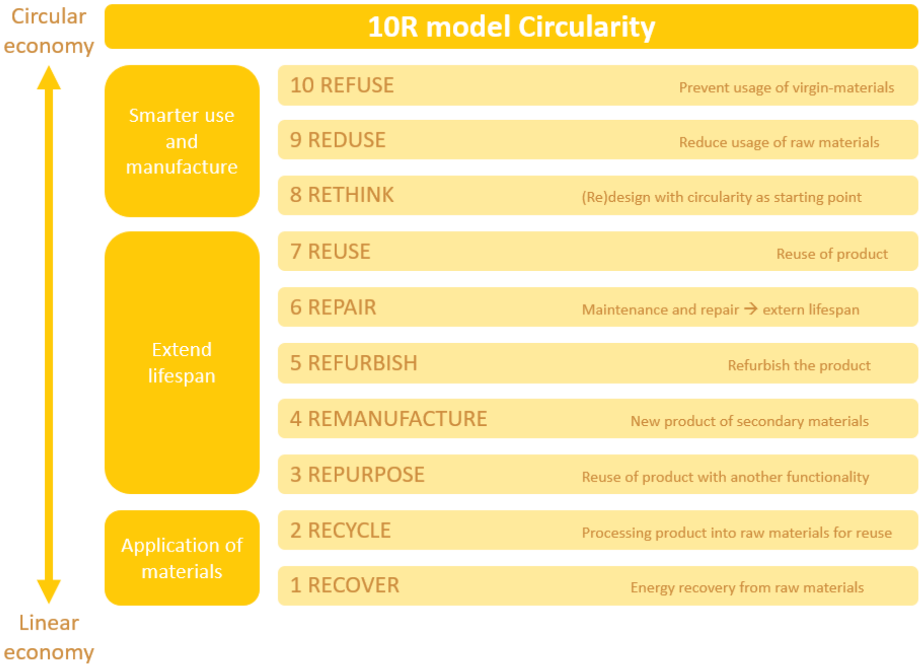


Figure C.1 10R Model of Circularity (Adapted from Archipunt, 2021)

C.1 REFUSE - Spinoza building – Nijmegen

The Spinoza building is located at the campus of Radboud University Nijmegen and was the former faculty building of social sciences, shown in Figure C.2. Nowadays the faculty is located in another building at the campus and the low-rise part of the building has been demolished. The high rise part of the building is currently empty.

Figure C.2 Refuse - Spinoza building (Reprinted from Heijmans Utiliteit B.V. Internal document, 2021)

Heijmans investigated the possibilities for reusing the structure of the Spinoza building when creating a new office building. This scenario is compared to the scenario in which the current structure will be demolished and a new building will be realized. When designing a new office building, the environmental impact can be reduced when recycling materials or reusing elements. The chosen structure typology will highly contribute to the environmental impact. The use of concrete in a new construction will result in the highest shadow costs, followed by the steel frame variant. Building in wood will result in the lowest environmental impact, therefore Heijmans advised to build a new structure in wood if a new construction is preferred (Heijmans Utiliteit B.V. Internal document, 2021).

With this research Heijmans gave insight in the environmental impact of new options for the building. This insight in the options and the environmental impact let the Utility department of the university rethink and eventually lead to no demolishment of the building. This is eventually a good example of a project in which the demolishment of the current building, and the execution of a building with new materials is *refused.*

C.2 REDUCE - Concrete casco of a warehouse – Amstelveen

The warehouse building (former V&D building) in Amstelveen is fully stripped till the concrete casco. This casco consists of mushroom-columns and cassette floors which are used in the renovation project designed by architect Rijnboutt. Using the current casco a new warehouse is created in which the structure is part of the interior, as shown in Figure C.3. By using the casco in the new warehouse building, the usage of new building materials for the structure is r*educed* (Heijl, 2021).

Figure C.3 Reduced - existing concrete casco (Reprinted from Heijl, 2021)

C.3 RETHINK - Concrete structure of historic shed - Rotterdam

The historical sheds Feniks I and Feniks II are built in 1922 since the Holland-America line was expanded. Two railway lines ran through the sheds and freight elevators were available for loading and unloading the trucks. Therefore the concrete foundation and structure is quite robust. On top of the Feniks I shed, office spaces and apartments are realized. In order to do so, a new steel table structure is placed above the existing concrete structure. In the original shed Feniks I an art school, dance school and circus school should be housed. Extra height was necessary for trapezes. This is solved by breaking some parts of the structure in order to create vides as shown in Figure C.4 (Kempenaar, 2022).

Figure C.4 Rethink - existing concrete structure (Reprinted from Kempenaar, 2022)

These examples shows that a building and structure can still be functional by *rethinking* and redesigning.

D. Background information Reusability Tool

In this appendix background information is included which is used for the development of the Reusability Tool. In Section D.1 the residual lifespan of a concrete structural element is explained, based on element condition. In Section D.2 details about deconstruction techniques, depending on element type are described which are included in the Reusability Tool. Besides, the environmental data used for environmental impact calculations is included in Section D.3. Since the building codes have been changed over the years, the evolution of building codes is explained in Section D.4. The reinforcement detailing rules according to NEN-EN 1992-1-1 which are included in the Reusability Tool are explained in Section D.5. Finally, the visualizations of the two monolith floor types and support systems which included in the tool are shown in Section D.6.

D.1 Residual lifespan

The residual lifespan indicates the lifespan of the reused element. There are several ways to indicate the residual lifespan of a structural element. Therefore, this appendix shortly addresses some calculation methods of the residual lifespan.

D.1.1 Residual lifespan – NEN 2767

NEN 2767 describes a method to define the residual lifespan of a structural element based on the technical lifespan and the condition of the element. According to NEN 2767 the technical lifespan is defined as: '*the period in which a building or installation component is assumed to be able to maintain a certain technical level.'* The condition of the element is determined based on a scoring system. Therefore the residual lifespan can only be roughly estimated with this model (Van Berlo, 2019; NEN 2767-1+C1:2019). The development of the condition of a structural element as a function of the lifespan is shown in Figure D.1.

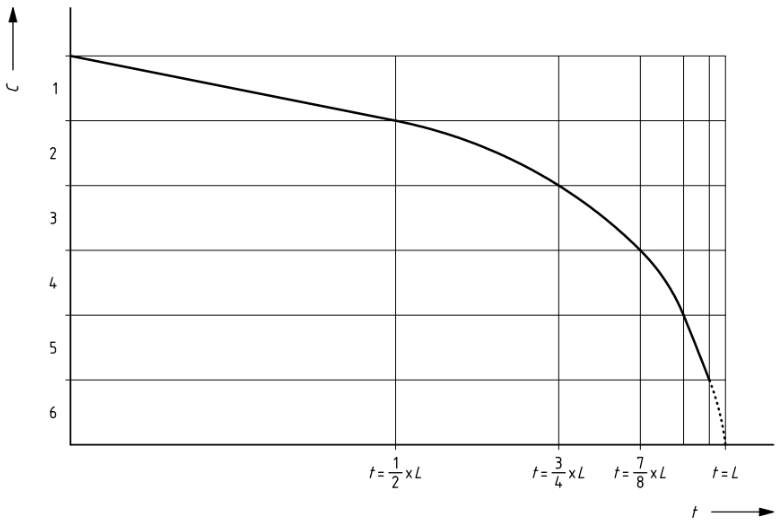


Figure D.1 Theoretical development of the condition as a function of lifespan (Retrieved from NEN 2767-1+C1:2019)

Based on those factors, the age of the element can be calculated using Equation D.1:

$$t = L - (L * \frac{1}{2}^{(C-1)}) \quad \text{(D.1)}$$

In which: C condition score of the structural element

t age of the structural element

L technical lifespan of the structural element

Condition score (NEN 2767)

In this research, the residual lifespan is calculated based on condition scores described in NEN 2767. The scoring system, used in this research, is shown in Table D.1.

Table D.1: Scoring system condition

Score 1 – Excellent condition	Input
Visibility of aging	No defects as result of aging
Visibility of defect	Slight damage/ damage of aesthetic nature
Visibility of external corrosion	No visible corrosion
Score 2 – Good condition	**Input**
Visibility of aging	First signs of aging
Visibility of defect	Degradation of material only occasionally
Visibility of external corrosion	No visible corrosion
Score 3 – Reasonable condition	**Input**
Visibility of aging	Aging starts locally
Visibility of defect	Degradation of material, locally
Visibility of external corrosion	Pitting of concrete surface; Delamination of concrete surface
Score 4 – Poor condition	**Input**
Visibility of aging	Regular occurrences of aging process
Visibility of defect	Degradation of material, regularly
Score 5 – Bad condition	**Input**
Visibility of aging	Aging process has become almost irreversible
Visibility of defect	Degradation of material to considerable extent
Score 6 – Very bad condition	**Input**
Visibility of defect	Maximum defect finding
Visibility of external corrosion	Spalling of concrete; Brown/red colour on concrete surface

D.1.2 Residual lifespan – CUR-recommendations

Besides, the residual lifespan can be determined based on CUR-recommendations 121. The reinforcement of a concrete structural element can potentially be corroded while it is not visible from the outside. Therefore the CUR-A-121 describes calculation methods indicating the time chlorides and carbonates can affect the reinforcement of a concrete structural element. For example, Nebest uses these calculation methods during their inspections to check the potential of corrosion.

Chlorides can affect the reinforcement. Especially structures which are partly constructed in water or structures which have been in contact with seawater should be checked for chlorides penetration. Based on potential chlorides penetration, the residual lifespan of a structure can be calculated according to Equation D.2 (Van Berlo, 2019 ; Nebest, 2022a):

$$C(x,t) = C_s - (C_s - C_i) * \mathrm{erf}(\frac{x}{\sqrt{4 * D_a * t}}) \qquad (D.2)$$

In which: C_s apparent chloride content

C_i initial chloride content

x depth

t	age
D_a	diffusion coefficient

Next to chlorides, carbonation can cause deterioration of the reinforcement. By covering the reinforcement, the penetration time of carbonation will be lower and therefore the corrosion risk can be reduced (Van Berlo, 2019). The CUR-Recommendation describes Equation D.3 for calculating the residual lifespan based on carbonation (Nebest, 2022a).

$$\left[\left(\frac{x_m}{x_{c,m}}\right)^2 - 1\right] * t_{insp} \qquad \text{(D.3)}$$

In which:

x_m	average concrete cover
$x_{c,m}$	average carbonation depth
t_{insp}	age structure at time of inspection

The residual lifespan can therefore be calculated based on the technical lifespan and condition score as described in NEN 2767-1+C1:2019. Besides, the residual lifespan can be indicated based on calculation methods for corrosion of the reinforcement of concrete elements as described in CUR-Recommendations.

In the Netherlands, the following postcodes refer to coastal areas (Bouwens, 2022):

2000-2799;
2900-3299;
4300-4699;
8600-9299;
9600-9999.

D.2 Deconstruction techniques

The way of deconstruction strongly depends on the element to be deconstructed. In Chapter 3, the main process of deconstruction is explained which holds for all analysed structural elements, shown in Figure D.2. Based on interviews with demolition contractors, more specific processes of deconstruction are explained for floor elements, columns, and beams.

Figure D.2: Deconstruction process (Own figure)

Moreover, the sawing time of a structural element depends on the element dimensions, amount of connections, and connection types. Therefore, the sawing rate differs per connection type. In case of floor elements it is possible to analyse monolith linearly supported floors which are supported by line supports, or to analyse monolith flat sab floors which are supported by point supports. For beams and columns, point supports are used. This results in the following assumptions shown in Table D.2:

Table D.2: Sawing rates

Environmental impact	Input
Sawing rate fixed line support	1/3 hour/m
Sawing rate hinged line support	1/6 hour/m
Sawing rate no support	1/6 hour/m
Sawing rate fixed point support	½ hour/m
Sawing rate hinged point support	1/3 hour/m
Economic impact	**Input**
Sawing costs fixed line support	€38,50/m
Sawing costs hinged line support	€35,00/m
Sawing costs no support	€35,00/m
Sawing costs fixed point support	€57,75/support
Sawing costs hinged point support	€52,50/support

The type of crane which should be used for hoisting, depends on the weight of the element. A tower crane has a hoisting capacity around 1800 kg. When the weight of the element is below 1800 kg, a tower crane can be used. When the weight is above 1800 kg, a telescopic crane should be used.

In the following sub-sections, the deconstruction of floor elements (Section D.2.1), beams (Section D.2.2), and columns (Section D.2.3) is explained.

D.2.1 Deconstruction of floor elements

The deconstruction process of floor elements includes one additional step: drilling anchors, shown in Figure D.3. When relatively wide and long elements should be hoisted, anchors are necessary in order to attach carrying straps for hoisting. For impact calculations the following assumptions are made, both independent of element dimensions, shown in Table D.3:

Table D.3: Assumptions deconstruction - floor elements

Environmental impact	Input
Drilling time anchors	1 hour/element
Economic impact	**Input**
Drilling costs anchors	€50,00/element

Figure D.3: Deconstruction process - floor elements (Own figure)

D.2.2 Deconstruction of beams

In case of deconstruction of beams, it is important to first saw concrete around the connections and saw the crossing elements, before sawing the connections. The process is shown in Figure D.4. When the beam is fully integrated with other elements a factor is used for calculating the sawing time. Therefore, for the impact calculations the following assumptions are made, shown in Table D.4:

Table D.4: Assumptions deconstruction - beams

Environmental impact	Input
Calculation factor full integration	1.1
Sawing rate crossing element	1 hour/crossing element

Economic impact	Input
Calculation factor full integration	1.1
Sawing costs crossing element	€50,00/crossing element

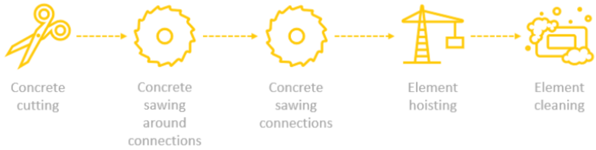


Figure D.4: Deconstruction process - beams (Own figure)

D.2.3 Deconstruction of columns

The deconstruction process of columns includes an additional step compared to the deconstruction process of beams, as shown in Figure D.5. Since in concrete structures in the 70s/80s often drop panels were used, these should be carefully removed. Therefore, if drop panels are present these should be sawn before sawing the crossing elements and concrete around the connections. For the impact calculations, the following assumptions have been made, shown in Table D.5:

Table D.5: Assumptions deconstruction - columns

Environmental impact	Input
Calculation factor full integration	1.1
Sawing rate crossing element	1 hour/crossing element
Sawing rate drop panels	½ hour/drop panel
Economic impact	**Input**
Calculation factor full integration	1.1
Sawing costs crossing element	€50,00/crossing element
Sawing costs drop panels	€30,00/drop panel

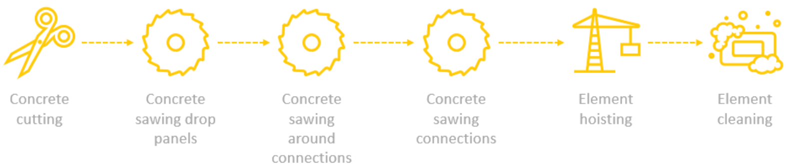


Figure D.5: Deconstruction process - columns (Own figure)

D.3 Environmental data

In this research, environmental data of the Nationale Milieudatabase is used for the calculation of the environmental impact of the circular strategies, expressed in an ECI value (€). This database contains environmental data of structural elements and materials, and processes like sawing with a concrete saw.

In EN 15804:2012, 11 impact categories are included for calculating the environmental impact. From January 2021, 19 impact categories should be used for calculating the environmental impact according to EN 15804:2012+A2:2019. Table D.6 shows the impact categories according to EN 15804:2012, and Table D.7 shows the impact categories according to EN 15804:2012+A2:2019.

Table D.6 Impact categories according to EN 15804:2012

Impact category	Indicator	Unit equivalent	Weight factor [€/kg equivalent]
Depletion of abiotic resources-elements	ADP-elements	kg Sb eq.	€0,16
Depletion of abiotic resources-fossil fuels	ADP-fossil-fuels	kg Sb eq.	€0,16
Acidification for soil and water	AP	kg SO_2 eq.	€4
Ozone Depletion	ODP	kg CFC 11 eq.	€30
Global Warming	GWP-100	kg CO_2 eq.	€0,05
Eutrophication	EP	kg $(PO_4)^{3-}$ eq.	€9
Photochemical ozone creation	POCP	kg C_2H_4 eq.	€2
Human Toxicity	HTP	kg 1.4-DB eq.	€0,09
Eutrophication aquatic freshwater	FAETP	kg 1.4-DB eq.	€0,03
Eutrophication aquatic marine	MAETP	kg 1.4-DB eq.	€0,0001
Eutrophication terrestrial	TETP	kg 1.4-DB eq.	€0,06

Table D.7 Impact categories according to EN 15804:2012+A2:2019

Impact category	Indicator	Unit
Climate change - total	GWP-total	kg CO_2 eq.
Climate change - fossil	GWP-fossil	kg CO_2 eq.
Climate change - biogenic	GWP-biogenic	kg CO_2 eq.
Climate change – land use and land use change	GWP-luluc	kg CO_2 eq.
Ozone Depletion	ODP	kg CFC 11 eq.
Acidification	AP	mol H^+ eq.
Eutrophication aquatic freshwater	EP-freshwater	kg PO_4 eq.
Eutrophication aquatic marine	EP-marine	kg N eq.
Eutrophication terrestrial	EP-terrestrial	mol N eq.
Photochemical ozone formation	POCP	kg NMVOC eq.
Depletion of abiotic resources – minerals and metals	ADP-minerals&metals	kg Sb eq.
Depletion of abiotic resources – fossil fuels	ADP-fossil	MJ net cal. Val
Water use	WDP	m^3 world eq. deprived
Particulate matter emissions	PM	Disease incidence
Ionising radiation, human health	IRP	kBq U235 eq.
Ecotoxicity (freshwater)	ETP-fw	CTUe
Human toxicity, cancer effects	HTP-c	CTUh
Human toxicity, non-cancer effects	HTP-nc	CTUh
Land use related impacts / soil quality	SQP	dimensionless

Since environmental data including 19 impact categories is not available or public yet, 11 impact categories are used in the Reusability Tool. The used environmental data is listed in Table D.8. All used data is of category 3, which is brand-unrelated data and property of Stichting NMD. This data is not tested according to the NMD protocol, resulting in some uncertainties. However, due to the fact this data is band-unrelated, it is the only data which is public.

Table D.8: Environmental data used in Reusability Tool

Material/Process	Environmental data (NMD)	Product part	Life cycle phases	Unit
Data independent of element type and concrete strength				
Scaffolding	Tijdelijke stalen stempel buispaal	Stalen buispaal	A1:A3, A5, D	m
		Transport	A4, A5, C2	m
Concrete cutting	Slopen (Graafmachine met sloophamer/knijper/grijper, hydraulisch (diesel))		A5	h
Concrete sawing/ Drill anchors/ Reshape element/ Creating openings	Asfalt-betonzaag (diesel)	Bewerken	A5	h
Concrete crushing/ Preparing rubble	Graafmachine klein (diesel)	Verplaatsen	A5	h
Data dependent of weight of element / amount of concrete				
Transport elements	Transport met vrachtwagen, EURO 4, diesel	Wegtransport	A1:A3	tkm
Transport in-situ concrete	Truck mixer 6m3	Wegtransport	A1:A3	m3km
	Truck mixer 10m3	Wegtransport	A1:A3	m3km
	Truck mixer 13.5m3	Wegtransport	A1:A3	m3km
Hoisting	Torenkraan (diesel)	Hijsen	A5	h
	Telekraan (diesel)	Hijsen	A5	h
Production (in-situ)	Cement	CEM I	A1	kg
		CEM III/A	A1	kg
		CEM III/B	A1	kg
	Sand	Sand, crushed	A1	kg
	Gravel/granulate	Gravel, crushed	A1	kg
		Granulate, recycled	A1	kg
Data dependent of concrete strength				
Production (in-situ)/ Additional concrete cover	Beton, in het werk gestort, C20/25; incl. wapening	Betonmortel	A1:A3, A4, C2, C3	kg
		Wapening	A1:A3, A4, C3, C4, D	kg
	Beton, in het werk gestort, C30/37; incl. wapening	Betonmortel	A1:A3, A4, C2, C3	kg
		Wapening	A1:A3, A4, C3, C4, D	kg
Production (prefab)	Prefab beton, C45/55; incl. wapening	Prefab beton C45/55	A1:A3	kg
		Wapeningsstaal	A1:A3	kg

D.4 Evolution of building codes

The general rules for designing and calculating concrete structures are described in Eurocode 2. This code is valid since 2012. Utility buildings constructed during the 70s/80s can therefore not be designed according to this code. In 1912 the first general rules for concrete structures were published, called the Gewapend Beton Voorschriften (GBV). After that, new versions were published in 1918, 1930, 1940, 1950, and 1962. During the years multiple additions were made. In versions of 1918 and 1930 not that much was adapted. In GBV 1940 the allowable tensions were increased because of new steel grades. Some important additions in the GBV of 1962 were the maximum crack width, stiffness, and minimum reinforcement percentage. Most concrete utility buildings constructed during the 70s/80s are based on those rules. In 1974/1984 new rules were published called Voorschriften Beton (VB) including information about prefab concrete and prestressed concrete. The Voorschriften Beton Constructies (VBC) published in 190/1995 includes detailed information about the construction process (Van Uffelen, 2012).

In Section D.4.1 concrete compression properties and rules are explained according to the different building codes. Besides, the reinforcement tension properties are explained in Section D.4.2. To see the results of element dimensions according to the different codes, Section D.4.3 shows some examples.

D.4.1 Concrete compression properties

Concrete compositions and their naming were different compared to the Eurocode of 2012. Therefore, rules for compression strength of concrete of GBV 1962, VB1974/1984, VBC 1995, and EC 2012 were compared in Table D.9.

Table D.9 Concrete compression strength properties (adapted from Van Uffelen, 2012)

Code	Strength class concrete	Cube strength (kg/cm^2)	Allowable compression stress (kg/cm^2)	Design value compression stress (kg/cm^2)	Safety factor
GBV 1962	K160	168[1]	40	-	4.2
	K225	236[1]	55	-	4.3
	K300	315[1]	75	-	4.2
VB 1974/1984	B30	375	-	180	3.6
	B45	525	-	270	3.2
	B60	675	-	360	3.2
VBC 1995	B25	330[2]	-	150	3.0
	B45	530[2]	-	270	2.7
	B65	730[2]	-	390	2.6
EC 2012	C25/30	380[2]	-	167	3.1
	C35/45	530[2]	-	233	3.1
	C45/55	630[2]	-	300	2.8

1) The cube strength is the average strength received by tests after 28 days.

2) In EC 2012 a cylindrical strength is used instead of a cube strength. For comparison the cylindrical strength has been converted to cube strength.

During her research, Bouwens compared the concrete grades to the grades described in Eurocode 2 of 2012. Table D.10 shows the comparison of the concrete grades (Bouwens, 2022).

Table D.10 Comparison concrete grades old norms with Eurocode 2 (2012) (adapted from Bouwens, 2022)

Old norm	Concrete grade	Concrete grade Eurocode 2 (2012)
GBV 1962	K160	< C8/C10
	K225	C12/C15
	K300	C8/10 – C12/15
VB 1974/1984	B30	C20/25 – C25/30
	B45	C30/37 – C35/45
	B60	C40/50 – C45/55
VBC 1995	B25	C12/15 – C20/25
	B45	C30/37
	B65	C40/50

D.4.2 Reinforcement tension properties

Also the tensile strength of the reinforcement of the concrete has changed over the years. Therefore, the reinforcement steel properties as described in GBV 1962, VB 1974/1984, VBC 1995, and EC 2012 are compared in Table D.11.

Table D.11 Steel tensile strength properties (adapted from Van Uffelen, 2012)

Code	Strength class steel	Yield-/0.2%-strain limit (kg/cm²)	Average tensile stress (kg/cm²)	Allowable tensile stress (kg/cm²)	Design value tensile stress (kg/cm²)	Safety factor
GBV 1962	QR 22	2200	3400	1300	-	2.6
	QR 24	2400	3600	1400	-	2.6
	QR 32 and QRn 32	3200	4200	1800	-	2.3
	QR 40 and QRn 40	4000	5000	2200	-	2.3
	QR 48 and QRn 48	4800	5800	2600	-	2.2
VB 1974/1984	FeB 220 HW	2200	3400	-	1900	3.1
	FeB 400 HW, HWL / FeB 400 HK	4000	5000	-	3500	2.4
	FeB 500 HKN	5000	5800	-	4350	2.2
VBC 1995	FeB 220 HWL	2200	3400	-	1900	2.4
	FeB 400 HWL, HK	4000	5000	-	3500	1.9
	FeB 500 HWL, HK / FeB 500 HKN	5000	5800	-	4350	1.8
EC 2012	FeB 400	4000	5000	-	3500	1.9
	FeB 500 (B500)	5000	5800	-	4350	1.8

During her research, Bouwens compared the reinforcement steel grades to the grades described in Eurocode 2 of 2012. Table D.12 shows the comparison of the steel grades (Bouwens, 2022).

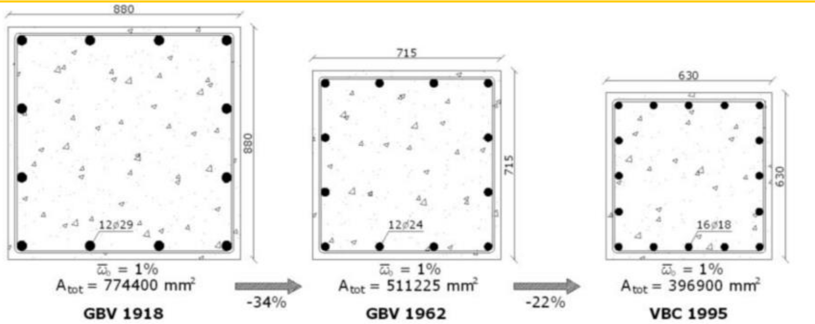
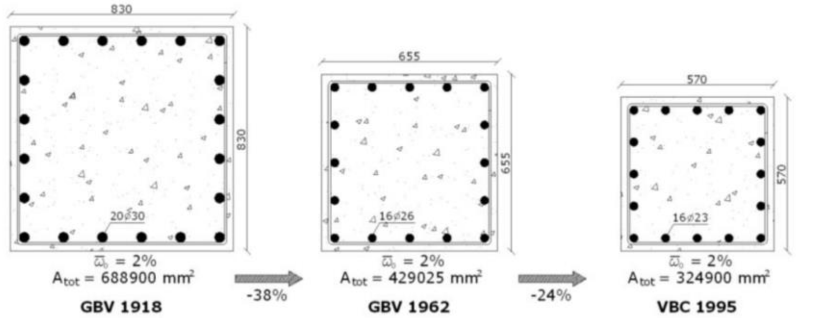
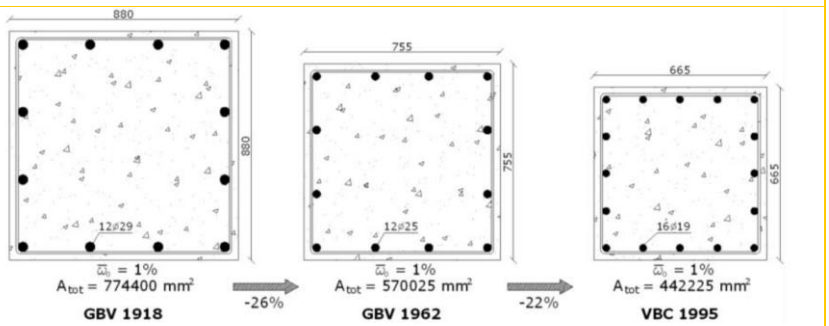
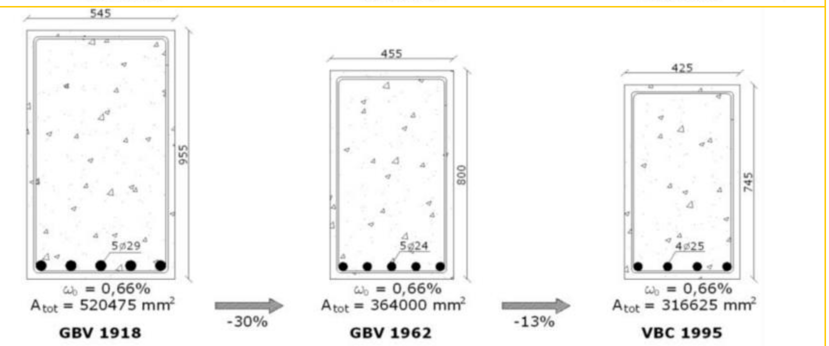
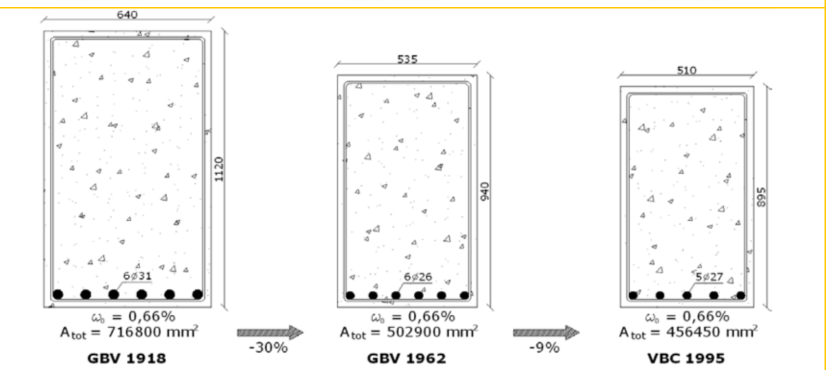
Table D.12 Comparison reinforcement steel grades old norms with Eurocode 2 (2012) (adapted from Bouwens, 2022)

Old norm	Steel grade	Steel grade Eurocode 2 (2012)
GBV 1962	QR 22	FeB 220 HWL
	QR 24	FeB 220 HWL
	QR 32 and QRn 32	FeB 220 HWL
	QR 40 and QRn 40	FeB 220 HWL
	QR 48 and QRn 48	FeB 400 HWL, HK

D.4.3 Changes in dimensions using different codes

Van Uffelen compared the designs of a column and beam according to different codes. From those calculations it can be concluded concrete structures are less robust over the years. Table D.13 shows the reduction of the column- and beam dimensions and their amount of reinforcement.

Table D.13 Reduction dimensions and reinforcement concrete elements (Adapted from Van Uffelen, 2012)

Concrete element	Reduction concrete and reinforcement
Column standard rules	
Column increased reinforcement percentage or reduced steel quality	
Column reinforcement steel grade FeB 220	
Beam standard rules	
Beam reinforcement steel grade FeB 220	

From these calculations it can be concluded that if a reused structural element will be checked according to the current code, and with the same strength as used in the first calculation according to a previous code, a higher load is applicable. In the current code calculations are based on characteristic material properties and therefore the scattering of the strength should be checked. It is expected that the scattering of the strength is higher in old concrete structures (Van Uffelen, 2012).

D.5 Reinforcement detailing

In this section the detailing of reinforcement is explained for concrete structural elements used in utility buildings. Since utility buildings constructed in the 70s/80s are designed according to other codes than Eurocode 2, it is important to check the reinforcement of the structural element with Eurocode 2. Therefore some basic detailing rules are shortly explained (NEN-EN 1992-1-1+C2; Braam & Lagendijk, 2011). In Section D.5.1 all the symbols used for the reinforcement detailing are shortly explained, followed by detailing rules independent of the element type in Section Section D.5.2. Moreover, detailing rules dependent on the element type are explained in Section D.5.3, Section D.5.4, and Section D.5.5.

D.5.1 Symbols

$\varnothing$	diameter of the rebar
d_g	Largest grain size (usually used d_g = 31.5 mm)
$A_{s,min}$	minimum area of the reinforcement in the tension zone
f_{ctm}	average value of axial tension strength of concrete
f_{yk}	characteristic yield-limit of reinforcement
f_{ck}	characteristic cylindrical compression strength of concrete after 28 days
b	total width of concrete cross-section
d	effective height of cross-section
$A_{s,max}$	maximum area of the reinforcement in the tension zone
A_c	area of the concrete cross-section
ρ_w	shear reinforcement ratio
A_{sw}	area of the shear reinforcement within length s
s	spacing of shear reinforcement
b_w	width of the flange of the element
α	angle between the shear reinforcement and longitudinal axis
$\rho_{w,min}$	minimum shear reinforcement ratio
$S_{l,max}$	maximum spacing of shear reinforcement
c_{nom}	nominal thickness of concrete cover
c_{min}	minimum thickness of concrete cover
$c_{min,b}$	minimum thickness of concrete cover based on annexation requirements
$c_{min,dur}$	minimum thickness of concrete cover is based on the environmental class and construction class
Δc_{dev}	execution tolerances

D.5.2 Detailing rules independent of element type

By comparing the reinforcement of the element with the rules of the Eurocode 2, it can be checked if the reinforcement of an element complies with the current code. First some detailing rules are explained which are independent of the element type.

Concrete cover

The nominal concrete cover is the summation of the minimum thickness of the concrete cover and the execution tolerances, expressed in Equation H.1:

$$c_{nom} = c_{min} + \Delta c_{dev} \quad \text{(H.1)}$$

Minimum thickness concrete cover:

The minimum thickness of the concrete cover should be the maximum value of:

- $c_{min,b}$;
- $c_{min,dur}$;
- *10 mm.*

The minimum cover based on annexation requirements $c_{min,b}$ should not be lower than:

Post-tensioned steel:

- The diameter of the post-tensioned steel with a minimum of 25 mm (circular channels);
- The largest value of the smallest dimension and half of the largest dimension (rectangular channels)

Pre-tensioned steel:

- *1.5 Ø of strand or smooth wires;*
- *2.5 Ø of profiled wires.*

The minimum cover is based on the environmental class and construction class, given by $c_{min,dur.}$ The recommended construction class is S4 (with a design service life of 50 years). The recommended construction classes are shown in Table D.14.

Table D.14 Recommended construction classes (Adapted from NEN-EN-1992-1-1, 2012)

Criterium / Environmental class	X0	XC1	XC3	XC4	XD1	XS1
Design service life 100 years	+ 2 classes	+ 2 classes	+ 2 classes	+ 2 classes	+ 2 classes	+ 2 classes
Strength class	≥ C30/37 + 1 class	≥ C30/37 + 1 class	≥ C35/45 + 1 class	≥ C40/50 + 1 class	≥ C40/50 + 1 class	≥ C45/55 + 1 class
Element with plate geometry	-1 class	-1 class	-1 class	-1 class	-1 class	-1 class
Guaranteed quality control of concrete production	-1 class	-1 class	-1 class	-1 class	-1 class	-1 class

The values of the minimum thickness of the concrete cover $c_{min,dur}$ for the durability of reinforcement (according to EN 10080) are shown in Table D.15.

Table D.15 Minimum thickness of concrete cover for the durability of reinforcement (Adapted from EN 10080)

Construction class / Environmental class	X0	XC1	XC3	XC4	XD1/XS1
S1	10	10	10	15	20
S2	10	10	15	20	25
S3	10	10	20	25	30
S4	10	15	25	30	35
S5	15	20	30	35	40
S6	20	25	35	40	45

D.5.3 Beams

By comparing the reinforcement of the element with the rules of the Eurocode 2, it can be checked if the reinforcement of the beam complies with the current code and if it is suitable for reuse.

Minimum diameters of rebars

The minimum required diameters for rebars and reinforcement meshes are shown in Table D.16.

Table D.16 Minimum required diameters for rebars and reinforcement meshes (Adapted from Braam, Lagendijk, 2011)

	B500 rebars	B500 Reinforcement meshes
Longitudinal reinforcement	8	6
Flange reinforcement	5	5
Stirrups	5	5

Longitudinal reinforcement

Spacing between main rebars (longitudinal reinforcement):

Spacing between main rebars should be the minimum value of:

- Ø
- d_g + 5 mm
- 20 mm

Area of main rebars (longitudinal reinforcement):

The area of the main rebars in longitudinal direction should be the minimum value of:

- $A_{s,min} = 0.26 \frac{f_{ctm}}{f_{yk}} b_t d$
- $0.0013 \, b_t d$
- $1.2 * required\ ULS\ area$ in case of reused elements.

The area of the main rebars in longitudinal direction should be the lower than:

- $A_{s,max} = 0.04 \, A_c$

Shear reinforcement

Shear reinforcement ratio:

The shear reinforcement ratio ρ_w should be the maximum value of:

- $\rho_w = A_{sw} / (s * b_w * \sin\alpha)$
- $\rho_{w,min} = \frac{(0.08\sqrt{f_{ck}})}{f_{yk}}$

Shear reinforcement spacing:

The shear reinforcement spacing should be the minimum value of:

- $s_{I,max} = 0.75\, d\,(1 + \cot\alpha)$
- 300 mm

D.5.4 Columns

By comparing the reinforcement of the element with the rules of the Eurocode 2, it can be checked if the reinforcement of the column complies with the current code and if it is suitable for reuse.

Minimum diameters of rebars

The minimum required diameters for rebars are shown in Table D.17.

Table D.17 Minimum required diameter for column reinforcement (Adapted from Braam & Lagendijk, 2011)

	B500 rebars
Longitudinal reinforcement	8
Stirrups	6 and $\frac{1}{4}$ $\emptyset_{max}$ of longitudinal reinforcement

Longitudinal reinforcement

Spacing between main rebars (longitudinal reinforcement):

Spacing between main rebars should be the minimum value of:

- Ø
- d_g + 5 mm
- 20 mm

Area of main rebars (longitudinal reinforcement):

The area of the main rebars in longitudinal direction should be the minimum value of:

- $A_{s,min} = 0.10\,\frac{N_{ed}}{f_{yd}}$
- $0.002\, A_c$

The area of the main rebars in longitudinal direction should be the lower than:

- $A_{s,max} = 0.04\, A_c$

Shear reinforcement (stirrups)

<u>Shear reinforcement (stirrups) spacing:</u>

The maximum shear (stirrups) reinforcement spacing $s_{cl,tmax}$ should be the minimum value of:

- *20 Ø of the thinnest rebar of the longitudinal reinforcement*
- *Smallest dimension of the column*
- *400 mm*

D.5.5 Floors

By comparing the reinforcement of the element with the rules of the Eurocode 2, it can be checked if the reinforcement of the floor complies with the current code and if it is suitable for reuse.

Minimum diameters of rebars

The minimum required diameters for rebars and reinforcement meshes are shown in Table D.18.

Table D.18 Minimum required diameters for rebars and reinforcement meshes (Adapted from Braam, Lagendijk, 2011)

	B500 rebars	B500 Reinforcement meshes
Main reinforcement	6	5
Dividing reinforcement	5	5

Longitudinal reinforcement

<u>Spacing between main rebars (longitudinal reinforcement):</u>

Minimum spacing between main rebars should be the minimum value of:

- Ø
- d_g + 5 mm
- 20 mm

Maximum spacing between main rebars should be the minimum of:

- 3 *h*
- 400 mm

Maximum spacing between main rebars located at maximum moments and concentrated loads should be the minimum of:

- 2 *h*
- 250 mm

<u>Area of main rebars (longitudinal reinforcement):</u>

The area of the main rebars in longitudinal direction should be the minimum value of:

- $A_{s,min} = 0.26\,\frac{f_{ctm}}{f_{yk}}\,b_t\,d$
- $0.0013\,b_t\,d$

The area of the main rebars in longitudinal direction should be the lower than:

- $A_{s,max} = 0.04\ A_c$

Dividing reinforcement

Dividing reinforcement spacing:

The maximum dividing reinforcement spacing should be the minimum value of:

- 3,5 *h*
- 450 mm

The maximum dividing reinforcement spacing located at maximum moments and concentrated loads should be the minimum value of:

- 3 *h*
- 400 mm

D.6 Monolith floors

In this research two floor types are included, since those types are the most common used in-situ concrete structural elements, in utility buildings constructed in the 70s/80s. A monolith linearly supported floor is supported by line supports (beams). A monolith two-sided linearly supported floor functions as a one-way slab, and a three- or four-sided linear supported floor distributed load in two ways and therefore function as a two-way slab. A monolith flat slab floor is a point supported floor without beams which distributes load in two ways and therefore function as a two-way slab (Braam, Lagendijk, 2011). The two floor types are shown in Figure D.6.

Figure D.6 Floor types included in Reusability Tool

Monolith linear supported floors can be supported in different ways. Therefore, it is important to analyse the support system of the floor element which will be sawn for reusage. The Reusability Tool includes options for one-sided linear supported floor elements, two-sided linear supported floor elements, three-sided supported floor elements, and four-sided supported floor elements.

D.6.1 Support system of linearly supported floors

All the options for one-sided supported floor elements, included in the Reusability Tool are shown Figure D.7. Figure D.8 shows the options for two-sided supported floor elements.

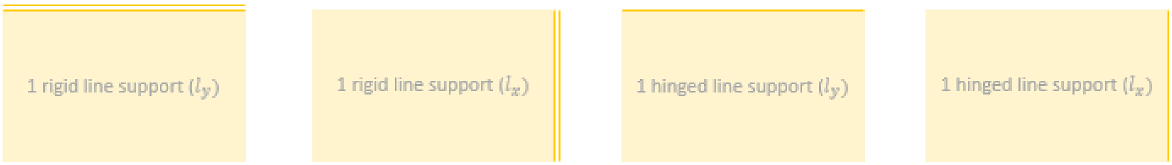


Figure D.7 Options for one-sided supported floor elements (Own figure)

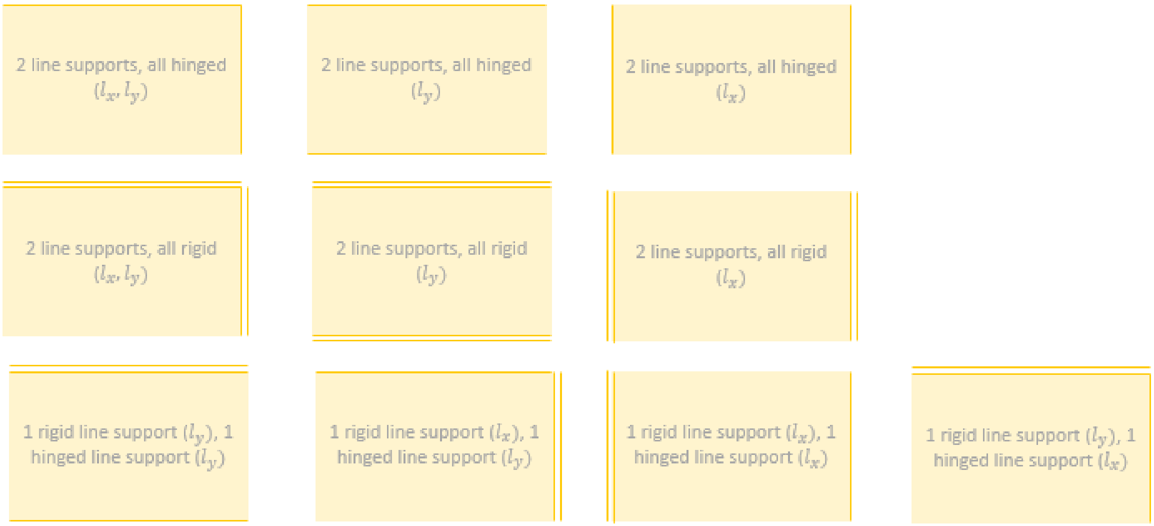


Figure D.8 Options two-sided supported floor elements (Own figure)

All the options for three-sided supported floor elements, included in the Reusability Tool are shown in Figure D.9. In Figure D.10 options for four-sided supported floor elements are visualized.

Figure D.9 Options for three-sided supported floor elements (Own figure)

Figure D.10 Options for four-sided supported floor elements (Own figure)

E. Assessment system of Reusability Tool

In this appendix, the assessment systems of the three main focus points of the Reusability Tool are explained. In Section E.1, the assessment of structural safety is explained. Section E.2 explains the calculation and assessment of the environmental impact and in Section E.3 the calculation of the economic impact is explained.

E.1 Assessment of structural safety

The structural safety is assessed based on the condition of the element and the structural applicability. For analysing the condition of the element, the same criteria will be used for all element types. The structural applicability strongly differs per structural element. Therefore, the assessment of the structural applicability is explained per element type. When analysing the condition of the element, the presence of toxic substances and the potential presence of deterioration is checked. In order to assess the structural applicability, the reinforcement detailing and loading capacity of the element is analysed. The total process is shown in Figure E.1.

Figure E.1 Assessment of structural safety

E.1.1 Condition

The condition is analysed for the presence of toxic substances and potential deterioration.

Toxic substances

When analysing the presence of toxic substances it should be checked if there is a potential of presence of chlorides. There is only a chance of chloride attack when the element is from a coastal area. Therefore, only elements from a coastal area should be further checked for chlorides (Van Berlo, 2019). Besides, it should be checked if the current structure has an asbestos free certificate. If this is not the case, the presence of asbestos should be checked on site.

Deterioration

Next to the presence of toxic substances, the potential deterioration of the element should be analysed. First the visibility of aging should be assessed as described in NEN 2767 resulting in a condition score. When no defects are visible as a result of aging, the score 1 is assigned. If first signs of aging are visible a score of 2 is assigned and when the aging has been started locally even a score of 3 can be applied. Regular occurrences of the aging process are visible leads to a condition score of 5 and when the aging process has become almost irreversible a score of 6 is assigned. Next to the visibility of aging, the visibility of defects should be checked. When only slight damage of aesthetic nature is visible, a score of 1 is assigned. Occasionally degradation of material leads to a score of 2, locally degradation to a score of 3, and regularly degradation leads to a score of 4. When degradation occurred to a considerable extent, a score of 5 will be assigned and maximum defect finding leads to a score of 6. Another aspect affecting the condition score is the visibility of external corrosion. When no corrosion is visible a score of 1 is assigned. Pitting of the concrete surface or delamination results in a score of 3. When spalling occurred or brown/red colour is visible on the surface, a score of 6 is assigned.

The visibility of aging, defects, and external corrosion leads to three condition scores. For the calculation of the residual lifespan, the maximum score of the three assigned scores will be used (the worst scenario). The calculation process of the residual lifespan is explained in Appendix D.1.

Next to deterioration aspects which are used for the calculation of the residual lifespan, cracks in the element should be analysed. Crackpatterns can be a warning for internal deterioration like Alkali-Silica Reaction (ASR) or Sulphate attack. Inhomogeneous anisotropic cracks in a map pattern types ASR reaction and inhomogeneous anisotropic cracks in a tree-shape pattern can be a sign of sulphate attack. When cement type CEM III/B is used and the element has an environmental class of X0 or XC1, there is no chance of ASR and therefore no need to check the crackpattern. Besides, checking the crackpattern for potential sulphate attack can be excluded when the element does not originally come from a coastal area (Appendix D.1) (Bouwens, 2022). Moreover, the crackwidth should be checked. According to NEN-EN 1992-1-1, when environmental class X0 or XC1 corresponds to the element, a maximum crackwidth of 0.4 mm is allowed. If the element has another environmental class, the maximum allowed crackwidht is 0.3 mm.

Advice based on condition

When no toxic substances are present in the element, the residual service life is above 40 years, there is no chance of internal corrosion, and the crackwidht is sufficient according to NEN-EN 1992-1-1, it is advised to reuse the element based on condition. When there is a chance of presence of toxic substances, or internal corrosion like ASR or Sulphate attack, additional checks should be necessary. When the condition score of the element is quite high, this will result in a low residual lifespan which does not makes it beneficial to reuse the element. Therefore it is advised to upcycle the element when the residual lifespan is lower than 40 years.

The complete process of analysing the condition of a structural element is visualized in the process tree in Figure E.2.

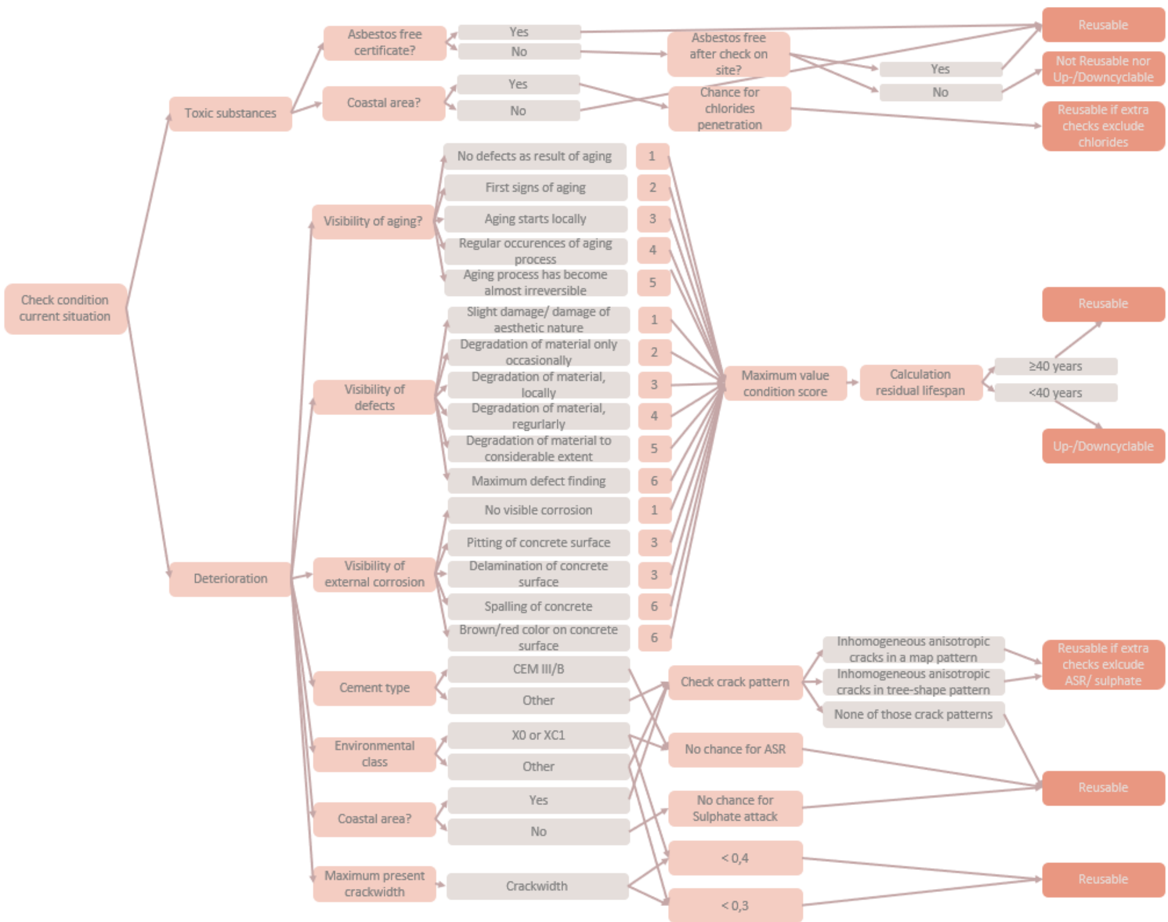


Figure E.2: Process tree - assessment condition (Own figure)

E.1.2 Structural applicability

The structural applicability is analysed based on reinforcement detailing and the loading capacity.

Reinforcement detailing

The detailing of reinforcement differs per element type which is described in NEN-EN 1992-1-1 and explained in Appendix D.5. Therefore the detailing of a one-way supported monolith floor element, a beam, and a column are shortly discussed.

Reinforcement detailing – Floor element

In a monolith floor element, usually main longitudinal reinforcement is used in the direction in which the floor is spanned. Next to the main reinforcement, dividing reinforcement is used in the direction perpendicular to the main reinforcement. Concrete has a 'transverse contraction coefficient' v of 0.2 and therefore the dividing reinforcement should be at least 20% of the main reinforcement. Often reinforcement meshes are used instead of rebars since the labour costs of reinforcement meshes are lower than rebars. However, the usage of reinforcement meshes often results in a surplus of steel usage (Braam & Lagendijk, 2011).

In order to check the reinforcement detailing of the element, the diameter of the bars of the main- and dividing reinforcement should be known, the number of bars in the element should be known, and the spacing should be known. In Appendix D.5.5, the rules for reinforcement detailing of monolith floors are explained.

Besides, the thickness of the concrete cover is an important factor. The required thickness is dependent of the environmental class and the diameter of the rebars of the main reinforcement. Moreover, the future required fire resistance of the element influences the thickness of the concrete cover, as explained in Appendix B.6.

Based on the diameter of the rebars, the number of bars, the spacing, and the thickness of the concrete cover, an advice about reusability based on reinforcement detailing can be given. When the reinforcement detailing is according to the rules stated in NEN-EN 1992-1-1, it is advised to reuse the element. When this is not the case, remanufacturing will be advised.

In Figure E.3, the process tree of the assessment of the reinforcement detailing of a floor element is shown.

Figure E.3 Process tree - assessment reinforcement detailing floor element (Own figure)

Reinforcement detailing – Beam

A concrete beam consists of main reinforcement, and often stirrups in order to deal withs shear forces. Besides, (additional) flange reinforcement can be used. Often reinforcement meshes are used instead of bars in order to reduce the labour costs. This results in designed concrete beams including more reinforcement than necessary (Braam & Lagendijk, 2011).

In order to check the reinforcement detailing of the element, the diameter of the bars of the main- and dividing reinforcement should be known, the number of bars in the element should be known, and the spacing should be known. In Appendix D.5.3, the rules for reinforcement detailing of beams are explained.

Besides, the thickness of the concrete cover is an important factor. The required thickness is dependent of the environmental class and the diameter of the rebars of the main reinforcement. Moreover, the future required fire resistance of the element influences the thickness of the concrete cover, as explained in Appendix B.6.

Based on the diameter of the rebars, the number of bars, the spacing, and the thickness of the concrete cover, an advice about reusability based on reinforcement detailing can be given. When the reinforcement detailing is according to the rules stated in NEN-EN 1992-1-1, it is advised to reuse the element. When this is not the case, remanufacturing will be advised.

In Figure E.4, the process tree of the assessment of the reinforcement detailing of a beam is shown.

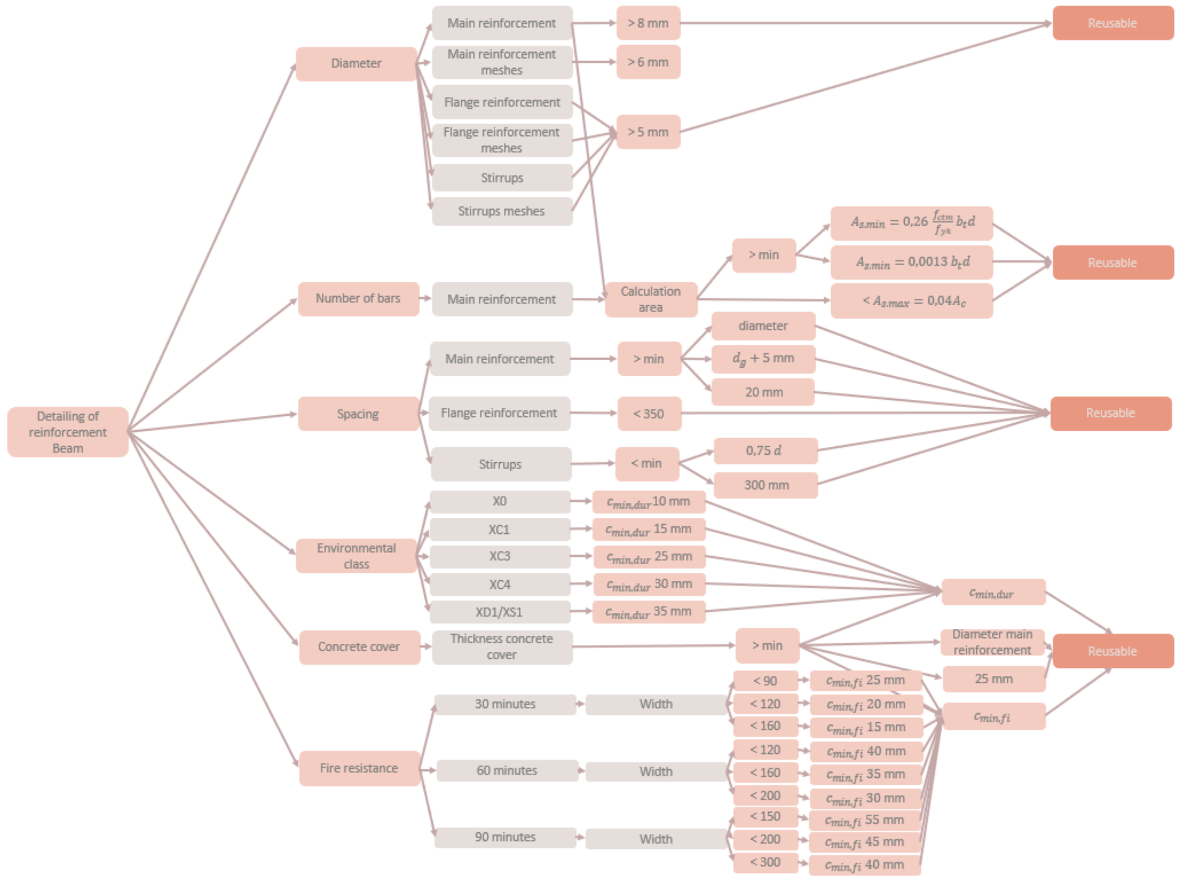


Figure E.4 Process tree - Reinforcement detailing beam (Own figure)

Reinforcement detailing – Column

The reinforcement of a concrete column consists of main reinforcement and stirrups. Just as in the design of reinforcement for concrete beams, in columns often meshes are used to reduce the labour costs (Braam & Lagendijk, 2011).

In order to check the reinforcement detailing of the element, the diameter of the bars of the main- and dividing reinforcement should be known, the number of bars in the element should be known, and the spacing should be known. In Appendix D.5.4, the rules for reinforcement detailing of columns are explained.

Besides, the thickness of the concrete cover is an important factor. The required thickness is dependent of the environmental class and the diameter of the rebars of the main reinforcement. Moreover, the future required fire resistance of the element influences the thickness of the concrete cover, as explained in Appendix B.6.

Based on the diameter of the rebars, the number of bars, the spacing, and the thickness of the concrete cover, an advice about reusability based on reinforcement detailing can be given. When the reinforcement detailing is according to the rules stated in NEN-EN 1992-1-1, it is advised to reuse the element. When this is not the case, remanufacturing will be advised.

In Figure E.5, the process tree of the assessment of the reinforcement detailing of a column is shown.

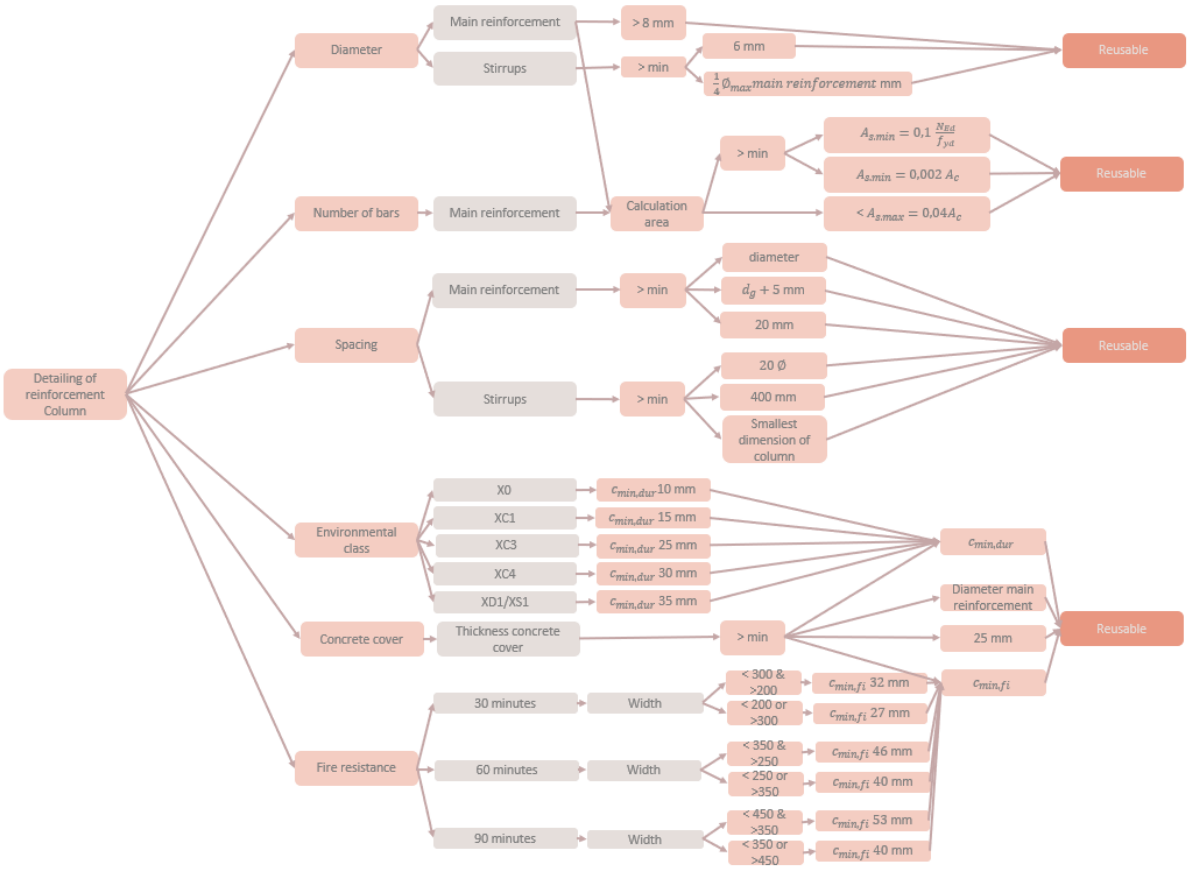


Figure E.5 Process tree - Reinforcement detailing column (Own figure)

Loading capacity

A very important aspect which should be analysed in order to give an advice about the structural safety, is the assessment of the loading capacity. The loading capacity of elements can be analysed based on the concrete- and reinforcement properties. An maximum allowable design load can be calculated. Moreover, when future applied loads are already known, the element can be checked for ultimate limit state (ULS) and serviceability limit state (SLS). The loading capacity of monolith floor elements, beams, and columns are explained.

Loading capacity – Floor element and beam

In NEN-EN 1992-1-1 rules are formulated for the design of concrete one-way supported floors. One-way supported floors can be considered as small beams when analysing the loading capacity. It is important to check if the floor is stiff enough in order to fulfil the bending requirements.

<u>Design stress</u>

The useful height *d* of a floor element can be estimated using rules of thumb (experience from practice) (Braam & Lagendijk, 2011). In Table E.1, the approximation formulas for the slenderness of floor elements are formulated for one-way simply supported floors.

Table E.1 Approximation formulas for slenderness

Scheme	L_{eff}/d ($l_{eff} \leq 7.0$ m)	L_{eff}/d ($l_{eff} > 7.0$ m)
	25	$175/l_{eff}$

Concrete structures should be sufficiently stiff to withstand deflection caused by bending without severe damage. Therefore, the floor element should fulfil the deflection requirement expressed in Equation E.1:

$$w_{max} \leq 0{,}004\, l_{eff} \quad \text{(E.1)}$$

In concrete there are several types of bending: time independent bending due to permanent loading, time dependent bending, and bending caused by quasi-permanent loading. In this research, in the analysis of floor elements a maximum allowable deflection of $0{,}004 l_{eff}$ is used.

The effective length of a floor element can be calculated using Equation E.2:

$$l_{eff} = l_n + 2 * \frac{1}{2} min\{h; t\} \quad \text{(E.2)}$$

In which (shown in Figure E.6):

l_n	*length between the support*
h	*height of the element*
t	*length of the support*

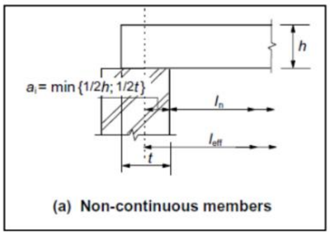


Figure E.6 Effective length

Based on the present main reinforcement in the floor element, the total area of reinforcement (per meter floor) can be calculated. From the total floor area, reinforcement strength, and effective height of the element, the maximum allowable moment can be calculated, as shown in Equation E.3.

$$M_{Ed} = A_{s,main,field} * f_{yd} * 0{,}9 * d \quad \text{(E.3)}$$

Using $W = \frac{1}{6}\, b\, h^2$ the maximum allowable design stress can be calculated using Equation E.4

$$\sigma_m = \frac{M_{Ed}}{W} \quad \text{(E.4)}$$

In NEN-EN 1992-1-1 the minimum value of the shear capacity can be calculated using Equation E.5. Factor *k* can be calculated using Equation E.6.

$$v_{Rd,c} = 0{,}035\, k^{3/2} \sqrt{f_{ck}} \quad \text{(E.5)}$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \quad \text{(E.6)}$$

The maximum allowable shear force (without analysing shear reinforcement) can be calculated using Equation E.7.

$$V_{Rd,c} = V_{Ed} = v_{Rd,c} * bd \quad \text{(E.7)}$$

Reinforcement ratio

The reinforcement ratio of the main reinforcement can be calculated using Equation E.8.

$$\rho_l = \frac{A_{s,main,field}}{bd} \quad \text{(E.8)}$$

There are two requirements for the minimum reinforcement area described in NEN-EN 1992-1-1, which should be fulfilled, expressed in Equation E.9 and Equation E.10.

$$A_{s,min1} = 0.20 \frac{f_{ctm}}{f_{yd}} bh \quad \text{(E.9)}$$

$$A_{s,min2} = 1{,}25 * A_{s,main,field} \quad \text{(E.10)}$$

Based on the requirements for minimum reinforcement area, the minimum reinforcement ratio can be calculated, as shown in Equation E.11.

$$\rho_{l,min} = \frac{min\{A_{s,min1}; A_{s,min2}\}}{bd} \quad \text{(E.11)}$$

The maximum allowable reinforcement ratio can be calculated using Equation E.12.

$$p_{l,max} = \frac{\frac{3}{4} * 0.535 * f_{cd}}{f_{yd}} \quad \text{(E.12)}$$

In case of floor elements, the amount of dividing reinforcement should be at least 20% of the main reinforcement.

In case of beams, the reinforcement ratio of the stirrups can be calculated using Equation E.13.

$$\rho_w = \frac{A_{s,stirrups}}{bd} \quad \text{(E.13)}$$

The minimum allowable reinforcement ratio of stirrups is given by Equation E.14.

$$\rho_{w,min} = \frac{0.08 * \sqrt{f_{ck}}}{f_{yk}} \quad \text{(E.14)}$$

ULS check

When the future loading on the floor element is already known, the bending stress can be compared to the maximum allowable design stress. First the future load should be calculated using the right load factors according to NEN-EN 1992-1-1. In Table E.2, the load combinations are shown depending on the consequence class of the future structure. The maximum of the two combinations per consequence class should be used for further ULS calculation.

Table E.2 Load combinations dependent on consequence class

Consequence class	Permanent loading	Variable loading
CC1	1,1 G_k	1,35 Q_k
	1,2 G_k	1,35 Ψ_0 Q_k
CC2	1,2 G_k	1,5 Q_k
	1,35 G_k	1,5 Ψ_0 Q_k
CC3	1,3 G_k	1,65 Q_k
	1,5 G_k	1,65 Ψ_0 Q_k

The Ψ_0 factor depends on the future function of the element as shown in Table E.3.

Table E.3 Function of element

Function	Ψ_0
Housing	0,4
Office	0,5
Meeting space	0,6
Shopping	0,4
Industrial	1
Garage	0,7
Roof (only accessible for maintenance)	0

Based on the calculated SLS load, the ULS bending moment M_{ULS} and ULS stress σ_{ULS} can be calculated using Equation E.3 and Equation E.4.

When Equation E.15 is fulfilled, the concrete floor element is sufficient in the ultimate limit state in the future situation.

$$UC = \frac{\sigma_{ULS}}{\sigma_m} \leq 1 \tag{E.15}$$

SLS check

For the serviceability limit state, the maximum deflection of the floor element should be checked. First the SLS load should be calculated. In SLS situation, all load factors equals 1 and therefore the SLS load is the summation of the permanent- and variable load.

The occurring deflection can be calculated using Equation E.16.

$$w_{SLS} = \frac{\frac{5}{384}\, q\, l_{eff}^4}{E_c\, I} \tag{E.16}$$

In which E_c is the modulus of elasticity and dependent of the concrete strength class, and $I = \frac{1}{12}\, b\, h^3$ is the quadratic surface moment.

When Equation E.17 is fulfilled, the concrete floor element is sufficient in the serviceability limit state in the future situation.

$$UC = \frac{w_{SLS}}{w_{max}} \leq 1 \tag{E.17}$$

The process of calculating the design stress and shear force, and checking the reinforcement ratio is visualized in a process tree. Figure E.7 shows the process tree of the analysis of beams and Figure E.8 shows the process tree of the analysis of floor elements. Furthermore, the SLS and ULS checks are visualized in the process tree shown in Figure E.9.

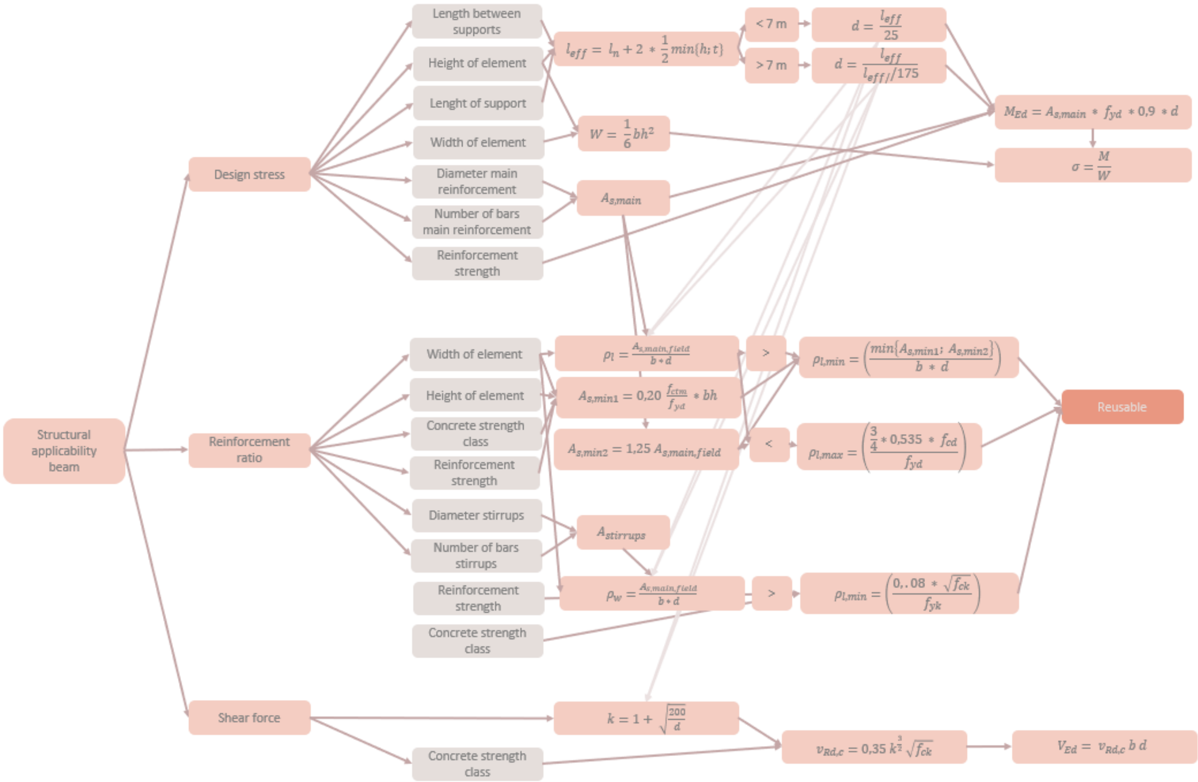


Figure E.7 Process tree - structural applicability beams (Own figure)

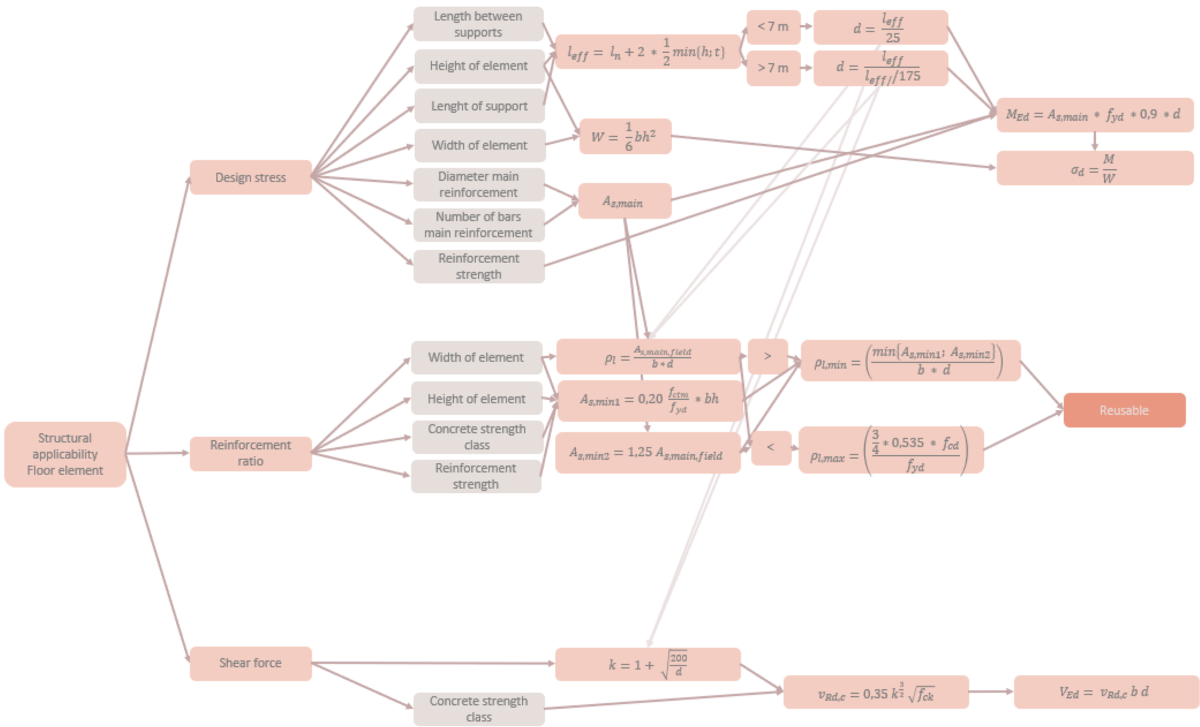


Figure E.8 Process tree - structural applicability floor elements (Own figure)

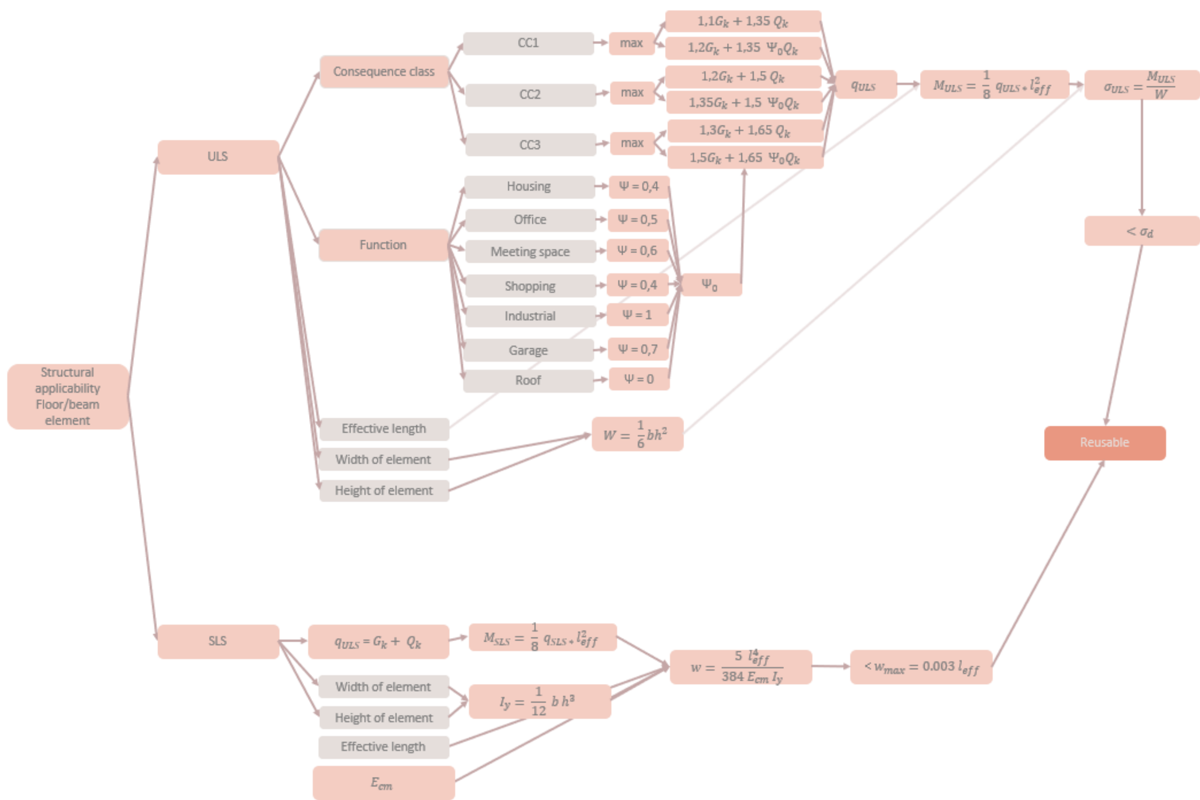


Figure E.9 Process tree - structural applicability ULS/SLS beams and floor elements (Own figure)

Loading capacity – Column

In the design of columns, the slenderness is an important factor. Columns are loaded by bending and normal force. The normal force lead to additional moments which are called second-order moments. The exact calculation of second-order moments is quite complicated. Therefore, in this research it is only analysed if second order calculations are necessary, based on the slenderness of the column (Braam & Lagendijk, 2011).

Design stress

The allowable design normal stress on a column with 'normal' slenderness' is given by f_{cd} which is dependent of the concrete strength class. Depending on the eccentricity of the future applied load, the allowed stress should be divided by a factor 1 for small eccentricities till a factor 1.5 for large eccentricities.

First it should be checked the column has a 'normal' slenderness by dividing the length of the column by the minimum transverse direction, shown in Equation E.18.

$$\lambda = \frac{l}{min\{w;h\}} \leq 15 \qquad \text{(E.18)}$$

Based on the eccentricity, the maximum allowable design normal stress can be calculated by Equation E.19.

$$\sigma_m = \frac{f_{cd}}{1.0 \text{ à } 1.5} \qquad \text{(E.19)}$$

ULS check

When the future loading on the column is known, the applied normal stress can be compared by the maximum allowable design normal stress. Therefore, first the load used in ULS calculations should be calculated based on the future consequence class of the structure. In Table E.4, the load combinations for ULS are shown.

Table E.4 Load combinations depending on consequence class

Consequence class	Permanent loading	Variable loading
CC1	1,1 G_k	1,35 Q_k
	1,2 G_k	1,35 Ψ_0 Q_k
CC2	1,2 G_k	1,5 Q_k
	1,35 G_k	1,5 Ψ_0 Q_k
CC3	1,3 G_k	1,65 Q_k
	1,5 G_k	1,65 Ψ_0 Q_k

The Ψ_0 factor depends on the future function of the element as shown in Table E.5.

Table E.5 Function of element

Function	Ψ_0
Housing	0,4
Office	0,5
Meeting space	0,6
Shopping	0,4
Industrial	1
Garage	0,7
Roof (only accessible for maintenance)	0

Based on the ULS load, the applied normal stress can be calculated using Equation E.20.

$$\sigma_{ULS} = \frac{q_{ULS}}{A_c} \tag{E.20}$$

When Equation E.21 is fulfilled, the concrete column is sufficient in the ultimate limit state in the future situation.

$$UC = \frac{\sigma_{ULS}}{\sigma_m} \leq 1 \tag{E.21}$$

<u>Check if second order calculations are required</u>

Buckling is a dangerous way of failing of the structure, since it happens quite suddenly. When the slenderness of the column is less than the limit value of the slenderness, there is no need for second-order calculations. In that case, the critical buckling force can be easily calculated.

The limit value of the slenderness can be calculated using Equation E.22.

$$\lambda_{lim} = \frac{20\,A\,B\,C}{\sqrt{n}} \tag{E.22}$$

In which *A* = 0.7, *B* = 1.1, *C* = 0.7, and $n = \frac{N_{Ed}}{A_c\, f_{cd}}$

In case $\lambda < \lambda_{lim}$ no second-order calculation is required and the critical buckling force can be calculated according to Equation E.23.

$$N_{buc} = \pi^2 \frac{Ei}{l_{buc}^2} \tag{E.23}$$

In simplified calculations the unity check for buckling can be described with Equation E.24.

$$UC = \frac{5 * N_{Ed}}{N_{buc}} \leq 1 \tag{E.24}$$

The complete process of calculating the design stress, and doing ULS check is visualized in the tree shown in Figure E.10. In Figure E.11, the check if a second order calculation is required is visualized, even as the calculation of the critical bending force.

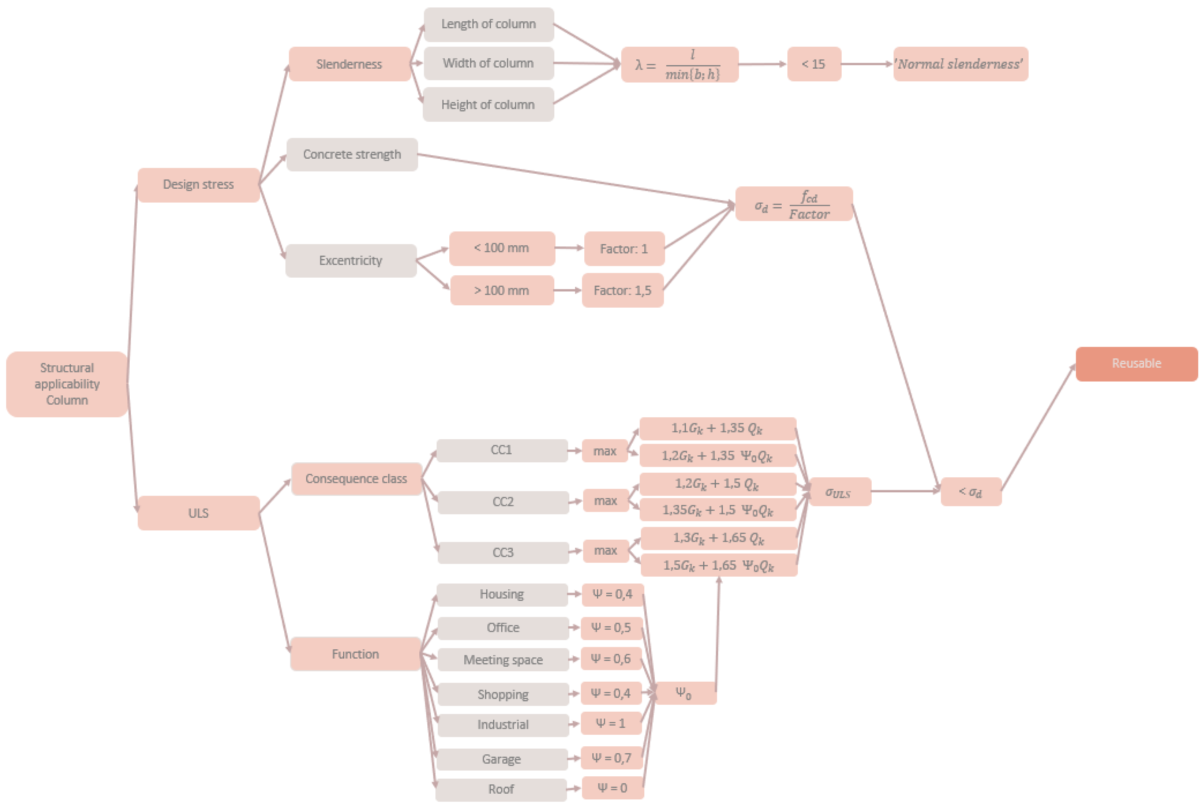


Figure E.10 Process tree - structural applicability column (Own figure)

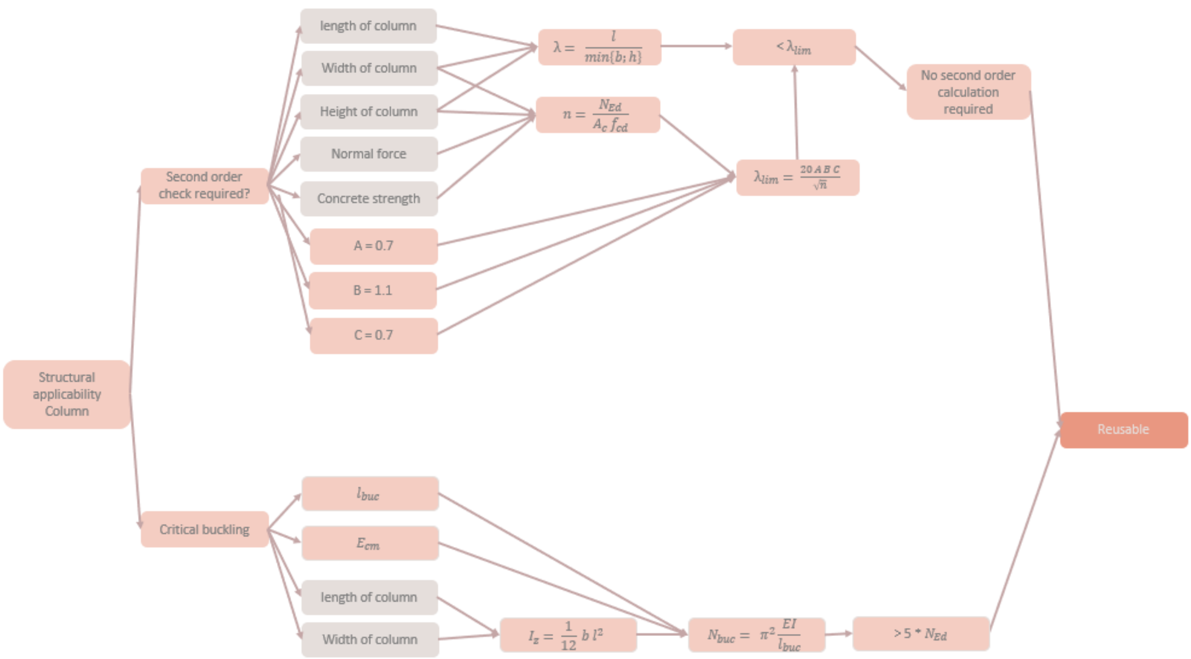


Figure E.11 Process tree - structural applicability column Second order (Own figure)

Advice based on Structural applicability

When the reinforcement detailing of the structural element is according to NEN-EN 1992-1-1 and the ULS- and SLS requirements are fulfilled (in case future loading is known) it is advised to reuse the structural element based on structural applicability. When the reinforcement detailing is not sufficient, it is advised to upcycle the element. When the ULS- and SLS requirements are not fulfilled based on the future loading, it is first advised to look at other options (other future loadings applied on the element). If it is still not possible to reuse the element based on structural applicability, it is advised to upcycle the element.

E.1.3 Advice about Reusability

The final advice based on structural safety will follow from the advice based on condition and structural applicability of the element. When both the advices based on condition and structural applicability are to reuse the structural element, the final advice is to reuse the element. In case the advice based on condition or structural applicability is to upcycle the element, the final advice is to upcycle the element.

E.2 Assessment of environmental impact

The environmental impact of the three circular strategies Reuse, Upcycling, and Downcycling is calculated according to the Bepalingsmethode of the Nationale Milieudatabase. Using this method, the environmental impact is expressed in an Environmental Cost Indicator (ECI). In the calculation of the ECI the life cycle phases of the current structure which are included are: the end of life stage, Benefits and loads. For the future structure the included life cycle phases are: the Product stage and transport of the construction process stage. The calculation of the ECI values of these stages result in a final ECI value of each circular strategy which can be compared to each other resulting in an advice about reusability as shown in Figure E.12.

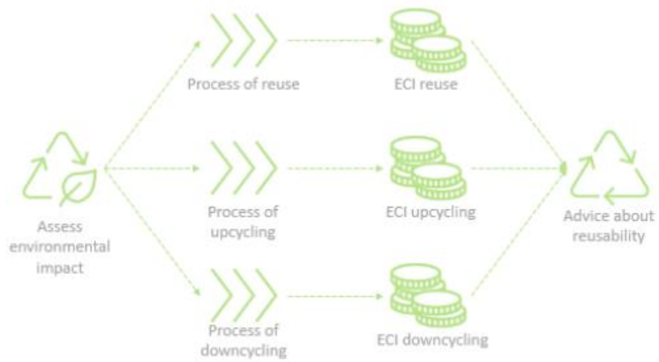
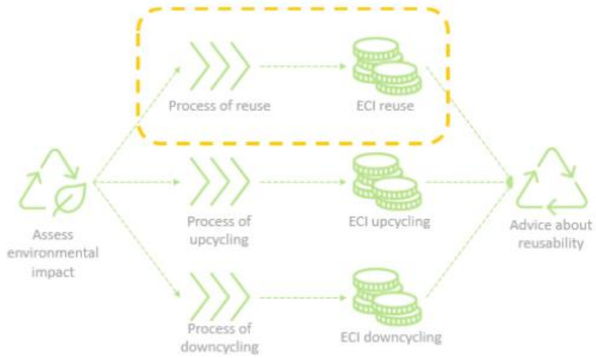


Figure E.12 Assessment of environmental impact

Data of the Nationale Milieudatabase is used for the ECI calculations. The calculation of the ECI value of each circular strategy is shortly discussed.

E.2.1 ECI calculation of Reuse

Based on the process of Reuse explained in Chapter 3, the environmental impact can be calculated and expressed in an ECI value.



Deconstruction stage (stage C1)

The deconstruction stage is divided in concrete cutting, concrete sawing, element hoisting, and element cleaning. It is assumed the environmental impact of cleaning is negligible. Besides, the temporarily supports of the element (which is part of the preparation phase) have some environmental impact and are therefore included in the calculation of the environmental impact. In Appendix D.3, it is shown which data (including stages) is used for the calculations.

Starting with temporarily supports, scaffolding pipes are required. Based on the internal floor height, the length of the scaffolding can be decided. Moreover, the own weight of the element, which will be supported by the scaffolding, is an important factor in order to decide about the amount of scaffolding pipes. Based on the internal floor height, the element dimensions, and density of the concrete, the total required length of scaffolding pipes can be calculated. Using this total length and data of NMD with functional unit in meters, the environmental impact can be calculated.

For the calculation of the impact of cutting concrete, the total cutting time should be calculated. Based on the cutting rate (explained in Chapter 3) and the element dimensions, the cutting time can be calculated. Together with data of NMD of a demolition crane, the ECI value of concrete cutting is calculated. The sawing of concrete using a diamond blade results in additional environmental impact. Therefore, the sawing time should be calculated. In order to calculate the sawing time, the number of connections, type of connections and edge inclusion should be clear. In case of columns and beams also the amount of crossing elements is an important factor. In case of linear supports, the element width and length should be used. Each type of support has its own sawing rate (which is explained in Appendix D.2) resulting in a sawing time. Using data of a concrete saw of NMD, the ECI value of sawing is calculated.

The last step included in the calculation of the environmental impact of the deconstruction phase is element hoisting. As explained in Chapter 3 and Chapter 4, the hoisting time of an element is around 15 minutes per element. Based on the own weight of the element, it is decided if a Tower crane can be used or a Telescopic crane is necessary.

The calculation of the ECI value of the deconstruction phase is visualized in the process tree shown in Figure E.13.

Figure E.13 Process tree - ECI value Reuse deconstruction (Own figure)

Transport – Element processing – Benefits (stages C2-D)

After the element is hoisted, it should be transported to the element processor. To calculate the environmental impact of transport, the distance between the building site and the element processor should be known. Moreover, the weight of the element should be lower than the maximum capacity of normal road transport (as explained in Chapter 3). Based on the element weight, and the transport distance, the environmental impact of transport is calculated.

In Chapter 3, it is explained that the post-processing stage consists of reshaping the element, removal of fixings, filling of holes, adding an additional concrete cover, and creating openings. The environmental impact of removal of fixings, and filling of holes is assumed negligible and therefore excluded from the environmental impact calculation. For reshaping the element, it is assumed only the width of the element is sawn. Therefore, the element width is required which together with the sawing rate results in the sawing time. Based on the sawing time and using data of a concrete saw of NMD, the ECI value of reshaping is calculated. If from the structural calculations turned out the concrete cover is not sufficient, an additional concrete cover should be poured. The amount of additional concrete depends on the element dimensions and the required thickness of the additional cover. Moreover, the strength class of the concrete of the element is an important factor, since the additional cover should be poured in the same strength class. Based on these inputs, the environmental impact of an additional concrete cover is calculated.

In order to reconnect the structural element, openings should be created using a concrete drill having a certain drilling rate. Based on the rate and element dimensions, the drilling time can be calculated. Together with data of a concrete drill of NMD, the ECI value of creating openings is calculated. Since the scaffolding pipes can be reused, this results in benefits and therefore in a negative ECI value.

The complete calculation process of transport, element processing, and benefits of the current structure is shown in the process tree in Figure E.14.

Figure E.14 Process tree - ECI Reuse Transport, Post-processing, Benefits (Own figure)

Transport (A4)

Since new production is prevented by reusing the structural element, the complete production stage (A1-A3) can be skipped. Therefore, only the impact of transport should be included.

As explained in Chapter 3, reusing a structural element results in additional transport movements. An element can be temporarily stored. In that case the element should be transported from the element processor to the storage location. After storage, the element should be transported from the storage location towards the building site. When the element can be directly reused after processing, the element should be transported from the processor towards the building site. The calculation process of the environmental impact of these transport movements is shown in the process tree in Figure E.15.

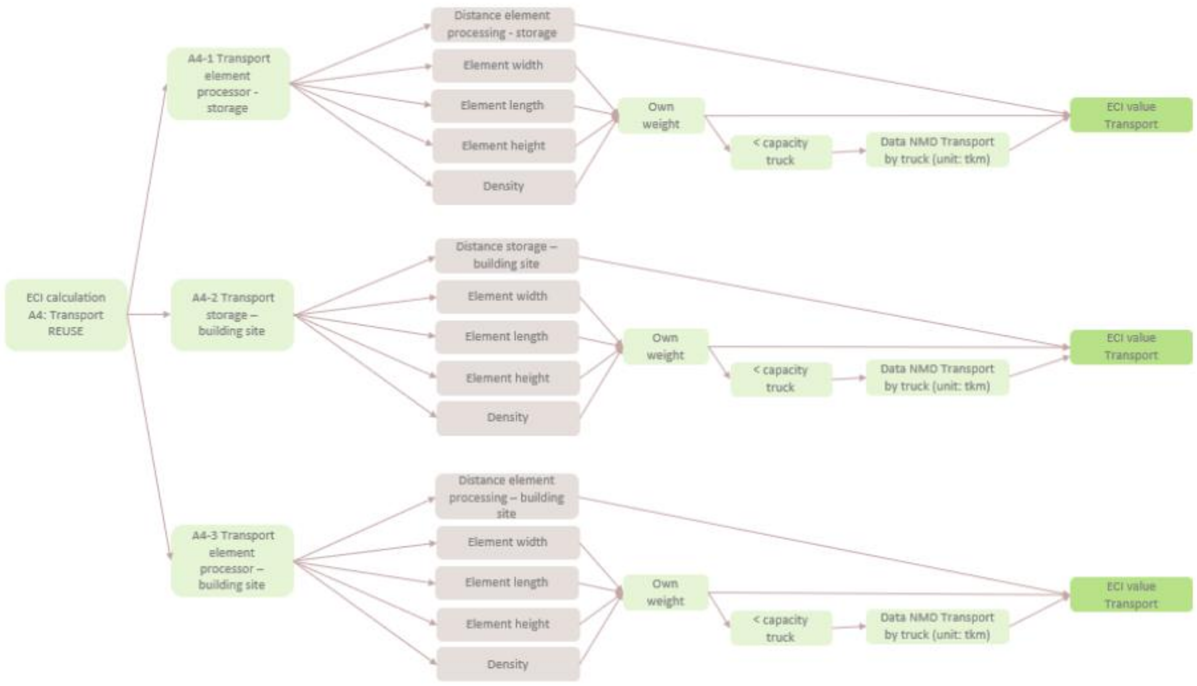
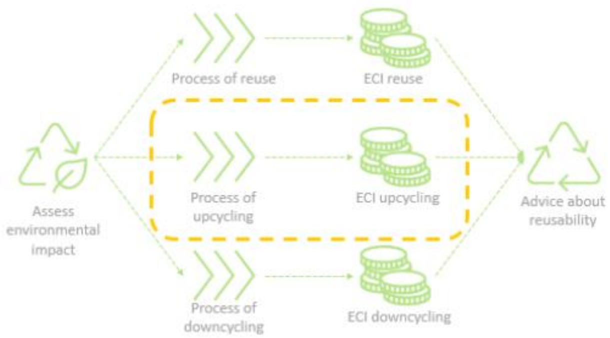


Figure E.15 Process tree - ECI Reuse Transport (Own figure)

E.2.2 ECI calculation of Upcycling

Based on the process of Upcycling explained in Chapter 3, the environmental impact can be calculated and expressed in an ECI value.



Demolition – Transport – Material processing – Disposal – Benefits (stages C1-D)

As explained in Chapter 3, the demolition stage can be divided into three steps: concrete cutting, concrete crushing, and preparing rubble. The impact of concrete cutting is calculated in the same way as in the process of Reuse, only the cutting rate differs which is explained in Appendix D.2. The impact of the crushing of concrete is calculated in a comparable way. For the calculation of the ECI value of concrete crushing data of a small crane is used. This data is also used for the calculation of the impact of preparing and sorting the concrete rubble for upcycling. The sum of the ECI values of these three steps result in the ECI value of the demolition stage.

In order to upcycle the concrete rubble, it should be transported to a material processor. Based on the own weight of the demolished element and the distance between the building site and material processor, the impact of transport is calculated. For the calculation of the environmental impact of material processing, data of concrete and reinforcement is used. The data of concrete depends on the strength class which is therefore an important input variable. Moreover, the total weight of the reinforcement is calculated based on the inputted diameters, number of bars, and spacing. This results in an ECI value for material processing. Reinforcement additionally results in some benefits.

The process from demolition towards benefits is shown in the process tree in Figure E.16.

Figure E.16 Process tree - ECI Upcycling Demolition, Transport, Post-processing, Disposal, Benefits (Own figure)

Raw materials supply – Transport – Manufacturing – Transport (stages A1-A4)

In case of Upcycling, it is assumed 20% of the new element consists of recycled cement, and 50% of the element consists of recycled granulate. Based on the required amounts of substitutes for the production of 1 m^3 concrete and the total amount of required concrete, the prevented impact of cement and gravel, and the impact of granulate can be calculated. Based on the distance between the material processor and the producer, the impact of transport of raw materials is calculated. In this research, the impact of the new production of in-situ concrete and the impact of the production of a prefab element is calculated. The environmental impact of the new production depends on the element dimensions, concrete density, and concrete strength class.

When the new element is produced, it should be transported to the new building site. In case of in-situ concrete, the impact of using a concrete mixer is calculated together with transport of reinforcement. In case of a prefab element, the impact of the element transport is calculated.

The calculation process is shown in the process tree in Figure E.17.

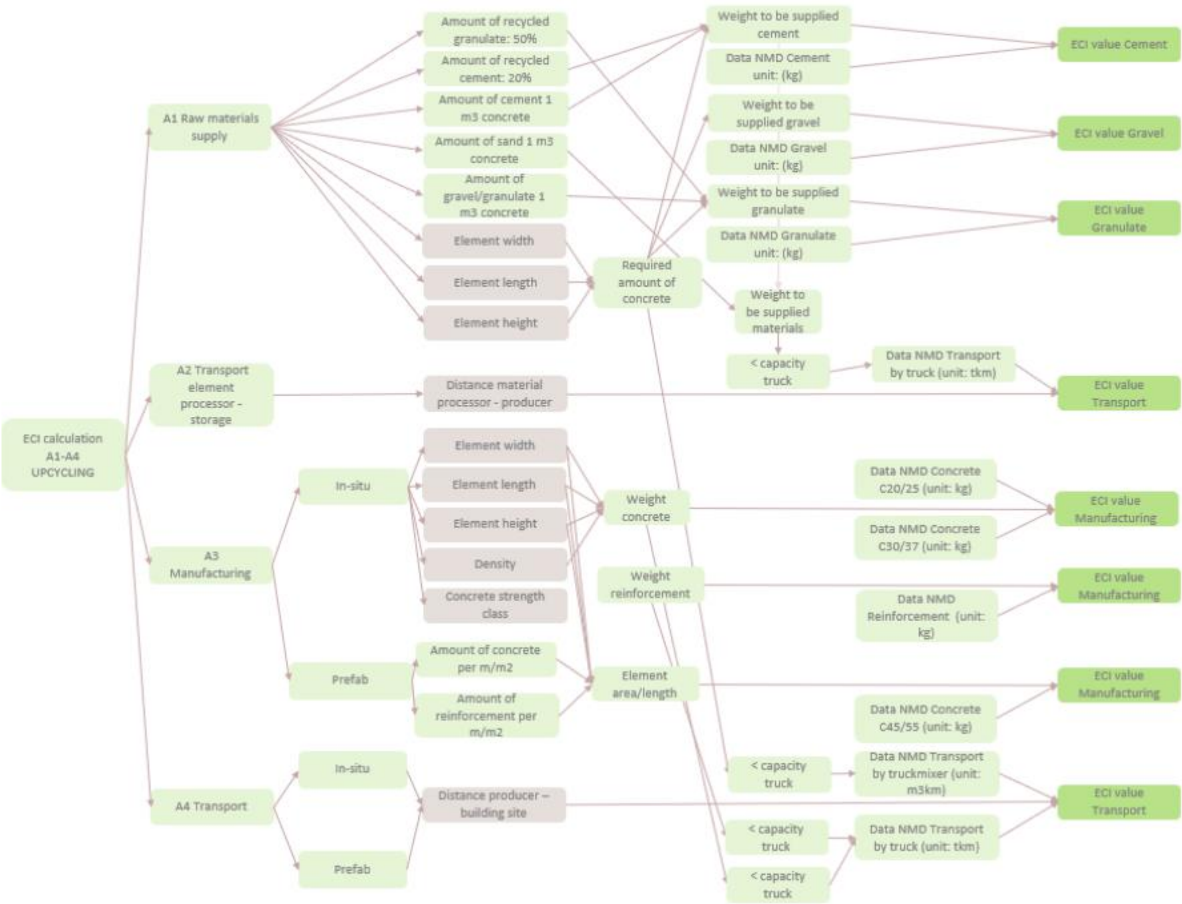
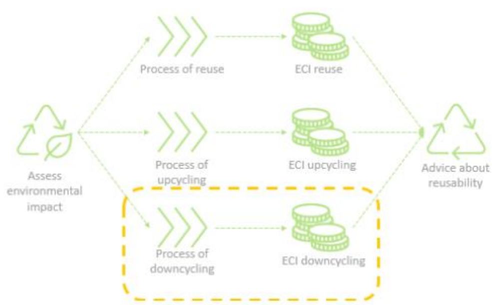


Figure E.17 Process tree - ECI Upcycling Production, Transport (Own figure)

E.2.3 ECI calculation of Downcycling

Based on the process of Downcycling explained in Chapter 3, the environmental impact can be calculated and expressed in an ECI value.



Demolition – Transport – Material processing – Disposal

As explained in Chapter 3, the demolition stage can be divided into two steps: concrete cutting, and concrete crushing. The impact of concrete cutting and crushing is calculated in the same way as in the process of Upcycling. The sum of the ECI values of these two steps result in the ECI value of the demolition stage.
Based on the weight of the rubble and the distance between the building site and the material processor, the environmental impact of transport is calculated. Also the calculation of the impact of the material processing and disposal is equal to the process of upcycling.

The process tree of the calculation of the environmental impact of the demolition stage, transport, material processing stage, and disposal is shown in Figure E.18.

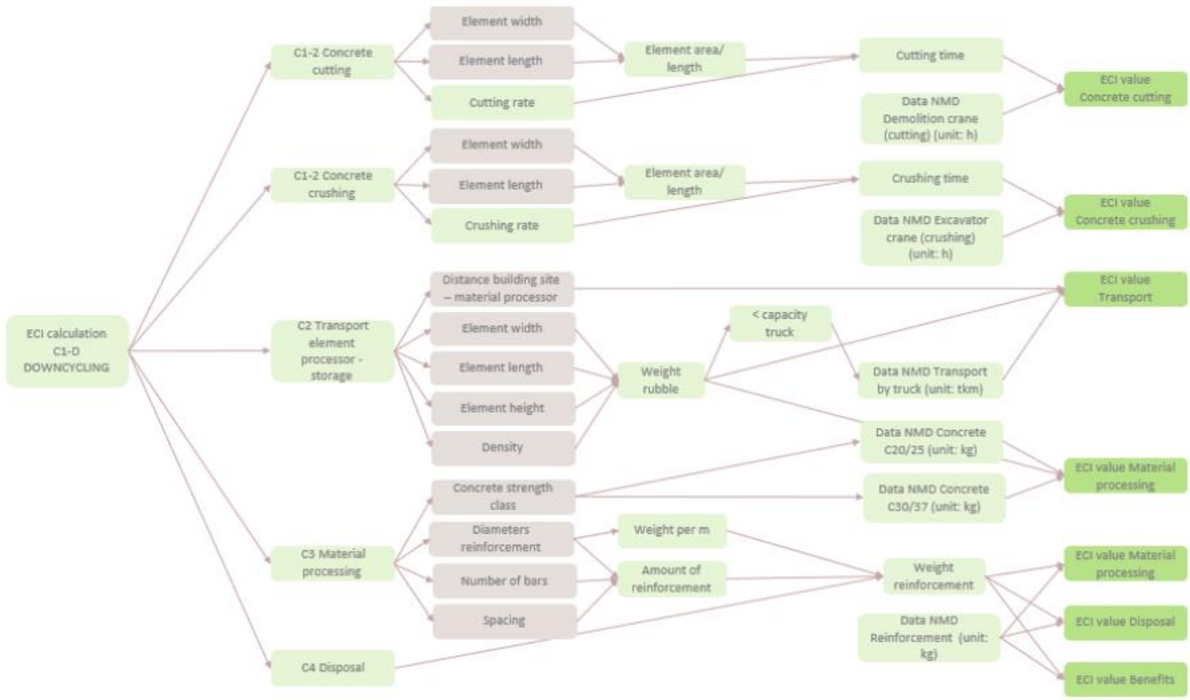


Figure E.18 Process tree - ECI Downcycling Demolition, Transport, Post-processing, Disposal (Own figure)

Production – Transport (stages A1-A4)

In this research, the impact of the new production of in-situ concrete and the impact of the production of a prefab element is calculated. The environmental impact of the new production depends on the element dimensions, concrete density, and concrete strength class.

When the new element is produced, it should be transported to the new building site. In case of in-situ concrete, the impact of using a concrete mixer is calculated together with transport of reinforcement. In case of a prefab element, the impact of the element transport is calculated.

The calculation process is shown in the process tree in Figure E.19.

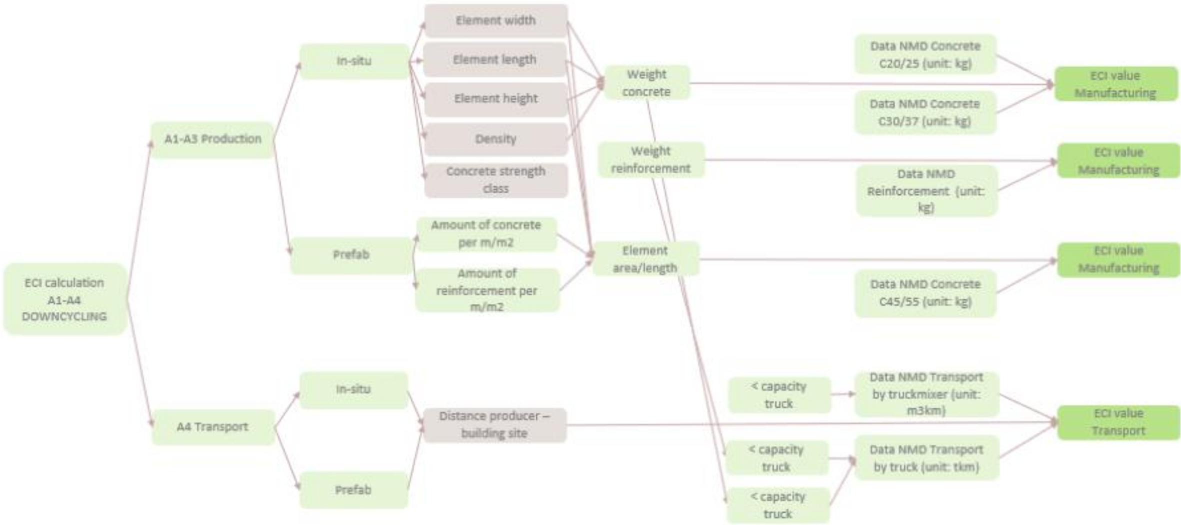
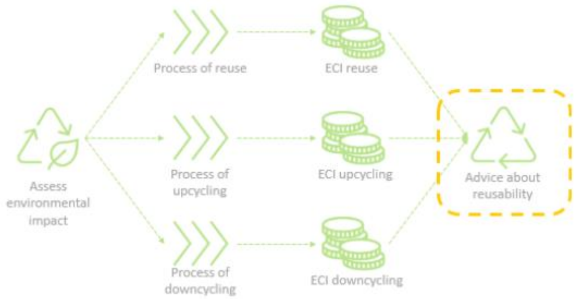


Figure E.19 Process tree - ECI Downcycling Production, Transport (Own figure)

E.2.4 Advice about reusability



The final advice based on environmental impact will follow from the total ECI values of each circular strategy. Since for Upcycling and Downcycling the impact is calculated for new production of in-situ concrete and a prefab element, two ECI values follow. The circular strategy resulting in the lowest ECI value, and therefore the lowest environmental impact, is advised. It should be noted that this advice is only based on environmental impact. Therefore the final advice of the assessment can differ, since the impact of structural safety and economics should also be included.

E.3 Assessment of Economic impact

In this appendix, all economic data resulting in costs factors are explained. Moreover, the formulas used for the calculation of the economic impact are explained.

E.3.1 Economic impact of Downcycling

The total economic impact of the process of demolition for downcycling is visualized in Figure E.20. The costs factors are shortly explained in the following sub-sections.

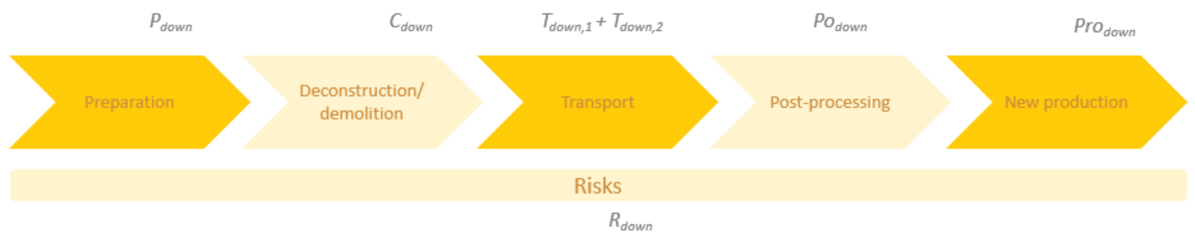


Figure E.20 Economic impact - Downcycling (Own figure)

Preparation of (traditional) demolition

The costs for preparation of (traditional) demolition P_{down} are estimated and shown in Table E.6. The costs for Inventory, Planning, and Stripping are estimated as an percentage of the total demolition costs.

Table E.6 Economic impact of Preparation - Downcycling

Process of preparing	Indicator	Costs	Description
Inventory	P_{down}	7% of total costs	According to Jabeen (2020) and Glias (2013), the preparation costs are estimated 7% of the total demolition costs.
Planning			
Stripping			

(Traditional) demolition

The traditional demolition process consists of concrete cutting and concrete crushing. The costs for (traditional) demolition C_{down} are estimated and shown in Table E.7.

Table E.7 Economic impact of Demolition - Downcycling

Process of demolition	Indicator	Costs	Description
Concrete cutting	C_{down}	€35/m^2 €30/m	According to Jabeen (2020), the costs for demolition of floor elements can be estimated between €31/m^2 and €38/m^2, based on the demolition rate described in Section 3.4.2.1. In this research a value of €35/m^2 is used for demolition. Besides, a value of €30/m is used for columns and beams.
Concrete crushing			

Transport

In case of traditional demolition two transport movements are included. The costs for transport $T_{down,1}$ and $T_{down,2}$ are explained in Table E.8.

Table E.8 Economic impact of Transport - Downcycling

Transport	Indicator	Costs	Description
Transport building site – material processor	$T_{down,1}$	€2,92/truck/km	According to cost calculations of Panteia (2018), the costs of transport with container trucks are €2,60/truck/km in which trucks are used of which the maximum loading capacity equals 25 tons. Including cost increases over the years the estimated costs for transport in 2022 equals €2,92/truck/km (Panteia, 2018, 2019a, 2019b).
Transport producer – building site	$T_{down,2}$	€2,08/truck/km	**Prefab element:** According to cost calculations of Panteia (2018), the costs of transport with long and heavy trucks are €1,85/truck/km in which trucks are used of which the maximum loading capacity equals 60 tons (RDW, 2022). Including cost increases over the years the estimated costs for transport in 2022 equals €2,08/truck/km (Panteia, 2018, 2019a, 2019b).
		€2,00/truck/km	**In-situ concrete:** According to cost calculations of Panteia (2018), the costs of transport with concrete mixer trucks are €1,78/truck/km in which trucks are used of which the maximum loading capacity equals 10 m^3. Including cost increases over the years the estimated costs for transport in 2022 equals €2,00/truck/km (Panteia, 2018, 2019a, 2019b).

Post-processing

As explained, the concrete rubble including reinforcement should be processed into raw materials. The estimated costs for downcycling R_{down} are shown in Table E.9.

Table E.9 Economic impact of Post-processing - Downcycling

Process of Downcycling	Indicator	Costs	Description
Downcycling rubble	Po_{down}	€90/ton	For the processing of waste, costs of €90/ton are used (Jabeen, 2020; Icibaci 2019).

Production new element

The costs for the production of a new element strongly depends on the new element type. In this research, only costs for the production of the in-situ concrete or the prefab element are included. For example, costs for pouring in-situ concrete or installing a prefab element are out of scope.

In Table E.10, the costs for production of new structural elements are shown in which material costs and labour costs are distinguished, even as the production of in-situ concrete or a prefab concrete element.

Table E.10 Economic impact of New production - Downcycling

Production	Indicator	Costs	Description
In-situ concrete	$Pro_{down,1}$	€110 - €120/m^3	The material costs for in-situ concrete are estimated on €110/m^3 in case of C20/25 concrete and €120/m^3 for C30/37 concrete (BouwTotaal, 2019; Bouwdelen, 2021; Betonstation, 2022; Verbouwkosten B.V., 2022).
		€40/h	The labour costs of the production of in-situ concrete are €40/h. For the production of a floor 1 hour is required for 6m^2

			(BouwTotaal, 2019; Bouwdelen, 2021). For the production of columns and beams it is estimated that 1 hour is required for 2m.
Reinforcement	$Pro_{down,2}$	€2,00/kg	The costs of reinforcement are estimated €2,00 per kg in 2017 (Schelfaut, 2017).
Floor element (prefab)	$Pro_{down,3}$	€48/m^2	In case of a prefab concrete floor, the costs of a hollow core slab floor are used. The material costs of a hollow core slab are €48/m^2 (BouwTotaal, 2019; Bouwdelen, 2021).
		€40/h	The labour costs of the production of an in-situ floor element are €40/h. For the production of a hollow core slab floor of 36m^2, around 4 hours are required (BouwTotaal, 2019; Bouwdelen, 2021).
Column/Beam (prefab)	$Pro_{down,4}$	€95/m	Based on Bouwkundig bureau Vuy (2013)k, the material costs for prefab columns are estimated €95/m. Also costs for beams are estimated as €95/m.
		€40/h	The labour costs of the production of a prefab column or beam are €40/h (BouwTotaal, 2019; Bouwdelen, 2021). For the production of columns and beams it is estimated that 1 hour is required for 3m.

Risks

Next to the costs for preparation, demolition, transport, post-processing, and the production of a new element, the costs for risks R_{down} are estimated based on the research of Glias (2013) and Jabeen (2020). The estimated costs for risks are shown in Table E.11.

Table E.11 Risks - Downcycling

Risks	Indicator	Costs	Description
Risks	R_{down}	3% of total costs	The costs for risks of (traditional) demolition projects can be estimated on 3% of the total demolition costs, since this process knows less uncertainties (Glias 2013; Jabeen, 2020).

Total economic impact Downcycling

As explained in the previous sections, the total costs for the circular strategy Downcycling are determined based on the costs of all the steps involved in the process of Downcycling. Therefore the total costs for downcycling can be calculated according to Equation E.24.

$$Costs_{downcycling} = P_{down} + C_{down} + T_{down,1} + T_{down,2} + Po_{down} + \begin{cases} Pro_{down,1} + Pro_{down,2} \\ Pro_{down,3} \\ Pro_{down,4} \end{cases} + R_{down} \quad (E.24)$$

In which:

$$P_{down} = 0{,}07\left(C_{down} + T_{down,1} + T_{down,2} + Po_{down} + \begin{cases} Pro_{down,1} + Pro_{down,2} \\ Pro_{down,3} \\ Pro_{down,4} \end{cases}\right)$$

And:

$$R_{down} = 0{,}03\ (C_{down} + T_{down,1} + T_{down,2} + Po_{down} + \begin{cases} Pro_{down,1} + Pro_{down,2} \\ Pro_{down,3} \\ Pro_{down,4} \end{cases})$$

E.3.2 Economic impact of Upcycling

The total economic impact of the process of demolition for upcycling is visualized in Figure E.21. The costs factors are shortly explained in the following sub-sections.

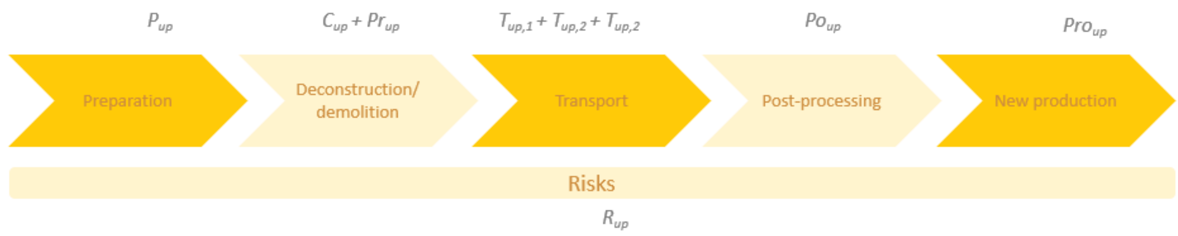


Figure E.21 Economic impact - Upcycling (Own figure)

Preparation of demolition

The costs for preparation of demolition P_{up} are estimated and shown in Table E.12. The costs for Inventory, Planning, and Stripping are estimated as an percentage of the total demolition costs.

Table E.12 Economic impact of Preparation - Upcycling

Process of preparing	Indicator	Costs	Description
Inventory Planning Stripping	P_{up}	9% of total costs	Based on the research of Jabeen (2020) and Glias (2013), the preparation costs for remanufacturing are estimated 9% of the total demolition costs. The increase of 2% compared to preparation costs for downcycling are based on the planning of preparing rubble and remanufacturing the element.

Demolition

The demolition process consists of concrete cutting and concrete crushing. The costs for concrete cutting and concrete crushing C_{up} and the preparation of concrete rubble Pr_{up} are estimated and shown in Table E.13.

Table E.13 Economic impact of Demolition - Upcycling

Process of demolition	Indicator	Costs	Description
Concrete cutting Concrete crushing	C_{up}	€35/m^2 €30/m	According to Jabeen (2020), the costs for demolition of floor elements can be estimated between €31/m^2 and €38/m^2 ,based on the demolition rate described in Section 3.4.2.2. In this research a value of €35/m^2 is used for demolition. For columns and beams, a value of €30/m is used.
Preparing rubble	Pr_{up}	€60/ton	According to Jabeen (2020), sorting material by a waste collector is a costlier option compared to sorting rubble on site. Based on the €90/ton fee for the sorting and processing of material, costs of €60/ton are used for the preparing of rubble on site.

Transport

In case of demolition for upcycling three transport movements are included. The costs for transport $T_{up,1}$, $T_{up,2}$ and $T_{up,3}$ are explained in Table E.14.

Table E.14 Economic impact of Transport - Upcycling

Transport	Indicator	Costs	Description
Transport building site – material processor	$T_{up,1}$	€2,92/truck/km	According to cost calculations of Panteia (2018), the costs of transport with container trucks are €2,60/truck/km in which trucks are used of which the maximum loading capacity equals 25 tons. Including cost increases over the years the estimated costs for transport in 2022 equals €2,92/truck/km (Panteia, 2018, 2019a, 2019b).
Transport material processor - producer	$T_{up,2}$	€2,92/truck/km	According to cost calculations of Panteia (2018), the costs of transport with container trucks are €2,60/truck/km in which trucks are used of which the maximum loading capacity equals 25 tons. Including cost increases over the years the estimated costs for transport in 2022 equals €2,92/truck/km (Panteia, 2018, 2019a, 2019b).
Transport producer – building site	$T_{up,3}$	€2,08/truck/km	**Prefab element:** According to cost calculations of Panteia (2018), the costs of transport with long and heavy trucks are €1,85/truck/km in which trucks are used of which the maximum loading capacity equals 60 tons (RDW, 2022). Including cost increases over the years the estimated costs for transport in 2022 equals €2,08/truck/km (Panteia, 2018, 2019a, 2019b).
		€2,00/truck/km	**In-situ concrete:** According to cost calculations of Panteia (2018), the costs of transport with concrete mixer trucks are €1,78/truck/km in which trucks are used of which the maximum loading capacity equals 10 m^3. Including cost increases over the years the estimated costs for transport in 2022 equals €2,00/truck/km (Panteia, 2018, 2019a, 2019b).

Post-processing

The separated concrete rubble and reinforcement steel can be processed by a material processor resulting in revenue for the demolisher. The revenue Pro_{up} for concrete rubble and reinforcement are shown in Table E.15.

Table E.15 Economic impact of Post-processing - Upcycling

Process of Upcycling	Indicator	Costs	Description
Processing material	Pro_{up}	€-4.5/ton	Selling concrete debris (separated from reinforcement steel) to a recycling plant result in a revenue of €4,5/ton (Icibaci, 2019).
		€-0,50/kg	Reinforcement steel even result in a revenue of €0,50/kg (Icibaci, 2019).

Production new element

The majority of the material will be processed into raw materials for upcycling. Since every year more concrete is produced than rubble being available, only 20-30% of the concrete production can be replaced. Therefore, in this research it is estimated 30% of the concrete of the upcycled element consists of secondary material. To explain the costs of upcycled elements Van Roekel often uses an example of a residential house. The use of secondary material only result in a couple of hundred euros increase in costs (Clahsen, 2021).

Entrepreneurs investing in remanufacturing can be eligible for tax benefits. When at least 30% of the material of the element consists of recycled content, this result in a benefit of €50/m^3 concrete in case of replacement of larger granulate. When 20% of the element consists of recycled cement, even €75/m^2 can be earned (Rijksdienst voor Ondernemend Nederland, 2022). In this research, elements are assumed of which 20% of the concrete consists of recycled cement and 50% of recycled granulate.

The costs for the production of a new element strongly depends on the new element type. In this research, only costs for the production of the in-situ concrete or the prefab element are included. For example, costs for pouring in-situ concrete or installing a prefab element are out of scope.

In Table E.16, the costs for production of new structural elements are shown in which material costs and labour costs are distinguished, even as the production of in-situ concrete or a prefab concrete element.

Table E.16 Economic impact of New production - Upcycling

Production	Indicator	Costs	Description
In-situ concrete	$Pro_{up,1}$	€110 - €120/m^3	The material costs for in-situ concrete are estimated on €110/m^3 in case of C20/25 concrete and €120/m^3 for C30/37 concrete (BouwTotaal, 2019; Bouwdelen, 2021; Betonstation, 2021; Verbouwkosten, 2022).
		€40/h	The labour costs of the production of in-situ concrete are €40/h. For the production of a floor 1 hour is required for 6m^2 (BouwTotaal, 2019; Bouwdelen, 2021). For the production of columns and beams it is estimated that 1 hour is required for 2m.
Reinforcement	$Pro_{up,2}$	€2,00/kg	The costs of reinforcement are estimated €2,00 per kg in 2017 (Schelfaut, 2017).
Floor element (prefab)	$Pro_{up,3}$	€48/m^2	In case of a prefab concrete floor, the costs of a hollow core slab floor are used. The material costs of a hollow core slab are €48/m^2 (BouwTotaal, 2019; Bouwdelen, 2021).
		€40/h	The labour costs of the production of an in-situ floor element are €40/h. For the production of a hollow core slab floor of 36m^2, around 4 hours are required (BouwTotaal, 2019; Bouwdelen, 2021).
Column/Beam (prefab)	$Pro_{up,4}$	€95/m	Based on Bouwkundig bureau Vuyk (2013), the material costs for prefab columns are estimated €95/m. Also costs for beams are estimated as €95/m.
		€40/h	The labour costs of the production of a prefab column or beam are €40/h (BouwTotaal, 2019; Bouwdelen, 2021). For the production of columns and beams it is estimated that 1 hour is required for 3m.

Risks

Next to the costs for preparation, demolition, transport, post-processing, and the production of a new element, the costs for risks R_{up} are estimated based on the research of Glias (2013) and Jabeen (2020). The estimated costs for risks are shown in Table E.17.

Table E.17 Risks - Upcycling

Risks	Indicator	Costs	Description
Risks	R_{up}	3% of total costs	The costs for risks of (traditional) demolition projects can be estimated on 3% of the total demolition costs, since this process knows less uncertainties (Glias 2013; Jabeen, 2020).

Total economic impact Upcycling

As explained in the previous sections, the total costs for the circular strategy Upcycling are determined based on the costs of all the steps involved in the process of Upcycling. Therefore the total costs for upcycling can be calculated according to Equation E.25

$$Costs_{upcycling} = P_{up} + C_{up} + Pr_{up} + T_{up,1} + T_{up2} + T_{up,3} + Po_{up} + \begin{cases} Pro_{up,1} + Pro_{up,2} \\ Pro_{up,3} \\ Pro_{up,4} \end{cases} + R_{up} \quad \text{(E.25)}$$

In which:

$$P_{up} = 0{,}09\left(C_{up} + Pr_{up} + T_{up,1} + T_{up,2} + T_{up,3} + Po_{up} + \begin{cases} Pro_{up,1} + Pro_{up,2} \\ Pro_{up,3} \\ Pro_{up,4} \end{cases}\right)$$

And:

$$R_{up} = 0{,}03\left(C_{up} + Pr_{up} + T_{up,1} + T_{up,2} + T_{up,3} + Po_{up} + \begin{cases} Pro_{up,1} + Pro_{up,2} \\ Pro_{up,3} \\ Pro_{up,4} \end{cases}\right)$$

E.3.3 Economic impact of Reuse

The total economic impact of the process of deconstruction for reuse is visualized in Figure E.22. The costs factors are shortly explained in the following sub-sections.

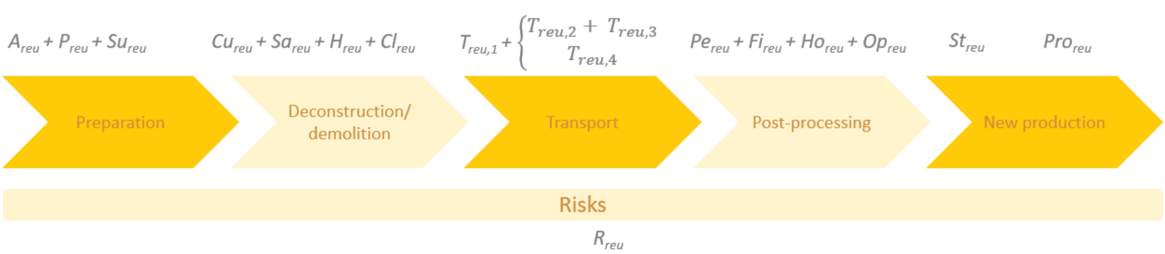


Figure E.22 Economic impact - Reuse (Own figure)

Preparation of deconstruction

The costs for preparation of deconstruction A_{reu}, P_{reu} and Su_{reu} are estimated and shown in Table E.18. The costs for Inventory, Planning, Stripping, and Condition inspection are estimated as an percentage of the total demolition costs.

Table E.18 Economic impact of Preparation - Reuse

Process of preparing	Indicator	Costs	Description
Analysis of documentary	A_{reu}	€90/h	The costs for the analysis of documentary are based on the costs of a structural engineer which are on average €90/h (De Lepper, 2022). The estimated analysis time is one working day (8 hours).
Inventory	P_{reu}	15% of total costs	According to Jabeen (2020) and Glias (2013), the preparation costs are estimated 15% of the total deconstruction costs.
Planning			
Stripping			
Condition inspection			
Temporarily support structure	Su_{reu}	€1/m^2 €2/m	Based on the research of Bleuel, the costs for scaffolding are estimated €1/m^2 of a floor element and €2/m for beams and columns.

Deconstruction

Based on the process of deconstruction, the costs for each step of the process Cu_{reu}, Sa_{reu}, H_{reu}, and Cl_{reu} are shown in Table E.19.

Table E.19 Economic impact of Deconstruction- Reuse

Process of deconstruction	Indicator	Costs	Description
Cut concrete around element	Cu_{reu}	€30/m^2	For cutting of concrete around the element using a crane for the large parts, and a hammer for the smaller parts close to the element, €30/m^2 are estimated, based on (Sloop concurrent, 2021).
Saw concrete element	Sa_{reu}	€35/m	According to Bleuel (2019), sawing using a diamond saw is estimated €35/m. The sawing time and sawing costs can differ per structural element and connection type. Therefore, detailed information about the sawing time and sawing costs per element and connection type is given in Appendix D.2.
Hoist element	H_{reu}	€93,75/h	The rent of a Tower crane is €150/day. Therefore, the rent per hour is €18,75 based on a 8-hour working day. The use of a Tower crane including crane machinist is estimated €75/h (Grondverzet, 2022). According to Glias (2013), the hoisting time of a structural element is approximately 15 minutes.
		€131,25/h	The rent of a Telescopic crane is €250/day. Therefore, the rent per hour is €31,25 based on a 8-hour working dat. The use of a Telescopic crane including machinist is estimated €100/h (Grondverzet, 2022). According to Glias (2013), the hoisting time of a structural element is approximately 15 minutes.
Clean element	Cl_{reu}	€3/m^2	For cleaning of the element costs of €3/m^2 are estimated. For beams and columns, cleaning costs of €1/m are estimated.

Transport

In case of deconstruction two transport movements are included, and in case of storage three transport movements are included. The costs for transport $T_{rem,1}$, $T_{rem,2}$,$T_{rem,3}$ and $T_{rem,4}$ are explained in Table E.20.

Table E.20 Economic impact of Transport - Reuse

Transport	Indicator	Costs	Description
Transport building site – element processor	$T_{reu,1}$	€2,08/truck/km	According to cost calculations of Panteia (2018), the costs of transport with long and heavy trucks are €1,85/truck/km in which trucks are used of which the maximum loading capacity equals 60 tons (RDW, 2022). Including cost increases over the years the estimated costs for transport in 2022 equals €2,08/truck/km (Panteia, 2018, 2019a, 2019b).
Transport element processor - storage	$T_{reu,2}$	€2,08/truck/km	According to cost calculations of Panteia (2018), the costs of transport with long and heavy trucks are €1,85/truck/km in which trucks are used of which the maximum loading capacity equals 60 tons (RDW, 2022).
Transport storage – building site	$T_{reu,3}$	€2,08/truck/km	**Prefab element:** According to cost calculations of Panteia (2018), the costs of transport with long and heavy trucks are €1,85/truck/km in which trucks are used of which the maximum loading capacity equals 60 tons (RDW, 2022). Including cost increases over the years the estimated costs for transport in 2022 equals €2,08/truck/km (Panteia, 2018, 2019a, 2019b).
Transport element processor – building site	$T_{reu,4}$	€2,08/truck/km	**Prefab element:** According to cost calculations of Panteia (2018), the costs of transport with long and heavy trucks are €1,85/truck/km in which trucks are used of which the maximum loading capacity equals 60 tons (RDW, 2022). Including cost increases over the years the estimated costs for transport in 2022 equals €2,08/truck/km (Panteia, 2018, 2019a, 2019b).

Post-processing

In order to estimate the modification costs of a structural element, costs are estimated for reshaping the element by sawing Re_{reu}, the removal of fixings Fi_{reu}, filling holes Ho_{reu}, and creating openings Op_{reu}. These costs are shown in Table E.21.

Table E.21 Economic impact of Post-processing - Reuse

Process of modification	Indicator	Costs	Description
Modification	Re_{reu}	€35/m	The element could needed to be additionally sawn in order to reshape the element. The costs for sawing using a diamond blade are estimated €35/m (Bleuel, 2019). For modification, the width of the floor elements, beams, and columns will be used for potential reshaping of the element.
	Fi_{reu}	€2,5/m^2 €1,5/m	The removal of fixings like anchors for hoisting is estimated €2,5/m^2 in case of floor elements (Bleuel, 2019). For beams and columns a removal price of €1,5/m is estimated, since these elements can be hoisted without anchors.

	Co_{reu}	€110,00 - €120/m^3	The material costs for in-situ concrete used for an additional concrete cover are estimated on €110/m^3 in case of C20/25 concrete and €120/m^3 for C30/37 concrete (BouwTotaal, 2019; Bouwdelen, 2021; Betonstation, 2021; Verbouwkosten, 2022).
		€40/h	The labour costs of the production of in-situ concrete are €40/h. For increasing the thickness of the concrete cover of a floor, 1 hour is required for 6m^2 (BouwTotaal, 2019; Bouwdelen, 2021). For the increasing the concrete cover of columns and beams it is estimated that 1 hour is required for 2m.
	Ho_{reu}	€0,8/m^2 €0,8/m	According to Bleuel (2019), the costs for filling the holes with concrete mortar can be estimated as €0,8/m^2 for floor elements and €0.8/m for beams and columns.
	Op_{reu}	€4,5/m^2 €4,5/m	An amount of €4,5/m^2 is estimated for creating openings in floor elements in order to reconnect the element in the new situation (Bleuel, 2019). For beams and columns, this is estimated €4,5/m.

Storage

Not all structural elements can be directly reused after modification. Therefore the costs for storage St_{reu} are analysed and shown in Table E.22.

Table E.22 Economic impact of Storage - Reuse

Storage	Indicator	Costs	Description
Storage	St_{reu}	€12/m^2/ year	According to Bleuel (2019) and Jabeen (2020), the storage costs can be estimated as €12/m^2/year for floor elements and €12/m/year for beams and columns.

Production new element

In case of reuse of the structural element, the material- and labour costs of the production of a new element can be prevented. Therefore, the costs for new production equal 0.

Risks

For the process of reuse, the costs for risks R_{reu} are estimated based on the researches of Glias (2013) and Jabeen (2020), shown in Table E.23.

Table E.23 Risks - Reuse (Own figure)

Risks	Indicator	Costs	Description
Risks	R_{reu}	10% of total costs	The costs for risks of deconstruction projects are estimated on 10% of the total deconstruction costs, since this process of deconstruction of in-situ concrete elements is new (Glias 2013; Jabeen, 2020). Demolishers have some experience with deconstruction of prefab elements, but deconstruction of in-situ concrete is new.

Total economic impact of reuse

As explained in the previous sections, the total costs for the circular strategy Reuse are determined based on the costs of all the steps involved in the process of Reuse. Therefore the total costs for Reuse can be calculated according to Equation E.26.

$$Costs_{reuse} = A_{reu} + P_{reu} + Su_{reu} + Cu_{reu} + Sa_{reu} + H_{reu} + Cl_{reu} + T_{reu,1} + \begin{cases} T_{reu,2} + T_{reu,3} \\ T_{reu,4} \end{cases} + Re_{reu} + Fi_{reu} + Ho_{reu} + Op_{reu} + St_{reu} + Pro_{reu} + R_{reu} \tag{E.26}$$

In which:

$$P_{reu} = 0{,}15\ (Su_{reu} + Cu_{reu} + Sa_{reu} + H_{reu} + Cl_{reu} + T_{reu,1} + \begin{cases} T_{reu,2} + T_{reu,3} \\ T_{reu,4} \end{cases} + Re_{reu} + Fi_{reu} + Ho_{reu} + Op_{reu} + St_{reu} + Pro_{reu})$$

And:

$$R_{reu} = 0{,}1\ (Su_{reu} + Cu_{reu} + Sa_{reu} + H_{reu} + Cl_{reu} + T_{reu,1} + \begin{cases} T_{reu,2} + T_{reu,3} \\ T_{reu,4} \end{cases} + Re_{reu} + Fi_{reu} + Ho_{reu} + Op_{reu} + St_{reu} + Pro_{reu})$$

E.3.4 Uncertainties costs

In 2021 the material prices have been raised drastically. These increases are firstly caused by the Covid pandemic in which the production capacity was reduced. Secondly, based on increased import duties, steel prices are increased. Transport costs are increased due to closure of Chinese ports and dislocation of containers (e.g. the blockage in the Suez-channel) (Bouwend Nederland, 2021).

Besides, the war between Ukraine and Russia results in increases of material- and energy prices, and logistic problems. At Heijmans it is not possible anymore to make closed price agreements, but indexations should be used (BNR, 2022).

Based on these factors, the uncertainty about the supply of raw materials is increased. This should function as an extra stimulant to seriously consider remanufacturing and reusage.

F. Case study

In order to make sure the Reusability Tool can be used in practice, the tool is validated using the test case. The test case of the Merin Building consists of in-situ elements of which the reuse potential can be assessed by the Reusability Tool. Since it is possible to assess in-situ floor elements, beams, and columns, the reuse potential of these elements is assessed with test-elements from the Merin Building. For each element typology, three test-elements are used.

Since the future project and potential new situation is unknown, either the form of collaboration is unknown. Design-bid-build methods are often used for residential- and commercial projects, and therefore this form of collaboration is assumed.

The accessibility is analysed for a fictive new building project located at the Gasthuiskwartier in ‘s-Hertogenbosch, as shown in the map in Figure F.1. For analysing the accessibility, material- and element processors, producers, and storage options are analysed in the neighbourhood of the location of the Merin Building and fictive new building project, shown in Table F.1.

Figure F.1 Location fictive future building project

Table F.1 Budget and planning

Influencing factors	Description	
Site area	(Assumed to be) large enough	
Accessibility	Distance building site – element processor	68 km (Chasséveld 3-13 - Korenhof Betonbewerking & Montage)
	Distance building site – material processor	42 km (Chasséveld 3-13 - Grond en Resttoffenbank Zuid-Nederland B.V.)
	Distance element processor – building site	38 km (Korenhof Betonbewerking & Montage – Gasthuiskwartier
	Distance material processor – producer	20 km (Grond en Reststoffenbank Zuid-Nederland B.V. – Voets Langeraap Beton BV)
	Distance producer – building site	10 km (Voets Langeraap Beton BV – Gasthuiskwartier ‘s-Hertogenbosch)
	Distance element processor – storage	37 km (Korenhof Betonbewerking & Montage – Shurgard Self-storage Den Bosch)
	Distance storage – building site	5 km (Shurgard Self-storage Den Bosch – Gasthuiskwartier)
Storage	(Assumed) 6 months	

Of the Merin Building, either architectural and structural drawings were available since these documentary was stored in the city archive of Breda. Besides, structural calculations could be analysed. Since the year of construction is known it is possible to check the properties and calculations with the code used for the design of the structure.

F.1 Columns

The tests include two columns of the Merin Building. The first column is an internal column, (situated on the first floor of Merin Building), of which 18 columns are present in the building. Of the second analysed column (situated on the first floor of Merin Building), 16 columns are present in the building.

Following the reusability factors which are described in Chapter 5, the *input sheet* of the Reusability Tool can be filled in.

Product choices

Structural drawings of the analysed columns are shown in Figure F.3 and Figure F.2.

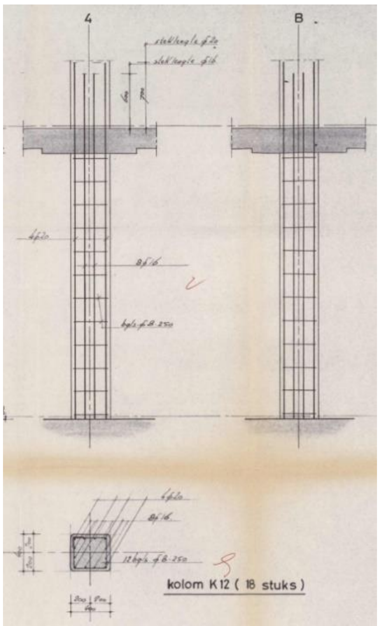


Figure F.3 Structural drawing Column 1

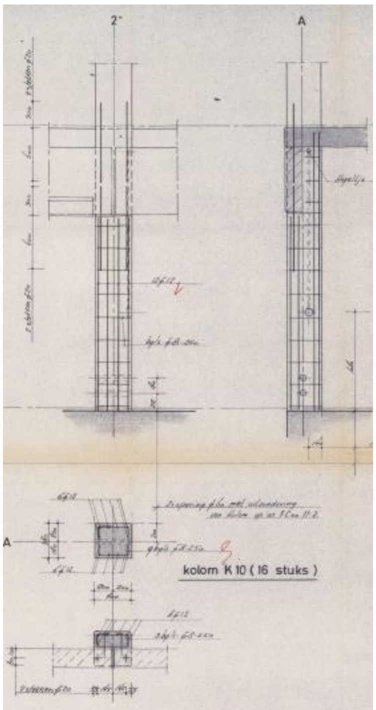


Figure F.2 Structural drawing Column 2

Element information

By analysis of the archive documentary, the element information used as input for the Reusability Tool is shown in Table F.2.

Table F.2 Element information - columns

Element information	Column 1	Column 2
Element type	Concrete column	Concrete column
Element dimensions	Height: 400 mm Width: 400 mm Length: 3180 mm	Height: 400 mm Width: 400 mm Length: 3180 mm
Concrete density	2400 kg/m3	2400 kg/m3
Technical lifespan	50 years (construction class S4)	50 years (construction class S4)

Element properties

The element properties of the columns used in the *Input sheet* of the Reusability Tool are shown in Table F.3.


MATERIAAL EIGENSCHAPPEN

MAT.	KWALITEIT	DICHTHEID
1	b25	24.000

Table F.3 Element properties - columns

Element properties	Column 1	Column 2
Cement type	CEM I	CEM I
Concrete strength class	B25	B25
Environmental class	XC1	XC1
Reinforcement strength	FeB 400	FeB 400

Applicability

The analysed columns are assumed to be reused as column. The internal floor height is 2880 mm.

Design choices

The loading capacity of the columns, detailing of the reinforcement, and demountability of the elements are analysed.

Loading capacity

Information about the loading capacity is shown in Table F.4

Table F.4 Loading capacity - columns

Loading capacity	Column 1	Column 2
Permanent loading	Since the future loading situation is not known, the same loading is assumed as the loading used in the design of the column. Since the column is carrying a floor element, the own weight of the floor is used which is around 5.2 kN/m2. Besides, a finishing of 1.3 kN/m2 is used, resulting in a total permanent load of 6.8 kN/m2.	Since the future loading situation is not known, the same loading is assumed as the loading used in the design of the column. Since the column is carrying a floor element, the own weight of the floor is used which is around 5.2 kN/m2. Besides, a finishing of 1.3 kN/m2 is used, resulting in a total permanent load of 6.8 kN/m2.
Variable loading	4 kN/m2	4 kN/m2
Consequence class	CC2	CC2
Function	Office	Office

Detailing of reinforcement

Based on the analysed drawings, the reinforcement detailing is shown in Table F.5.

Table F.5 Reinforcement detailing - columns

Reinforcement details	Column 1	Column 2
Diameter of bars	Biggest longitudinal bars: 20 mm Smallest longitudinal bars: 16 mm Stirrups: 8 mm	Biggest longitudinal bars: 12 mm Smallest longitudinal bars: 12 mm Stirrups: 8 mm
Number of bars	Biggest longitudinal bars: 4 Smallest longitudinal bars: 8 Stirrups: 12	Biggest longitudinal bars: 6 Smallest longitudinal bars: 6 Stirrups: 9
Spacing of bars	Longitudinal bars: 80 mm Stirrups: 250 mm	Longitudinal bars: 80 mm Stirrups: 250 mm
Concrete cover	30 mm	30 mm
Fire resistance	60 minutes	60 minutes

Demountability of element

The demountability of the elements are analysed based on the factors as described in Section 5.3.3, which are shown in Table F.6.

Table F.6 Demountability - columns

Demountability	Column 1	Column 2
Number of connections	Two	Two
Type of connection	Rigid (wet connection)	Rigid (wet connection)
Accessibility of connection	Accessible with additional action without causing damage	Accessible with additional action causing repairable damage
Crossings	Crossing of one or multiple elements (structural dependencies)	Crossing of one or multiple elements (structural dependencies)
Edge inclusion	Closed at multiple edges	Closed at multiple edges

Column specific design choices

Some column specific design choices of the analysed columns are shown in Table F.7.

Table F.7 column specific design choices - columns

Demountability	Column 1	Column 2
Excentricity normal force new situation	Unknown. Excentricity of 50 mm is used.	Unknown. Excentricity of 50 mm is used.
Drop panels available at column?	Yes	No
Amount of drop panels in column	1	0
Crossing elements	0	1

Condition of the element

The condition of the elements are analysed by a site visit. The external condition of the first column is shown in Figure F.4.

Figure F.4 Condition - Column 1

The external condition of the second column is shown in Figure F.5.

Figure F.5 Condition - Column 2

The potential presence of toxic substances is analysed and shown in Table F.8.

Table F.8 Toxic substances - columns

Toxic substances	Column 1	Column 2
Chlorides	No chance for chlorides penetration, no additional checks necessary (since building is not located in coastal area).	No chance for chlorides penetration, no additional checks necessary (since building is not located in coastal area).
Asbestos free	(Assumed) Asbestos free certificate	(Assumed) Asbestos free certificate

Potential deteriorations are checked on site by externally analysing the elements, as shown in Table F.9.

Table F.9 Deterioration - columns

Deterioration	Column 1	Column 2
Visibility of aging	No defects as result of aging	No defects as result of aging
Visibility of defect	Slight damage/ defects of aesthetic nature	Degradation of material, aging of finish layers and sub-components, only occasionally
Visibility of (external) corrosion	No visible corrosion	No visible corrosion
Cracks	Since CEM I cement is used, there is a chance for Alkali-Silica reaction. Therefore the crackpatern is checked. From the check on site it turns out no inhomogeneous anisotropic cracks in a tree- or map pattern were visible.	Since CEM I cement is used, there is a chance for Alkali-Silica reaction. Therefore the crackpatern is checked. From the check on site it turns out no inhomogeneous anisotropic cracks in a tree- or map pattern were visible.
Crackwidth	0.2 mm	0.2 mm

F.2 Beams

Since the Merin Building consists of a monolith flat slab floor supported by columns, little beams are involved. Though, there are several beams of which the reuse potential can be assessed by the Reusability Tool. To validate the Reusability Tool for the assessment of the reuse potential of beams, two test-beams of the Merin Building are used.

The first internal beam is situated on the ground floor of the Merin Building as shown in Figure F.6. The second internal beam is situated on the ground floor near the elevator shaft of the Merin Building as shown in Figure F.7.

Following the reusability factors which are described in Chapter 5, the *input sheet* of the Reusability Tool can be filled in.

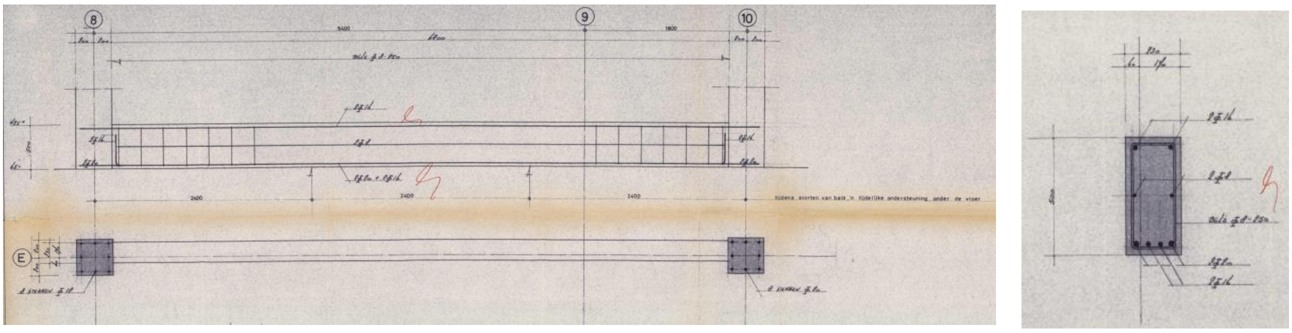


Figure F.6 Structural drawing - Beam 1

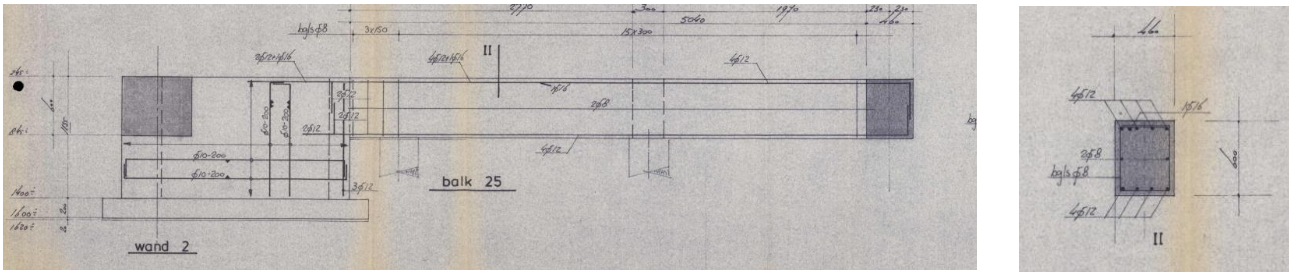


Figure F.7 Structural drawing - Beam 2

Product choices

Structural drawings of the analysed beams are shown in Figure F.4 and Figure F.5.

Element information

By analysis of the archive documentary, the element information used as input for the Reusability Tool is shown in Table F.10.

Table F.10 Element information - beams

Element information	Beam 1	Beam 2
Element type	Concrete beam	Concrete beam
Element dimensions	Height: 500 mm Width: 230 mm Length: 6800 mm	Height: 600 mm Width: 460 mm Length: 5500 mm
Concrete density	2400 kg/m3	2400 kg/m3
Technical lifespan	50 years (construction class S4)	50 years (construction class S4)

Element properties

The element properties of the beams used in the *input sheet* of the Reusability Tool are shown in Table F.11.

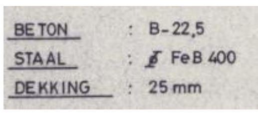

BETON : B-22,5
STAAL : ∅ FeB 400
DEKKING : 25 mm

Table F.11 Element properties - beams

Element properties	Beam 1	Beam 2
Cement type	CEM I	CEM I
Concrete strength class	B22,5	B22,5
Environmental class	XC1	XC1
Reinforcement strength	FeB 400	FeB 400

Applicability

The analysed beams are assumed to be reused as beams. The internal floor height is 2880 mm.

Design choices

The loading capacity of the beams, detailing of the reinforcement, and demountability of the elements are analysed.

Loading capacity

Details of the loading capacity of the analysed beams are shown in Table F.12.

Table F.12 Loading capacity - beams

Loading capacity	Beam 1	Beam 2
Permanent loading	Since the future loading situation is not known, the same loading is assumed as the loading used in the design of the beam. The own weight of the beam is used. Besides, a finishing of 1.3 kN/m2, and a load of walls of 0.8 kN/m2 is included.	Since the future loading situation is not known, the same loading is assumed as the loading used in the design of the beam. The own weight of the beam is used. Besides, a finishing of 1.3 kN/m2, and a load of walls of 0.8 kN/m2 is included.
Variable loading	4 kN/m2	4 kN/m2
Consequence class	CC2	CC2
Function	Office	Office

Detailing of reinforcement

Based on the analysed drawings, the reinforcement detailing is shown in Table F.13.

Table F.13 Reinforcement detailing - beams

Reinforcement details	Beam 1	Beam 2
Diameter of bars	Main reinforcement: 20 mm Flange reinforcement: 8 mm Stirrups: 8 mm	Main reinforcement: 12 mm Flange reinforcement: 8 mm Stirrups: 8 mm
Number of bars	Main reinforcement bars: 6 Flange reinforcement bars: 2 Stirrups: 14	Main reinforcement bars: 9 Flange reinforcement bars: 2 Stirrups: 5
Spacing of bars	Main reinforcement bars: 60 mm Flange reinforcement bars: 225 mm Stirrups: 250 mm	Main reinforcement bars: 100 mm Flange reinforcement bars: 270 mm Stirrups: 150 mm
Concrete cover	25 mm	30 mm
Fire resistance	60 minutes	60 minutes

Demountability of element

The demountability of the elements is analysed based on the factors as described in Section 5.3.3, which are shown in Table F.14.

Table F.14 Demountability - beams

Demountability	Beam 1	Beam 2
Number of connections	Two	Three
Type of connection	Rigid (wet connection)	Rigid (wet connection)
Accessibility of connection	Accessible with additional action causing repairable damage	Accessible with additional action causing repairable damage
Crossings	Crossing of one or multiple elements (structural dependencies)	Crossing of one or multiple elements (structural dependencies)
Edge inclusion	Closed at multiple edges	Closed at multiple edges

Beam specific design choices

Some beam specific design choices of the analysed beams are shown in Table F.15.

Table F.15 Beam specific design choices - beams

Demountability	Beam 1	Beam 2
Length between supports	6800	5040
Length of support	400	300
Crossing elements	1	2

Condition of the element

The condition of the elements is analysed by a site visit.

The potential presence of toxic substances is analysed and shown in Table F.16.

Table F.16 Toxic substances - beams

Toxic substances	Beam 1	Beam 2
Chlorides	No chance for chlorides penetration, no additional checks necessary (since building is not located in coastal area).	No chance for chlorides penetration, no additional checks necessary (since building is not located in coastal area).
Asbestos free	(Assumed) Asbestos free certificate	(Assumed) Asbestos free certificate

Potential deteriorations are checked on site by externally analysing the element, as shown in Table F.17.

Table F.17 Deterioration - beams

Deterioration	Beam 1	Beam 2
Visibility of aging	No defects as result of aging	No defects as result of aging
Visibility of defect	Slight damage/ defects of aesthetic nature	Slight damage/ defects of aesthetic nature
Visibility of (external) corrosion	No visible corrosion	No visible corrosion
Cracks	Since CEM I cement is used, there is a chance for Alkali-Silica reaction. Therefore the crackpatern is checked. From the check on site it turns out no inhomogeneous anisotropic cracks in a tree- or map pattern were visible.	Since CEM I cement is used, there is a chance for Alkali-Silica reaction. Therefore the crackpatern is checked. From the check on site it turns out no inhomogeneous anisotropic cracks in a tree- or map pattern were visible.
Crackwidth	0.2 mm	0.2 mm

F.3 Floor elements

The Merin Building consists of a monolith flat slab floor supported by columns. According to demolition contractors, from those in-situ floors, elements with preferred dimensions can be sawn. Though, it is important to check the amount of active reinforcement in the floor element.

To validate the Reusability Tool for the assessment of the reuse potential of floor elements, two test-floor elements of the Merin Building are used.

The first analysed floor element is located at the first floor of the Merin Building, as shown in Figure F.8 in purple. The second analysed floor element is also located at the first floor, indicated in orange. In the construction of the floors of the building, reinforcement meshes are used assigned by numbers.

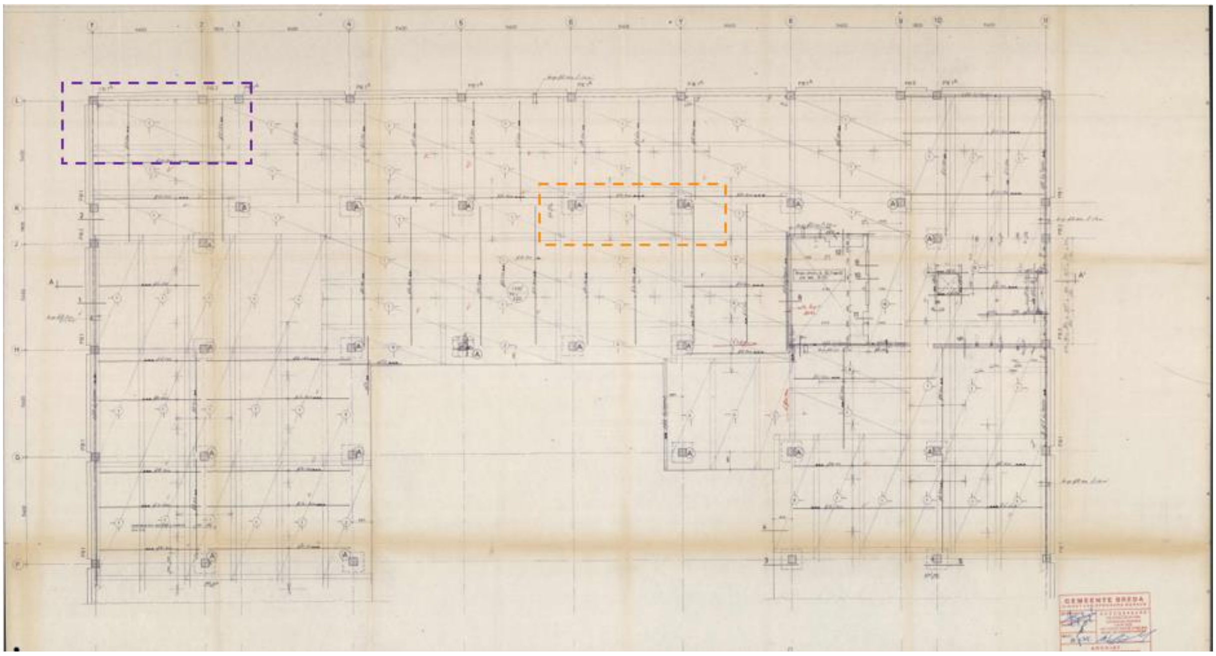


Figure F.8 Structural drawing - Floor elements 1 and 2

By zooming in on the bottom and top reinforcement of the first floor element (Figure F.9), reinforcement meshes of type 1 are used with dimensions 5950 mm x 2500 mm.

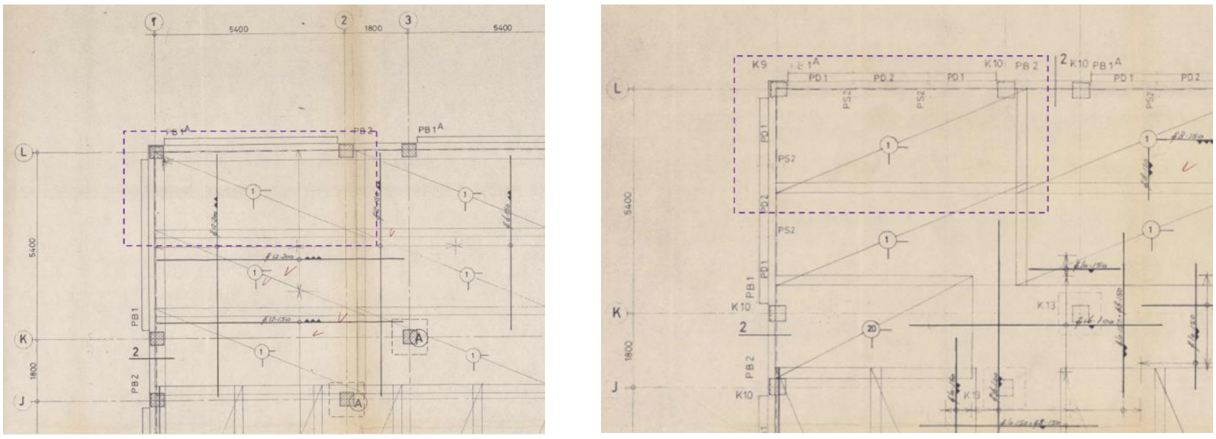


Figure F.9 Top- and bottom reinforcement - Floor element 1

The bottom- and top reinforcement of the second floor element is shown in Figure F.10, also in this element reinforcement meshes of type 1 are used with dimensions 5950 mm x 2500 mm.

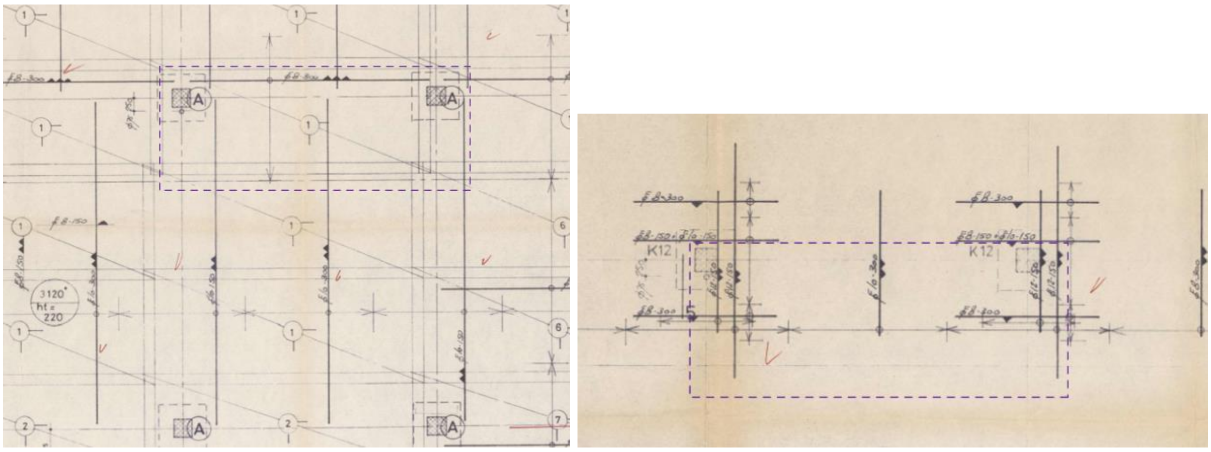


Figure F.10 Top- and bottom reinforcement - Floor element 2

Following the reusability factors which are described in Chapter 5, the *input sheet* of the Reusability Tool can be filled in.

Product choices

Of the Merin Building, either architectural and structural drawings were available since these documentary was stored in the city archive of Breda. Besides, structural calculations could be analysed. Since the year of construction is known it is possible to check the properties and calculations with the code used for the design of the structure.

Element information

By analysis of the archive documentary, the element information used as input for the Reusability Tool is shown in Table F.18.

Table F.18 Element information - floor elements

Element information	Floor 1	Floor 2
Element type	Monolith flat slab floor	Monolith flat slab floor
Element dimensions	Height: 220 mm Width: 2500 mm Length: 6000 mm	Height: 220 mm Width: 2500 mm Length: 6000 mm
Concrete density	2400 kg/m3	2400 kg/m3
Technical lifespan	50 years (construction class S4)	50 years (construction class S4)

Element properties

The element properties of the floor elements used in the *input sheet* of the Reusability Tool are shown in Table F.19.

MATERIAAL EIGENSCHAPPEN

MAT.	KWALITEIT	DICHTHEID
1	b25	24.000

Table F.19 Element properties - floor elements

Element properties	Floor 1	Floor 2
Cement type	CEM I	CEM I
Concrete strength class	B25	B25
Environmental class	XC1	XC1
Reinforcement strength	FeB 400	FeB 400

Applicability

The analysed floor elements are assumed to be reused as floor elements. The internal floor height is 2880 mm.

Design choices

The loading capacity of the floor, detailing of the reinforcement, and demountability of the elements are analysed.

Loading capacity

Details of the loading capacity of the analysed floor elements are shown in Table F.20.

Table F.20 Loading capacity - floor elements

Loading capacity	Floor 1	Floor 2
Permanent loading	The own weight of the floor element is included. Besides, a finishing of 1.3 kN/m2 and a wall load of 0.8 kN/m2 is used.	The own weight of the floor element is included. Besides, a finishing of 1.3 kN/m2 and a wall load of 0.8 kN/m2 is used.
Variable loading	4 kN/m2	4 kN/m2
Consequence class	CC2	CC2
Function	Office	Office

Detailing of reinforcement

Based on the analysed drawings, the reinforcement detailing is shown in Table F.21.

Table F.21 Reinforcement detailing - floor elements

Reinforcement details	Floor 1	Floor 2
Diameter of bars	Main reinforcement bars: 12 mm Main reinforcement meshes: 8 mm Dividing reinforcement bars: 12 mm Dividing reinforcement meshes: 8 mm	Main reinforcement bars: 8 mm Main reinforcement meshes: 8 mm Dividing reinforcement bars: 10 mm Dividing reinforcement meshes: 8 mm
Number of bars	Main reinforcement bars: 13 Main reinforcement meshes bars: 17 Dividing reinforcement bars: 30 Dividing reinforcement meshes bars: 40	Main reinforcement bars: 9 Main reinforcement meshes bars: 17 Dividing reinforcement bars: 20 Dividing reinforcement meshes bars: 40
Spacing of bars	Main reinforcement bars: 200 mm Main reinforcement meshes bars: 150 mm Dividing reinforcement bars: 200 mm Dividing reinforcement meshes: 150 mm	Main reinforcement bars: 300 mm Main reinforcement meshes bars: 150 mm Dividing reinforcement bars: 300 mm Dividing reinforcement meshes: 150 mm
Concrete cover	30 mm	30 mm
Fire resistance	60 minutes	60 minutes

Demountability of element

The demountability of the elements are analysed based on the factors as described in Section 5.3.3, which are shown in Table F.22.

Table F.22 Demountability - floor elements

Demountability	Floor 1	Floor 2
Number of connections	Two	Two
Type of connection	Rigid (wet connection)	Rigid (wet connection)
Accessibility of connection	Accessible with additional action causing repairable damage	Accessible with additional action causing repairable damage
Edge inclusion	Closed at multiple edges	Closed at multiple edges

Floor specific design choices

Some floor specific design choices of the analysed floor elements are shown in Table F.23.

Table F.23 Floor specific design choices - floor elements

Floor specific	Floor 1	Floor 2
Future length between supports	5800 mm	5800 mm
Future length of support	400 mm	400 mm

Condition of the element

The condition of the elements are analysed by a site visit. The external condition of the floor element is shown in Figure F.11.

Figure F.11 Condition - floor elements

The potential presence of toxic substances is analysed and shown in Table F.24.

Table F.24 Toxic substances - floor elements

Toxic substances	Floor 1	Floor 2
Chlorides	No chance for chlorides penetration, no additional checks necessary (since building is not located in coastal area).	No chance for chlorides penetration, no additional checks necessary (since building is not located in coastal area).
Asbestos free	(Assumed) Asbestos free certificate	(Assumed) Asbestos free certificate

Potential deteriorations are checked on site by externally analysing the element, as shown in Table F.25.

Table F.25 Deterioration - floor elements

Deterioration	Floor 1	Floor 2
Visibility of aging	No defects as result of aging	No defects as result of aging
Visibility of defect	Slight damage/ defects of aesthetic nature	Slight damage/ defects of aesthetic nature
Visibility of (external) corrosion	No visible corrosion	No visible corrosion
Cracks	Since CEM I cement is used, there is a chance for Alkali-Silica reaction. Therefore the crackpatern is checked. From the check on site it turns out no inhomogeneous anisotropic cracks in a tree- or map pattern were visible.	Since CEM I cement is used, there is a chance for Alkali-Silica reaction. Therefore the crackpatern is checked. From the check on site it turns out no inhomogeneous anisotropic cracks in a tree- or map pattern were visible.
Crackwidth	0.2 mm	0.2 mm

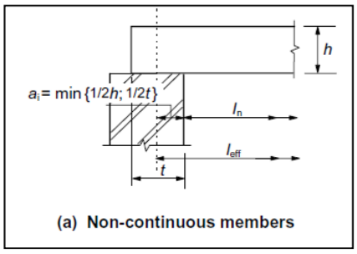
G.Properties of Reusability Tool

In this appendix properties and assumptions of the tool are shortly discussed. Furthermore, default settings of the tool are explained in case it is not possible to get information from drawings and/or calculations.

G.1 Additional input information

The Reusability Tool requires input information of six categories which is asked in the *Input sheet*. However, depending on the analysed element type, some additional input information is required. The additional required information is explained in Table G.1.

Table G.1 Additional input information Reusability Tool

Analysed element type	Design choice	Explanation
Floor element	Length between supports (l_n according to Figure 1)  ***Figure 1: Floor specific design choices***	This information is required in order to calculate the effective length of the element which is used for the calculation of the loading capacity of the floor element in the future situation.
	Length of support (t according to Figure 1)	This information is required in order to calculate the effective length of the element which is used for the calculation of the loading capacity of the floor element in the future situation.
Beam	Future length between supports (l_n according to Figure 1)	This information is required in order to calculate the effective length of the element which is used for the calculation of the loading capacity of the floor element in the future situation.
	Length of support (t according to Figure 1)	This information is required in order to calculate the effective length of the element which is used for the calculation of the loading capacity of the floor element in the future situation.
	Crossing elements	Number of crossing elements should be filled in. This influences the environmental- and economic impact.
Column	Eccentricity normal force new situation	Excentricity of normal force should be filled in [mm]. This influences the loading capacity and potential second order check.
	Drop panels available at column?	Dropdown option: Yes; No This infleunces the environmetnal- and economic impact.
	Amount of drop panels in column	Number of drop panels of column should be filled in. This infleunces the environmetnal- and economic impact.
	Crossing elements	Number of crossing elements should be filled in. This infleunces the environmetnal- and economic impact.

G.2 Assumptions of the Reusability Tool

The Reusability Tool is based on some assumptions. Therefore, this section shortly explains important properties and assumptions on which the (output of the) Reusability Tool is based.

Environmental calculations

The calculations of the environmental impact are based on some assumptions dependent on the analysed element type. Therefore, these assumptions are shown in Table G.2. In Appendix D.2, the deconstruction techniques per element type are shortly addressed.

Table G.2 Assumptions Environmental calculations

Element type	Circular strategy	Environmental aspect	Assumption
Floor element	REUSE	Rate concrete cutting	15 m²/hour
		Rate concrete sawing – rigid connection	1/3 hour/m
		Rate concrete sawing – hinged connection	1/6 hour/m
		Rate concrete sawing – no support	1/6 hour/m
		Rate concrete sawing – rigid point connection	½ hour/point connection
		Rate concrete sawing – hinged point connection	1/3 hour/point connection
		Time drilling anchors in floor	1 hour
		Rate drilling openings in floor	15 m²/hour
	UPCYCLING/ DOWNCYCLING	Rate concrete cutting	30 m²/hour
		Rate concrete crushing	30 m²/hour
Beam/column	REUSE	Rate concrete cutting	5 m/hour
		Rate concrete sawing – crossing element	1 hour/element
		Factor crossing elements	#crossing elements*1.1
		Rate concrete sawing – rigid point connection	½ hour/point connection
		Rate concrete sawing – hinged point connection	1/3 hour/point connection
		Rate drilling openings in beam	5 m/hour
	UPCYCLING/DOWN CYCLING	Rate concrete cutting	10 m/hour
		Rate concrete crushing	10 m/hour
Column	REUSE	Estimated future normal force on column	100 kN
		Rate concrete sawing – drop panels	½ hour/drop panel
All elements	REUSE	Factor edge inclusion	If input sheet Edge inclusion = 'Closed at one edge': 1.05 If input sheet Edge inclusion = 'Closed at multiple edges': 1.1 Otherwise: 1.0
		Reshaping length element	2 times width of the element
		Hoisting time	¼ hour/element
	UPCYCLING	Rate preparing rubble	1/12 hour/ton
		Recycled materials - granulate	50%
		Recycled materials - cement	20%

The used environmental data for calculation of the ECI values of the circular strategies Reuse, Upcycling, and Downcycling are included and explained in Appendix D.3. The Reusability Tool calculates ECI values per building life cycle phase, per circular strategy. For this calculation data of the Nationale Milieudatabase is used containing environmental information including 11 impact categories. First, the ECI value is calculated per unit by a sum-product of the environmental data per impact category and the weight per impact category. Thereafter, the ECI value per unit is multiplied with the unit resulting in the ECI value. The *output* *sheet* contains the final ECI value of each circular strategy which is the sum the ECI values per building life cycle phase.

Economic calculations

All (estimated) costs are explained in Chapter 4. Besides, some additional assumptions are made, dependent on the analysed element type, in order to calculate the economic costs. These assumptions are included in Table G.3.

Table G.3 Assumptions Economic calculations

Element type	Circular strategy	Environmental aspect	Assumption
Floor element	REUSE	Costs concrete sawing – hinged connection	€35/m
		Costs concrete sawing – rigid connection	€38.50/m
		Costs concrete sawing – no connection	€35/m
		Costs concrete sawing – hinged point connection	€52.50/point connection
		Costs concrete sawing – rigid point connection	€57.75/point connection
		Costs drilling anchors in floor	€50.00
Beam/column	REUSE	Costs concrete sawing – hinged point connection	€52.50/point connection
		Costs concrete sawing – rigid point connection	€57.75/point connection
		Factor crossing elements	#crossing elements*1.1
Column	REUSE	Costs concrete sawing – drop panels	€30.00/drop panel
All elements	REUSE	Factor edge inclusion	If input sheet Edge inclusion = 'Closed at one edge': 1.05 If input sheet Edge inclusion = 'Closed at multiple edges': 1.1 Otherwise: 1.0

G.3 Default settings Reusability Tool

It is not always possible to gather all required information to fill in the *Input Sheet* of the Reusability Tool. When for example archive drawings are not available, it can be difficult to gather information about product choices and reinforcement detailing. Therefore, this appendix includes a default setting which can be used to analyse a structural element in case not all properties are known. It should be noted that using default settings always result in a less reliable output. However, the Reusability Tool is developed to be used in an early design stage and therefore always additional detailed structural calculations are required.

Product choices

Table G.4 contains default properties which can be used if information is unknown including some explanation about the default option.

Table G.4 Default settings product choices

Reusability factor	Default option	Explanation
Concrete density	2500 kg/m^3	If the concrete density is unknown, a density of 2500 kg/m^3 can be used since this is the most commonly used density of normal reinforced concrete. In case no reinforcement is included, a density of 2400 kg/m^3 can be used (Kamp, 2021).
Technical lifespan	50 years	According to NEN-EN 1990:2002, for buildings and normal structures, a technical lifespan of 50 years should be used. Therefore, a value of 50 years should be used in case the technical lifespan of the structural element is unknown.
Cement type	CEM I	According to Kamp (2021) CEM I can be assumed as a conservative lower limit.
Concrete strength class	C20/25	C20/25 is the most commonly used in-situ concrete and can therefore be used as lower limit when it is not possible to measure the concrete strength.
Environmental class	XC4	In case the environmental class is unknown, the class can be estimated based on the explanation given in Appendix B.5. If it is still not clear which environmental class suits for the analysed element, the class XC4 can be used indicating a varying dry and wet environment.
Fire resistance	90 minutes	If the (future) fire resistance is not known, 90 minutes can be used as an upper limit. According to Appendix B.6, this fire resistance indicates a utility building with sleeping function having a height above 13 meters.
Reinforcement strength	FeB 220	If the reinforcement strength is unknown, and it is not possible to somehow measure the strength, a strength of FeB 220 can be used as a lower limit.
Forms of collaboration	Design – bid - build	Since the design-bid-build methods are mostly used for residential, commercial, and industrial constructions, this form of collaboration can be used in case the future collaboration form is unknown.

Reinforcement detailing

In case it is not possible to analyse the reinforcement detailing from (archive) drawings and/or calculations, the present reinforcement can be analysed using other techniques. Especially techniques using electromagnetic fields and high-frequency sounds are used to analyse reinforcement diameters, number of bars, spacing, and concrete covering. For example, Nebest uses the following non-destructive measuring equipment: 3D-concrete radar, Ferroscan, GPR Live, and covering measurement equipment. However, measurements of most equipment will still result in a conservative assumption of the reinforcement diameter. In order to analyse the exact diameter of the reinforcement, destructive research is necessary (Nebest, 2022b).

Budget and planning

The Reusability Tool asks for all future transport distances. For example the distance between the building site and the element processor is of importance for the calculation of the environmental- and economic impact. In case these transport distances are not known (yet), the end user can do an estimation. This estimation can be based on analysing facilities located near the current- and future building site. In case the location of the future building site is not known, the end user can just do some estimations. In case multiple elements of the same building are analysed for the same future project, it is important to use the same distances in the *input sheet* to do a fair comparison.