High-quality reuse of materials in the building sector

Master Thesis

Thijs Noordhoek

14 September 2022

TU Delft NEBEST

"The future of humanity and indeed all life on earth depends on us"

– Sir David Attenborough

Figure cover page: abandoned office building dating from 1979, located in Waddinxveen (Own picture)

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High Quality reuse of materials in the building sector

A Research into the possibilities for reuse of monolithic- and hollow core slab floors coming from office buildings with a construction date between 1970 and 1990 in the new construction of serial housing.

By

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Acknowledgements

Five years ago, I started the bachelor Civil Engineering, eager to learn all aspects involved in the structure of a building. After this bachelor, I followed the master Building Engineering with a track in Structural Design. This report is the final product for the master and marks the end of my student days. Now, the time has come to apply this obtained knowledge in practise.

In front of you lies the report ‘High quality reuse of materials in the building sector’ in which two tools are developed which pursue to accelerate the reuse of floor elements in practise. It was clear for me that sustainability needed to form a main aspect in my master thesis. Currently different issues related to climate change are arising. In my opinion everyone needs to add their contribution in saving the planet and thus I wanted to add my part with this master thesis. The idea of reuse arose due to the building on the cover of this report. This building is located in my street and every time I walk past this building, I feel sorry for all materials which are overlooked. I started the research with a material flow analysis to see where the potentials lie. From there I made the focus on floor elements.

During this research I was supported by the engineering firm Nebest. My supervisor on behalf of Nebest was Wouter van den Berg. I want to thank Wouter for his advice, encouragement, feedback, and help throughout the project. Wouter always made time to guide me through the master thesis and was willing to share his network with me when I was in need of help from other specialists. Besides Wouter, I want to thank all colleagues at Nebest for their time and help. During my thesis I felt part of the Nebest family. I want to give special thanks to the other graduates at Nebest: Joost, Jens, Thieme, and Andries. We referred to the group as ‘Team Reuse’ and helped each other during the process and had a lot of fun together. Next to Nebest, I had meetings (both online and offline) with persons from a variety of different companies. I want to thank the persons involved for their time and knowledge. The different companies which supported me with a meeting are stated on the following page.

Also I would like to thank my committee of Delft University of Technology who gave feedback and advice throughout the process. Henk, besides being the chair of the committee, I want to thank you for sharing your knowledge on the topic of sustainability and giving practical advice during the meetings. Secondly, I want to thank Hoessein for his help. You held a mirror for me which made me reflect on my own work and let me think about the follow up steps during the project. Next I want to thank Roy for his critical eye on the work and the advice regarding the formulation and structuring of the report. Throughout the process I felt supported by my committee. Henk, Hoessein, and Roy: Thank you for your support during the thesis!

Besides, the companies and the university I want to thank my friends and family. They formed a sympathetic ear when I wanted to discuss my thesis and gave me accompanying advice. I look back at my student days with a smile and I enjoyed working on my thesis. However, the time as a student has come to an end which is the starting signal of my ‘serious life’. I want to thank all persons who helped me during my thesis. All that for me remains is to wish you a lot of fun reading my thesis!

Thijs Noordhoek

Waddinxveen, August 2022

CONSOLIS VBI

IMd Raadgevende Ingenieurs

GEAR coöperatie

WONINGBELANG

HEIDELBERGCEMENT

IDDS

deKey ontwikkelt en verbindt

VAN WIJNEN

Wijngaarde & Partners vastgoed in beweging

SPIE

MARKUS BV

NEBEST

GBN 20 JAAR

TNO innovation for life

Pieters BOUWTECHNIEK

BOUWGROEP DIJKSTRA DRAISMA

VLASMAN

dusseldorp infra · sloop · milieutechniek

PLAN LOGIC

haitsma BETON

SGS

Abstract

Motive: Waste generation is an environmental problem which is a result of the current linear economy. Materials are used whereafter they are discarded which results in large quantities of waste that contribute to climate change and air pollution, but also directly affect many ecosystems and species (European Environment Agency , 2014). The generation of waste also means the loss of raw materials which is a problem when taking into consideration the finite material supply on earth. Therefore, the current linear economy needs to move towards a circular one in which materials are reused and thus kept in the circle.

Problem: This research is focussed on the Dutch building sector, which was responsible for 50% of the raw material usage and 40% of the waste generation in the Netherlands in 2019 (Kootstra & Werf, 2019). This sector needs to become more circular to reach the climate goals set for 2030 and 2050 (50% and 100% less raw material usage). Currently there are pilot projects conducted in which structural elements from buildings are reused. However, there is still a lot of knowledge lacking regarding the structural feasibility, potential savings on environmental impact, and costs related to reuse. Besides the lacking knowledge about reuse there is no clear image where the potentials for reuse are located within the sector. Therefore this research starts with a material flow analysis of the Dutch building sector which checks the potentials for reuse. Subsequently two tools are developed which check the reuse possibilities considering structural feasibility, environmental impact, and costs.

Methods and results: During the material flow analysis of the Dutch building sector, an image was obtained where the potentials for reuse are located within the sector. In the analysis both the ingoing and the outgoing material flows were examined. The outgoing material flow is mostly related to demolition and the ingoing material flow can mainly be linked to new construction. It was found that office buildings with a construction date between 1970 and 1990 form a big contribution to the outgoing material flow. The new construction of serial houses forms the majority of the ingoing material flow. In both these building types the bulk of the material is located in the floors which are usually made from concrete. The most common floor types, applied in office building from the seventies and eighties, are monolithic floors and hollow core slab floors. In the new construction of serial houses plank floors and hollow core slab floors are predominantly used. Figure 0.1 presents the summary of the material flow analysis and shows the demarcation on the demand and supply side.

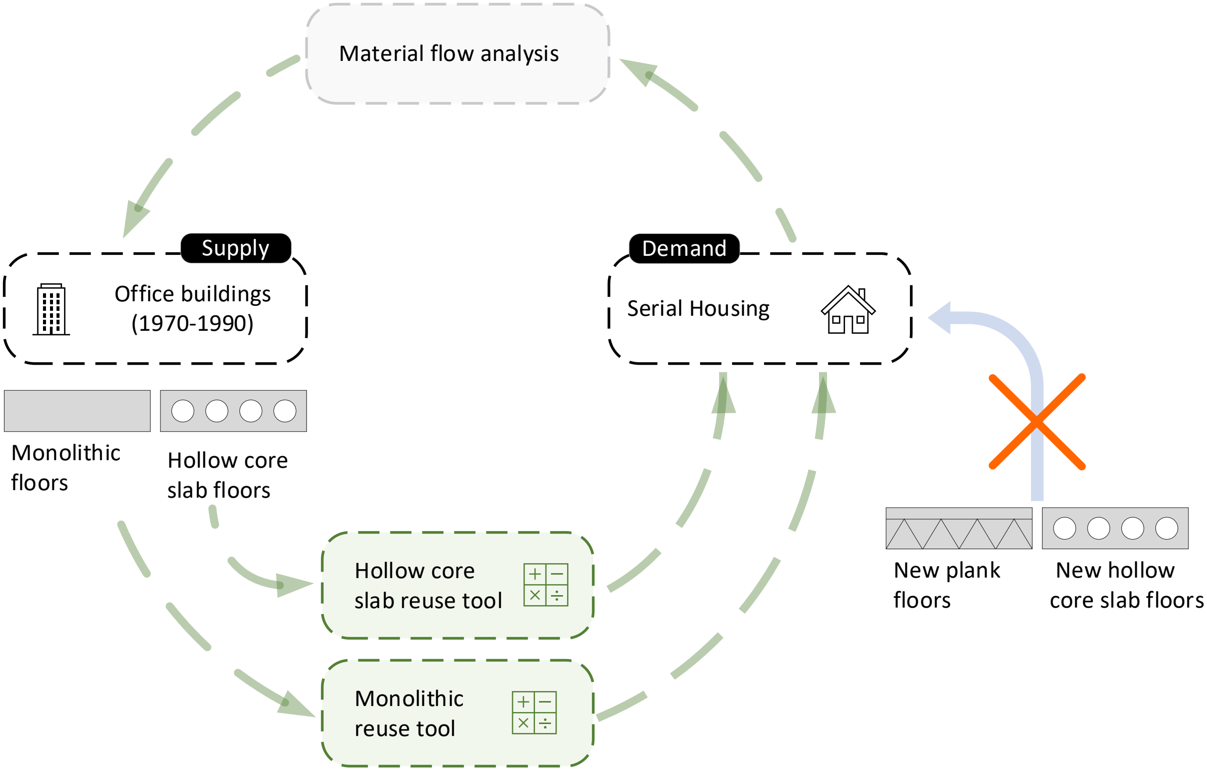

Figure 0.1: Outline of the material flow analysis and the research demarcation (own figure)

Subsequently, two tools (one for monolithic floors and one for hollow core floors) were developed which check the potentials for reuse considering structural feasibility, environmental impact and costs. The structural feasibility in the tools is addressed based on the Eurocode and the Dutch building decree for new construction level. The tools perform the relevant ULS and SLS checks whereafter a conclusion can be drawn if reuse is structurally feasible. In the tools the environmental impact related to a reused element is compared to that of a new element. For both these elements solely the LCA stages A1-A3 are considered which are related to the production process of the element. For the reused element it is assumed that only the different processes which are needed to make the element reusable (i.e. supporting, sawing, and hoisting) contribute to the environmental impact of the element. The environmental impact of a new element can be traced from environmental product declarations or the National Environmental Database. The third aspect which is treated in the tools is costs. A comparison is made between the costs of a reused element and a new one. The costs of a reused element are based on the expenses of the handlings which need to be taken to make the element reusable (i.e. supporting, sawing, hoisting, and material testing). The costs of a new element can be based on interviews or information from other sources. The input parameters for the tools can be divided into three different categories: dimensions, reinforcement (+prestressing) and material qualities and loads. Using these input parameters the tools calculate the structural feasibility, environmental impact and costs related to reuse. The output of these calculations is presented in different graphs which show the UC's related to the structural feasibility and a comparison of the environmental impact and costs between a new and a reused element. The input and output parameters of the tools are summarised in figure 0.2.

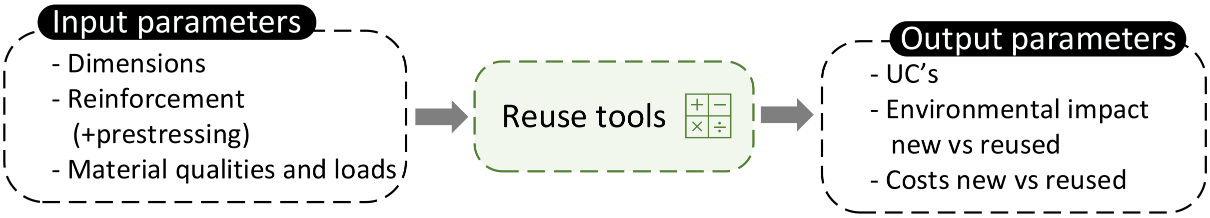

Figure 0.2: Summary of the reuse tools (own figure)

Conclusion and implication: It can be concluded that there are potentials for reuse of floor elements from office buildings in the new construction of serial houses. Several office buildings and serial houses were used in the tools to check the potentials for reuse. The following conclusions can be derived from the tools:

- Structural feasibility: In all examined cases it was structurally feasible to apply reused monolithic floors or hollow core slab floors in the new construction of serial houses.
- Environmental impact: The following savings on environmental impact can be achieved when a reused floor element is applied instead of a new floor element:

Reuse of:	Environmental impact reused compared to new
Hollow core slab floor (with struc. top. in donor build.)	Saving of 40-60* %
Hollow core slab floor (without struc. top. in donor build.)	Saving of 70-90* %
Monolithic floor	Saving of 80-90* %

- Costs: The application of a reused floor element can be more expensive or cheaper as a new element, depending on the type of floor:

Reuse of:	Costs reused compared to new
Hollow core slab floor (with struc. top. in donor build.)	30-50* % more expensive
Hollow core slab floor (without struc. top. in donor build.)	10-40* % cheaper
Monolithic floor	20-35* % cheaper

* Different cases were checked, therefore a range of values is given.

The tools show promising results which could lead to an acceleration of reuse in practise. Application of the tools can give insights in the reuse potentials in a fast and easy way in an early stage of the process. These insights can result in material testing and ultimately reuse. This research states where the potentials for reuse are located in the sector and presents two tools which check the reuse potentials considering structural feasibility, environmental impact, and costs. These tools make reuse more accessible. During different interviews it was found that companies are eager to use the tools. So, due to this research more knowledge and tools are available which contribute to the alteration of the economy towards a more circular one.

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Terms and abbreviations

10R ladder	Classification system developed by Cramer (2014) to describe the circularity of a process/product. From the top (most sustainable) to the bottom (least sustainable) the following levels are given: Refuse, Reduce, Rethink, Re-use, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover.
Building Decree	(Dutch = 'Bouwbesluit') Regulations regarding construction in the Netherlands
CB23	Circular Building in 2023. CB23 is a platform which wants to link parties and give advises on the circularity of the building sector. CB23 was started in 2018 and has set a goal for the year 2023. The goal of CB23 is to share knowledge, investigate the problems, and come with agreements. See: https://platformcb23.nl/over-platform-cb-23 for more info.
Closing The Loop	A project conducted by a consortium of parties of which Nebest was the initiator. In this project the one-on-one reuse of viaduct girders was investigated and is now actually conducted in practise.
Demand side	The demand side is referred to as the buildings which are newly constructed. These projects need materials and thus have a demand which can possibly be answered by reused materials.
Demountability	Possibility to dismantle/demount. Is dependent on e.g. the connection and the number of intersections. Is a key aspect regarding the reusability.
Disk action	The possibility to transfer forces in the plane and act as a stiff disk.
Donor building	Building which is being demolished. From this building materials are becoming available for reuse.
ECI	Environmental Cost Indicator
EPD	Environmental Product Declaration
Fitstrips	Special hollow core elements with deviant dimensions to fit at certain locations (Dutch = passtroken)
HC	Housing Construction
High quality reuse	Reuse refers to reimplementing materials on element level, not on material level. High quality reuse is the reuse of an element in the same function (or higher).
Hollow core slab	Prestressed prefabricated concrete element with channel shaped opening in length direction.
LCA	Life Cycle Analysis, elaborately explained in appendix E.
M-k diagram	Bending moment vs curvature diagram, states something about the stiffness of the material/element
MKI	Milieu Kosten Indicator (Dutch) = Environmental Cost Indicator (English)

Monolithic floors	Monolithic floors are in situ floors which are poured in one go.
NL/SfB	Classification system for building parts
NMD	Nationale Milieu Database (Dutch) = National Environmental Database (English), is a database with environmental data of different materials and (half)products
NRC	Non Residential Construction = buildings which are not designed to reside/live in.
Plank floors	Floor which consists of a prefab and an in situ part. Also referred to as: 'composite lattice girder soffit slab'
Python	Scripting language which is used for the tool.
Reusability scan	Tool developed by Nebest to assess the reuse potential of elements. Originally designed for infrastructural works but during this thesis adjusted to be made usable on buildings too.
Reuse potential	The reuse potential is given based on three different aspects: the structural feasibility, the environmental impact and the costs. These three aspects determine whether an element is reused in practise. Reuse potential refers to the possibly that an element is reused based on these three aspects.
SBIR	Small Business Innovation Research
Serial housing	Is a house which is attached to other houses on the sides. These houses are constructed in series. Also referred to as 'terraced house'.
SLS	Serviceability Limit State, is related to proper functioning of the building
Supply side	The supply side is referred to as the buildings which are being demolished/dismantled. In these projects materials come available which potentially can be reused in other projects.
ULS	Ultimate Limit State, is related to the strength of the building

1 Introduction

In this chapter an introduction to the topic is given. The chapter starts with an explanation of the context in which the research can be placed. Thereafter the current state of art is presented. In the third paragraph the problem definition is sketched. This problem definition forms the basis of the research approach as described in chapter 2.

1.1. Research context

Taking care of the environment is becoming more important by the day. The world's climate as we know it is changing due to the pollution related to human activities. The world is warning us by showing different problems related to climate change, all over the world. At moment of writing, there is a heatwave in Japan with the highest temperatures since 1875 (Veere, 2022). Floods are happening from Suriname to India (NOS news, 2022) (NOS news abroad, 2022) . And fires, droughts and hurricanes are plaguing a third of America (Charter, 2021). It is safe to say the climate has reached a tipping point. These different climate problems are mostly related to human actions, especially to the way how materials are used.

Currently the building process is linear as is outlined in figure 1.1. The process starts with raw materials which are taken from the earth. These materials are finite and the world' reserves are being depleted (Martins & Castro, 2020). With the raw materials, (half) products are produces which are assembled to obtain a structure. This structure is used for a period whereafter it is demolished. The scrap material is usually landfilled or used as a basis for roads.

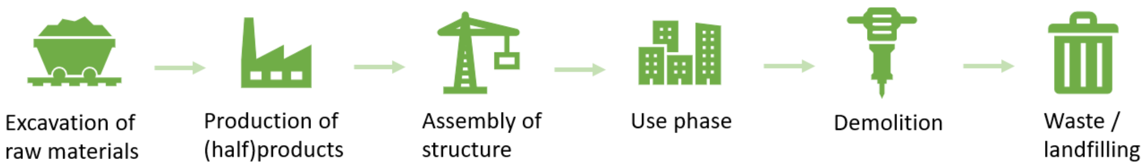


Figure 1.1: Linear economy, own figure inspired by Jonkers (2020)

The building industry is responsible for almost 40% of the total CO2 emissions worldwide (Lammerse, 2020). The building sector in the Netherlands is responsible for circa 35% of the total CO2-emissions in the country (Nelissen, et al., 2018). Raw material usage in the sector is even higher with 50% of the total amount used (Nelissen, et al., 2018). This usage results in a lot of waste. In 2016 the building industry was responsible for 23.5 % of the total amount of waste in the Netherlands (CBS, 2016).

Different climate goals are set for the Netherlands and the world. These targets are not achieved when the current linear system with finite elements is used. Different possibilities are already developed to lower the environmental impact related to construction. The development of, for example, biobased materials has increased in the past years. "Bio-based materials are the type of sustainable materials that are biodegradable and created from biomass" according to Gorji and Menjivar (2021). So these materials result in no finite element usage and only biodegradable waste. However, they are still part of a linear system. A way to alter the linear system into a circular one is to give elements a second life. By reusing elements one can close the loop of materials which results in less waste and no need for new raw materials in the circle. Reuse of elements is only possible when the elements have a residual life. The lifespan of different building layers is described by Brand (1994) and shown in figure 1.2.

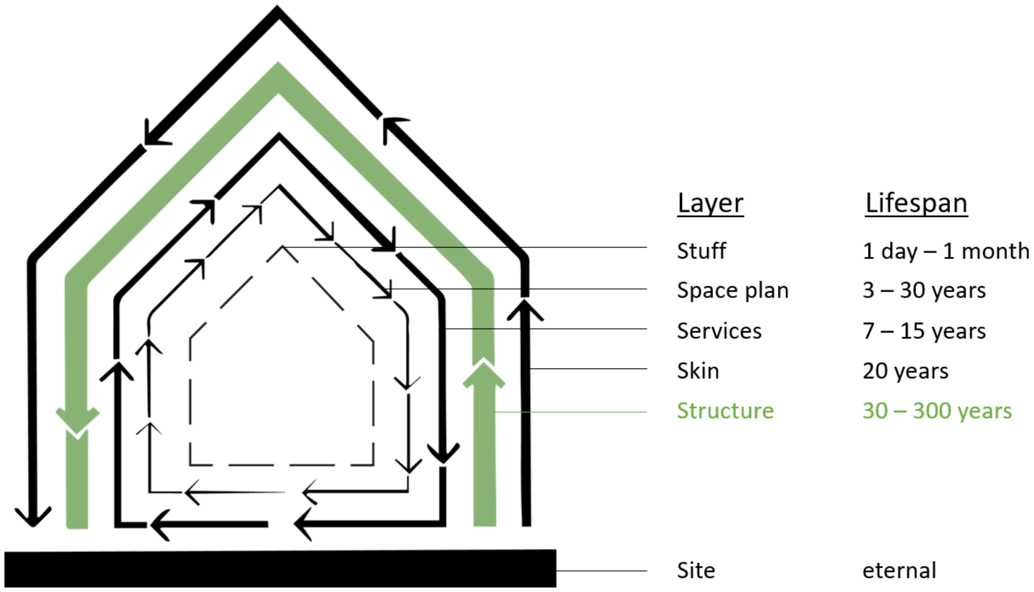


Figure 1.2: Layers of Brand (1994), (Openbuilding.co, n.d.) (adjusted)

This report is focussed on structural elements in a building, as explained in chapter 2. According to figure 1.2 these elements have a lifespan of 30-300 years. The functional lifespan of a building is usually between 40 and 60 years (Dobbelsteen, 2004). Based on the Eurocode it is common to design buildings for a life of 50 years. It can be concluded that the lifespan of the structure is longer than the lifespan of the building. Therefore, the building is usually demolished before the structure meets is end of life, which is a shame. The structure can be used in different buildings before its expected lifespan is met which opens op the possibility of reuse.

Reuse relates to the reimplementation of the element in the same or even a higher function. On the 10R ladder this is a level 7 out of 10 (Cramer, 2014). Concerning existing structures this is one of the highest levels which can be aimed for. The levels 10 to 8 are respectively: refuse, reduce, and rethink which are all more applicable to the new design of a structure. An older model to describe circular strategies is Lansink's Ladder which was developed in 1979. In this model there are 6 levels of circularity: prevention, reuse, recycle, energy, incinerate, and landfill (Lansink, 1979). So, reuse is located high up the ladder which means it is a circular process.

Reuse is a circular process and the possibilities are big. However, it is still not a common practise. By making reuse of elements more common, the burden on the environment can be lowered and the building process can be made (more) circular.

1.1.1. Closing The Loop project

This research is carried out on behalf of the Faculty of Civil Engineering of Delft University of Technology and the consultancy- and engineering firm Nebest B.V.. The rationale of this research is the 'Closing The Loop' project which was carried out by a consortium of different parties including Nebest, as is shown in figure 1.3. The basis for this project was a 'Strategic Business Innovation Research' (SBIR) issue given by Rijkstwaterstaat. In this SBIR, Rijkswaterstaat dared different parties to come up with sustainable solutions for the demolition and rebuild of different infrastructural works which they have in their possession. The Closing The Loop consortia was one of three winners with their idea to 1-on-1 reuse viaduct girders for the construction of new viaducts. Throughout this project Nebest developed the 'Reusibility Scan' (green area in the middle of figure 1.3) which checks the reuse potentials of infrastructural works. The question arose if there are similar possibilities for reuse in the building sector. This issue forms the basis for this report. In appendix A an area defining is done to see where the possibilities within the building sector lie.

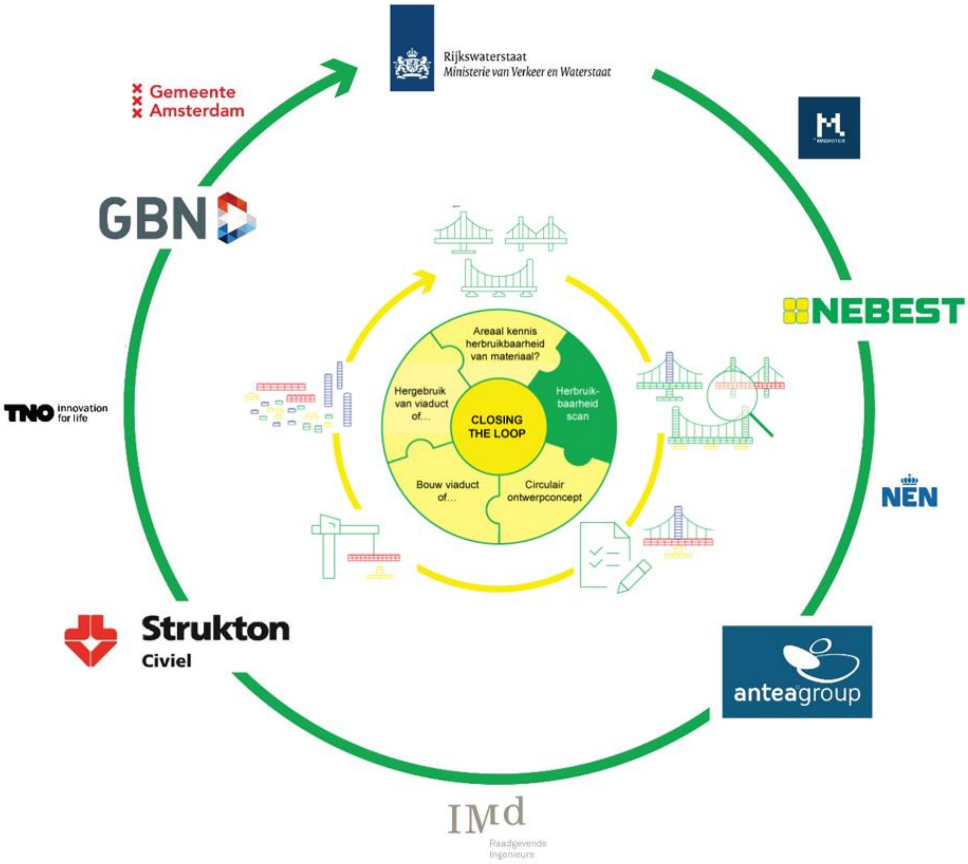


Figure 1.3: Closing The Loop consortia

1.2. State of art

A paradigm shift needs to happen to reach the sustainability goals set by the government and world. The economy needs to shift from linear to circular as fast as possible to contain the damage on the environment and make sure the earth stays liveable. One possible way of making the economy more circular is by reusing elements on a more regular basis. This means new constructions need to be designed demountable. Demountable construction is a principle which was already mentioned by Bovée in 1988. In his book 'Prefabricage in beton' (Prefab in Concrete) he not only discussed the possibilities and needs of demountable structures, but he also specified environmental issues which were arising at the time. He for example discussed the big amount of concrete which was being wasted when demolishing a building. For already more than three decades it is clear that there are environmental issues upon which society needs to act. This is also specified in the CB23 guide 'Circular Design': "It is clear for many people that construction needs to become circular. However, it is unclear what this transition looks like and what is needed is a quest. " (CB'23, 2021).

The current environmental issues are urgent which led to different indispensable goals. The Dutch government specified two main goals in their program 'The Netherlands Circular in 2050' (Rijksoverheid, 2016). The first goal is to use 50% less raw materials in 2030. The second goal is to be 100% circular in 2050. Not only the Dutch government set goals on its own, but there are also goals made together with 194 countries over the world. These climate goals were made during the Paris Conference of Parties in 2015. During this conference the Climate Agreement was made.

The main item in this agreement is the restriction of the rising world temperature to a maximum of 1.5 degrees Celsius (United Nations Climate Change , 2015). This agreement is already seven years old and during this time the world has encountered different issues related to climate change, such as extreme weather. The Intergovernmental Panel on Climate Change (IPPC) released a report on the 28th of February 2022. In this report the researchers concluded that we have no time left to start acting on climate change because the results are now already partly irreversible (IPCC, 2022).

One aspect which could help reaching these goals is the reuse of materials. However, there is still a lot of knowledge and experience missing in this field. Several projects are constructed in which reused materials are applied. Two examples are Superlocal and Prinsenhof A. The first project is a special project in which all materials stayed on the same construction site. A 50-year-old apartment building was dismantled and the materials coming from it were reused to construct new ground bounded houses with. This project is shown in the left part of figure 1.4. More information about this project can be found at: https://www.superlocal.eu/.The right part of figure 1.4 shows the Prinsenhof A project. In this project an old office was dismantled and reused. The hollow core slab floors were taken from the old office building and reused in different other projects. Details about this project can be found on: https://www.gelderland.nl/themas/duurzaamheid/circulaire-economie/prinsenhof. Both of the abovementioned projects are used in chapter 9 for the validation of the different tools. The projects are currently all pilot projects and they are not common (yet). Most of the time these pilot projects are conducted using subsidies from the government and without them the projects are most likely not possible.

Figure 1.4: Supelocal project (left) (SUPERLOCAL HEEMwonen, 2021), Prinsenhof A project (right) (provincie Gelderland , 2022)

Besides projects there are also numerous studies done into the reuse of materials. Two examples are master's theses done by Bente Kamp (2021) and Noortje Bouwens (2022). In both these theses tools are developed which asses the reuse potential of different structural elements in a building. Where Bente's tool focusses on concrete elements and Noortje focusses on concrete and steel elements. Both these tools give the reuse potential of different elements based on different quality-, geometric-, and structural aspects. The tools can be used for several different elements and check the reuse potential of the elements in general. There is no specific building type which is designed/constructed with the reused elements (demand side). The supply side (donor buildings) in Noortje's thesis consists out of SE school buildings. Bente's tool can be used for all types of concrete buildings. Currently there is still a knowledge gap related to the reuse of structural elements because there is no research done which focusses on the whole process of reuse whilst considering the structural feasibility, environmental impact and costs.

Thus, there is the desire for more insights in the reuse process. When this research is focussed on one material flow it is possible to calculate the potential savings on the environment and the needed investment costs for reuse.

1.3. Problem statement

The ingoing flow of materials, in the material mass balance of the building sector in the year 2019, was a factor 4.5 bigger than the outgoing flow (EIB & Metabolic , 2022). So, even if all materials are reused, the supply cannot match the demand. In this material balance the main material is concrete. Concrete takes up 70% of the mass balance and therefore it is obvious to focus on concrete. Most structures have a load bearing structure made of concrete. As earlier described, there is a gap between the technical and the functional lifespan of concrete which opens up the possibilities for reuse. Another interesting aspect of concrete is the ongoing hydration over time. Concrete has ongoing hydration which means the concrete strength will only rise as a function of the time (Courage et al., 2012). A limiting factor concerning reuse can be the presence of damages to the element. This research is conducted in cooperation with Nebest which is an engineering firm specialised in the inspection of existing structures. After several interviews with inspectors who have surveyed different floors a general conclusion can be drawn; It is uncommon to encounter damages on interior storey floors. This means that the storey floors are most likely interesting for reuse purposes.

Based on the different aspects mentioned it can be derived that the market of reuse is attractive. However, there are still several limiting factors which have as a result that the reuse of elements is still not a common practise. The main aspect is the hassle related to reuse. Parties do not know the reuse possibilities of an element beforehand and they do not have insights in the possible savings on environmental impact and the investments which are needed. It is also not clear where the potentials for reuse are located within the sector.

Therefore, there is the demand for insights into the reuse potentials considering structural feasibility, environmental impact and costs.

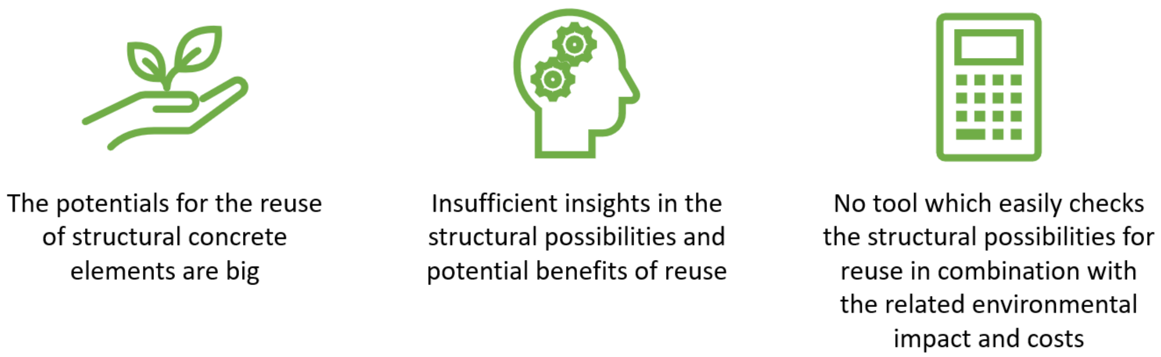


Figure 1.5: Problem statement (own figure)

PART 1: Research framework

Abandoned office building in Waddinxveen – own figure

2 Research approach

In this chapter the different aspects involved in the research are explained. The chapter starts with the explanation of the research objective, which is the main goal. After the objective different research questions are given. Answers to the different sub-questions combined form the answer to the main research question. Next the scope, research strategy, and research outline are explained. All five aspects combined form the research approach of this thesis.

The different research questions were refined throughout the research. These refinements were based on findings during the process.

2.1. Research objective

The overarching goal is the increase of material reuse. As explained in the introduction, actions are needed to save the environment on earth. One of the possible actions which can contribute to a more sustainable and circular future is the reuse of materials. Therefore the overall goal can be formulated the following:

> *"To lower the environmental burden by increasing the amount of materials which are being reused in practise."*

This overarching goal is too big to solve solely by this master's Thesis. Therefore this main objective is refined into an objective which can be covered by this report. The main objective in this thesis is captured in the conclusion of section 1.3:

> *"Give insights in the reuse potentials of floor elements based on structural feasibility, environmental impact and costs."*

It is desired that, by fulfilling this demand, the amount of reuse is accelerated. By doing so this thesis would help reaching the overarching goal.

2.2. Research questions

The full research can be captured in one question which it the main research question. This main research question can be divided into different sub-questions. First the main research question is stated, then the different sub-questions are given.

2.2.1. Main Research Question

The main research question is the basis for this thesis. The question is formulated the following:

> *What is the potential for reuse of structural floor elements in existing office buildings to be applied in new serial houses, considering the structural feasibility, environmental impact, and costs?*

2.2.2. Sub-questions

The main research question can be split up into different sub-questions. These different sub-questions can be divided over two more general sub-question, which together form the main research question.

The two general sub-question and divided sub-questions are:

- *How can floor elements coming from office buildings be reused in serial housing?*
    - *What type of floor elements are used in office buildings built between 1970-1990 and which elements are possibly reusable?*
    - *What construction methods are used for the construction of serial housing and which types of floors are used?*
    - *Which floor elements have a linkage between the supply and demand side and can thus possibly be reused?*
    - *Which steps are involved in the process of reuse?*

- *How can the structural feasibility, environmental impact, and costs regarding reuse be quantified?*
    - *How can the structural feasibility concerning reuse be checked and is it structurally feasible to reuse floor elements?*
    - *How can the environmental impact of a reused element be quantified and how does it compare to that of a new element?*
    - *Which costs need to be made to make reuse possible and how do these costs compare to those of a new element?*

2.3. Scope

It is impossible to cover all aspect involving the reuse of materials, therefore certain limitations need to be made. These limitations form the outline of the research which is also called the scope of the research. The scope of the research can be subdivided into different aspect. The different aspects and the scope limitations involved are given in the following table:

Table 2.1: Scope definition

Subject	Boundary
Construction type	*Buildings* In this report the focus is made on buildings. Infrastructural works and other types of structures are not considered. This demarcation is made because the thesis is conducted on behalf of the master Building Engineering. This master is mainly focussed on buildings and therefore this thesis is also framed on buildings.
Sector	*Dutch building sector* Only the Dutch building sector is dealt with. The rules and data used in this report apply solely to the Dutch building sector and can differ for other sectors/countries.
Process	*Complete demolition and new construction* Materials are used in different processes in a building’s life. The main three phases which result in material flows are: demolition, construction, and renovation/ maintenance. In this thesis only complete

	demolition and new construction is dealt with. The thesis focusses on structural elements, these elements are usually not subjected to renovation or maintenance. It is common that they are left as is. Therefore the material flows related to renovation and maintenance are not treated.
Building type supply side (available elements from demolition)	*Office buildings (1970-1990)* In appendix A the material flows in the Netherlands are examined. Based on the research done in appendix A1 a demarcation is made on office buildings on the supply side. The office building stock (supply) is further elaborated on in appendix A2. It was concluded in this part that office buildings with a construction date between 1970 and 1990 are the most promising ones concerning reuse. The different floor systems in these buildings are treated in chapter 3 .
Building type demand side (needed elements for new construction)	*Serial housing* In appendix A the material flows in the Netherlands are examined. Based on the research done in appendix A1 a demarcation was made on residential buildings. In appendix A3 more elaborate research was done into the different housing types. Based on this part a demarcation is made on serial housing on the demand side. This choice is supported by the building decree as specified in appendix B. The building decree has lower limits for serial housing. Therefore is it most likely easier to apply reused elements in them. The different floor systems and structural typologies used for serial housing are discussed in chapter 4 .
Element type	*Floors* Based on the element focus as described in appendix A4 the demarcation is made on floor elements. Other structural elements which were considered are: beams, columns, and walls. The floors which are treated are storey floors because ground floors are harder to reuse because of their needed insulation values.
Material	*Concrete* The main material which is considered in this thesis is concrete. Concrete is the most common material used to construct floors with. According to page 79 and 83 of the EIB report into material flows (EIB & Metabolic , 2022), concrete represents the bulk of the materials in the different material flows. Therefore, it is obvious to focus on concrete.
Aspects	*Structural, environmental, and cost* In this thesis structural, environmental, and cost aspects are treated. These aspects are specified in part 2.1 and 2.2.
LCA stages	*Stages A1- A3* Only the stages A1-A3 are treated in this report. In the end the reused elements are compared to new elements coming from the factory. The level at which this is done is product level. A more elaborate explanation of the demarcation made for the LCA is given in appendix E.

Costs	*Only related to the product itself* Only costs related to the production process are treated. Costs related to transport or storage are out of the scope.
Loads	*Variable and permanent loads* The loads considered in the tools are variable and permanent loads as specified in the Dutch Eurocode. Extreme loads such as explosions or earthquakes are not treated.
Environmental class	*X0/XC1* The floors are used as interior story floors. Therefore they are not exposed to harmful elements or water.

2.4. Research strategy

The different research questions mentioned in section 2.2 form the basis of the research strategy. This strategy needs to be shaped in such a way that all these research questions are treated. The final goal of the research is to meet the objective set in section 2.1, therefore this objective is taken into consideration whilst designing the research strategy. An overview of the research strategy is shown in figure 2.1. A circular shape can be distinguished in this figure. This circle indicates a closed loop of materials between office buildings and housing construction.

Before the actual research starts a prior literature study is conducted. This literature study is used to derive the scope of this thesis as presented in part 2.3. The different findings of this study are explained in the scope.

The research starts with an area defining of the Netherlands, which is given in appendix A. In this area defining the material flows in the Netherlands are examined. Based on these material flows a demarcation can be made on office buildings on the supply side and housing construction on the demand side. After these two markets are detected, these two markets are examined more in depth. Based on this research a further demarcation can be made on office buildings with a construction date between 1970 and 1990 on the supply side and serial housing on the demand side.

Next the different floor systems used in the offices and serial houses are examined. This research is related to the first two sub-questions. After these questions are answered, potential matches can be checked for. These potential matches form the answer to the third sub-question.

When potential matches are located the development of the tools can start. Two tools are developed for the two matches with the highest potential. The tools are developed based on the comparison of the current properties with the desired properties for new construction. In table 2.2 the desired specifications of the tools are given. These tools are a method to the reach the main objective of this research. With these tools insights in the reuse potentials of floors can be gained.

The different steps involved in the process of reuse, the fourth sub-question, are dealt with during the tool development. When the tool is developed all processes involved need to be checked and this will answer the fourth question. The tools can be applied on different cases. The outcomes of these tests result in answers to the remainder of the sub-questions.

In the research strategy, as explained above, all sub-questions are treated. The answers to the sub-questions combined form the answer to the main research question.

Table 2.2: Desired tool specifications

Tool aspect	Description
Purpose	The purpose of the tool is to assess the reuse potential of floor elements coming from office buildings in the new construction of houses. The tool needs to give the structural feasibility of this interchange of elements. Also it is desired that the tool gives an indication of the possible gains on environmental impact compared to the use of a new floor and an estimation of the costs of the project. These aspects are all related to the reuse potential of the floor elements in practise. It is desired that the tool gives a quick estimation of the possibilities for reuse based on the above stated three aspects.
User	The user of the tool can be diverse. The tool can be handy for demolition companies which want to check the reuse potential of the to be demolished building. But the tool can also be handy for developers/owners who want to check whether they can reuse elements of the current building in a new building or to get insights in the reuse potential of a building.
Phase	The phase in which the tool can be applied can differ between the use phase of the building and the demolished phase. In both these stages and the stages in between the tool can be used to obtain the reuse possibilities of the floor elements.
Execution	The tool can be executed in an early stage with estimated data. In this stage the tool can be used as an aid which can result in more in depth research. It is also possible that the tool is used after the properties are known based on research or data. In this case the tool gives a more accurate outcome.
Software	The software which is used for the tool is Python. Python is a scripting method which can be accessed online. In this way the data can easily be shared between different parties. It is also easy to adjust different aspects which makes the tool highly adaptable. Another advantage of Python is the application of it for different other tools. Therefore, by using Python it is easy to implement the tool into other tools. The last advantage Python has over, for example Excel, is the usage in combination with parametric design. Python can be incorporated into Grasshopper which makes it also usable in parametric design.
Results	The tools need to give the different unity checks related to the structural safety in the ultimate limit state and the serviceability limit state. Besides these checks the tool needs to give the possible savings on the environment expressed in euros and the needed investment costs to make reuse possible.

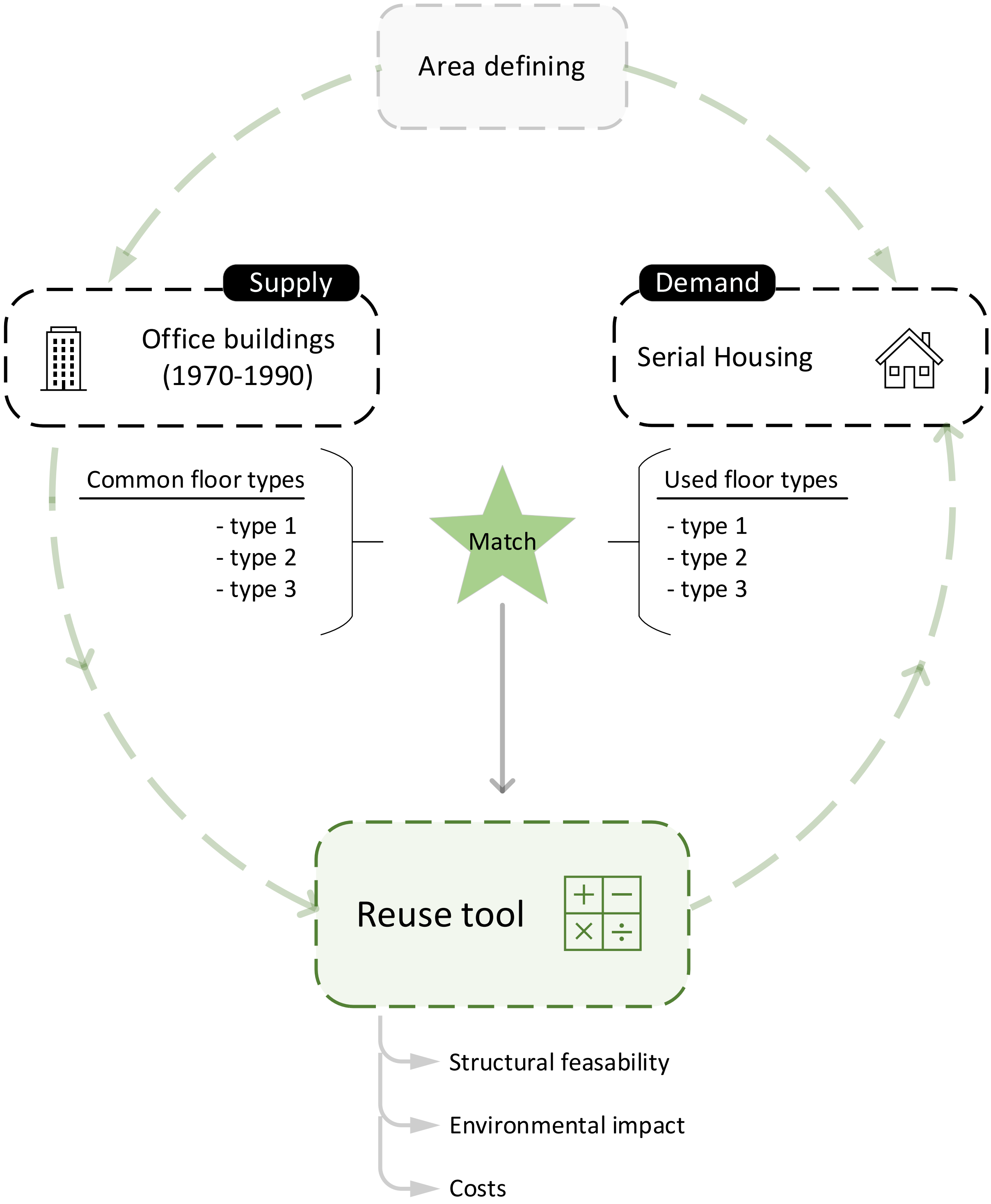


Figure 2.1: Research strategy (own figure)

2.5. Research outline

The research outline is shown in figure 2.2. As can be seen in the figure the research is divided into three different parts:

I. Research framework
II. Research methods
III. Results and final remarks

The different parts all have their own contribution to the full report. The first part, the research framework, forms the main literature study. In this research framework different sub-questions are answered. During the research in part I the rest of the research is shaped. Based on the findings in part I the scope and some research questions can be tweaked slightly before moving on to the other parts. The second part consists of the research methods, this is the research part where the majority of the work is located. In this part new knowledge is constructed before it is validated in the third and final part. This third part can be seen as a concluding part of the research. The results are obtained whereafter conclusions and recommendations are made. This is also the part where the recommendations for further research are given. The whole research outline is also presented in the following figure:

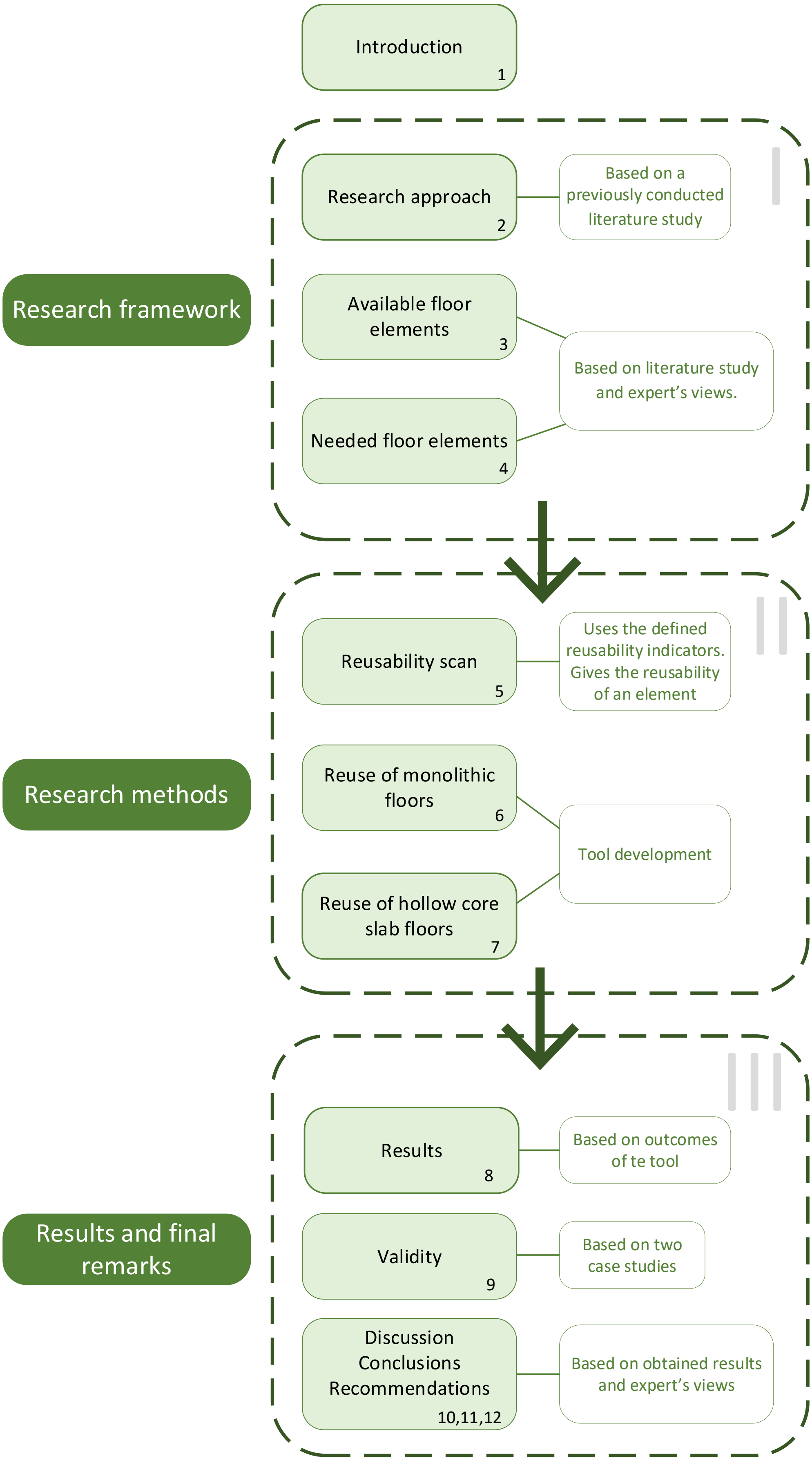


Figure 2.2: Research outline (own figure)

3 Available Floor Elements

Based on appendix A, a demarcation was made into three different floor systems. In this chapter more information is given about the different floor systems. The chapter starts with some general information about floor systems used in office buildings dating from seventies and eighties. Thereafter the three most common systems are treated. The given information in this chapter is mainly based on a literature study on books of the specific time period. These books were consulted because they give the most accurate insights in the construction principles used in this time period. As shown in figure 3.1 this chapter is related to the supply side of the material flows.

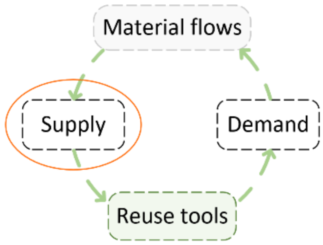


Figure 3.1: Location in research strategy (own figure)

3.1. General information

According to Jellema et al. (1977) it was common to use concrete as a material for storey floors. They described that the most common way of constructing a floor was using a slab floor with a flat surface. Concrete can be used in two different ways: in situ (poured on site) or prefab (made in a factory). In situ concrete is seen as the 'usual' way of applying concrete in this period (Atzema et al. 1981). This material usage is in line with the main structural principle used. In 1981 it was common to use point supported structures which are favourably made of in situ concrete, line supported structures were used but a lot less often (Atzema et al. 1981). This is also in line with the figure presented in appendix A2, in which can be seen that line supported structures are rising in the late seventies and eighties.

Floors have as a main task to transfer vertical loads, which can be imposed on their surface or permanent loads such as self-weight, towards the columns and ultimately into the foundation. However, they also have a task in the horizontal force distribution. The spread of horizontal forces goes through the floors towards the stabilizing elements (Bovée, 1988). Floor elements can be seen as the coherent factor of a building. If the floors are not able to transfer these horizontal forces the system can become unstable. Therefore the floors need to act as a stiff disk. This disk action is easy for floors which consist out of one big element, but harder for floors made up out of multiple elements. This disk action is further explained for the different floor types in the following paragraphs.

The most common span in office buildings in the seventies and eighties is a span of 7,2 m (Jellema & Tol, 1983). For spans smaller than 9 m it is cheaper to use a point supported structure (Kamerling & Kamerling, 1997). If the spans get larger the amount of material rises significantly with point supported structures. Therefore, weight reducing measures are made if bigger spans are desired (Bruggeling, Prefabricage in beton , 1977). Two examples of weight reducing measures are cassettes and hollow cores, these two measures are treated more in depth in the following paragraphs.

3.2. Monolithic floor

A monolithic floor is a floor which is casted in situ in one piece. The main structural principal used for monolithic floors is a point supported structure, which implies that no beams are used in the load bearing structure. The structure consists of floors which are attached to the columns. A monolithic floor is one flat slab of concrete. Monolithic floors are really interesting economically and constructively. Besides, they are really good executable. These three factors are all related to force distribution in two directions of the floor (Atzema et al., 1981). A picture of a monolithic floor can be seen in figure 3.2. In this picture it can be seen that a formwork is made and the concrete floor is poured in one go.

Figure 3.2: Monolithic floor under construction (Gomeniuk, n.d.)

A floor type worth mentioning in this paragraph is the plank floor. This floor is a hybrid system which is partly prefab and partly casted on site. If this floor is completely hardened it acts similar to a monolithic floor and can therefore be treated the same way (Kamerling & Kamerling, 1997). The main differences are the pouring process, as described above, and the reinforcement layout as will be explained in part 3.2.4.

3.2.1. Spans

The spans in monolithic floors are relatively small because the floors get really thick otherwise. This thickness causes a high self-weight which means higher loads and an even thicker floor and so on. Therefore, the floors span relatively small lengths of 5-10 m (Spierings, 1998). These spans are spans in both directions. There is no standard length in these spans because all floors are made case specific.

3.2.2. Thickness

The thickness of the floors can be really different because the spans can differ substantially. The thickness of a monolithic floor can be estimated based on rules of thumb. According to Spierings (1998) the ratio thickness over span is around 1 over 35. With the above stated spans this results in estimated floor thicknesses of 140 to 290 mm. The actual thicknesses can differ from this value but it gives a good estimation.

3.2.3. Load transfer and disk action

Monolithic floors transfer loads in two directions. The floors are elements spanning in two directions and transferring loads in two directions (Spierings, 1998). In a standard monolithic floor no beams are used. The forces travel through the floor towards the nearest column, as can be seen in Figure 3.3.

As mentioned in part 3.1 floors need to act as a stiff disk to transfer horizontal forces. Monolithic floors are usually well capable of transferring these horizontal loads without any help of extra precautions such as a structural topping (Bovée, 1988).

When monolithic floors are casted they are supported by a formwork. The reinforcement is placed on this formwork whereafter the formwork is filled with concrete. Next, time is needed for the concrete to cure. After the concrete is hardened the formwork is dismantled and the process is repeated for new floors or columns. Because the floor is supported during hardening, the floor will have bending moments under self-weight when finished. These bending moments occur not only over span length, as is normal with prefab elements, but also support moments are present. In figure 3.3 a typical bending moment line of monolithic floors is presented.

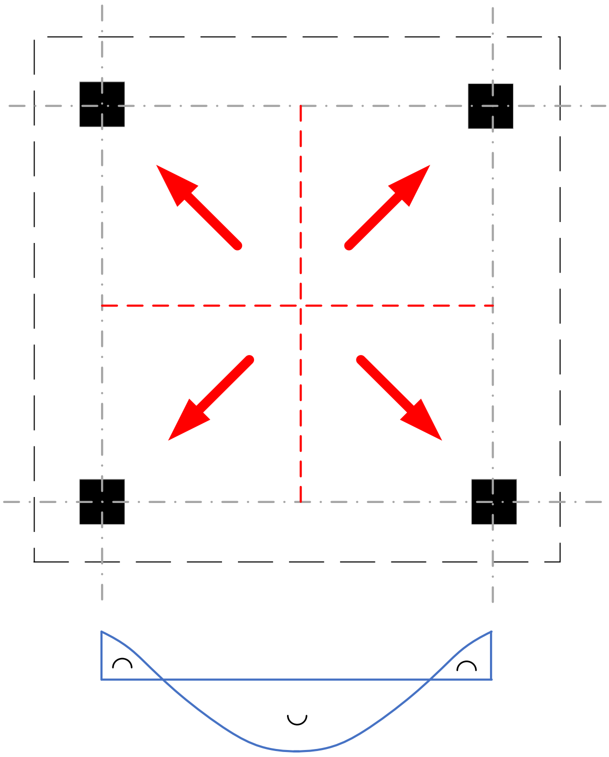


Figure 3.3: Load spread and bending moment line in monolithic floor (own figure)

3.2.4. Reinforcement

As can be seen in figure 3.3 there are upward bending moments near the supports and downward bending moments in the middle of the span. Therefore, both top and bottom reinforcement are usually present in the floors. The floor transfers load in both directions, therefore the reinforcement is also placed in two directions.

There are no standard reinforcement configurations for monolithic floors. So, it can be hard to know the reinforcement configuration when the original drawings are not available. It is also possible that the actual reinforcement is different from the reinforcement on the drawings. Therefore it is advisable to scan the reinforcement. Based on an interview with a material expert of Nebest it can be concluded that it is possible to chart the reinforcement layout and properties based on scans and small tests.

Coming back to the plank floor; The reinforcement of a plank floor is placed in the prefab part and sticks out when delivered to the building site. Part of this reinforcement consists of lattice girders which holds the top reinforcement in place until the in situ concrete is hardened. Because of these lattice girders it is hard to scan the reinforcement layout, according to a specialist of Nebest. Therefore, the plank floor is disregarded.

3.3. Cassette floor

Another floor type is the cassette floor. The cassette floor can be specified as: "an in situ floor with a rib pattern in two directions on the underside of the floor" (BetonLexicon, 2021). This pattern is made by placing boxes in the formwork. The rib pattern in a cassette floor is made because of weight reduction (Kamerling & Kamerling, 2004). Usually a cassette floor is used in a point supported structure without beams. However, this statement can be argued because the ribs in a cassette floor act comparable to beams. Therefore sometimes cassette floors are specified as line supported structures (as done in appendix A2). The height of the ribs can be up to one meter. One of the most famous cassette structures is the roof of the Pantheon in Rome. For figures of a cassette floor see appendix A2.

3.3.1. Spans

The special pattern lowers the weight of the floor while simultaneous strengthening it due to beam action. Therefore cassette floors are really strong which means it is possible to make big spans (NBD, 2017). According to Spierings (1998) common spans for cassette floors are between 7 and 18 meters. Compared to the monolithic floors the spans can be almost a factor two bigger. Constructing a cassette floor is much more labour intensive as a monolithic floor. A cassette floor becomes economically feasible when spans approach 8 to 9 m (Atzema et al., 1981).

3.3.2. Thickness

The thickness of a cassette floor depends strongly on the height of the ribs. Based on a rule of thumb it is possible to estimate the thickness. The thickness of a cassette floor can be estimated based on a ratio thickness over length of approximately 1 over 35 (Spierings, 1998). With the abovementioned spans this results in thicknesses of approximately 200 – 515 mm. However, as mentioned previously it is also possible to use far bigger ribs with a maximum height of around 1 meter. This means the thickness of the floor can also become bigger than 1 m.

3.3.3. Load transfer and disk action

The ribs in a cassette floor act as beams. Therefore each part of floor in between the ribs can be seen as a flat slab placed on four edge beams. The forces in a floor part travel towards the nearest rib, as can be seen in figure 3.4. Then the ribs transfer the loads towards the columns, which transfer the loads into the foundation. This principle occurs in both directions of the floor; therefore a cassette floor can transfer loads in two directions.

A cassette floor is most of the time an in situ poured element as specified previously. Therefore the floor can be seen as one big element, similar to the monolithic floor. Because the floor is one big element, it is easy for the floor to act as a stiff disk when transferring horizontal forces.

Cassette floors are usually poured in situ in a special formwork. After the concrete is cured the formwork is removed and the floor is finished. Because the formwork is removed after hardening the floor will experience support bending moments under self-weight, similar to the monolithic floor. In figure 3.4 a typical bending moment line can be seen.

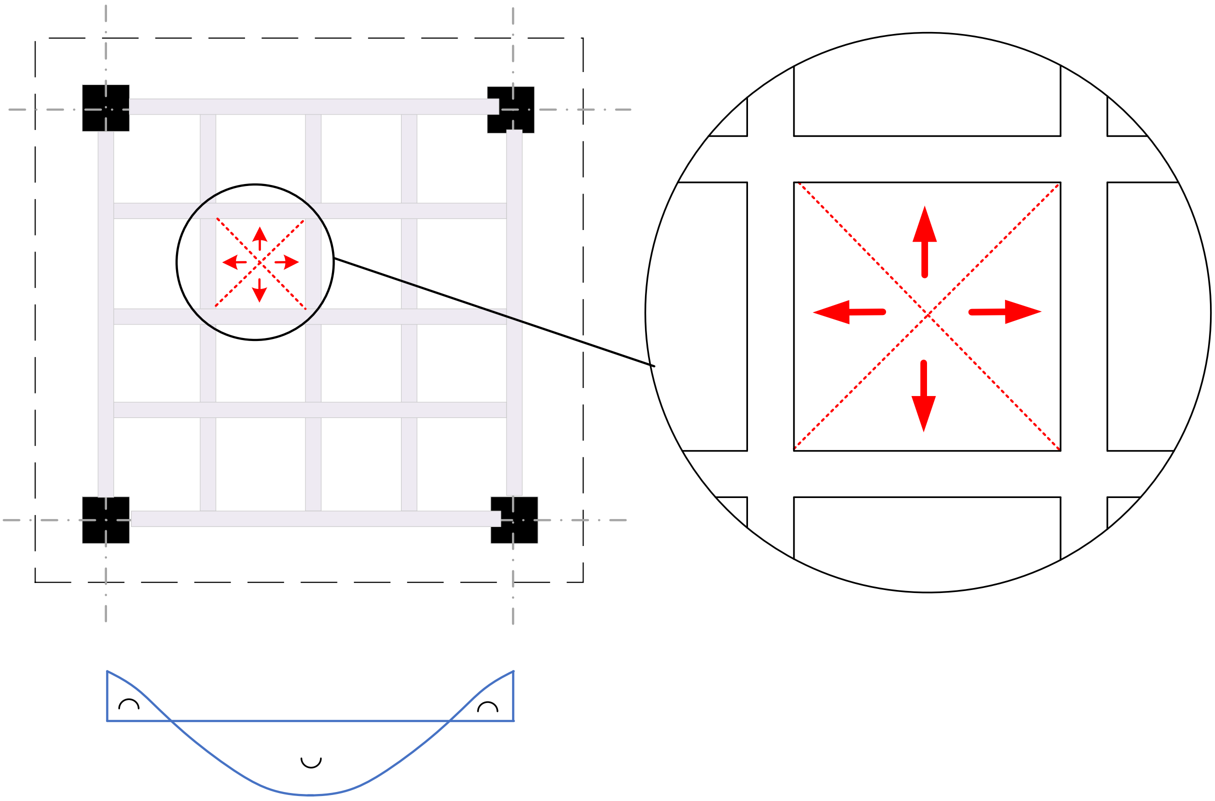


Figure 3.4: Load spread and bending moment line of cassette floor (own figure)

3.3.4. Reinforcement

Both upward and downward bending moments are present, as can be seen in figure 3.4. Therefore both top and bottom reinforcement is needed in monolithic floors. The reinforcement layout of monolithic floors is quite complex because of the ribs which act as beams. The reinforcement is placed in both directions because the floor transfers load in two directions.

It is hard to estimate the reinforcement configuration beforehand, because cassette floors are usually case specific. Therefore, the original drawings are important. If these drawings are not available, it is possible to scan the reinforcement according to a specialist of Nebest. However, this is much more difficult compared to a monolithic floor.

3.4. Hollow core slab floor

The third floor type which is dealt with is the hollow core slab floor, which is a prefab floor system consisting of rectangular elements. These elements are delivered in standard widths, the most usual width is 1200 mm. The elements have empty channels in length direction to lower the self-weight (Kamerling & Kamerling, 2004). Because of this lowered self-weight the acoustic properties are lower; therefore the hollow core slaps cannot be used for dividing walls between houses. Hollow core slabs are commonly used in prefab construction (Bovée, 1988). The main rise in application of hollow core slabs was in the eighties (Bennenk & Huijben, 2002). A hollow core slab floor is based on a line supported structure. The rectangular elements are placed on beams which run in between the columns. It is also possible that hollow core slabs are used in combination with load bearing facades. In this case the floor elements are placed directly on the façades. Buildings using this principle of load bearing facades do not need to have columns and beams.

Figure 3.5: Hollow core slab element (Bison Precast , n.d.)

3.4.1. Spans

Hollow core slabs can span relatively large distances because of their low self-weight and prestressed reinforcement (elaborated on in part 3.4.4). The elements can span distances varying from 5 meters up to 15 meters (Spierings, 1998). The most common spans are around 10 m which is almost a factor 2 bigger than monolithic floors (Bruggeling & Huyge, 1982).

3.4.2. Thickness

Thicknesses of hollow core slabs can be estimated based on rules of thumb. The ratio between thickness and span can vary from 1 over 40 to 1 over 25 (Spierings, 1998). Using these ratios in combination with the previously mentioned spans one can conclude that the thicknesses vary between 150 and 600 mm. However, it needs to be added that with a thickness of 320 mm it is possible to span up to 12 meters (Bruggeling & Huyge, 1982). An interview was held with different experts of VBI. They specified that the most common thickness, used in these specific office buildings, is a slab with a thickness of 260 mm.

3.4.3. Load transfer and disk action

Load transfer in hollow core slabs is in one direction. The element spans in one direction between the beams or walls. This direction is the same direction in which the forces travel, as shown in figure 3.6. The force travels in longitudinal direction through the hollow core slab towards the beam on which it is supported. Via these beams the force travels into the column and ultimately into the foundation.

Hollow core slabs are separate elements when placed. There is only little friction between the different elements and therefore the elements do not always act as a stiff disk. It is quite common to apply a structural layer on top of the different elements. The main goal of this layer is to make sure that the different elements will cooperate together and form a stiff disk. According to an estimation made by experts of VBI (during an interview), approximately 80% of the floors are executed with a compression layer. Another possibility is to use a bond around the different elements to make sure they cooperate together. A third possibility is to use a stability system in which floors do not need to act as a stiff disk, in this case no structural topping is needed.

The elements span in one direction and are simply supported when they are placed. Therefore no support moments are present under self-weight. The bending moment line is similar to that of a simply supported beam, as can be seen in figure 3.6. One needs to pay attention that sometimes a wet connection is used after placing. When this is the case supporting moments can occur under variable loads.

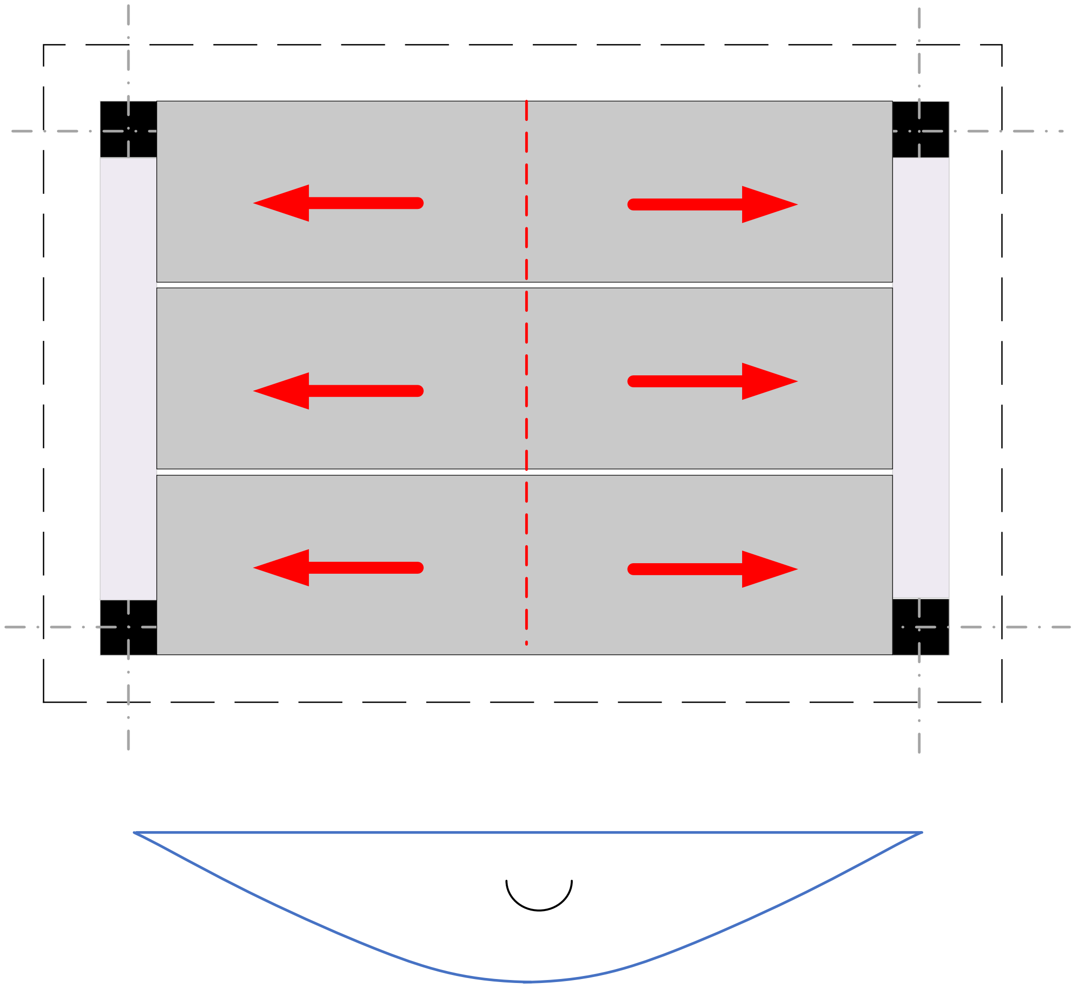


Figure 3.6: Load spread and bending moment line of hollow core slab (own figure)

3.4.4. Reinforcement

The reinforcement in hollow core slabs is usually prestressed and placed in the spaces in between the hollow cores. Different prestressing forces can be used for the same plate thicknesses. The reinforcement is only placed in one direction because the element only spans and transfers load in one direction.

When the original drawings of the element are available the prestressing load and reinforcement ratio are known. If these drawings are not available it can be hard to obtain the reinforcement ratio and prestressing. An expert of Nebest specified that the scanning equipment gives difficulties due to the hollow cores in the element. The only way in which the reinforcement ratio can be measured is by boring cores in the elements, which make the element almost unusable. The original prestressing force cannot be measured, the force can only be estimated based on the steel quality used for the reinforcement. This quality can be checked by tests on the drilled core.

3.5. Summary and reuse potential

Three commonly used floor systems are treated in the previous paragraphs. A summary of the most important aspects is given in table 3.1.

Table 3.1: Properties of different floor systems

	Monolithic	Cassette	Hollow core
Prefab or in situ	In situ	In situ	Prefab
Point or line supported	Point	Point	Line
Span	5-10 m	7-18 m	5-15 m
Thickness	140-290 mm	200-515+ mm	150-600 mm (320 common)
Load transfer	2 directions	2 directions	1 direction
Connection	In situ with reinforcement	In situ with reinforcement	In situ
Ducts	Not possible	Not possible	In structural layer

Based on the findings it can be concluded that a cassette floor is the hardest to reuse; The reinforcement layout is difficult to map, there is no standardisation, and the ribs make dismantling hard. On top of that the floors are relatively thick which is not desired. Therefore the reuse of cassette floors is not treated in this research. Both monolithic and hollow core floors create opportunities for reuse. Therefore, the reuse of these two floor types is examined in chapter 6 and 7. In the following chapter the demand side is treated. When the needed materials in this demand side are examined, it is possible to check whether there are potential matches between supply and demand of floor elements.

4 Needed Floor Elements

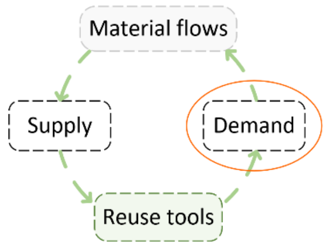


Figure 4.1: Location in research strategy (own figure)

The focus on the demand side is made on serial houses (single family). This demarcation is made based on appendix A, in which can be seen that 36% of the new houses is a serial house. When looking at the area, serial housing represents 40% of the total area of new built houses. Another important aspect taken into consideration whilst demarcating are the building rules as presented in appendix B. In this appendix it can be read that the building rules for apartments are much more strict compared to those of serial single family houses and thus it will be easier to reuse elements in the serial houses. As shown in figure 4.1 this chapter discusses the demand side of the material flows.

There are different construction techniques used for the construction of serial houses in the Netherlands. The most common ones are: stacking, casting/pouring, and prefab (Pielkenrood & Heidinga, 2017). For all of these different systems the walls are mostly leading because the floors are often constructed using concrete. The market shares of the three methods are respectively 45%, 30%, and 25% (Pielkenrood & Heidinga, 2017). Looking at the high quality reuse potential one method can be disregarded immediately, the casting/pouring. With this method all elements are poured on site. Therefore, it is not possible to apply reused elements. Pouring/casting construction forms a big opportunity for material recycling. For example, the implementation of crushed concrete as aggregate in new concrete. However, this thesis is focussed on the high quality reuse of elements and thus is pouring/casting out of the scope. The two other construction techniques, prefab, and stacking, are discussed in the following paragraphs. These paragraphs start with general information about the construction technique whereafter the floor elements used in these construction techniques are explained.

4.1. Stacking Construction

In stacking construction the different elements are stacked onto each other during construction. It is most of the time referred as the ‘traditionel method’ in the Netherlands. Usually different materials are used for the walls and floors. The walls are usually composed of two layers: an outer layer of ordinary masonry which is not load bearing and a load bearing inner layer of sand lime brick (Vree, n.d.). The floors are placed on this inner layer of sand lime bricks. In figure 4.2 the process of stacking construction is shown. Two commonly used floors systems in stacked construction are: plank floors and hollow core slab floors (Bouwkunde Oline, n.d.). These two floor systems are explained in the following paragraphs.

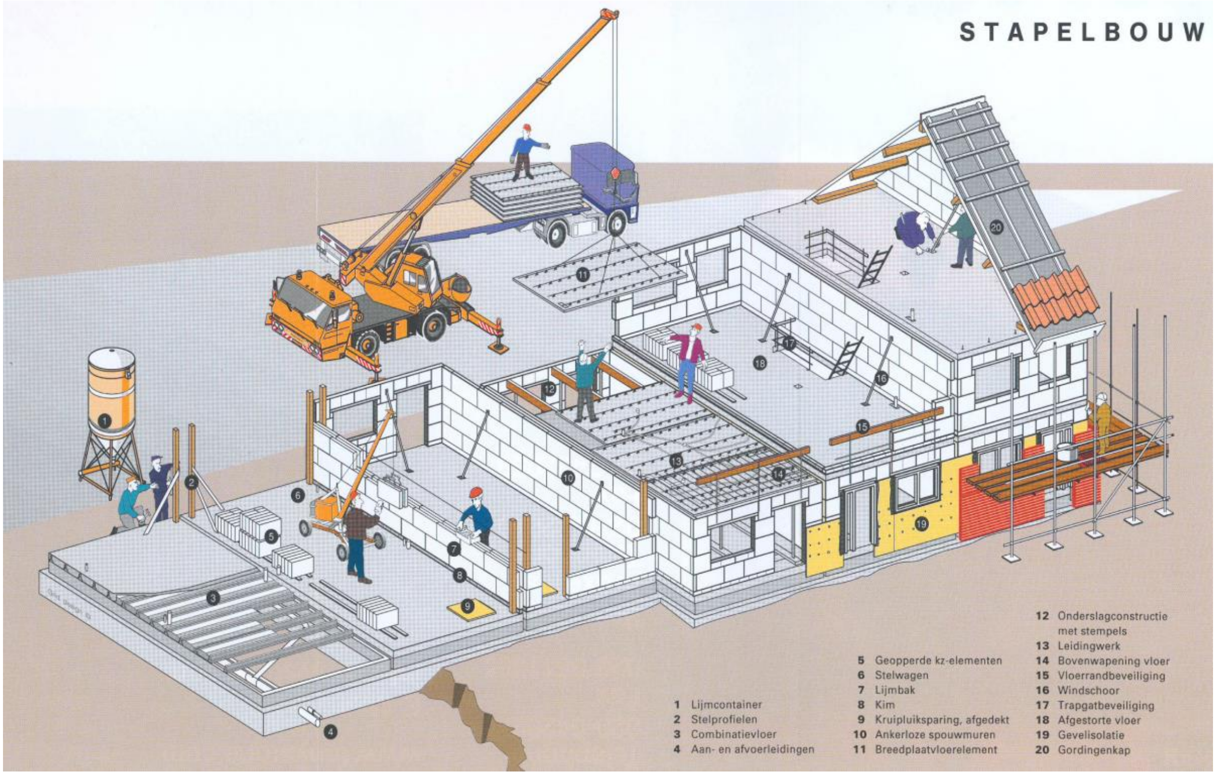


Figure 4.2: Representation of stacking construction (Abspoel, et al., 2018)

Plank floor

A plank floor is a special kind of floor. It is not a prefab floor but also not an in situ floor. A thin concrete slab is produced in the factory. This thin slab usually has a thickness between 50 and 100 mm (Boom et al., 2005) The reinforcement for the floor is placed in this thin layer and sticks out of it when placed. On site a layer of concrete is poured on top of this prefab part, as is shown in figure 4.3. The prefab part can be seen as a formwork for the rest of the floor. The reinforcement is present in both the prefab as the in situ layer and makes sure that both parts cooperate together. This reinforcement is usually ordinary reinforcement but it is also possible to prestress the reinforcement in plank floors. By doing so it is possible to deal with bigger spans and/or make slimmer constructions possible.

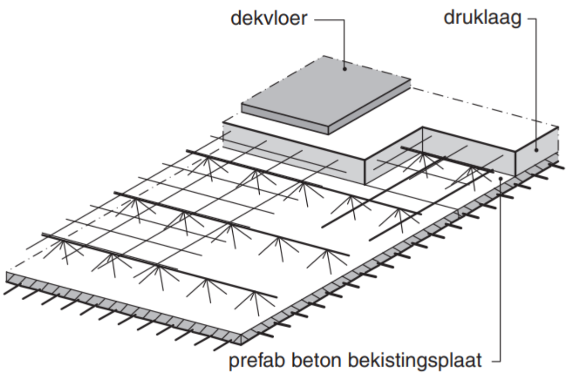


Figure 4.3: Representation of plank floor (Boom, Maessen, Noy, & Raadschelders, 2005)

Most of the time plank floors span in one direction but it is also possible to apply them for spans in two directions (Hordijk, et al., 2020). Thus the force distribution can be in one or two directions. Plank floors have a width between 1.2 and 3 meters and a maximum span of around 10 meters (Betonhuis, n.d.). The thickness is usually between 200 to 300 mm excluding a 50 mm topping, but the floors are often >300 mm in total because of sound proofing (Vree, n.d.).

Ducts can easily be placed in plank floors. The ducts can be placed on top of the prefab part in between the reinforcement which sticks out of it. When topping the floor with the in situ layer the ducts get covered with concrete and become part of the floor. A diversity of different ducts, pipes, and cables can be placed in a plank floor in this way (STIPB, 2008).

Plank floors in a stacked construction are usually placed on top of the inner load bearing wall. After all elements are placed the in situ layer of concrete is poured. This layer makes sure the floor becomes one unity and will act similar as a monolithic flat slab. Standard connections between an edge wall and a plank floor, and an intermediate wall and a plank floor are shown in figure 4.4.

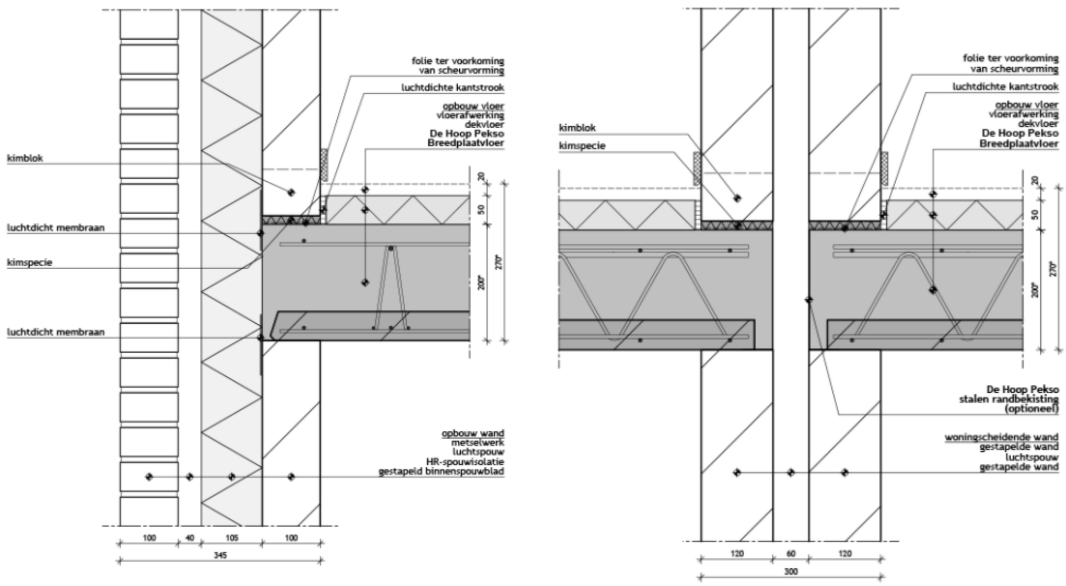


Figure 4.4: Details of connection between plank floor and wall (Bouwdetails, n.d.)

Hollow core slab floor

Hollow core slab floors are made up out of prefabricated hollow core elements. These elements have empty channels in length direction to reduce the self-weight of the floor. Due to this reduced self-weight it is possible to make larger spans compared to other floor systems, as will be mentioned in the next paragraph. The reinforcement lays in between the different channels of the hollow core and is pre-tensioned. It is common to apply a structural layer on top of the slabs after they are placed. This layer needs to fill the gabs in between the different elements and also needs to make sure that the different elements can cooperate as one stiff disk (disk action). In figure 4.5 a representation of a hollow core slab floor is given. In this figure insulation is shown on the bottom of the hollow core, this is usually done when the floor is used as a ground floor. The scope of this thesis is made on storey floors, where this insulation layer is not applied.

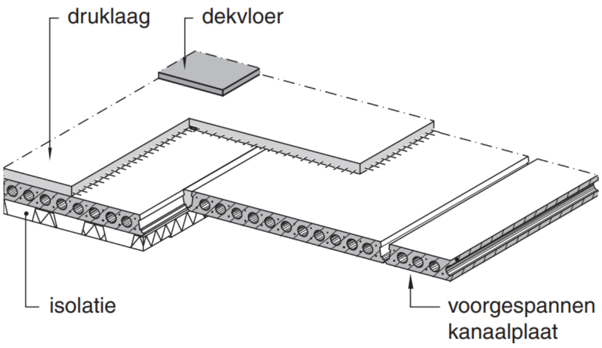


Figure 4.5: Representation of hollow core slab floor (Boom, Maessen, Noy, & Raadschelders, 2005)

Hollow core slabs span in one direction, in length direction. The reinforcement in the elements is only placed in this direction and the force transfers in this same direction. Hollow core elements have a standard width of 1.2 meters and it is possible to make spans up to 18 meters. However, in residential construction it is more common to use elements with a maximum span of 6 to 8 meters (Wikipedia, 2020). The thickness of hollow core slabs can vary between 135 and 500 mm.

When using hollow core slabs it can be hard to implement ducts and cables in the floor (Vree, n.d.). There are special kinds of hollow core slabs in which ducts and cables cab be placed, for example hollow core slab with ducts as mentioned in 4.2. But with ordinary hollow core slabs it is not possible to place ducts in the floor elements itself. It is possible to lay ducts and cables in the structural topping on top of the floor. However, this can result in a thicker structural layer which results in a thicker floor system with a higher self-weight.

Connections between hollow core slabs are made by applying a structural topping on top of them. This topping combines the different floor elements to one element. The connection between the floors and the walls is usually made by anchors or by pouring mortar between the slab and the wall (so called wet connection). In figure 4.6 connections between an edge wall and a hollow core slab floor, and an end wall and a hollow core slab floor can be seen.

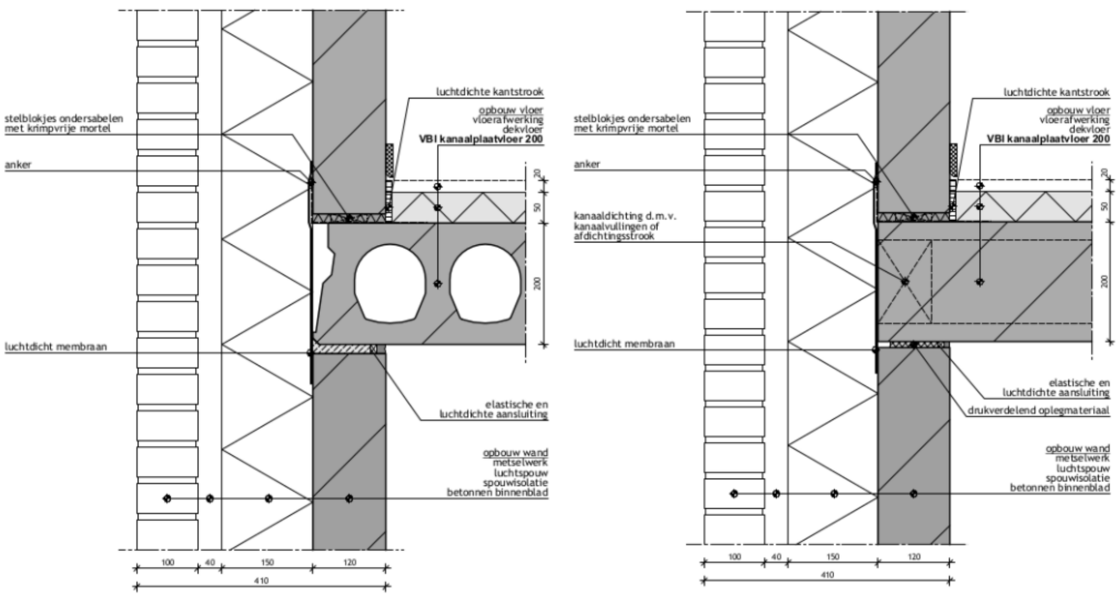


Figure 4.6: Detail of connection between hollow core slab and wall (Bouwdetails, n.d.)

4.2. Prefab Construction

Prefab construction is sometimes referred as assembly construction (Vree, n.d.). This name is related to the process. In prefab construction all elements are construction in factory and transported to the building site. On the building site these elements are assembled into a building. Due to this prefabrication little work is needed at the construction site which results in a shorter construction period. However, one needs to be aware of the longer preparation time which is needed to produce prefab elements. The different elements are usually made of concrete and the maximum size depends on the maximum transportable dimensions (Bouwkunde Oline, n.d.). In figure 4.7 a representation of prefab construction is given.

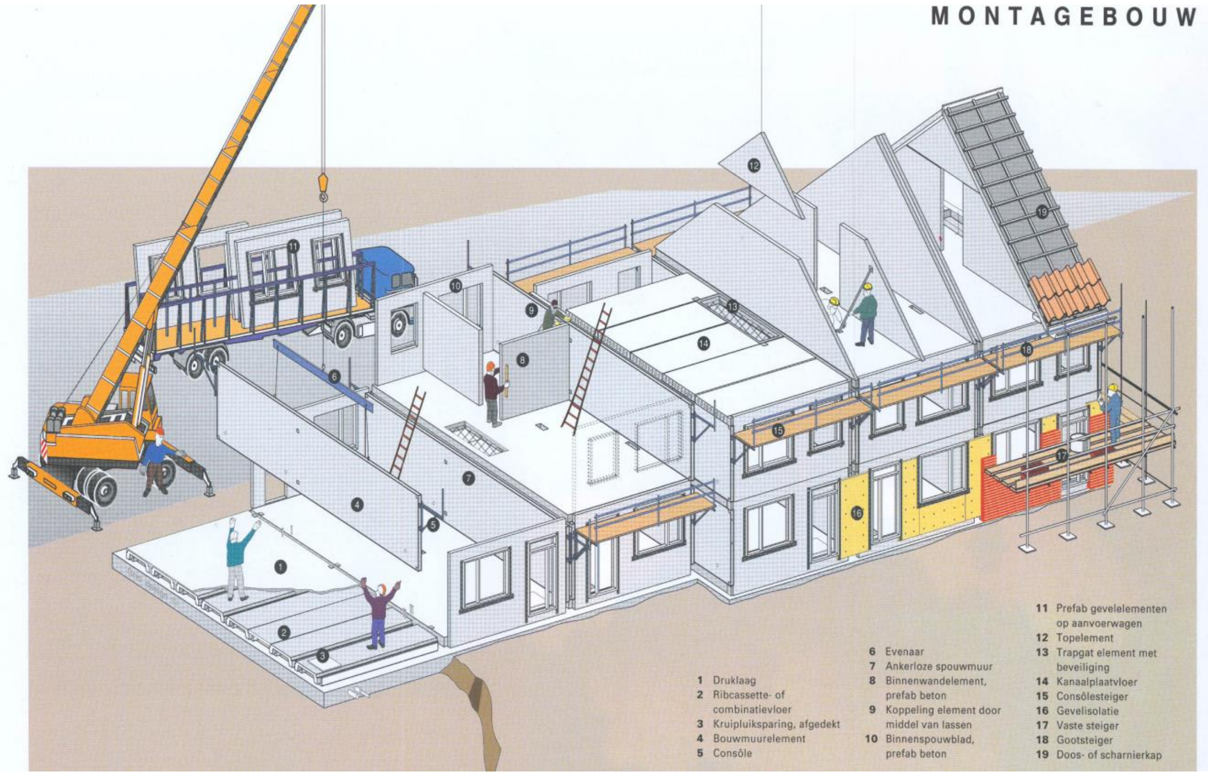


Figure 4.7: Representation of prefab construction (Abspoel, et al., 2018)

Hollow core slab floor with ducts

A hollow core slab floor with ducts is similar to an ordinary hollow core slab floor. The main difference is that there are channels/slots in the hollow core elements to place ducts in. The principles mentioned before about the ordinary hollow core slabs are also applicable to this floor type. The channels in the hollow cores are used to reduce the self-weight and a structural topping is needed to make one unity of the floor.

Hollow core slabs with ducts are usually placed alongside ordinary hollow core slabs. On locations where ducts/cables are desired, for example the wet zone of the bathroom, a hollow core slab with ducts is used. On locations where no cables/ducts need to be located an ordinary hollow core slab floor is used.

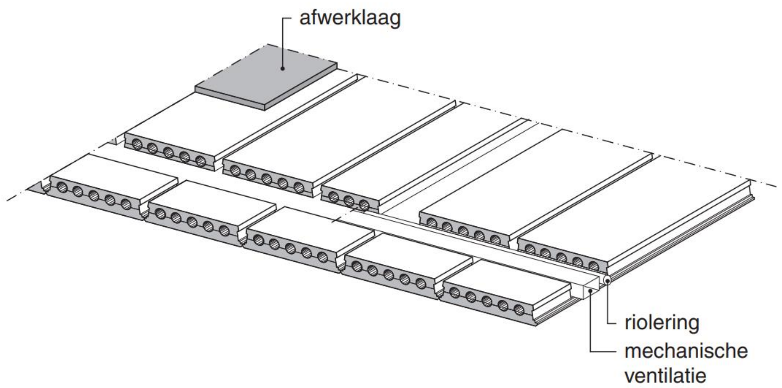


Figure 4.8: Representation of hollow core slab floor with ducts (Boom, Maessen, Noy, & Raadschelders, 2005)

The force distribution and spans are also quite similar compared to an ordinary hollow core slab floor. The floor elements span in one direction and the floor transfers loads in one direction as well. However, one needs to take into consideration that the load path is sometimes interrupted by a duct which means that the loads need to take a different path. The elements have a standard width of 1.2 meters which is similar to that of an ordinary hollow core element and a length of up to 12 meters. In residential construction spans up to 6.5 meters are quite common. A common element thickness at these spans is 200 mm (Driesen, 2012).

In hollow core slab floors with ducts it is no problem to place cables, ducts etcetera. Unlike ordinary hollow core slabs these elements have slots in which the different cables/ducts can be placed. After these ducts are placed, the structural topping is applied to the floor. By doing so the ducts become part of the floor.

The connections are similar to the connection of an ordinary hollow core slab. The ends of the elements have no ducts and therefore the same principles can be applied. For an elaborate explanation, and images about connections of hollow core slabs, see previous part about ordinary hollow core slabs.

Prefab casco floor

A prefab casco floor is a floor which is fully fabricated in factory. The floor is delivered to the construction site as one solid plate which already has all ducts and cables integrated. It is sometimes preferable to apply the ducts and cables on site. In this case the floor can be made with slots which are filled with concrete after the cables and ducts are placed (Heembeton , n.d.). When applied fully prefab only the cables and ducts of the different elements need to be coupled on site which means the likelihood of errors is small and the construction speed is high. The bottom of the floor does not need any finishings because it is a smooth surface. The elements are usually made for a specific project. Therefore, the elements have a perfect fit in the layout and the properties are as desired. In figure 4.9 the installation of a casco floor element can be seen.

Figure 4.9: Prefab casco floor (Eisma Content Marketing , 2018)

The elements are usually spanning in one direction and transferring loads in one direction. However, it is also possible that one element spans the complete floor area of the building. In this way the floor is spanning in two directions. But when spanning in two directions the loads transfer will mainly be in one direction because the forces travel towards the closest support. The standard width and span of elements strongly depends on the manufacturer. The Bestcon MPV140 and MPV160 floors have a standard width of 3.5 meters and can span approximately 6/7 meters (Bestcon, n.d.). Other manufactures also produce floors which can span a complete storey.

Ducts and cables are already placed in the floor as previously mentioned. The prefab casco floors are usually a plug and play systems which means that only the different parts need to be coupled. Because all ducts and cables are already implemented in the floor no extra in situ topping is needed.

The connections of the different elements are usually done by bolting the different elements together. These bolts are placed in specially made slots which are already incorporated in the elements. Another possible connection is made by openings in the elements which fit into each other. Different connection methods are used and usually differ between the different manufactures. However, it is quite common to use a dry connection such as bolting. An example of a bolted connection is shown in figure 4.10.

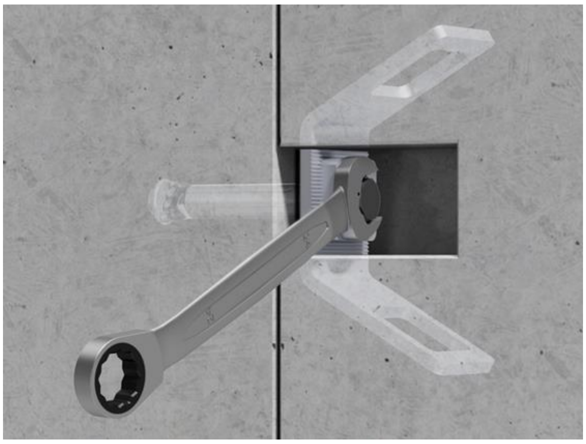


Figure 4.10: Prefab bolted connection (Halfen, n.d.)

4.3. Summary and reuse potential

Four different floor types, which are used in two construction methods, are mentioned in the previous paragraphs. A summary of the properties of the different floors is given in table 4.1.

Table 4.1: Properties of different floor systems

	Plank	Hollow core	Hollow core with ducts	Prefab casco
Prefab or in situ	Prefab and in situ	Prefab	Prefab	Prefab
Point or line supported	Line	Line	Line	Line
Span	3-10 m	Up to 18 m (6-8 common)	5-15 m	Case specific 5-6 m
Thickness	200-300 mm +50 mm topping (>300 mm)	135-500 mm	200-260mm	Case specific
Load transfer	1 or 2 directions	1 direction	1 direction	1 or 2 directions
Connection	In situ	In situ or dry	In situ or dry	Dry
Ducts	Easy in top layer	Only small ducts	Easy	Implemented

It can be concluded that it is hard to implement reused elements instead of a prefab casco floor. Prefab casco floors are specifically made to fit in a certain prefab system which differs between manufacturers. The floor is precisely made according to the specifications and all ducts are usually preinstalled which both is not possible with reused elements. The second floor type which cannot be substituted by a reused floor is a hollow core slab floor with ducts. These elements are specially made hollow core elements in which ductwork can be placed. It is not possible to apply ductwork in reused floors. Besides the possibilities it is not desired to place ducts and cables in the structural layer of the floor. As can be derived from figure 1.2, the structural layer and the services have a different lifespan according to Brand (1994). Therefore, it is not desired to combine these two. Another argument to leave ducts out of the floor is the potential for additional reuse. When ductwork is placed in the floor reuse is more difficult. So the floors which can possibly be substituted with reused floor elements are plank floor and hollow core slab floors.

4.4. Matching

In chapter 3 it was found that monolithic - and hollow core slab floors have reuse potentials. In chapter 4 it is concluded that plank – and hollow core slab floors can potentially be substituted for reused floor elements. On both the supply and demand side hollow core slab floors are present which means there is a potential match between supply and demand for this floor type. Another possible match is present between monolithic floors and plank floors. If monolithic floors are cut into pieces they can potentially be applied as a substitute for plank floors. Thus there are two possibilities for reuse: one for the reuse of monolithic floors as a substitute of plank floors which is treated in chapter 6 and the reuse of monolithic which is dealt with in chapter 7.

PART 2: Research methods

VBI factory – own figure

5 Reusability scan

The reusability scan is a tool, developed by Nebest, to assess the reusability potential of an object. Originally the reusability scan was developed for infrastructural works during a Strategic Business Innovation Research (SBIR) set by Rijkswaterstaat. In this SBIR process different consortia made plans for the reuse of viaducts. Nebest, together with the Closing The Loop consortium, was one of three winners of this SBIR (elaborated on in the chapter 1). Throughout this thesis the reusability scan was further developed to also be applicable for buildings. The development was based on a case study: the office building of the cooperation 'Woningbelang'. This case was found by the author during an online session with different parties which had demolition plans. The author of this report was closely involved in this process and therefore the different tools explained in the subsequent chapters are made fit on the output of the reusability scan. The tools form an extension of the reusability scan. In this chapter the reusability scan is explained, in chapter 6 and 7 the extension tools are treated. In figure 5.1 the location of the reusability scan within the research strategy is shown. As can be seen in the figure the Reusability scan gives the input for the reuse tools which are developed in the subsequent chapters.

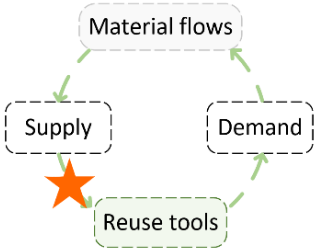


Figure 5.1: Location in research strategy (own figure)

5.1. Layout of the tool

In the tool there are three different levels which are explained in the following paragraphs. These levels are based on the decomposition of buildings according to the NEN 2767. The NEN 2767 is developed to assess the condition of a building and takes different levels into account during this measurement (NEN , 2018). These three levels are widely known and used in practice and therefore identical levels are used in the reusability scan. The levels are constructed from course to fine and can be placed below each other. The structure of the different levels according to the NEN2767 can be seen in figure 5.2.

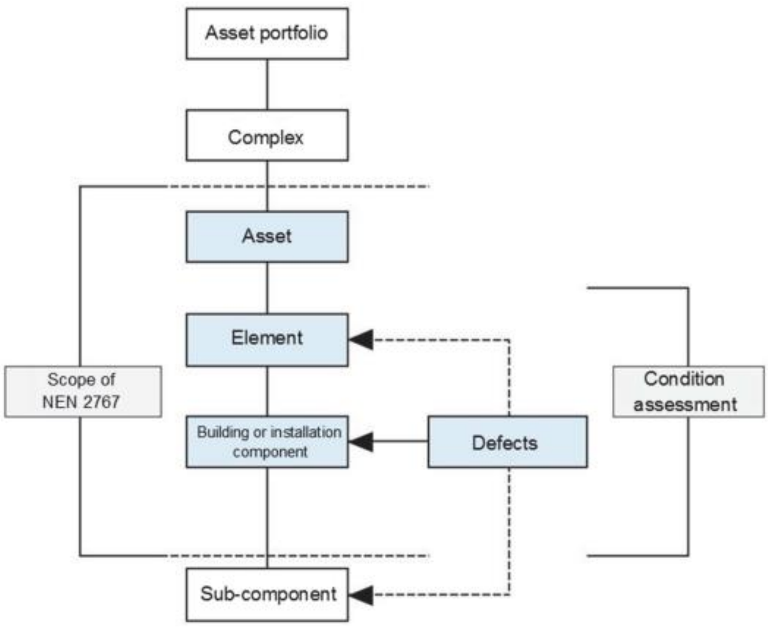


Figure 5.2: Classification of the NEN2767

5.1.1. Level 1: Asset

The first level is the 'highest' level, which describes the asset. In the case of the reusability scan this level describes the building as a whole. Parameters which are defined in this level form the basis for the subsequent levels. A parameter which, for example, is defined in level 1 is the number of floors. This data can then be used in the following levels as an input. If it is known that there are three story floors the next level can describe these three floors. The goal of this level is to get a general impression of the building which forms the basis for further research.

5.1.2. Level 2: Element

The second level is an intermediate level which describes the building elements. A building element is "an identifiable part of an asset that is distinguished exclusively on the basis of the function required and that consists of one or more building or installation components" (NEN , 2018). Examples of elements are: floor, wall, or foundation. In this level a decomposition of the building is made. Based on different parameters a reusability potential is given for the different elements. This potential is stated as one of the levels in the 10R ladder. For the elements which are interesting considering reuse a level three analysis is done. The elements which are not reusable, or not worthwhile, are kept on a level two. By making this limitation no time is wasted during the scan.

5.1.3. Level 3: Building component (subcomponent)

The third and final level in the reusability scan is the building component level. In this level the interesting elements of level two are examined more in depth. A building component is an identifiable part of an element, for example a pilar. There is also a following level, the subcomponent level, which is used when a building component is split up into different parts. In the reusability scan this subcomponent part is also treated in level three. In this level the information which is needed for reuse is gathered. The information on this level can directly be placed on a 'marketplace'. An example of a marketplace is: https://marktplaats.insert.nl/ .

The different levels of the reusability scan can be seen in the following figure:

Figure 5.3: Levels in the reusability scan (screenshot)

5.2. NL/SfB coding

The coding, as can be seen in figure 5.3 (number 21), is according to the NL/SfB. NL/SfB is one of the most used classification systems for building decompositions in the Netherlands (BIMloket , n.d.). To make the reusability scan fit with current practices it is convenient to use NL/SfB coding. The NL/SfB handbook consists of five different tables, which are (Cornips, 2005):

- Table 0 – Spatial facilities
- Table 1 – Functional building elements
- Table 2 – Construction methods
- Table 3 – Construction materials
- Table 4 – Activities, characteristics, and properties

From these five tables only table 1 is used in the reusability scan. The reusability scan gives the reuse potential of different building elements/components and therefore the other tables are not suitable. Table 1 has two levels: a main level and a sub level. These two levels are separated by a dot. The first number tells something about the element and therefore this coding is used in level two. The second number gives more detailed information and is therefore used in level three. An example of the different levels and the corresponding coding is given in table 5.1.

Table 5.1: Levels and coding used in the reusability scan

Level	Description	NL/SfB coding
2	Outer wall	21
3	Outer wall; load bearing; cavity wall	21.12

5.3. Reusability parameters

On level 2 of the tool a reusability potential is given. Based on this reusability potential a choice is made whether an in-depth study on level 3 is conducted. The reusability potential is given in the form of a level on the 10R ladder (Cramer, 2014). The score is based on different parameters. These parameters are derived from interviews with 16 different companies all involved in reuse. These parties are for example demolition companies, architect firms, and contractors. Besides the interviews, the CB'23 guideline 'Passports in Construction' (CB'23 , 2020) is used as a basis for the parameter list. The parameters in the tool can be divided into five main categories:

1. General data
   - e.g. length, width, amount, material
2. Structural properties
   - e.g. material quality, reinforcement layout
3. Residual lifespan
   - e.g. concrete cover, damages, condition
4. Demountability
   - e.g. type of connection, intersections
5. Environmental data
   - e.g. environmental costs, captured CO2, harmful materials (chrome 6)

Under each category a few examples of parameters are given. The total list with reusability parameters is extensive and therefore it is chosen to only give a few examples per category.

Generally it is chosen to conduct a level 3 analyses if the element scores 'Reuse' on the 10R ladder. It can be possible that a level 3 analyses is conducted even if the element scores lower on the ladder. This choice can be made based on expert judgement.

5.4. Execution process

The reusability scan starts with a desk study of the object/building. First this desk study is based on open source data such as data from Google Maps or Kadaster. Thereafter, the original drawings of the building are consulted if these are still available. Using these documents a first decomposition of the building is made in the tool environment. In this first decomposition as much information as possible (depends on the availability of drawings/documents) is already entered in the tool. After the decomposition is finished in the tool, an on-site inspection is conducted. During this inspection the condition of the materials/elements is checked and the information of the drawings is validated. It is also possible that extra elements need to be added to the decomposition because they were not available on drawings. After the inspection all data is inside the tool. Thereafter, it is possible to automatically generate a material passport from the building using the tool. The whole process is illustrated in figure 5.4.

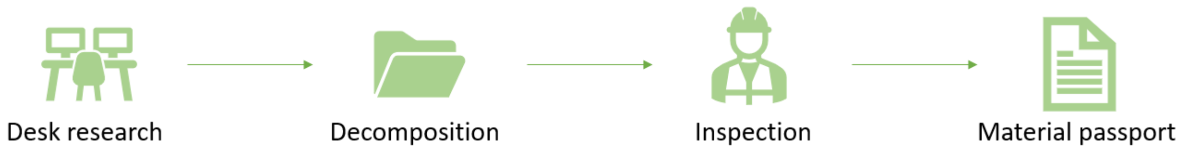


Figure 5.4: Reuse tool process (own figure)

5.5. In depth study

The lowest, most detailed, level is level 3. On this level the different components are studied in depth to obtain as much parameters as possible which are necessary for reuse. Examples of these parameters can be: specific dimensions, material type and quality, degradation mechanism, and residual lifespan. These parameters influence the way in which the component can be reused and are needed as input to design new objects with them. During this in depth study several measurements and tests are conducted. The needed tests for reuse depend strongly on the component, material, and the intended application of the reusable material. It can be possible that some tests are placed on hold because there is not yet a new application found. The needed tests for the reuse of monolithic – and follow core slab floors are described in 6 and 7 respectively. The eventual goal of the in depth study is to obtain sufficient data of the component so that redesign with the component is possible.

5.6. Output and linkage to tools and platforms

The output of the tool is a report which is a decomposition of the building with different promising components elaborated on (level 3 study). These components are the 'reuse gems' in the building. The properties specified in the report can directly be uploaded to marketplaces and can therefore easily be implemented in new designs.

The output of the tool can also be used as input for the tools specified in the following chapters. These tools form an extension on the original reusability scan. The tools use the input and take the reuse potential to the next step by checking the possible reuse application on technical-, environmental-, and economical aspects. The goal of the tool is to easily check whether an element is reusable and what the potential savings on environmental impact and the accompanying investment costs are.

Figure 5.5 shows the summary of the reusability potential of the different elements of the building decomposition (level 2). In the top part of figure 5.6 the level 2 study can be seen (EL = element level). In the bottom part of this figure the level 3 study is shown (BD = building component level). As can be seen in this figure the level 3 analysis gathers much more data.

Samenvatting - Elementen beheerobject				
Element	**Toelichting**	**Materiaal**	**10-R Score**	**Toelichting op score**
13 VloerenOpGrondslag - begane grond	Betonnen vloer op grondslag, breedplaatvloer	Beton	2. Recycle	Vanwege beperkte losmaakbaarheid slecht herbruikbaar. Kan als toeslagmateriaal dienen voor nieuw beton.
13 VloerenOpGrondslag - bijgebouw	Betonnen vloer bijgebouw	Beton	2. Recycle	Vanwege beperkte losmaakbaarheid slecht herbruikbaar. Kan als toeslagmateriaal dienen voor nieuw beton.
13 VloerenOpGrondslag - kelder	Vloer van de kelder, doorgestort beton	Beton	2. Recycle	Vanwege beperkte losmaakbaarheid slecht herbruikbaar. Kan als toeslagmateriaal dienen voor nieuw beton.

Figure 5.5: Summary of the reusability scan output (screenshot)

Element - 27 Daken - carport			EL
Bouwwerklaag CB23:	Constructie (Fundering en draagconstructie)		
Score o.b.v. 10R Ladder	7. Re-use		
Toelichting:	Stalen balken met houten balken en dakplaten. Zit een lichtkoepel op		
Dominant materiaal:	Hout en staal	Conditie	2 - Goede conditie


Bouwdeel (detailniveau) - Daken;Constructief - houten balken (42 Stuks)			EL BD
Bouwdeelnaam NEN:	daken; constructief	Bouwdeel (NLsFB):	27.2
Materiaalsoort:	Hout	Kwaliteit/sterkteklasse	
Conditie	2 - Goede conditie		
Toelichting en informatie:	42 stuks van 2911 mm 10 stuks van 1900 mm 3 stuks van ca 4300 mm 14 stuks van ca 300 mm		
Lengte	167 mm	Breedte	57 mm
Hoogte	2911 mm	Inhoud	- m³
Score (ladder van Lansink):	B - Hergebruik	Score (10R-model):	7. Re-use


Documentnaam tekening:	

Figure 5.6: Output sheet of reusability scan (screenshot)

6 Reuse of monolithic floors

As can be read in part 3 of this report, one of the available floor systems is a monolithic floor. On the other side of the spectrum, on the demand side, it was found that plank floors are often used. Plank floors have a prefab base on which an in situ layer is poured. It would be interesting to combine the available monolithic floors with the needed plank floors because they can be used in a similar way. In this chapter it is checked if and when it is possible to use reused monolithic floors instead of a plank floors in serial housing. A tool is made which checks the structural possibilities of this interchange of elements. The tool will also consider the financial and environmental aspects involved. Based on these three aspects reasoned conclusions can be made if the reuse of monolithic floors as plank floors is worthwhile. As can be seen in figure 6.1 the reuse tool is located between supply and demand.

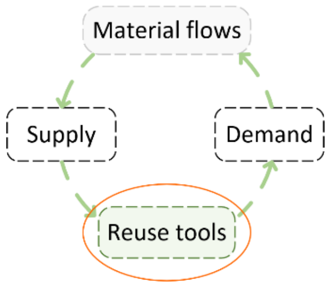


Figure 6.1: Location in research strategy (own figure)

The chapter starts by explaining the general idea and the steps involved when reusing monolithic floors. Thereafter the possible sawing pattern of the floors is explained. After the sawing pattern, the methodology to verify the structural feasibility of the reused elements is described. This methodology is implemented in the tool so that the structural feasibility can easily be checked by only filling in the properties of the original structure and the new design. Subsequently the environmental impact and costs related to reuse are treated. In the of the chapter a summary is given. In chapter 8 the tool is shown and the results which are obtained using the tool are given. These results are validated in chapter 9.

6.1. General idea

The idea is to use a reclaimed monolithic floor instead of a newly produced plank floor. The monolithic floor is cut into different pieces which can be placed in a new construction. The dimensions of these pieces can be made based on the design of the to be built houses. In the following figure a proposed sawing pattern is sketched. In this pattern the floor is cut into pieces with a length of 5,4 m and a width of 3 m, which are common dimensions for plank floors as can be read in chapter 4. It would also be possible to saw one big piece of floor, which would cover the complete area of a house. However, due to transport limitations and workability of the elements this option is disregarded.

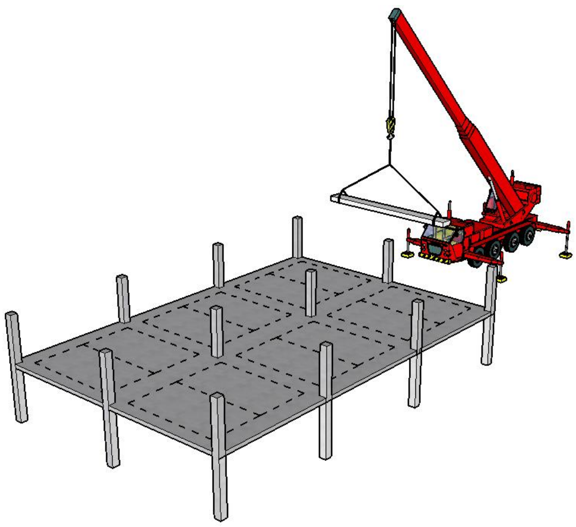


Figure 6.2: Representation of the dismantling process (own figure)

An important aspect which is not shown in the figure is the temporary support structure of the floor. During sawing the floor needs to be supported by a temporary structure, for example scaffolding (stamping). This structure is necessary to prevent the sawn elements from falling. After the different elements are cut, they can be loaded on a truck and transported to the new construction site. On this construction site they can be placed in the structure. Thereafter, floor finishing and ductwork can be installed as are discussed in appendix G. The monolithic floor elements from the office buildings do not have ductwork in them because it is common to use a lowered ceiling in offices.

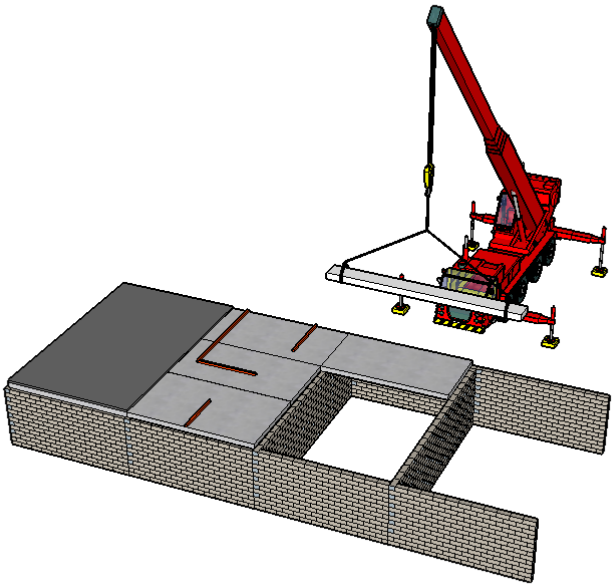


Figure 6.3: Representation of the reapplication of element (own figure)

6.2. Steps

There are numerous steps involved in the process of reuse. These steps need to be taken to come from a donor building (office) to a new construction made out of reused elements (serial house). In figure 6.4 the different steps are shown. These steps need to be taken from top to bottom to make reuse possible. In the following paragraphs the steps are explained and important aspects involving them are given.

From the figure it can be derived that the steps involving reuse can be divided into three main stages. These three main stages are similar to the three phases mentioned in the 'Deconstruct and Reuse Method' of Kamp (2021). The first stage is the Research Stage, in which the building is still standing. At this point the tool can be used and different tests can be conducted to come up with the needed properties. In the next stage, the Demolition Stage, the reusable elements are dismantled from the building and the building itself is demolished. The Construction Stage follows this Demolition Stage. During the Construction Stage the elements are reused in a new construction. In the case of this report the new construction is serial housing. It is preferable to reuse the elements in such a way that they can possibly be reused once again and thus can have a third life.

As can be seen in figure 6.4 the tool developed in this report can be used at two different steps (red circled in the image). The tool can be used right after the reusability scan. At this step the tool can show the potentials before further research is carried out. The tool can also be implemented at the end of the research stage. At this moment there is more data available and the tool can give more accurate results. The tool usage at the two different steps is more elaborately explained in part 6.2.2 and 6.2.4.

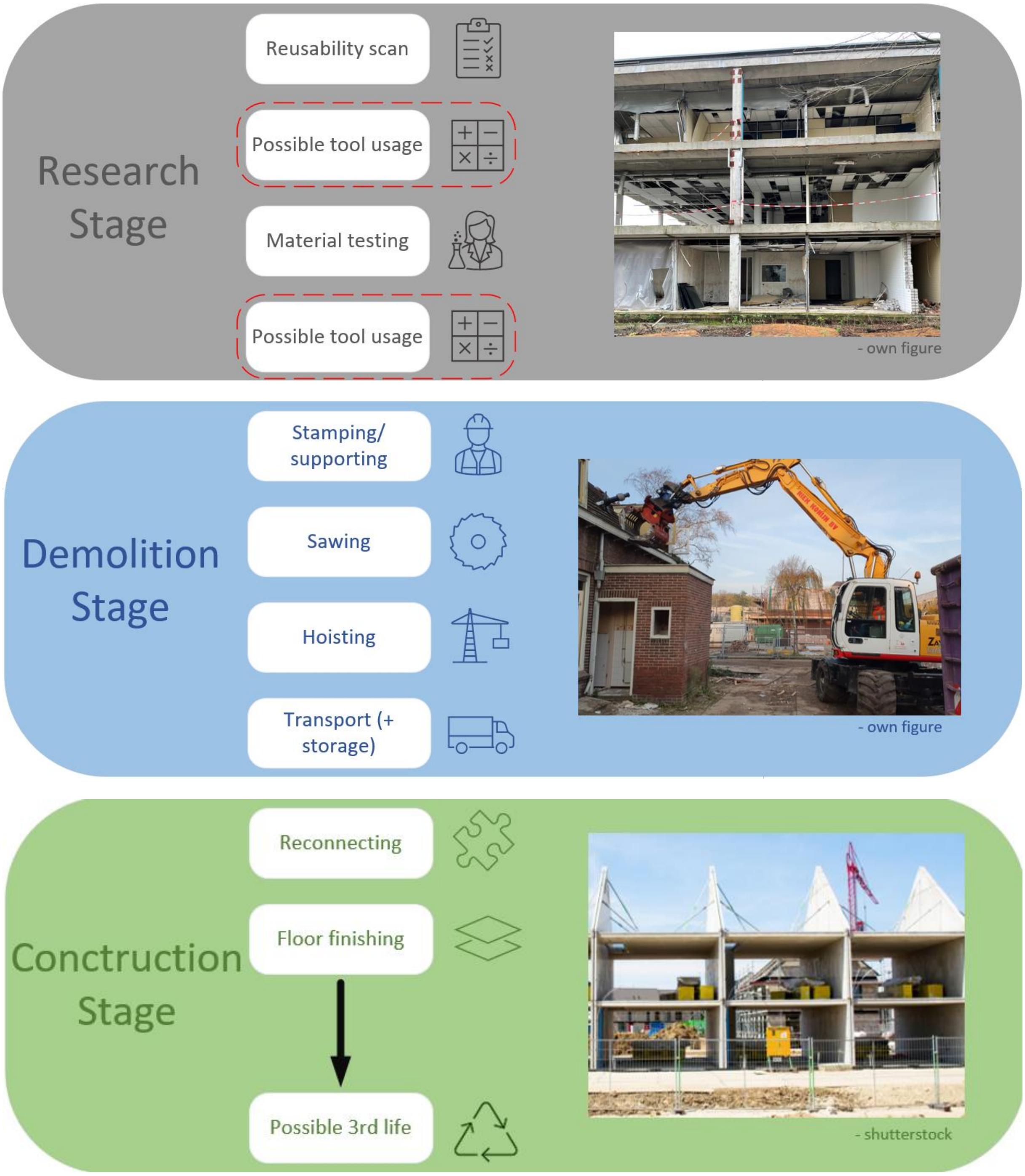


Figure 6.4: Steps related to the reuse of monolithic floor (own figure)

6.2.1. Reusability scan

The process starts with a reusability scan of the building, as is elaborated in chapter 5. The reusability scan gives the reuse potential of the different elements in the building. The output of the scan consists out of a decomposition of the building with a score based on the 10-R ladder. Based on this score it can be chosen to further investigate the reuse potential or neglect the element because it can better be recycled.

During the reusability scan an expert goes through the building and examines the current condition of the elements. The condition scores given for the different elements are based on visual inspections and documents about the building. Mayor defects or damages which influence the reuse potential severely are detected during this scan. If this is not the case and the element has potential, the following steps can be taken.

6.2.2. Possible tool usage

When the elements have a possible reuse score, the tool developed in this chapter can be used to check the reuse potentials more in detail. The tool checks whether the elements can be reused in the construction of serial housing, what the possible savings on ECI are, and what the needed investment costs for reuse are. At this stage it is possible that not all properties of the element are known. It is for exempla likely that the exact reinforcement layout and material qualities are unknown. It is advised to estimate the unknown properties/parameters based on expert judgement or rules of thumb.

This estimated data can be used in the tool to see the potentials at an early stage. The estimations can be quite rough and therefore it is possible that the exact results differ. However, by using the tool at this point and getting insights in the potentials, the investments for further research can easier be made.

6.2.3. Quality check + material testing

After the preliminary potentials are obtained, the material needs to be checked and tested. From these tests the actual properties of the element are obtained. These properties are needed to make the calculations for permits and certification possible. The different tests needed are described in appendix C. It is advised to discuss with the structural engineering and the authoritative party which properties are necessary to do the calculations needed for the different permits.

The different material tests are quite expensive. Therefore, it is nice that the potential benefits of reuse are given by the tool used in the previous step. If it was concluded that high quality reuse is not beneficial it is advised to look at other possibilities of element or material reuse. This can, for example, be the reuse in another application or the reuse of material to make new elements (more recycling as reuse).

6.2.4. Possible tool usage

In the previous step the different properties are obtained by conducting different tests. Thus the actual properties of the material are known. Next it is possible to run the tool again with the properties derived from the different tests. Now the tool can give more specific results and the actual potential can be calculated. In this way it is possible to get the exact structural feasibility of reuse, the potential environmental savings, and the needed investment costs.

Now the research stage is completed and the building can actually be dismantled and demolished. The steps involving the dismantling and demolition of the building are explained in the following paragraphs.

6.2.5. Stamping/supporting

One step takes place between the end of the research stage and the stamping/supporting of the floors. The building is first dismantled/stripped back to casco. This means that different elements are taken from the building such as: the lowered ceilings, inventory, and non-load-bearing interior walls. This process of dismantling/stripping back to casco before touching the structural elements is also a common practise in non-circular demolition as is derived from several interviews with demolition companies. Because the stripping of the building is a common practise, both in a circular and in a traditional way of demolition, it is not separately mentioned in the steps of figure 6.4.

Before the floor can be sawn into elements, the floor needs to be supported by stamping it or by applying scaffolding. These supports are applied for two reasons: the floor elements need to be supported when sawn otherwise they will fall down and the floors possibly need extra supports when taking up the high loads of the sawing machine.

The scaffolding or stamps need to be applied from bottom to top whereafter the dismantling process can start from top down. It is important that the lower floor is already stamped before the floor above is stamped. This is because the stamping can cause high loads on the floor below the stamped floor which can result in damages if this lower floor is not supported as is shown in figure 6.5.

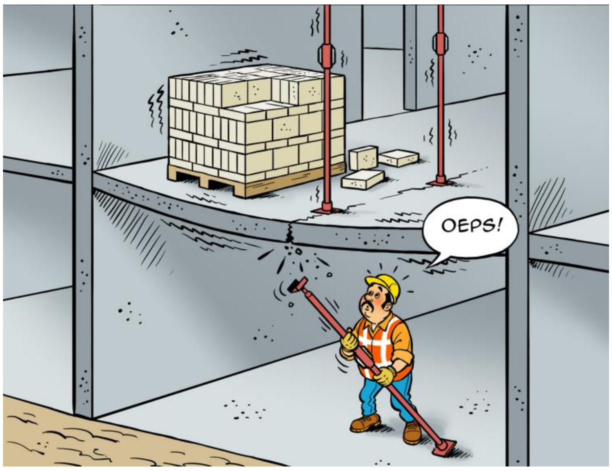


Figure 6.5: Stamping of floors (Betonhuis, n.d.)

Both stamps and scaffoldings can be used to support the floors. The easiest and most common option of these two is the application of stamps. Stamps have as an advantage that they are easy to apply and can support high loads.

An important aspect which needs to be considered is the stability of the floor element when it is resting on the stamps. The stamps are mainly applied in vertical direction which means they are bad in dealing with horizontal forces. Therefore it is advisable to apply some diagonal stamps to ensure the horizontal stability. It is desired to contact a scaffolding/stamping company about the stamping plan of the floors. These companies have a lot of experience with similar cases and therefore their knowledge can be beneficial during the process of reuse.

6.2.6. Sawing

A vital aspect in the reuse process is the sawing of the floor. Before the sawing can be conducted, the equipment needs to get to the desired floor. The equipment can be hoisted to the desired floor with a crane. This aspect is not considered in the environmental impact and costs because it is assumed that it can be disregarded.

The floor is sawn into different elements which eventually can be reused as new floor elements in serial housing. The sawing is done using a saw specifically made to saw concrete (also often used for asphalt). In image Figure 6.6 and Figure 0.41 two different types of saws can be seen. These saws can either be electrically powered or diesel powered. During the environmental calculations it is assumed that a diesel powered one is used.

Figure 6.6: Sawing of concrete (Stelling, n.d.)

From the two figures it can be derived that the saws can differ in size. The most important aspect regarding the dimensions is the size of the sawing blade. If the blade is bigger it is possible to make cuts in thicker floors. During an interview with an employee of Markus (demolition company) a case was discussed in which a floor with a thickness of 55 cm was cut. From chapter 3 it can be derived that the floors used in office buildings have a thickness of less than 55 cm. Therefore it is assumed that all floors, which lay in the scope of this report, can be cut.

One important note needs to be added to the thickness of the floor. The sawing speed, and thus the related ECI and costs, are strongly dependent on the thickness of the floor and the amount of rebar in it. If the floor has a bigger thickness and more reinforcement is present in the floor, the sawing speed decreases.

It is important to mention that the saw needs space to make the cuts possible. Therefore, it is advised that some space is left between, for example, the desired cut in the floor and the column. In the sawing plan, as proposed in part 6.3, this space is taken into consideration.

6.2.7. Hoisting

After the floor is sawn into different elements, these elements need to be hoisted from the donor building to make reuse possible. The hoisting of the elements can be difficult because the floor is originally constructed on site (in situ) and not transported before. Therefore there are no facilities located in the floor to make hoisting possible (e.g. lifting eyes). Thus a different approach needs to be taken to hook the elements to the crane. A case where in situ elements were hoisted from a donor building is Superlocal. In this project they made holes in which cables were placed. These cables were attached to a beam which supported the element as can be seen in figure 6.7.

Figure 6.7: Hoisting of the in situ element (SUPERLOCAL HEEMwonen, 2021)

A similar approach can be applied for the sawn floor elements. Holes can be made in the floor element through which cables can be placed. These cables can be attached to beams which support the floor element. In the following figure this principle is displayed:

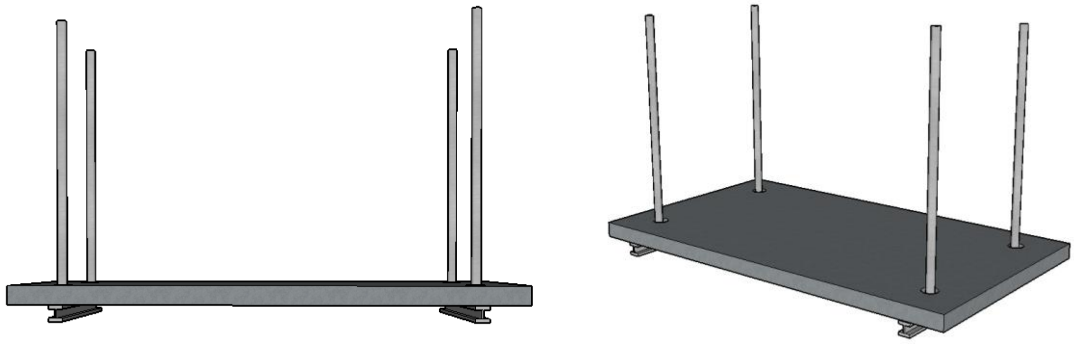


Figure 6.8: Proposed hoisting option (own figure)

During the tests, as described in appendix C, different cores are drilled from the floor to obtain the properties of the material. It could be possible to use these holes to run the cables through.

The forces in the floor, during the proposed hoisting method, are similar to the forces when the floor is located in the new building. The elements are line supported on both ends which results in little punching shear forces. Punching shear would be a problem if the floor is only hoisted from a few points as would be the case with hoisting eyes in the floor. Because the force distribution is similar during hoisting as is in the new building it is assumed that the floor can cope with the induced forces.

When the floor is placed, the holes need to be filled with mortar to make a closed floor. This filling can be done in combination with the filling of the gaps in between the different elements.

6.2.8. Transport (potential storage)

After the elements are hoisted from the donor building, they need to be transported to the new construction site. It is advisable that this new construction site is located in the proximity of the donor building to have small transport distances which results in less emissions and costs.

The elements can be loaded on a flat truck. It is important that a soft material is placed between the element and the truck and between the different elements because otherwise high stresses can occur which could damage the concrete. A material which could easily be used to place the elements on is wood, as is shown in figure 6.9.

Figure 6.9: Storage of concrete elements (Ratchat, n.d.)

It is important that the wooden beams are located above each other as is the case in figure 6.9. In this way the force travels in a straight line to the truck bed. The distance between the wooden beams needs to small enough that the elements do not experience big deflections under self-weight.

There is the possibility that the elements need to be stored before they are reused in a new building. This is not a desired situation but it is not unlikely. When the elements are stored, they can be stacked in a similar way as during transportation. During storage it is important that the surface on which the elements are stored is capable of holding the weight of the elements without settlements. If settlements take place the elements can be loaded in an unfavourable way which could lead to damage.

6.2.9. Reconnecting

When the elements are transported to the construction site they can be used for the construction of serial housing. The floor elements are connected to the walls to make the structure complete. It is advisable that these connections are applied in a demountable way. This means that for example no wet connections are used. The usual way of connecting a floor with a wall is given in figure 4.4. In this detail it can be seen that the floor is located in between the wall elements which makes dismantling of the floor element a lot harder.

A connection is needed which could transfer vertical and horizontal forces as can be derived from the stability calculations (appendix H). Different demountable solutions are possible for this connection. Two possible options to connect the floor to the walls, in a demountable way, are shown in figure 6.10. It is recommended that further research is conducted in these demountable connections in serial housing.

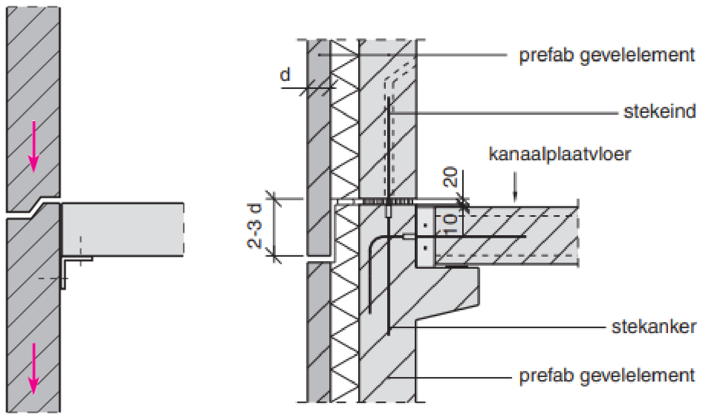


Figure 6.10: Demountable connection options (Rentier, Reymers, & Salden, 2005)

The reconnection of the floor elements is not only between the floor elements and the walls but also between the different elements. The gaps between the different elements need to be filled to make sure the floor can have disk action (needed for stability see appendix H) and to ensure a flat surface. These gaps are filled with mortar. The mortar in these gaps can easily be removed when the floor elements need to be dismantled form the structure which makes the reuse potential big.

6.2.10. Floor finishing

When the floors are placed in the structure, different ducts need to be placed in the building. It is common that ductwork is located in the floor. From a reuse standpoint it is advised that these ducts are placed in a layer which easily can be removed from the floor. Different possibilities for floor finishings in which ductwork can be located are given in appendix G.

6.2.11. Possible further reuse (3rd life)

The floor elements are reused in serial housing. After a certain period of time these buildings will also be demolished which means the floor elements come available once more. Therefore it is important that the elements are applied in a demountable way which ensures that they can easily be taken from the building. Another important aspect is data storage. Different tests were conducted before the elements were applied. It is advised that this data is stored which makes further reuse easier.

If the floor elements are no longer useable in the same function it is advised to see whether there are other possible reuse applications, for example as a wall or foundation. It is advised to reuse the element in the highest possible way to make sure the most sustainable solution is chosen.

6.3. Sawing pattern

In appendix F the force distribution and reinforcement layout of monolithic floors are explained. From this part it can be concluded that the middle floor part is the governing part regarding bottom reinforcement and the parts near the columns are governing for the top reinforcement. In this appendix it is also explained that it is not uncommon that local strengthenings are made for the column strips. Near the columns there are probably stirrups applied to cope with the high shear forces.

In the new design the floor elements are placed on two supports (walls) and transfer the loads in one direction. Therefore the reinforcement in length direction is governing. The main reinforcement layer used in the new design is the bottom reinforcement because of the sagging bending moments in the new application. Shear forces are probably not a governing aspect because the elements are line supported in the new design.

The reinforcement, located in middle part of the floor, is probably standardized throughout the field which makes reuse very well possible. The column strips can have local thickenings/strengthenings which make them harder to reuse. Therefore, it is advised to cut middle strips from the floor field.

By leaving the column strips in the building, there is no big chance of complete collapse of the building. This results in a safer demolition process.

In appendix A it was found that the most common span in office buildings, from the seventies and eighties, is 7.2 m and the most common span in housing 5.4 m. The common width of a plank floor is 3 m as described in chapter 4. Therefore, it is perfectly possible to cut the middle strips out of the floor and leave the column strips untouched. The watchful reader would notice that part of the column strips is used when this proposed sawing pattern is used. However, the local widenings and deviant reinforcement layouts are usually applied directly between the columns over a width similar to the column's width. Therefore, the deviant part is left untouched which results in sawn elements with a standardised reinforcement layout.

The abovementioned sawing pattern is shown in figure 6.11. The floor elements which are sawn from the monolithic floor have a length of 5.4 meters and a width of 3 meters which is perfectly suitable for the construction of serial housing. In this figure it can also be seen that the parts between the columns are left untouched.

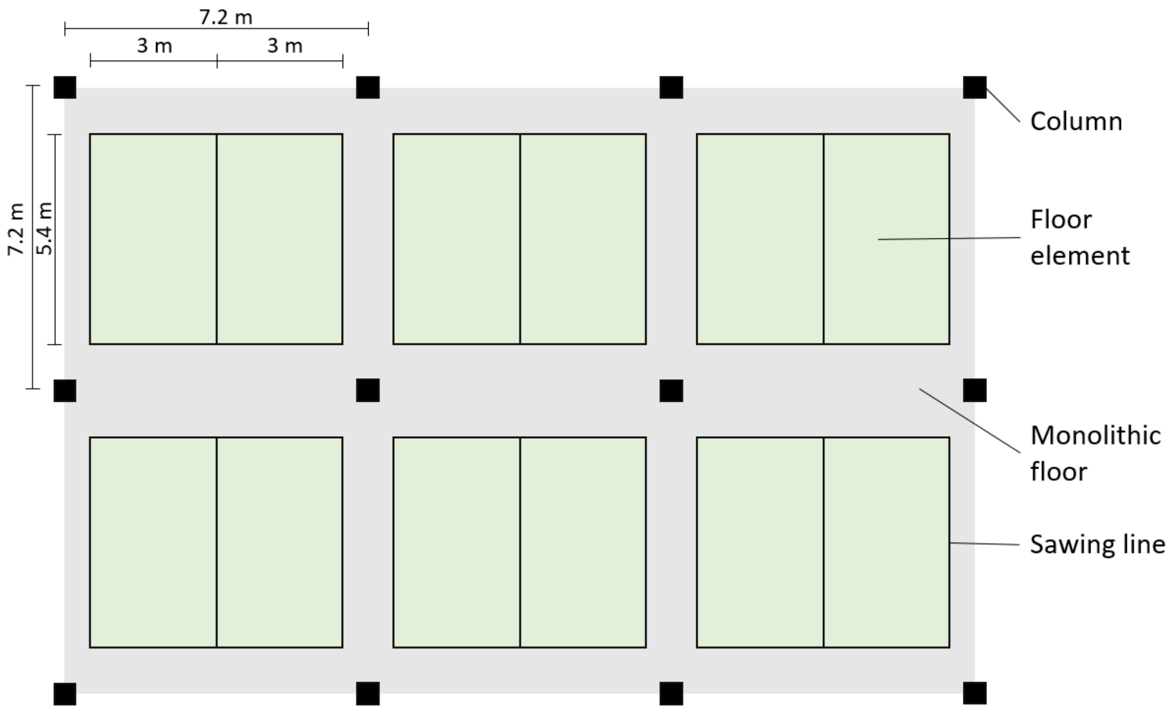


Figure 6.11: Proposed sawing pattern (own figure)

The above shown sawing pattern is based on the most common spans used in the donor office buildings from the seventies and eighties and the to be constructed serial houses. It is possible that different spans are present in the donor building or are needed in the serial houses. In this case the proposed sawing plan can be altered. But it is advised to keep in mind the force distribution as described in appendix F and the considerations as mentioned above. If the spans in the office buildings are for example smaller in one direction it is possible to cut smaller element of less than 3 meters width. This will not cause obstructions if the desired dimensions of the serial houses are kept in mind. If the spans get a lot bigger it is also possible that for example three elements are cut besides each other. In the rest of the report the sawing pattern as given in figure 6.11 is taken into consideration.

6.4. Structural feasibility

The structural feasibility of reuse is checked both in the ULS and the SLS. These checks are automated in the tool which makes it possible to see potentials by the click of a button. In the ULS the floor elements are checked on shear resistance and bending moment resistance. In the SLS the elements are checked on deflection and maximum crack width. An elaborate explanation of these calculations is given in appendix H.

The formulas used in the calculations, as are explained in appendix H, are taken from different sources. The main source which is used is the book 'Constructieleer Gewapend Beton' by Braam & Lagendijk (2011). Besides this book, the lectures of the course 'CTB2220 Concrete – and steel structures' (Hordijk & Lagendijk, 2018) are used as a basis for the calculations.

Besides the checks in the ULS and SLS, the stability of the structure is addressed. The explanation of the structural stability is addressed in appendix H.

6.5. Environmental impact

Environmental costs are important to consider whilst designing a new building. In this part the environmental impact of a reused monolithic floor and that of a new plank floor are calculated.

In appendix E the LCA is explained. In the following paragraphs a LCA is used to quantify the environmental impact of the different elements. The boundary conditions used are also stated in appendix E. For a complete picture of the environmental impact it is advised to read the appendix first before reading the following paragraphs.

6.5.1. Environmental impact reused monolithic floor

The environmental impact of a reused floor element is dependent on the different steps which need to be taken to prepare the element for reuse. As can be read in appendix E the environmental impact of the material itself is set at €0. The processes needed for reuse are:

- Supporting/stamping of the floor (to make sure the element does not fall down when sawn)
- Sawing the floor into elements
- Hoisting the elements out of the building and placing them on a truck

When these processes are completed, the elements can be seen as new elements which leave the factory on a truck. Therefore, only stages A1-A3 are taken into consideration, as is more elaborately explained in appendix E.

Next the environmental impact of the different processes is described in the following paragraphs. The sum of these different impacts is the total environmental impact of a reused element.

Supporting/stamping

The floor needs to be supported using stamps or scaffolding. This process consists of, mostly, manual labour. Therefore, it is assumed that this process does not have an environmental impact. It can be argued that the stamps/scaffoldings itself have an environmental impact. This is right but these stamps/scaffoldings are used over and over and therefore it is assumed that the environmental impact of them is neglectable.

Sawing

The sawing of the monolithic floor into different elements is a key process in the reuse path. Without sawing the elements it is not possible to dismantle them from the donor building and reuse them in the new building.

Concerning the length which needs to be sawn an assumption is made. It is assumed that two elements are sawn next to each other (see figure 6.11).

From the figure it can be derived that the sawing length per element is equal to:

$$L = \frac{3 * length_{element} + 4 * width_{element}}{2}$$

By multiplying this length per element with the total amount of elements, the total cutting length is obtained.

The speed of sawing is derived based on interviews with two different demolition firms. The first one was with Markus B.V.. During the interview they spoke about the sawing speed in two recent projects. In one project they cut 80 m^1 of floor with a thickness of 300mm with an average sawing speed of 6.5 m^1/hour. In the other project they had a similar floor thickness but there was more reinforcement in this floor. Therefore the sawing speed dropped to 4 m^1/hour. A second interview was held with Vlasman. They described that the sawing speed strongly depends on the equipment used. According to them the sawing speed varies between 4 m^1/hour and 7 m^1/hour. So, based on these two interviews the sawing speed is assumed to be 5.4 m^1/hour.

When the total sawing length is divided by the abovementioned sawing speed, the total time is obtained. In the National Environmental Database (NMD) the environmental impact per hour sawing is stated. On the reference date (see appendix D) this value was €4.7805/hour. Using this value the environmental impact of sawing can be calculated. This calculation is done in the tool.

Hoisting

When the floor is cut into different pieces, these pieces need to be removed from the donor building and loaded on a truck. Thereafter, the elements can be transported to a new construction site and reused. The transport of these elements to the new construction site is out of the boundaries set in appendix D. Therefore only the hoisting of the elements is dealt with.

The time required to hoist one floor element is 0.24 hours according to the Bouwkosten website (Bouwkosten, 2022). On this website reference times are given for common processes in construction. This 0.24 hours is a gross number which means it already covers different losses such as breaks and difficulties.

In the National Environmental Database (NMD) the environmental impact per hour hoisting is stated. This environmental impact differs between different crane types and therefore the crane type is an input parameter. On the reference date (see appendix D) the environmental impact of a diesel crane was €15.935/hour and €11.1545/hour for a hybrid crane. Both these cranes are 100 ton cranes which are according to the lifting tables are able to hoist the floor elements out of the building (Verticaal Transport Nederland , 2022).

By multiplying the total amount of elements by 0.24 (hours per element) the total amount of hoisting hours is derived. Using this time and the above mentioned environmental impact it is possible to calculate the total impact due to hoisting.

6.5.2. Environmental impact new plank floor

A plank floor consists out of two parts: a prefab bottom part and a cast in situ compression layer on top. These two parts are both stated in the NMD. The environmental impact of the two parts can be calculated using this data.

The thickness of a new plank floors would be interesting to consider because it actually influences the environmental impact because more material is used. However, the different thicknesses of plank floors are not described in the National Environmental Database (NMD), which is a shortcoming. Because these are not stated it is not possible to make this distinction in the tool. Therefore it is assumed that the thickness is a set value.

Prefab part

The prefab lower part usually has a thickness between 50 and 100 mm, as is described in chapter 4. It is a reinforced concrete slab with rebar sticking out of it.

In the NMD there are two different data sets available for this prefab lower part. These datasets are both category 2 data which means that the environmental impact per life stage is not available. Only the environmental impact over alle stages combined is available. In this report only stages A1-A3 are dealt with (see appendix E for explanation). To convert the NMD data from all stages into data applicable to stage A1-A3 an assumption needs to be made. Based on different prefab elements, which have category 3 data available, an assumption is made what percentage of the total environmental impact is represented by stage A1-A3. In table 6.1 it is calculated which percentages represent stage A1-A3 for the different prefab elements.

Table 6.1: Environmental impact of different prefab elements (values from NMD)

Element	A1-3 (€)	tot (€)	%
VBI 150 mm	2.82	2.87	98.26%
VBI 200 mm	3.18	3.24	98.15%
VBI 260 mm	4.37	5.05	86.53%
VBI 320 mm	5.29	6.08	87.01%
VBI 400 mm	6.39	7.28	87.77%
foundation pile 1	0.0098	0.0123	79.67%
foundation pile2	0.0098	0.0123	79.67%
Average			88.15%

Based on this table it can be concluded that 88% of the total environmental impact can be traced to stage A1-A3.

There are two datasets available which give the following values:

Table 6.2: Environmental impact prefab part (values from NMD)

Name	total (€/m^2)	A1-A3* (€/m^2)
AB-FAB	2.605	2.293
Betonhuis	4.0264	3.543
Average		2.918

*Calculated using the assumption that 88% of the impact is related to A1-A3.

So based on the available data it can be concluded that the environmental impact of the prefab layer in stage A1-A3 is equal to 2.918 €/m^2. Using this value it is possible to calculate the impact of the new floor (prefab part).

In situ compression layer

The in situ layer is poured on top of the prefab part after this is placed. This in situ part needs to act as a compression layer. The thickness of this layer may vary. But this variation is not taken into consideration in the environmental impact calculated in this report, as previously explained.

In the NMD there are two different datasets with category 3 data available of compressive layers. These datasets are public, so it is possible to only use the values related to stage A1-A3. Because the data is category 3 it needs to be lowered by 30% (as explained in appendix E). The data is presented in the following table:

Table 6.3: Environmental impact in situ compression layer (values taken from NMD)

Type	Total A1-A3 (€/m²)	Total A1-A3* (€/m²)
C20/27	6.34224	4.439568
C30/37	6.65514	4.658598
Average		4.549083

*after lowering it 30%

Because it is not known which material quality is applied, the average of the two values is used to compute the environmental impact of the floor. So based on the data presented above it can be concluded that the environmental impact of the in situ compressive layer is equal to 4.549 (€/m²). This value can now be used to compute the environmental impact of the compression layer.

6.5.3. Material savings

In the previous two parts the environmental impact of new- and reused floors are explained. Besides the differences on monetary environmental impact there is also the potential of material savings when reused floor elements are applied. If reused floor elements are implemented there is no need to construct new elements which results in no raw material usage. Therefore, the reuse of elements also results in savings on material. The material savings are equal to the volume of concrete which is reused because this volume does not need to be replaced by new concrete. In the tool the amount of material savings is expressed in kg.

6.6. Costs

Costs are an important item when designing and constructing a building. Therefore it is interesting to compare the costs of a new plank floor with that of a reused monolithic floor. In this part both these costs are estimated. The different prices used in this part are explained in appendix D. The expenses are automated in the tool.

In the tool and this chapter, only the costs related to the structural floor layer are treated. Costs related to the top floor as described in appendix G are not calculated because these costs can be similar for both the reused and the new floor.

6.6.1. New plank floor

The price of a new plank floor can bet estimated based on the total area of flooring. In appendix D the costs of a new plank floor are estimated to be €111/m². When this value is multiplied by the total area of flooring the estimated costs for a new plank floor are obtained. This calculation is automated in the tool to give quick results.

6.6.2. Reused monolithic floor

When it is chosen to reuse a monolithic floor, instead of using a new plank floor, also different expenditures are present. The demolition of the donor building happens in a circular way which consist out of stamping, sawing, and hoisting. Besides these dismantling processes there are different material tests which need to be conducted. In this part the expenditures for all these processes are estimated. An assumption is made regarding the donor material: It is assumed that the donor material is for free.

Stamping/supporting

Before the elements can be freed from the structure, the floors need to be stamped/supported. As explained in part 3.2, monolithic floors are usually point supported. Therefore, the elements can fall down when they are cut, which means supporting them in necessary. In appendix D it is assumed that stamping results in a cost of €8,22/m^2. This value can be multiplied by the area to obtain the total costs related to stamping/supporting.

Sawing

The monolithic floor needs to be sawn into different pieces to make reuse possible. The price of sawing depends on the total length which needs to be sawn. In part 6.3 a proposed sawing pattern is given. Based on this pattern the total sawing length can be calculated. In appendix D the sawing costs are estimated to be €65,50/m^1. When the total sawing length is multiplied by these costs per meter, the total costs related to sawing are obtained.

Hoisting

The sawn elements need to be hoisted from the building. In appendix D the costs of hoisting are estimated. It was found that the costs of hoisting can be estimated to be €61.14 per element. Multiplying the total amount of elements by this price gives the total costs.

Material testing

Reuse is not possible without knowing different material properties and therefore tests need to be conducted. The needed tests and quantity of them are estimated based on an interview with a material specialist at Nebest. The needed tests and quantities are:

Table 6.4: Estimated test quantities

Test	Quantity
Mapping of reinforcement	Total area
Drilling cores	One every 100 m^2
Testing cores	One every 100 m^2
Surface opening	10 times
Steel pulling test	10 times

By combining this table with the prices of the different costs as explained in appendix D it is possible to calculate the total costs related to testing. This calculation is done in the tool.

Traditional demolition

When a new plank floor is used there is no use for the monolithic floor of the donor building. Therefore, this floor needs to be demolished in a traditional way. A plank floor and a monolithic floor have a lot of resemblance and therefore the demolition costs are also similar. The costs of traditional demolition are estimated to be €43,78/m^2 in appendix D.

The costs of traditional demolition can be deducted from the costs of the reused floor. They can be seen as a sort of discount on the estimated price. If the floor is reused in a circular way, there is no need for traditional demolition of the floor. Therefore, these costs are saved in the process which means they can be transferred as a sort of discount to the reused floor element.

A remark needs to be made on this approach. The buyer of the reused floor elements is usually not the one paying for the demolition of the donor building. Therefore, it can be argued if these two costs can be combined. In the tool the costs of a reused floor with and without the 'traditional demolition discount' are given.

7 Reuse of hollow core slabs

The next reuse potential is a more straightforward one. Hollow core slabs are used in new construction and come available during the dismantling of office buildings. Therefore, it is straightforward to link these two material flows. In this chapter a process is developed which checks the structural feasibility of applying reused hollow core slabs in the construction of serial housing. Besides the structural aspects, environmental and financial aspects are treated in this process. The goal of this process is to check whether it is possible to reuse hollow core slabs and what the potential environmental benefits and the financial costs are. By doing so, reasoned conclusions can be made if the reuse of hollow core slabs is worthwhile. As can be seen in figure 7.1 the reuse tool is located between supply and demand.

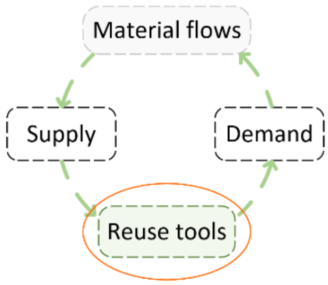


Figure 7.1: Location in research strategy (own figure)

The chapter starts with the explanation of the general idea. Thereafter the different steps related to the reuse of hollow core slabs are explained. One of the steps in the process of reuse is sawing. After the different steps are explained a suggested sawing pattern is given. Next the structural feasibility, environmental impact, and costs regarding reuse are addressed. In chapter 8 the tool is shown and the results are given.

7.1. General idea

On both the supply- (chapter 3) and the demand side (chapter 4) hollow core slabs are used. Therefore, it is predictable to check whether it is possible to reuse the elements from the donor office buildings for the new construction of serial housing. Before reuse is possible different steps need to be taken. The different steps involved in the process of reuse are more elaborately explained in part 7.2. The main steps are the quality checks, dismantling, and reimplementation of the elements.

The donor buildings are office buildings with a construction date between 1970 and 1990, as explained in chapter 2. In appendix A it was found that common grid sizes for office buildings with these construction dates are 7.2 by 7.2 meters. In the seventies and eighties the width of hollow core elements was standardised at 1200 mm, which is currently still the case for newly produced elements. There are also different special elements used which are placed on the edges of the floor fields or near openings in the floor. These special elements are called ‘fitstrips’ (passstroken). From a reuse standpoint these elements are less attractive because they do not have standardised dimensions which make them less reusable. In this report these special floor elements are disregarded. The report only focusses on the standardised hollow core floor elements.

Thus the available elements are probably 7.2 m long and 1.2 m wide. In serial construction it is common to have spans of 5.4 meters. Therefore it is unavoidable that the elements need to be shortened before reuse is possible. The waste due to shortening is not considered in the tool. Only the part which is reused is considered.

It is possible that a structural topping is applied on top of the donor floor. This structural topping was applied to give the floor disk action. When the floor elements are reused, this structural topping is cut in between the different elements to separate them, as explained in 7.2.2. The structural topping is not taken form the element because this is a labour intensive process. The structural topping is seen as a deadweight on top of the floor. According to an estimation made by experts of VBI during an interview, approximately 80% of the hollow core floors used in office buildings in the seventies and eighties is applied with a structural topping.

So the elements are taken from the office building as is shown in the top of figure 7.2. Thereafter they are taken to the construction site of serial houses and they are reused as new floor elements in these houses, as is shown in the bottom of figure 7.2.

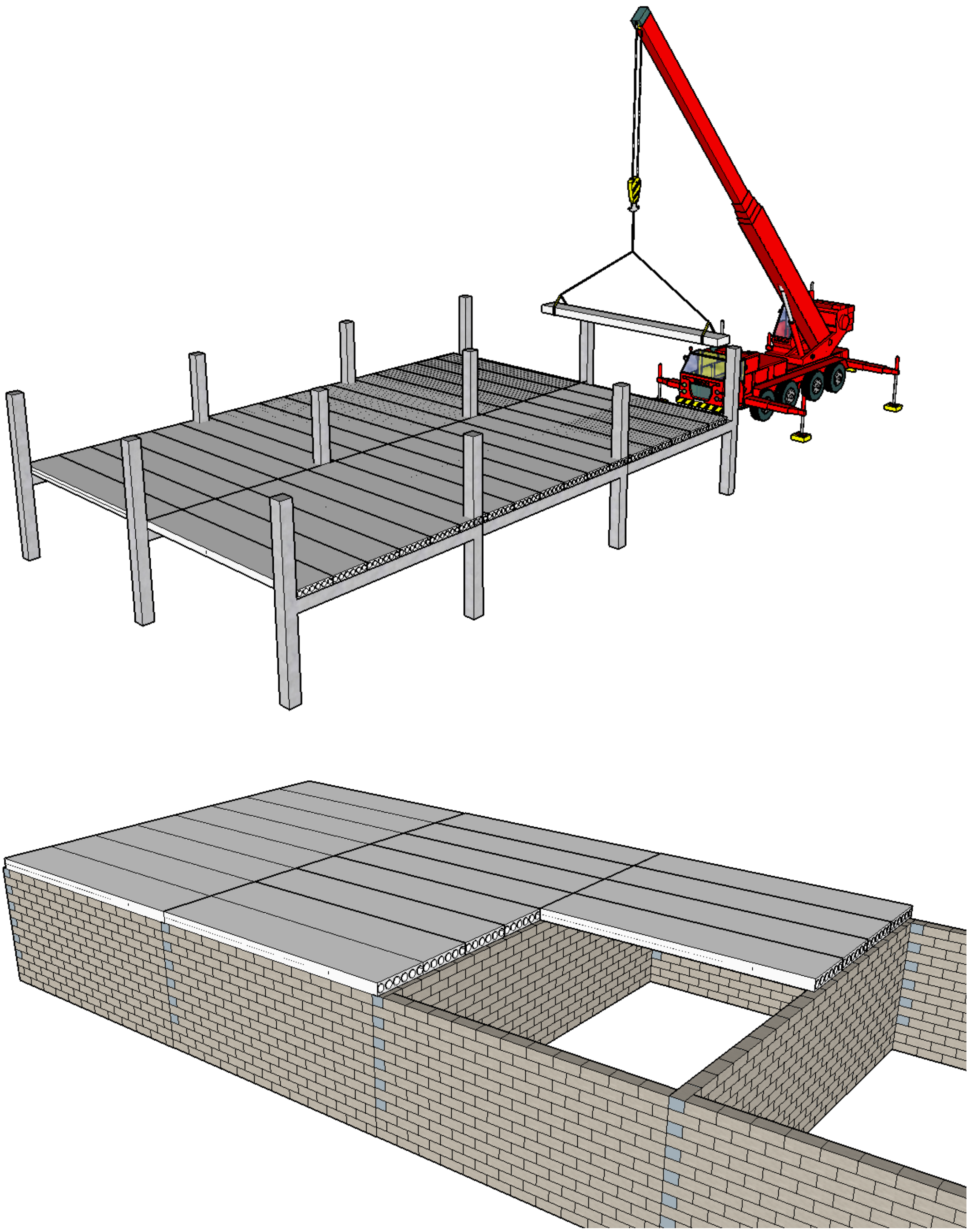


Figure 7.2: Disassembly (top) and reimplementation (bottom) of hollow core slabs (own figure)

7.2. Steps

The steps involving the reuse of hollow core slab floors are similar to the steps specified in part 6.2. A similar process with a research-, demolition-, and construction stage (as shown in figure 6.4) can be used for the reuse of hollow core slab floors. Only the differences in steps between the reuse of hollow core slab floors and monolithic floors are explained in this chapter. The steps which are not mentioned in the following paragraphs are similar to those mentioned in chapter 6.

In figure 7.3 the steps in the reuse path of the different floor types are illustrated. The top line illustrates the steps related to the reuse of monolithic floors as explained in chapter 6. The middle line is similar for the reuse of both the monolithic - and the hollow core slab floors and is explained in chapter 6. The bottom line is related to the reuse of hollow core slabs specifically. The steps which differ between the reuse of monolithic - and hollow core slab floors are:

- Stamping/supporting
- Sawing
- Hoisting
- Reconnecting

These four steps are explained in this part. For the explanation of the other steps, which are similar for the reuse of monolithic floors, see part 6.2.

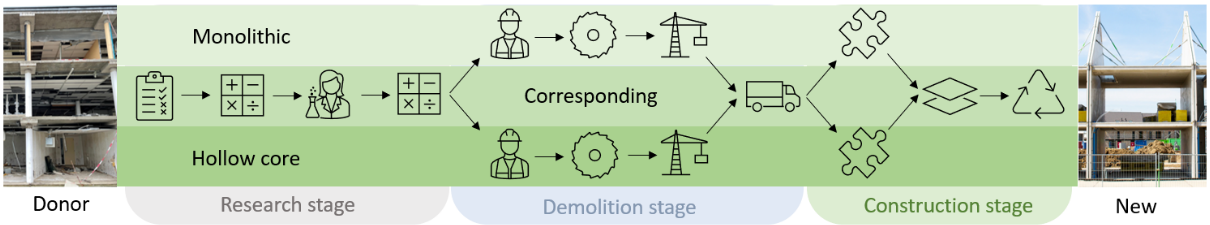


Figure 7.3: Steps involved in reuse (own figure)

7.2.1. Stamping/supporting

If the desired element length is identical to the original length, the elements do not need to be shortened. In this case it is possible to dismantle the elements without the need of a temporary support structure because they can be supported by the original beams. The elements can thereafter simply be hoisted. However, if the elements need to be cut to the right length, a support structure is indeed needed. Based on chapter 3 and 4 it can be concluded that it is likely that the elements need to be shortened. Therefore, in the different calculations the aspects due to stamping/supporting are considered.

Concerning the stability of the sawn elements, a similar matter as with the monolithic elements is present. The elements need to be stabilised because they otherwise can fall down. A more elaborate explanation about this is given in 6.2.5.

7.2.2. Sawing

The total sawing length of hollow core slabs is depended on the fact whether or not a structural layer is applied. If this layer is applied the joints in between the different elements need to be sawn. If no structural layer is applied it is not necessary to saw these joints according to experts of VBI. In this case it is possible to separate the different elements using hand tools.

It is most likely that the elements need to be shortened before they can be used in the serial houses. This shortening can be done when the elements are still in the donor building (supports are needed). Therefore only 2 saw cuts need to be made in the width direction of the element.

According to a meeting with several experts of VBI it is not a problem to shorten the elements. However, shortening the elements means there will be waste due to the sawing process. This waste is not taken into consideration in this report. The reuse-area as specified in the tool is the area which is sawn and reused without waste.

There are also different special slab shapes which are used on certain locations. These elements are disregarded in this report.

7.2.3. Hoisting

There are two different methods which can be used to hoist hollow core elements. Both of these methods are also used during the installation of new hollow core slabs. The elements can be hoisted using two different kinds of equipment:

- a hoisting clamp
- a hosting key

Which method can be used is dependent on the way in which the elements are placed in the donor building. If a structural topping is applied in the donor building, it is not possible to hoist using a hoisting clamp according to experts of VBI. In this case the elements need to be hoisted using a hoisting key.

A hoisting clamp is a special device used for the installation of hollow core elements in a structure. This clamp 'grabs' the element by it sides and can lift it in this way. In figure 7.4 a hoisting clamp is shown. There is a lot of knowledge and experience with the use of these clamps. There are different handbooks available on for example the VBI website.

The other method uses a hoisting key. A hoisting key is a device which is placed in a hole in the hollow core slab. In figure 7.4 this hoisting key is shown. There is also a lot of knowledge regarding the use of these hoisting keys. Different manuals and guidelines are written.

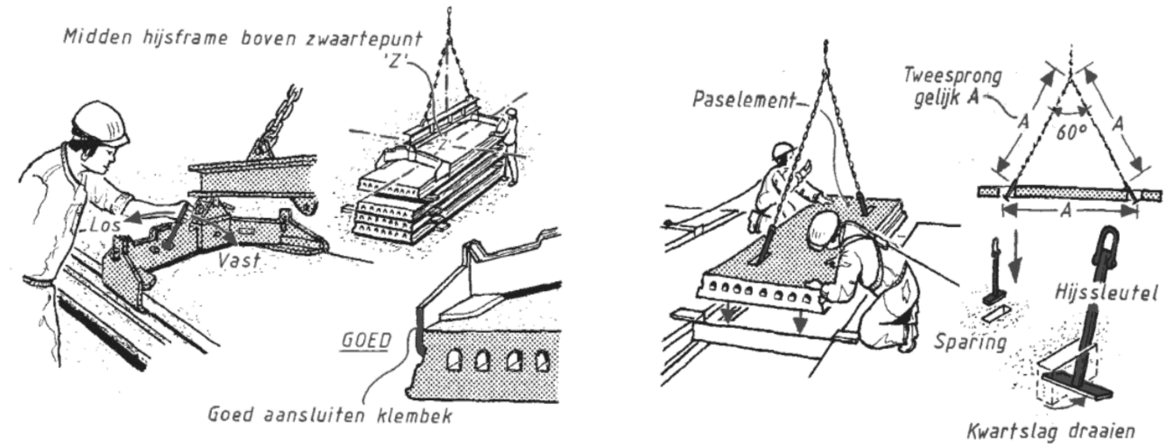


Figure 7.4: Hoisting clamp and hoisting keys (VBI, n.d.)

Thus it is perfectly possible to hoist hollow core elements. It is only important to check whether or not a structural topping is applied on top of the element to make the right chose between the two hoisting methods.

7.2.4. Reconnecting

When the elements are reused in the serial houses they need to be reconnected to the structure. These connections need to transfer the vertical forces applied on the floor towards the load bearing walls. Besides vertical forces they need to be able to transfer horizontal forces due to the disk action of the floors as explained in appendix H.

It is desired that the new connections are made demountable. By connecting the elements in a demountable way, it is possible to reuse the elements again. Currently it is common to place hollow core slabs in between the walls which makes them hard to dismantle and thus reuse. Therefore different connections need to be applied if demountability is desired. Several demountable connections are developed by different companies. Two options for demountable connections of hollow core slab are given in figure 7.5. The left option in this figure is already applied in practise as is shown in figure 7.6.

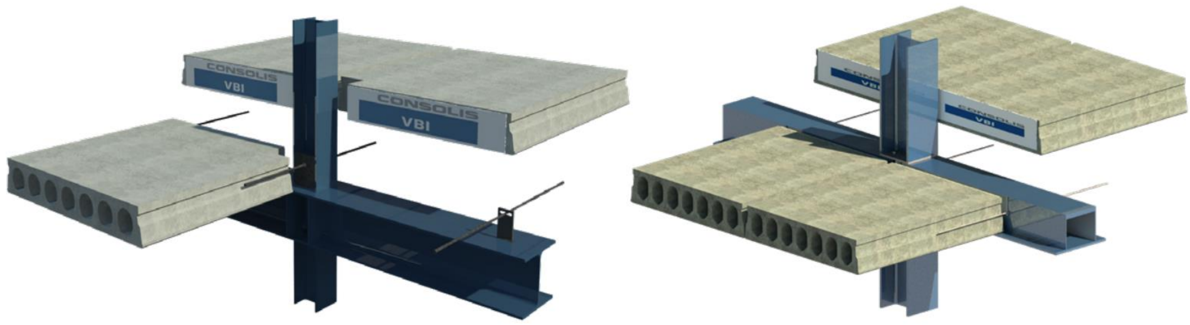


Figure 7.5: Dismountable connections with hollow core elements (VBI, 2021)

Figure 7.6: Dismountable connection in practise (VBI NL, 2017)

Both these options are related to the connection of a hollow core slab to a steel beam. As is discussed in chapter 4, it is common to have sand lime brick or prefab concrete walls in serial housing. Therefore, these connections cannot be applied without adjusting them. It is advised to do more research into demountable connections of floor elements in serial housing. During this research it is important to take the construction- as well as the demolition process into account.

7.3. Sawing pattern

The sawing pattern for the dismantling of hollow core slabs is a straightforward one. The original elements need to be freed from the building. Therefore, the elements need to be separated at the intersections between the elements and the intersections with the rest of the structure (beams). Based on an interview done with several experts from VBI (big hollow core manufacturer) it was found that the mortar between the elements in length direction is easy to loosen. During several projects they found that the mortar between the elements can easily be loosened with some hand tools. Therefore, there is not the necessity to use sawing equipment for these parts. However, if a structural topping is applied this is no longer possible which results in the need of sawing.

The tool for the reuse of hollow core slabs is constructed for different situations. Therefore, a division is made between hollow core slabs with or without a structural topping. In figure 7.7 the needed sawing lines for hollow core slabs with or without a structural topping are shown.

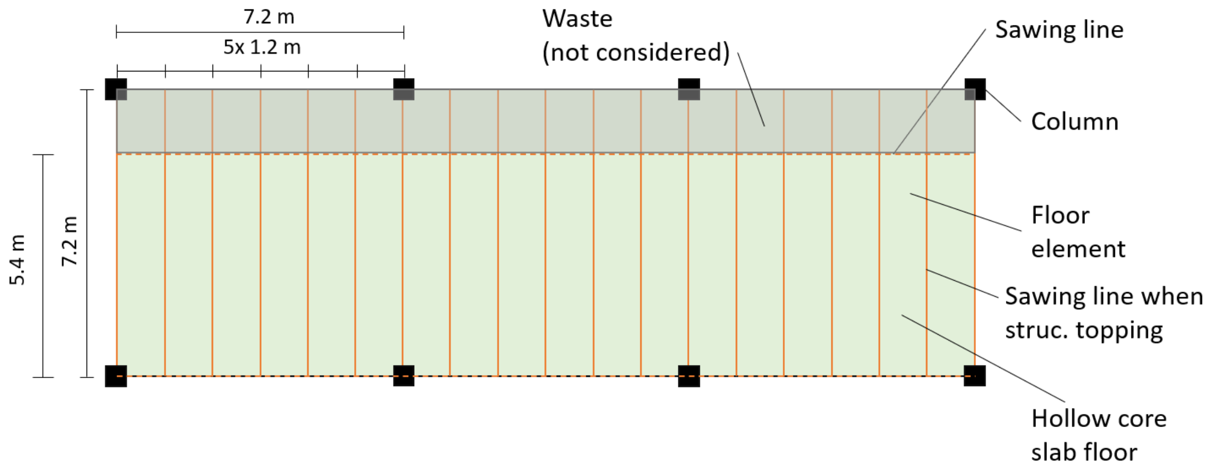


Figure 7.7: Proposed sawing pattern (own figure)

There is also the possibility that the elements need to be shortened because they do not have the desired length, or the ends have notches for columns. These saw cuts are related to the steps involved in reuse and are explained in part 7.2.2. In the above shown figure it is assumed that the elements need to be shortened to 5.4m.

7.4. Structural feasibility

Both the SLS- and the ULS checks, related to the structural feasibility of reuse, are done in the tool. By doing so it is easy to change parameters and obtain results. In the ULS the elements are checked on shear resistance and bending moment capacity. For the SLS the cracking bending moment and deflecion are calculated. The differnet calculations are explained in appendix H.

The approach which is used for the the differnet calculation is derived from three different sources. All formulas used in appendix H are derived from: a lecture about prestressed concrete by the Avans technical school (2021), the book prestressed concrete by Braam & Walraven (2019), or the lectures of the CIE4160 course by Sandra Nunes (2021). These three sources have overlap between each other because they all explain the calculations of prestressed concrete based on the NEN-EN1992-1-1.

The stability of the structure is also addressed. The calculations related to the stability of the structure can be found in appendix H.

7.5. Environmental impact

The environmental impact of buildings is import in current practise. Therefore it is interesting to check whether a reused/reclaimed element is more environmentally friendly as a new one. In this chapter a comparison is made between the environmental impact of a new hollow core floor in comparison to a floor made up out of reused elements.

In appendix E a thorough explanation of a LCA given. The boundary conditions set in this report are also discussed in this appendix. It is advised to read this appendix before reading this chapter.

7.5.1. Environmental impact reused hollow core slab floor

As described in appendix E, the environmental impact of a reused floor element is dependent on the impact of the different steps which are needed to make reuse possible. After the different steps are taken the element can be seen as a new element which leaves the factory. In the calculation of the environmental impact of the reused floor element it is assumed that the material itself has an impact of €0 as is explained in appendix E.

The processes which are needed to transform the donor floor into reusable elements are:

- Supporting/stamping
- Sawing the elements loose
- Hoisting the elements out of the building

Supporting/stamping

During the dismantling process it is necessary to support/stamps the floor as was explained in the steps. This supporting/stamping is usually done with stamps or scaffolding which are applied manually. Because they are placed manually there are no harmful emission due to machines. Therefore it is assumed that there is no environmental impact related to the sawing/supporting of the floor elements.

Sawing

The hollow core slabs in the donor building are most likely connected to each other using mortar or a structural topping. These connections need to be cut to free the elements for potential reuse. If a structural topping is applied it is necessary to cut the joints in length direction of the elements. If no structural topping is applied it is possible to loosen the elements using hand tools as explained in 7.2.2.

Concerning the length which needs to be sawn an assumption is made. It is assumed that five elements are sawn next to each other. Based on this assumption it is possible to compute the total sawing length per element using the following formula:

$$L = \frac{6 * length_{element} + 10 * width_{element}}{5}$$

This formula holds for floors which have a structural topping. When no structural topping is applied the seams in length direction do not need to be sawn which means the first part of the formula, the length part, can be disregarded. By multiplying this length per element with the total amount of elements, the total cutting length is obtained.

The speed of sawing is explained in part 6.5.1, and was found to be 5.4 m^1/hour. Dividing the total sawing length by the sawing speed, the total sawing time is obtained. In the National Environmental Database (NMD) the environmental impact per hour sawing is stated. On the reference date (see appendix E) this value was €4.7805/hour. Multiplying this value with the total sawing speed results in the environmental impact due to sawing.

Hoisting

After the elements are separated they need to be taken out of the donor building. The elements are hoisted from the building, loaded on a truck, and transported to a new construction site where they are reused. As explained in appendix E the transportation of the elements is not considered in this report.

The environmental impact related to hoisting is stated in the National Environmental Database (NMD). In this database the impact per hour usage is stated for different crane types. The crane types considered in this report are 100 ton crane which, according to the lifting tables (Verticaal Transport Nederland , 2022), are able to lift the floor elements. On the reference date (see appendix E) the environmental impact of a diesel crane was €15.935/hour and €11.1545/hour for a hybrid crane.

On the Bouwkosten website a standard gross time which is needed to hoist one element is stated. According to the website it takes 0.24 hours to hoist one element. When this value is multiplied with the number of elements, the total time needed for hoisting is obtained. When this time is multiplied with the values stated in the NMD the environmental impact related to sawing is found.

7.5.2. Environmental impact new hollow core slab floor

The environmental impact of a new hollow core slab can easily be found in Economic Product Declarations (EPD's) made by the producer. In the NMD this data is category 1 data which means it is not open to public. Luckily one of the biggest producers of hollow core slabs, VBI, has EPD's of their products available on their website (VBI, n.d.). These EPD's can be downloaded and the environmental impact per stage is given.

These EPD's are used to calculate the environment impact of a new hollow core slab floor with. The EPD's are specific for one producer but it was found on the NMD website that the total environmental impact of a VBI slab is similar to that of a different manufacturer.

The following values, taken from the VBI EPD's (VBI, n.d.), are used to calculate the environmental impact with:

Table 7.1: Environmental impact hollow core slabs (from VBI website)

Element	A1-3 (€/m^2)
VBI 150 mm	2.82
VBI 200 mm	3.18
VBI 260 mm	4.37
VBI 320 mm	5.29
VBI 400 mm	6.39

In the tool these values are multiplied with the total area and by doing so the environmental impact of a new floor is calculated.

7.5.3. Material savings

The environmental impact of reused- and new hollow core slabs are addressed in the previous paragraphs. Besides the potential savings on environmental impact (monetary value) there is also less/no raw material usage if elements are reused. Due to reuse, there is no need to construct new elements which results in material savings. These material savings are equal to the amount of material which is reused. In the tool, as shown in chapter 8, the amount of material savings is given in kg. The webtool illustrates the potential material savings based on amount of concrete truck mixers.

7.6. Costs

The main interesting aspect about the costs is the difference between the use of reused elements or new elements. In this part the costs of both options are calculated. In appendix D the different expenses are elaborated and values are computed. These values are used in this chapter to compute the total costs related to a floor made up out of new elements and one made up out of reused elements.

In this report only the costs related to the structural floor layer are considered. Costs related to floor finishings as described in appendix D can be similar for both a new and a reused floor and are therefore disregarded.

7.6.1. New hollow core floor

The costs of a new hollow core floor were estimated to be €80/m^2 (see appendix D). Using the reuse area and the price per square meter the costs of a new hollow core floor can be estimated. This calculation is done in the tool as can be seen in chapter 8. The calculation results in an estimated price of a new hollow core floor.

7.6.2. Reused hollow core floor

When floor elements are reused, different costs are made. The demolition happens in a circular way and can better be referred to as dismantling. No traditional demolition costs need to be made when the floor is reused. The costs of reuse are made up out of four different aspects: supporting/stamping costs, sawing costs, hoisting costs, and the costs of material testing. In this calculation it is assumed that the donor material is for free. If this is not the case these costs need to be added.

The costs of traditional demolition do not have to be paid when the building is dismantled in a circular way. Therefore, these costs can be seen as a discount on the circular demolition costs. However, it is possible that the developer of the new construction is not the owner of the donor building. In this case the discount can be argued. In the tool both the total costs, as the costs with a 'traditional demolition discount' are computed.

Stamping/supporting

It is likely that the elements need to be shortened for the new application. In this case the floor elements need to be supported during sawing because they can otherwise fall down. In appendix D the costs related to stamping were estimated to be €8,22/m^2. Using this value it is possible to compute the costs related to stamping for the reuse area. No waste is considered in the reuse area; therefore it is possible that the stamping costs are slightly higher in practise.

Sawing

The floor elements need to be sawn to make dismantling possible. In part 7.3 a proposed sawing pattern is shown. In the total sawing length it is assumed that five elements are sawn next to each other. Using this assumption and the proposed sawing pattern it is possible to compute the total sawing length. When the total sawing length is multiplied with the assumed costs per meter (€65,50/m in appendix D), the total costs related to sawing are obtained.

Hoisting

After the elements are sawn loose, they need to be hoisted out of the building. The costs related to hoisting depend on the number of elements and is assumed to be €61.14 per element (see appendix D for explanation).

Material testing

To make reuse possible different properties need to be obtained. These properties are gathered by doing different tests. The needed tests and quantity of them are estimated based on an interview with a material specialist at Nebest. The needed tests and quantities are shown in table 7.2.

Table 7.2: Estimated quantity of tests

Test	Quantity
Mapping of reinforcement	Total area
Drilling cores	6 times
Testing core	6 times
Surface opening/chopping	6 times
Steel pulling test	6 times

Multiplying the quantity of tests with the costs of testing as explained in appendix D results in the total costs related to testing.

Traditional demolition

Traditional demolition is needed when the donor building is not demolished/dismantled in a circular way. The costs of demolishing a hollow core floor in a traditional way are estimated to be €55,03/m^2 (see appendix D). Using this value and the total area of flooring, the total costs made when demolishing in a traditional way are obtained.

These traditional costs can be seen as a discount on the circular demolition costs as is previously described in the beginning. In the tool both the total circular demolition costs and the costs with the 'traditional demolition discount' are given.

PART 3: Results and final remarks

Tour at Haitsma, f.l.t.r. Thijs (me), Joost, Jens, Thieme – own figure

8 Results

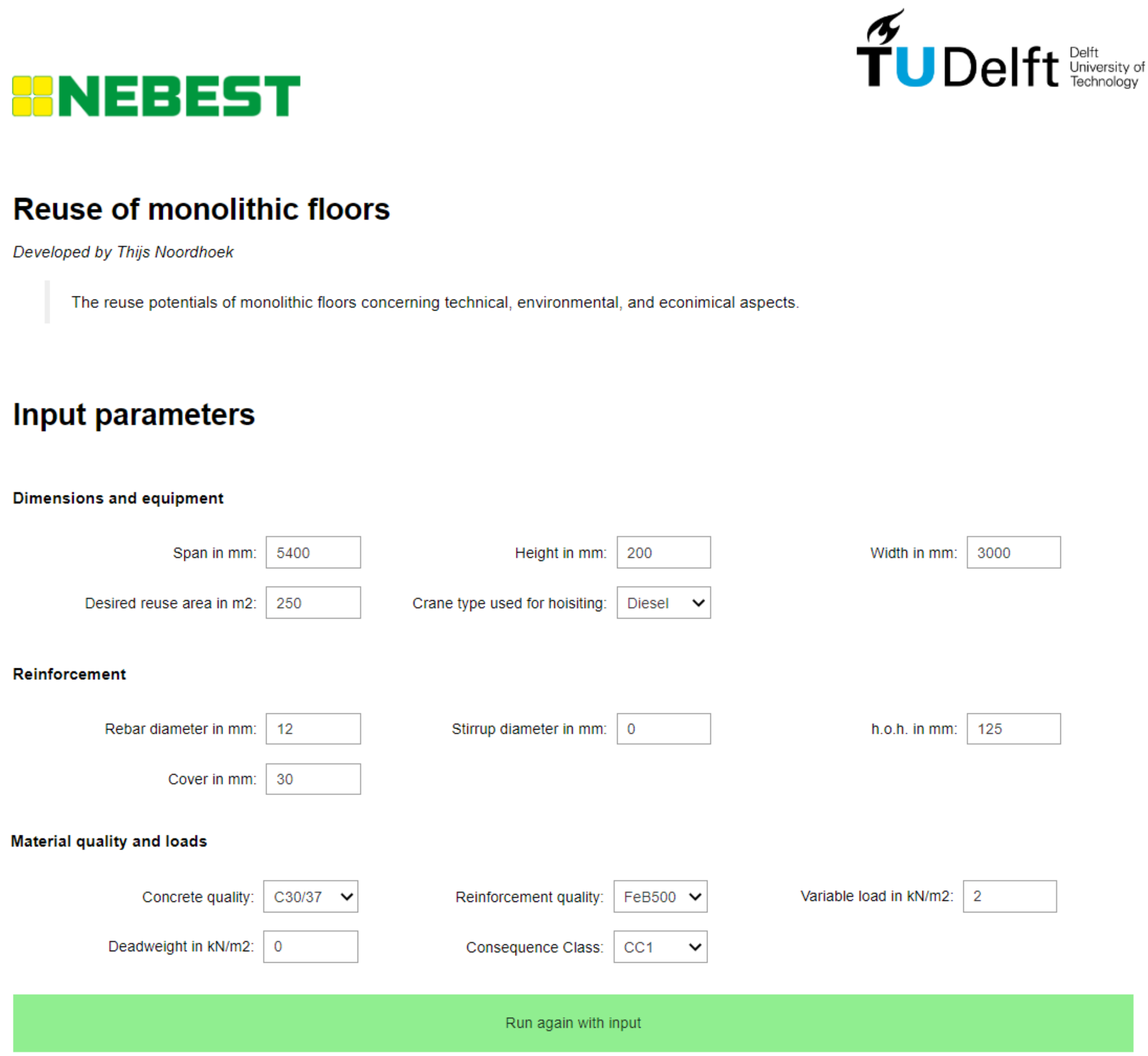
In this chapter the results from the prior chapters are discussed/shown. In the first part the results related to the reuse of monolithic floors are discussed. The results related to the reuse of hollow core slab floors are discussed in the second part.

8.1. Monolithic floor reuse tool

In chapter 3 it was found that monolithic floor elements have reuse potentials. The method to check the structural feasibility, environmental impact and costs related to the reuse of these elements is discussed in chapter 6. Based on this chapter a tool is made which automatically checks the reuse potential considering structural feasibility, environmental impact and costs. This tool is accessible locally via Python as well as via a web application. Screenshots of the Python based tool are given in 8.1.1, in 8.1.2 the link to the web version is given. In part 8.1.3 the reuse potential of monolithic floors is elaborated on.

8.1.1. Screenshots tool

On the next pages screenshots of the tool are given. These screenshots show the Python based tool. The values used in the screenshots are fictive values.



Structural Feasibility

- ULS

Bending moment resistance (Mrd)

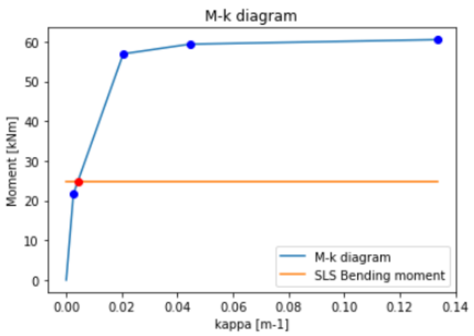
```
The bending moment resistance of the cross section (Mrd) is: 60.51940174708946 kNm
A simple check of the bending moment resistance in the cross section results in a capacity of 58.09222019991925 kNm
The unity check on bending moment gives an UC of: 0.5138705787271872
The cross section is safe ✓
```

Shear resistance (Vrd)

```
The shear resistanve Vrd =  88.9236976289223 kN.
The unity check on shear capacity gives an UC of: 0.2590580533001525
The cross section is safe ✓
```

- SLS

> In the SLS the deflection of the cross section is checked. This check is done using an EI-value derived from the M-k diagram. Besides the deflection the maximum crack width is calculated and compared to the limits given in the Eurocode.




```
Bending stiffness EI, at SLS load case, equals 5958.721896403963 kNm2.
```

Deflection

```
The deflection in the SLS stage is 12.634836179455762 mm.
The unity check on deflection gives an UC of: 0.5849461194192482
The cross section is safe ✓
```

Crack width

```
The maximum crack width in the SLS stage is 0.11987694101492817 mm.
The unity check on deflection gives an UC of: 0.2996923525373204
The cross section is safe ✓
```

Environmetal impact

> In this part the environmental impact for reused and new elements are calculated and compared.

Environmental impact sawing

```
The environmental impact due to sawing is: € 187.23624999999998
```

Envrionmental impact hoisting

```
The environmental impact due to hoisting is: € 57.366
```

Environmental impact new floor

```
The environmental impact of a new floor is: € 1866.7907500000001
```

Costs

> In this part the costs of a new and reused floor are calculated.

Costs new floor

```
The costs of a new plank floor are: € 27750
```

Cost traditional demolition

```
The costs of ordinary demolition are: € 10945.0
```

Sawing costs

```
The costs of sawing are: € 13853.25
```

Hoisting costs

```
The costs of hoisting are: € 917.1
```

Costs of stamping/supporting

```
The costs of stamping are: € 2055.0
```

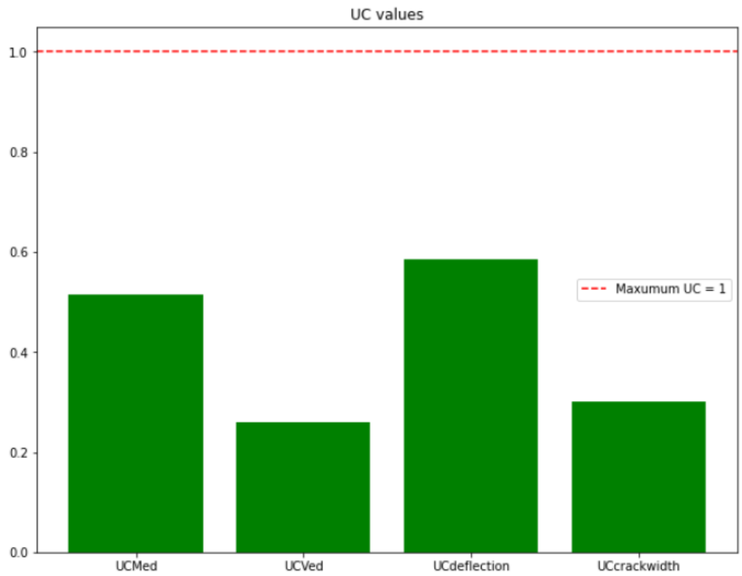
Testing costs

```
The costs related to testing are: € 4717.5
```

Conclusion

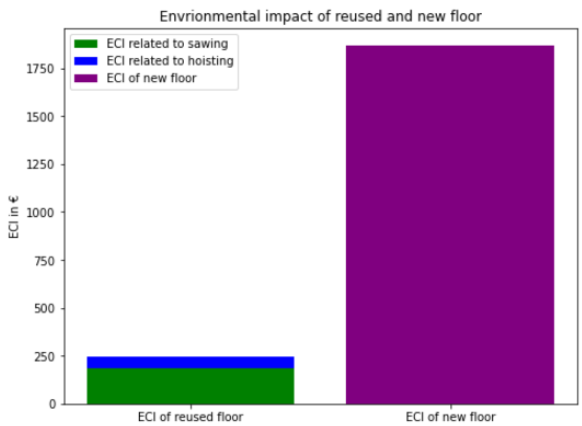
> This part summarises the calculations and gives the reuse potential of the floor elements.

Structural



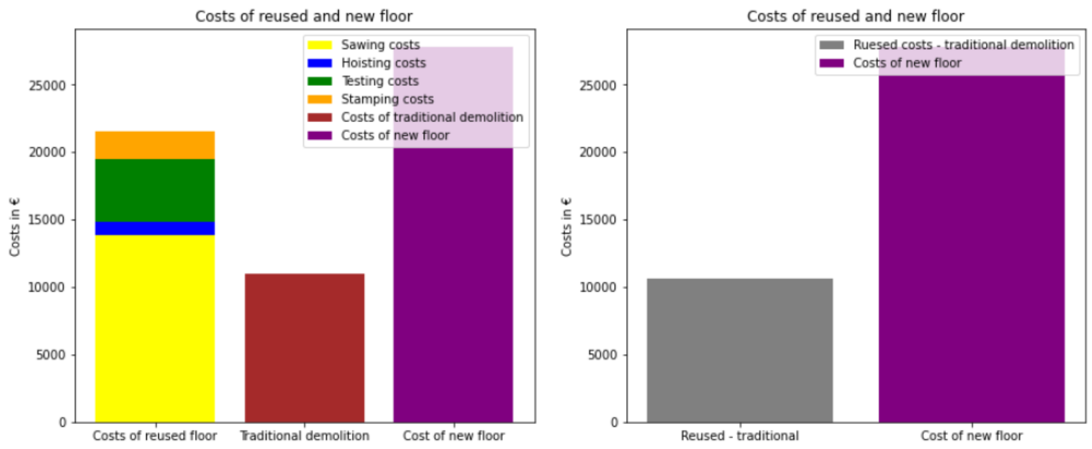

```
The cross section is safe ✓
```

Environmental




```
The potential savings on environmental impact are: € 1622.1885000000002
By implementing reused elements there is no need to produce 120000.0 kg of new concrete. This amount of material is saved from
lower level recycling.
```

Financial




```
The needed investment costs when comparing a reused floor with a new one are: € -8262.150000000001
The needed investment costs when comparing a reused floor and the traditional demolition costs (discount) with a new floor are:
€ -17152.15
```

Potential benefit

```
The potential benefit on environmental impact and costs is: € 18774.3385
```

8.1.2. Hyperlink

Besides the Python tool, as shown in 8.1.1, a standalone webapp is constructed. This webapp is constructed to make the tool more userfriendly for people without programming knowledge. The web based tool can be accessed via the following link:

- https://mybinder.org/v2/gh/Thijsn99/monoo/HEAD?urlpath=%2Fvoila%2Frender%2Fmonovoila.ipynb

When this link is opened a Binder webpage opens. This page will start the webtool which could take 1 or 2 minutes at most. When the page is fully loaded, reuse potentials can be obtained by clicking the button 'Get results!' on the left bottom of the screen. The different input parameters can be changed using drop down menus or integer boxes. When the button 'Get results!' is pressed once more the new results are computed in the tool. The tool returns different graphs and the potential benefit, savings on CO_2, and material savings when elements are reused.

8.1.3. Reuse potential

The reuse potential in this report is given based on the structural feasibility, environmental impact and costs. The values related to these aspects are all calculated automatically in the tool as shown above. Different cases were used in the tool to check the reuse potential of monolithic floors. These cases were practical cases as well as fictive cases which are derived from rules of thumb. In the different test cases the following results are obtained:

Structural feasibility

Different cases were used in the tool to check the structural feasibility related to reuse. In all of the cases it was structurally feasible to reuse the elements in serial houses. Thus it is likely that it is structurally feasible to reuse monolithic floor elements coming from office buildings in the new construction of serial housing.

Environmental impact

In the tool a comparison is made between the environmental impact of a new floor and that of a floor made of reused elements. Different cases were used in the tool to check the environmental impact related to reuse. It was found that a potential saving of 80-90% on environmental impact can be obtained when reused monolithic floor elements are applied instead of a new plank floor. The range of values is related to the different cases which are checked.

Costs

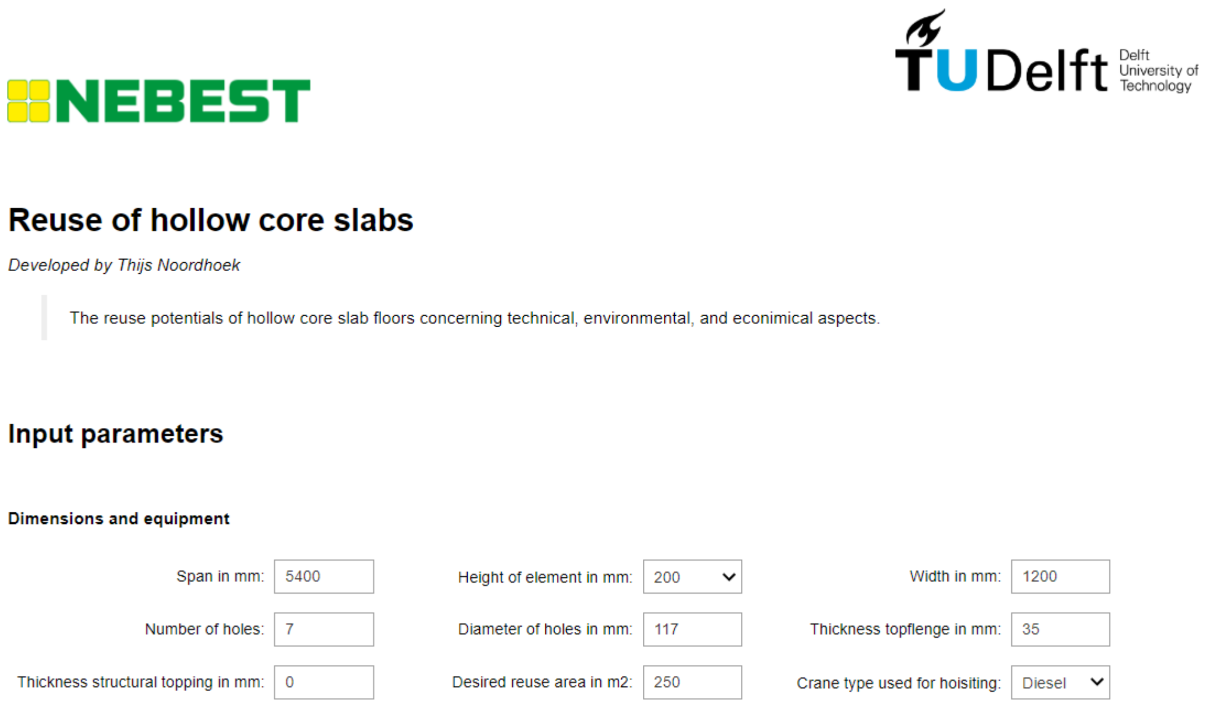
The tool compares the costs related to reuse with the price of a new floor. Different cases were used to check how the costs of a new floor compare to those of a reused floor. Based on the outcomes of these cases it was found that a reused monolithic floor is 20-35% cheaper as a new plank floor.

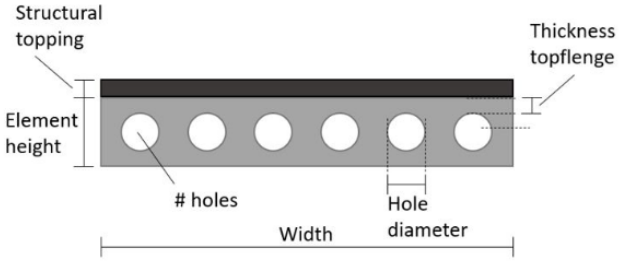
8.2. Hollow core slab reuse tool

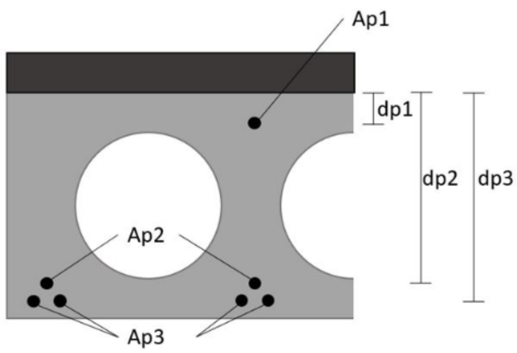
In chapter 3 it was concluded that hollow core floor elements are available for reuse. In chapter 7 the structural feasibility, environmental impact and costs related to reuse are discussed. These three parameters are also implemented in a tool which automatically returns the reuse potential based on these three aspects. Screenshots of this tool are shown in 8.1.1. The tool shown in this part is a Python based tool. A web version of this tool is also accessible as explained in 8.1.2. Using the tool, the reuse potential of different cases considering structural feasibility, environmental impact and costs was computed. The results from these cases are given in 8.1.3.

8.2.1. Screenshots

On the next pages screenshots of the tool are given. These screenshots show the tool in Python. The values as given in the screenshots are sample values.







Reinforcement and prestressing

Ap1 in mm2: 50 | Ap2 in mm2: 100 | Ap3 in mm2: 300

dp1 in mm: 50 | dp2 in mm: 120 | dp3 in mm: 160

Prestressing in N/mm2: 1100

Material quality and loads

Concrete quality: C30/37 | Steel quality: Y1860S7 | Variable load in kN/m2: 2

Deadweight in kN/m2: 0 | Consequence Class: CC1

Run again with input

Structural Feasibility

- ULS checks

Height of the concrete compressive zone (Xu)

> The height of the concrete compressive zone needs to be obtained via an iterative process. A loop is carried out to compute xu.

```
The height of the concrete compressive zone, xu, euguals: 39.350757507575075 mm
According to NEN-EN 1992-1-1 3.3.6, the total strain in the prestressing steel has the following limit: εud = 0.9*εuk.
The strain in the prestressing steel =  13.366105224494333 ‰ < εud = 0.9*εuk = 0.9*35 = 31.5
```

Bending moment resistance (Mrd)

```
The bending moment resistance Mrd, when taking into account the bending moment due to prestressing, is: 71.33142510427065 kNm.
The unity check on bending moment capacity gives an UC of: 0.19514263461658182
The cross section is safe ✓
```

Shear resistance cracked zone

> In this part the shear resistance is calculated using the lower bound vmin of the shear resistance of the concrete cross-section.

```
The unity check on shear capacity gives an UC of: 0.5256523755578202
The cross section is safe ✓
```

Shear resistance uncracked zone (tensile splitting)

> In this part the tensile splitting resistance of the prestressed member is checked.

```
The unity check on shear capacity gives an UC of: 0.2135100917247625
The cross section is safe ✓
```

- SLS

Deflection

```
The total deflection at midspan is: 5.9810881863296705 mm.
The unity check on deflection gives an UC of: 0.27690223084859583
The cross section is safe ✓
```

Environmetal impact

> In this part the environmental impact for reused and new elements are calculated and compared.

Environmental impact sawing

```
The environmental impact due to sawing is: € 82.862
```

Envrionmental impact hoisting

```
The environmental impact due to hoisting is: € 149.1516
```

Environmental impact new floor

```
The environmental impact of a new floor is: € 795.0
```

Costs

> In this part the costs of a new and reused floor are calculated.

Costs new hollow core floor

```
The costs of a new hollow core floor are: € 20000
```

Cost traditional demolition

```
The costs of ordinary demolition are: € 13757.5
```

Sawing costs

```
The costs of sawing are: € 6130.799999999999
```

Costs of stamping/supporting

```
The costs of stamping are: € 2055.0
```

Hoisting costs

```
The costs of hoisting are: € 2384.46
```

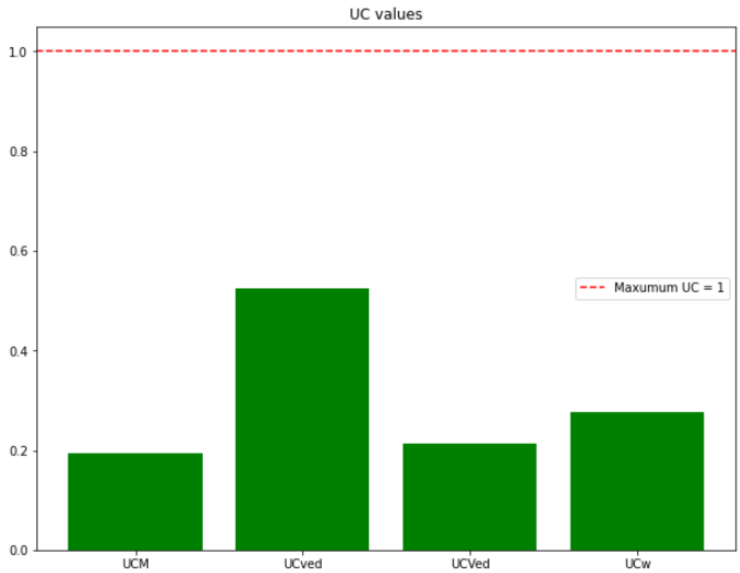
Testing costs

```
The costs related to testing are: € 3503.0
```

Conclusion

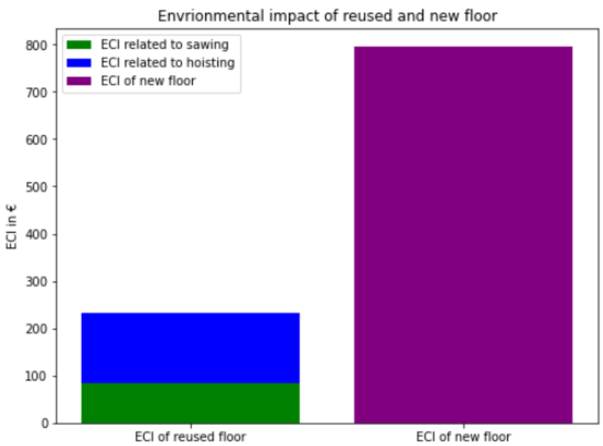
> This part summarises the calculations and gives the reuse potential of the floor elements.

Structural



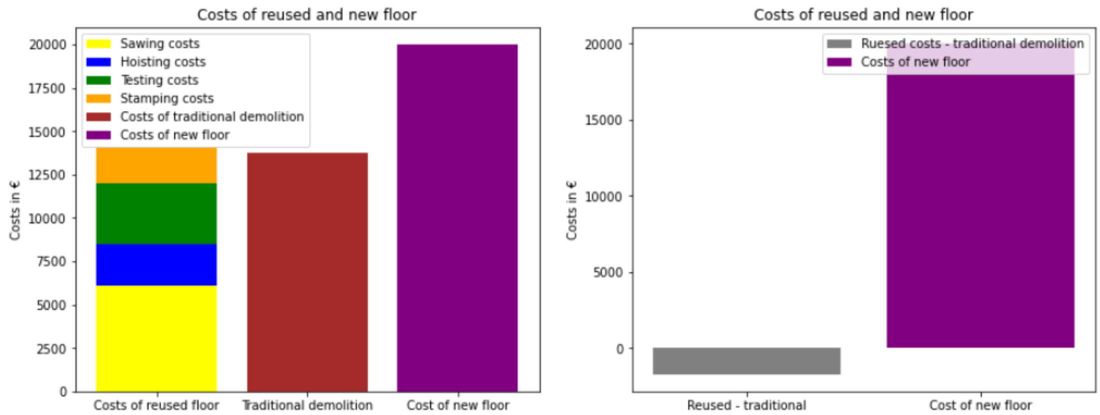

```
The cross section is safe ✓
```

Environmental




```
The potential savings on environmental impact are: € 562.9864
By implementing reused elements there is no need to produce 82370.39589438317 kg of new concrete. This amount of material is sa
ved from lower level recycling.
```

Financial




```
The needed investment costs when comparing a reused floor with a new one are: € -7981.740000000002
The needed investment costs when comparing a reused floor and the traditional demolition costs (discount) with a new floor are:
€ -21739.24
```

Potential benefit

```
The potential benefit, when combining environmental impact and costs, is: € 20247.226400000003
```

8.2.2. Hyperlink

Similar to the monolithic floor reuse tool a standalone web app of the tool is available. The web tool of the hollow core slab floor reuse tool can be accessed via the following link:

- https://mybinder.org/v2/gh/Thijsn99/holoo/HEAD?urlpath=%2Fvoila%2Frender%2Fholovoila.ipynb

When the link is accessed a web browser page is opened which will load the webtool. The loading of the webtool can take a few minutes at most. When the webtool is opened, different parameters can be changed using the dropdown menus or integer boxes. When the ‘Get results!’ button in the left bottom is pressed the tool is run and the results are given. The webtool returns different graphs as well as the potential benefit, savings on CO2, and material savings.

8.2.3. Reuse potential

The reuse potential of floors is given based on the structural feasibility, environmental impact and costs. The reuse potential for different hollow core slabs coming from office buildings were checked using the tool. Based on these cases the following results related to the three different aspects are obtained:

Structural feasibility

In all cases which were checked using the tool it was structurally possible to reuse the hollow core elements from the donor office building for the construction of serial housing. Therefore it can be concluded that it is likely that the structurally feasibility related to the reuse of hollow core floor elements out of office building for the construction of serial houses is met.

Environmental impact

As described in 7.5, the tool compares the environmental impact of a new floor to that of a reused floor. Based on the different cases which were checked using the tool the following two conclusions can be made:

- When a hollow core slab floor which was applied with a structural topping in the donor building is reused, it is possible to save 40-60% on environmental impact compared to the usage of a new floor.
- When a hollow core slab floor which was applied without a structural topping in the donor building is reused, it is possible to save 70-90% on environmental impact compared to the usage of a new floor.

Costs

The tool compares the costs of a reused floor to that of a new floor. In the different cases the following results are obtained:

- When a hollow core slab floor which was applied with a structural topping in the donor building is reused, the costs are 30-50% higher as when a new floor is used.
- When a hollow core slab floor which was applied without a structural topping in the donor building is reused, the costs are 10-40% lower as when a new floor is used.

9 Validity

The validity of the tool is related to the validation and the verification of it. Verification is associated with the tool itself. Common questions which are treated during the verification of a product are: Is the tool designed as specified, and does the tool give the desired results? Both tools are developed in a similar way in the same program. Therefore, the verification of both tools is combined in part 9.3. The validation of a tool is related to the outcome of the tool. Questions which are treated in the validation process are: do the outcomes make sense and are the outcomes comparable to results obtained in practise? The two tools are related to the reuse of different floor elements and therefore the outcomes are different as well. The validation of the two tool is done in part 9.1 and 9.2 for the monolithic- and the hollow core floors respectively. In the end of this chapter the different results are summarised and a conclusion is drawn whether the validity of the tool can be proved.

9.1. Validation of monolithic floor reuse tool

The validation of the monolithic floor reuse tool is done using two different sources. The first one is the book 'Constructieleer Gewapend Beton' by Braam & Lagendijk (2011). This book is used to validate the structural calculations with. The environmental impact and costs are validated using a case project. For these two aspects the Superlocal project was used as validation. This project is one of the few (only) projects where monolithic storey floors are sawn into elements and reused in a new building.

9.1.1. Structural feasibility

The structural feasibility of reuse is calculated in the tool using different checks. As specified in appendix H it is allowed to calculate a floor element in the same way as a beam with a width of 1 meter. In the book 'Constructieleer Gewapend Beton' (Braam & Lagendijk, 2011) different examples of calculations on reinforced concrete beams are given. It is also possible to calculate these beams using the tool. In this way it is possible to check if the calculations in the tool are valid.

In the tool two ULS and two SLS checks are done. The output of the tool is compared to results of the examples. The first aspect which is checked is the bending moment capacity. In example 3.1 on page 51 of the booklet, the bending moment capacity of a beam with the following properties is calculated: width = 300 mm, height = 400 mm, stirrups = Ø 8 mm, reinforcement = 4 Ø16, concrete quality = C20/25, and steel quality = B500.

In the example of the booklet it was found that the bending moment capacity of the beam is equal to 107.9 kNm. If the same input parameters are used in the tool, a bending moment capacity of 107.9 kNm is found. This is exactly the same value which is not strange because the same approach and formulas are used in the tool.

The following ULS check which is done is the check on shear resistance. For the shear resistance the minimum shear resistance (vmin) is used in the tool. According to the book this value is a lower bound value for reinforced concrete elements without shear reinforcement. For floor elements, shear reinforcement is not needed as is explained in appendix H. In table 7.1 of the book, shear resistances for different effective heights and concrete qualities are given. This table gives a minimum shear capacity of 0.50 N/mm^2 for a cross-section with an effective height of 250 mm and a concrete quality of C30/37. If these parameters are used in the tool a similar value of 0.50 N/mm^2 is obtained which means the calculation of shear capacity is correct.

Next, two different SLS checks are done in the tool: a check on deflection and one on crack width. The deflection is calculated using a bending stiffness (EI) which is traced from the M-k diagram. This EI value is used in a forget-me-not to compute the deflection. Filling in the values in the forget-me-not is not error prone and therefore not validated. The establishment of the M-k is checked because this is a more elaborate process which could result in errors. The M-k diagram is constructed based on four specific bending moments which are: the rupture-, the yielding-, the plastic deformation-, and the ultimate bending moment. Example 5.1 of the book is used to check the calculations of these bending moments with and thus if the M-k diagram is constructed in the right way. In table 9.1 the outputs of the tool are compared to those in the booklet.

Table 9.1: Comparison of the bending moments

Bending Moment	Value in booklet [kNm]	Value from tool [kNm]	Difference [%]
Mr	49.7	50.39	+ 1.4
My	169.5	172.8	+ 1.9
Mcpl	172.8	176.8	+ 2.3
Mrd	177.9	181.64	+ 2.1

Based on this table it can be concluded that the deflection is calculated in the right way. The last check which is done is a check on crack width. This check is done using only one formula. Because only one formula is used, this calculation is not prone to errors. Therefore, only the formula is checked with the formula as specified in the Eurocode. A validation using a calculation example is disregarded because of the simplicity of the formula.

Thus it can be concluded that all calculations give valid results. This is not an unexpected finding because the calculations are similar to those carried out for new elements as specified in the book. The main difference, regarding reuse, are the inputs which are used in the calculations. For new elements these properties are provided/known whereas these properties need to be obtained using tests as specified in appendix C when reused elements are used. Therefore the most important aspect regarding the structural calculations for reuse is the acquisition of the needed parameters.

9.1.2. Environmental impact

The environment is the main motivation for the reuse of elements. In the tool the environmental impact of a reused monolithic floor element is compared to that of a newly fabricated plank floor. As described in appendix E, the life cycle stages A1 – A3 are treated. The environmental impact resulting from the tool is validated using the Superlocal project. In this project an apartment building dating from the sixties was dismantled and new houses were constructed using the materials coming from the dismantling process. There are no elaborate calculations and outcomes related to the savings on the environmental impact of this project available. This is a shame because it makes validating the tool more difficult and it is harder to draw conclusions from the project. During an interview with the project leader of the demolition company of the project (Dusseldorp) the savings on environment were discussed. He told about the unclarity/incompleteness of the calculations regarding the savings on environmental impact of the project. The only aspect of which he was sure is that there was a lot of environmental benefit obtained in the project even though not all processes were optimised. He for example stated that they used a crane which was too big for the project which resulted in extra measures which needed to be taken to place the crane on the location (soil improvement).

There is an estimation made by W/E of the potential environmental savings in the project. They assumed that there is the potential saving of 27% on CO2 emissions when comparing the houses out of reused materials with traditional houses (W/E adviseurs , n.d.). A house is approximately 5 x 10 meters as explained in appendix H. Therefore, the reuse area of storey floors is 100 m^2. If this area is used in the tool, it is found that there is a potential saving on environmental impact of 86%. This value is much higher as the 27 % as calculated by W/E. However, they calculated it for the complete house and there are also elements in the house which are new, which results in lower savings. On top of that the process of the Superlocal project was far from optimum which also results in less savings.

There are several reasons which make it hard to compare the results of the Superlocal project with the results of the tool. It is for example not known which parameters and stages are used in the calculations of the Superlocal project. Another vital difference it that only floor elements are taken consideration in the tool and in the Superlocal project all elements/items are put together. The main conclusion which can be derived from both the interview and the data from the Superlocal project is the fact there is a big potential saving on environmental impact when reusing elements/floors. During the interview, the different assumptions regarding the environmental impact, as calculated in the tool, were discussed and found to be valid. It is advised to validate the tool with values which only relate to the reuse of monolithic floor elements. However, this data is not available in current practise and therefore only the above stated interview and project can be used for validation.

9.1.3. Costs

In both reuse and traditional project the costs are an important aspect. The tool shows potential savings on costs when reused elements are used. It is interesting to see whether the Superlocal project had similar results. By comparing the results between the tool and the Superlocal project it is possible to see if and where the tool differs from the actual project.

In the Superlocal project an apartment building was dismantled and the goal was to reuse as much materials as possible. Only insights in the costs of the total project are available, it is not possible to see the costs only related to the floor elements. Therefore, it is not possible to one-on-one compare the results however the results of the Superlocal project can give a guidance to see if the tool comes up with valid results.

When the tool is run with a fictive 1000 m^2 of possible floor reuse it is found that the costs of circular demolition are almost a factor 2 higher compared to the costs of traditional demolition. The person which was interviewed about the Superlocal project (project leader demolition company) did not know the exact costs of the project or the distribution over the different expenses. However, he knew that the project was a factor 4 to 5 times more expensive compared to traditional demolition of the building. He discussed that this related to several aspects. He confirmed that the different expenses which are treated in the tool are important to the total costs of the project. A key aspect which he mentioned were the costs made by the structural engineers in the project. In the Superlocal project there was the problem that the building became unstable when the structural elements were taken out. This resulted in numerous calculations and the placement of different supports and counterweights in the building. The aspect of instability of the donor building is mentioned in part 6.2.5, however this aspect is not considered in the cost calculation. It would be interesting for further research to do a more in depth study into the aspects related to the demolition process. Another aspect which resulted in the high costs was the usage of over dimensioned equipment. The crane used in the project was a 450 ton crane which was overkill for the project. Due to the immense weight of this big crane, different soil improvements needed to be made to the construction site.

Based on the validation with the case it is safe to say that the tool gives results which give a good image of the costs regarding the reuse of materials. However, there are different expenses which can be added to the tool. These costs are mostly related to the demolition process and therefore it is advised to do more study on the dismantling of elements.

Another key item which was discussed during the conversation about the costs is the particularity of the project. Reuse project are currently still not common which results in a process which is far for perfect. The employee of Dusseldorp compared it to the construction process of a Formula 1 car compared to that of a VW Golf. Currently we are comparing a specialised one off project (reuse or F1) with a product which is optimised over many years (traditional or Golf). Therefore, he predicted that the costs of reuse will lower in the future if more knowledge and experience is obtained with the process of dismantling and the reuse of materials.

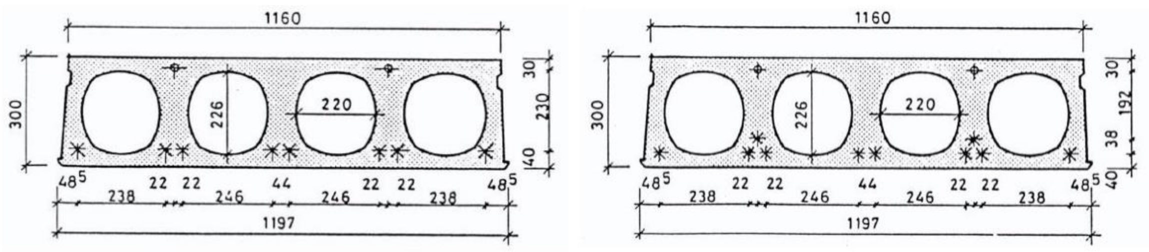
9.2. Validation of the hollow core slab floor reuse tool

The reuse of hollow core slab floors is addressed in a tool which is constructed in chapter 7. This tool is validated using two different sources: the results of the Prinsenhof A project and a meeting with 5 experts of VBI. Prinsenhof A is a building in Arnhem which is dismantled and reused. The floors in this building were made out of hollow core slabs. These elements are dismantled from the building and reused in other projects. The results of the Prinsenhof A project are obtained during an interview with the technical manager of the project.

9.2.1. Structural feasibility

In the tool different structural checks in both the SLS and ULS are executed. These calculations are validated based on two different sources: calculations from the Prinsenhof A project and an interview with different experts. The latter one was conducted in a live meeting at the VBI headquarters. During this meeting the different calculations were discussed and several improvements were given. There were two main aspects which needed adjustments. Regarding the shear capacity it was found that not only the shear capacity in the cracked zone but also the capacity in the uncracked zone needs to be considered. The capacity in the uncracked zone is calculated using the tensile splitting force. The second aspect which needed modification was the reinforcement layout. In the version discussed during the meeting it was only possible to use one layer of prestressing reinforcement. The experts advised to implement several possible players of reinforcement in the tool. These two aspects were adjusted, alongside other small points, which resulted in the current tool. This tool can now be validated using an actual case.

The case which is used in the validation process is the Prinsenhof A project. The outputs of the different calculations were obtained from the technical manager of the project. These calculations are performed by Dycore which is the original supplier of the hollow core elements and the engineer regarding the reuse of the elements. The calculations are classified, therefore only the outcomes are discussed in this report. In the project there were two different hollow core slabs reused. Cross-sections of these elements are given in figure 9.1.



Plaatdoorsnede H30208 Plaatdoorsnede H30210

Figure 9.1: Cross-section of hollow core elements (Dycore)

The tool, as specified in chapter 7, checks the hollow core elements for bending moment capacity and shear resistance in the ULS and for deflection in the SLS. These are similar tests as performed by Dycore. The two different elements are calculated in the tool and the results are compared to the values of Dycore. The different results are shown in table 9.2.

Table 9.2: Comparison of values between tool and Dycore

Slab type H30208	Calculation by Dycore	Calculation in tool	Difference [%]
Mrd	228.2 kNm	221.98 kNm	- 2.1
Mcr	91.5 kNm	135.51 kNm	+ 32.5
Vrdc (cracked)	110.7 kN	92.90 kN	- 19.2
Vrdc (uncracked)	241.5 kN	198.92 kN	- 21.2
Deflection	11.2 mm	17.28 mm	+ 54.3

Slab type H30210	Calculation by Dycore	Calculation in tool	Difference [%]
Mrd	308.7 kNm	256.86 kNm	- 20.2
Mcr	109.0 kNm	150.19 kNm	+ 27.4
Vrdc (cracked)	148.2 kN	92.90 kN	- 59.5
Vrdc (uncracked)	218.3 kN	209.0 kN	- 4.4
Deflection	20.0 mm	17.28 mm	- 15.7

From this tables it can be concluded that the outcomes of the tool differ a bit from the outcomes obtained by Dycore. However, there are several reasons which need to be considered before a conclusion is made whether the tool gives valid outcomes. Firstly, only the outcomes of the calculations done by Dycore are known. The assumptions made in the calculations are not known and can therefore not be compared. In the calculations one important assumption is mentioned. Dycore uses the structural aspects of the structural topping which is applied on the floor. There are tests conducted to obtain the bond strength between the structural topping and the hollow core element. In the calculation in the tool it is assumed that the structural topping does not affect the strength of the element. The structural topping is seen as a deadweight on top of the floor. Secondly, the exact properties of the slab are not known. Different aspects cannot be found in the provided output sheets and therefore need to be assumed. The actual amount of prestressing steel (Ap) is for example not known. This property is estimated based on other slabs and available data but is of great importance in the calculations. Another important aspect is the way in which the slab is calculated. In the calculations of Dycore the slab is calculated on several locations whereas the tool only calculates the governing location. So, it can be concluded that the differences are explainable because the exact input parameters and assumptions can differ between the two calculations. The outcomes of the calculations are in the same magnitude. Therefore, it can be concluded that the calculations in the tool are probably valid.

Based on the outcomes, as explained above, it is not possible to state with 100% certainty that the tool is valid. Therefore, an additional test is conducted. Using the tool the strength of a new element can also be calculated because the calculation for new elements is similar. The outcome of this calculation can be compared to the design graphs provided by the manufacturer to see whether the outcomes are valid. In this case a slab with a height of 200 mm is calculated. In table 9.3 the outcomes of this calculation are checked with values traced from design graphs of Dycore.

Table 9.3: Comparison between tool and design graph

Slab 200 mm	Design graph by Dycore	Calculation in tool	Difference [%]
Mrd	99.22 kNm	107.82 kNm	- 8.0

As shown in the table, the values are comparable from which it can be concluded that the results are probably valid. It is assumable that the differences with the Prinsenhof A project are related to the differences in assumptions and properties used in the calculations.

9.2.2. Environmental impact

The structural aspects were validated using data of the Prinsenhof A project. Regarding the savings on environmental impact there were no accurate results available. Therefore, it is not possible to validate the environmental impact as calculated in the tool with the Prinsenhof A project. Thus another case needs to be used. During the meeting with the experts of VBI they showed a presentation in which they elaborated on the potential environmental saving when reusing a hollow core slab. According to the study, as explained in the presentation, a reused element was responsible for 18% of the environmental impact of a new element. Thus according to this research the reused element would impact the environment approximately five times less as the new element.

In the tool an area of 1000 m^2 is examined to see if a similar result is found. This calculation is conducted for different heights and with or without a structural topping. These values are thereafter compared to the value stated by VBI. The potential savings per floor type are shown in table 9.4.

Table 9.4: Possible environmental savings when reused elements are applied

Slab type	MKI reuse / MKI new
200 m (no struc. top)	29 %
200 mm (with struc. top)	57 %
260 m (no struc. top)	21 %
260 mm (with struc. top)	41 %
320 m (no struc. top)	17 %
320 mm (with struc. top)	34 %
400 m (no struc. top)	14 %
400 mm (with struc. top)	28 %

Based on these values it can be concluded that the potential savings on environmental impact as calculated in the tool are similar to the values obtained by VBI. In the table it can be seen that the values for elements without a structural topping are similar to the 18% stated by VBI. The elements as explained by VBI were also elements without a structural topping and therefore it can be concluded that the values obtained in the tool are valid.

9.2.3. Costs

Costs are important in every project and therefore it is important that the cost estimations in the tool are correct. The main interesting item regarding the costs is the price of reused element compared to a new one. Data of the Prinsenhof A project is used to see whether the tool gives similar results as was found in the case project. The actual cost structure of the Prinsenhof A project is not known/given. Therefore, it is not possible to check the tool with costs only related to the floors. According to the technical project manager the reuse of elements was approximately 30% more expensive compared to traditional. In the project a total area of 4500 m^2 was reused. The elements which are reused have a height of 300 mm and a structural topping of 120 mm. By using these values in the tool, it is possible to calculate the costs related to reuse and the traditional costs. These costs can thereafter be compared to see whether a similar difference between the costs is found in the tool as was found in the project.

When the above stated values are used in the tool it is found that the costs of reuse are 36% higher compared to the those of a traditional floor (new). This value is similar to the value given for the Prinsenhof A project. Thus it can be concluded that the costs as calculated in the tool are valid.

9.3. Verification of the tools

During a verification process it is checked whether the tool operates as intended and without errors. In table 2.2 the desired properties of the tool are described. In this part it is checked whether these desired properties are reached, if the tool is easy to use, and if the tool has no errors or bugs.

The main goal of the tool is to assess the reuse potential of structural floor elements based on the structural feasibility alongside with the accompanying effects on the environmental impact and costs. When the tool is run it can be seen that these aspects are all outputs and are obtained in an easy and quick way. Different guinea pigs used the tool and gave feedback on the user-friendliness. They all concluded that the tool is easy to use. Due to the availability of a web app it is also possible for people without programming knowledge to use the tool. A desired aspect was the usage of the tool in different stages of the project. In chapter 7 and 8 the steps involved in the reuse process of monolithic- and hollow core slab floors are explained respectively. These parts explain that the tool can be used in an early stage of the project or at a more developed stage after tests are conducted. In the earlier stage more assumptions are made for input parameters which results in less accurate outcomes. The tool gives outcomes within seconds which make it really easy to check different assumptions or options.

In a verification process it is important to check whether the tools do not give errors or bugs. Therefore, the tools are tested with a big variety of values to see whether they result in possible errors. For reasonable values, which could actually come across in practise, no errors were obtained. When the combination of values is unrealistic the tool can result in errors. This can for example be a cross-section where the holes have a bigger diameter as the height of the cross-section or when an immense amount of prestressing force is present in a small element. Thus it can be concluded that the tool works as intended for slabs which are used in practise.

9.4. Conclusions

In the previous paragraphs the different tools are validated using different case projects. The Superlocal project was used for the validation of the monolithic floor reuse tool. The data from this project was not related to only the floor elements which made the validation difficult. It was not possible to validate the costs and environmental impact with 100% certainty because of this. The structural aspects were validated using a book in which the calculations of reinforced concrete are explained. The structural calculations in the tool gave similar results as the calculations in the book. Therefore it can be concluded that these calculations are valid.

For the hollow core reuse tool the Prinsenhof A project was used for validation. The results of the calculations for the floor elements were available. These results were compared to the results from the tool when similar input parameters were used. It was found that these values differed. However, a sidenote needs to be added; The exact assumptions in the calculations of the Prinsenhof A project were not known. Besides the assumption not all parameters were known. This lacking data is most probably the reason for the deviations because results for a new element were similar to those in design graphs. Regarding the cost and environmental impact similar results as in the Prinsenhof A project and the assumption by VBI were obtained. Therefore, it can be concluded that these values are valid.

Regarding the verification of both tools it was found that both tools operate as intended. They give the desired results and do not have errors when reasonable values are used as input. The tools are validated using the most suitable projects available. However, it is still not possible to verify all results with certainty because of the missing data. If more/better data was available, the tools could have been verified with more certainty.

10 Discussion

In this chapter the results obtained in the report are discussed. The chapter start with the research relevance in which the research is placed in broader context. Thereafter the different limitations of the research and the two tools are explained.

10.1. Research relevance

Different climate goals are set by the Dutch government and the world. Regarding the Netherlands the two most important ones are: the lowering of raw material usage by 50% in 2030 and the desire to have a fully circular economy by 2050. The Dutch economy is currently not on track for reaching these goals. There are still a lot of raw materials used and this will not change unless actions are taken (quick). A possible way forward towards less raw material usage could be the reuse of materials. This is a step in the good direction towards a circular economy. However, it is still not clear if there are possibilities for reuse and where these possibilities lie. Therefore, the materials flows in the Netherlands were examined in this report. In this research two potential material flows were detected. For these material flows two tools were developed which quantify the reuse potentials regarding structural feasibility, environmental impact, and costs. In the tools detailed structural calculations are automated which show the possibilities for the interchange of floor elements between office buildings and serial houses. These structural calculations are based on the new construction guidelines and several meetings with experts. On top of the structural feasibility the possible savings on environmental impact are calculated based on a LCA conducted on stage A1-A3. Thirdly insights in the possible expenditures are given based on interviews with several parties involved in the reuse process. By giving these insights the tools could accelerate the reuse of floor elements in practise.

The potential application area of the tool is defined by the total area of demolished office buildings dating from the seventies and eighties. In the material flow analyses it was found that the ingoing material flow is significantly bigger as the outgoing material flow, which means the supply of materials is governing in the reuse process. In 2019 approximately 150,000 m^2 of offices (dating between 1970-2000) were demolished (EIB & Metabolic , 2022). If it is assumed that these buildings have two storeys, the scope of the thesis consists of 100,000 m^2 of floor area in 2019. In chapter 3 it was found that three floor systems are used in these office buildings. If it is assumed that these floors are used in equal amounts the scope of the tools combined is approximately 66,000 m^2 (this is most likely an underestimation because cassette floors are less common). It was found that the savings on environmental impact are estimated to be:

- 70-90% - When reused hollow core slabs without a structural topping (in donor building) are applied instead of new elements.
- 40-60% - When reused hollow core slabs with a structural topping* (in donor building) are applied instead of new elements.
- 80-90% - When reused monolithic floor elements are applied instead of a new plank floor.

* Is the case for 80% of the floors as approximated by experts of VBI. Thus 33,000 *0.8 = 26,400 m^2 with structural topping and 33,000 *0.2 = 6,600 m^2 without a structural topping.

The environmental impact of new floors is given in part 6.5 and 7.5. When the two tools were used and floor elements were reused, the potential savings on environmental impact in the year 2019 were € 298,603.80 (see table 10.1). This value represents the saving of 5,972,076 kg of CO2 emission (1 kg

CO_2 = €0.05), which is similar to driving more than 55,000,000 kilometres with a standard car! So it can be concluded that the tools are certainly relevant.

Table 10.1: Potential savings on environmental impact if the tools would have been applied in 2019

Reuse of	Area	Potential savings	Environ. impact new	Savings on envir. impact
Hollow core (with struc. in donor)	26,400 m2	50%	4.41 €/m2	€ 58,212.00
Hollow core (without struc. in donor)	6,600 m2	80%	4.41 €/m2	€ 23,284.80
Monolithic	33,000 m2	85%	7.74 €/m2	€ 217,107.00
Total				€ 298,603.80

10.2. Research limitations

The main limitations of the research are the scope boundaries as explained in chapter 2. Besides these scope boundaries different limitations were found throughout the process. During the validation process it was found that the tools potentially do not cover all aspects which are involved in the demolition process. During the interview about the Superlocal project it was found that the instability of the donor building during dismantling could be an important issue. This aspect was mentioned in the steps however not investigated in depth. Therefore it can be concluded that the needed steps in the reuse process are mentioned however the steps regarding the dismantling of the donor building are limited. Another limitation of the report is the lack of a case study. Therefore different general assumptions are made which could differ in practise. But lack of a case also has a benefit: the tool has a broader application field now.

Besides these general limitations there are also assumptions made regarding the different aspects of the tool. These assumptions result in different limitations and are explained in the following paragraphs.

Structural feasibility

In the calculations, related to reuse of floor elements, different assumptions are made. These assumptions are mentioned in part 6.4 and 7.4 and result in limitations. The main assumption made in the calculations regarding the reuse of monolithic floors is the concrete quality. In the calculations it is assumed that concrete with a maximum quality of C50/60 is applied. Concrete floors with a higher quality cannot be calculated in the tool because otherwise several factors need to be adjusted in the tool. The main assumption made in the calculations of the hollow core slab floors is the amount of prestressing losses. It is assumed that the total prestressing losses are 20% and that no further creep or shrinkage are present in the concrete. This results in the limitation that the tool cannot be used or needs to be adjusted if these aspects are present or when different prestressing losses are found. In the stability calculation it is assumed that the walls have enough capacity to act as stabilising elements. They are not treated in detail because they are similar as in ordinary new construction. It is not possible to calculate the needed strength of the walls or the forces in the walls using the tool.

Environmental impact

The environmental impacts are calculated in the tool using an LCA. In the LCA only stages A1-A3 are considered because the production of new elements is compared to preparation of the reusable elements which is similar to a production process. Because only these stages are considered it is not possible to compare the values to full EPD's of other elements. The data which is used in the calculations is retrieved mainly form the NMD. Not all data in this database is transparent/insightful which resulted that several assumptions needed to be made. It is assumed that the data of the NMD is valid, otherwise the environmental impact calculated in the tool could be wrong.

Costs

In the calculations of the costs it is assumed that the donor material itself is for free. Using data from different sources the reuse costs are estimated. These values were all translated to a value per square meter of flooring. This assumption is not completely true for small reuse areas because the costs are not linear with the area. In practise the costs related to the reuse of a big area are lower per m^2 as the costs for a smaller area. Therefore, the costs for reuse are underestimated when a small reuse area is implemented. The next aspect which needs to be considered is the process. It is possible that there are aspects needed in the process which are not incorporated in the tool. Another important aspect is the knowledge and experience of reuse. Currently reuse is a very specialized operation whereas the usage of new floors is a standardised process. Therefore the costs for reuse will lower in the future if more experience and knowledge is obtained.

Validity of the tool

The different tools were validated using two case projects, the Superlocal project and the Prinsenhof A project. However, the data provided of these two projects was not fully comprehensible and was related to the whole project and not only to the floors. This made the validation of the tools difficult and has as a result that they are not validated with 100% certainty. These projects were the most appropriate projects available. Reuse of floor elements is still in a preliminary stage and therefore there are no available projects which are better suitable to validate the tools with. Another important aspect which was found during the validation process is that several aspects are really case specific which makes it harder to develop a tool which can be used for different cases.

11 Conclusions

In this chapter the conclusions of the research are given. The main objective throughout the research was stated the following in part 2.1:

> *"Give insights in the reuse potentials of floor elements based on structural feasibility, environmental impact and costs."*

This research goal forms the basis for the main research question. The main research question can be split into two parts which are both subdivided into smaller sub-questions. The answers to all sub-questions combined form the answer to the main research question and by doing so meet the main research objective. First the different sub-questions are answered whereafter the main research question is treated.

11.1. Sub-questions

The sub-questions are divided between two more general sub-questions. In this part the different sub-questions are given and answered one by one.

How can floor elements coming from office buildings be reused in serial housing?

1 *What types of floor elements are used in office buildings built between 1970-1990 and which elements are possibly reusable?*

This sub-question is treated in chapter 3 and appendix A. The floor elements used in office buildings from the seventies and eighties which have reuse potentials are:

- Monolithic floors
- Hollow core slab floors

2 *What construction methods are used for the construction of serial housing and which types of floors are used?*

This sub-question is treated in chapter 4. The construction methods and floor types are:

- Stacking construction in which plank floors or hollow core slab floors are used.
- Prefab construction in which hollow core slab floors (with ducts) or prefab casco floors are used.

3 *Which floor elements have a linkage between the supply and demand side and can thus possibly be reused?*

This sub-question is treated in chapter 3 and 4. Between the supply and demand side the following linkages are possible:

Table 11.1: Possible matches between supply and demand

Supply side (offices)	Demand side (serial houses)
Monolithic floors	Plank floors
Hollow core slab floors	Hollow core slab floors

4 *Which steps are involved in the process of reuse?*

This sub-question is treated in parts 6.2 and 7.2. The process of reuse can be split into three different stages: the research stage, demolition stage, and construction stage. These stages are split up into different steps which are given in the following figure:

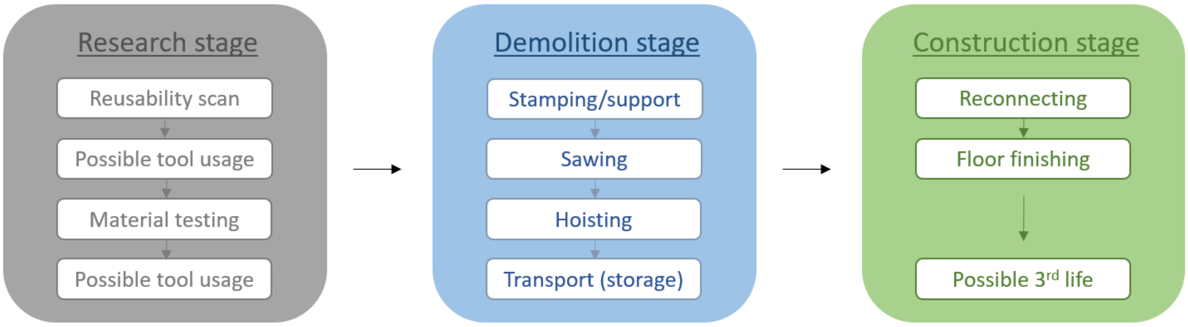


Figure 11.1: Steps in the process of reuse

How can the structural feasibility, environmental impact, and costs regarding reuse be quantified?

1 *How can the structural feasibility concerning reuse be checked and is it structurally feasible to reuse floor elements?*

This sub-question is treated in parts 6.4, 7.4, 8 and appendix H. The structural feasibility can be checked based on the Building Decree for new construction. The structural feasibility was checked for different cases. For all checked cases it was structurally feasible to reuse floor elements.

2 *How can the environmental impact of a reused element be quantified and how does it compare to that of a new element?*

This sub-question is treated in parts 6.5, 7.5, 8 and appendix E. The environmental impact of a reused element can be quantified using an LCA for the stages A1-A3. A comparison between the environmental impact is given in table 11.2.

Table 11.2: Environmental impact of reused elements

Reuse of:	**Environmental impact reused compared to new**
Hollow core slab floor (with struc. top. in donor build.)	Saving of 40-60* %
Hollow core slab floor (without struc. top. in donor build.)	Saving of 70-90* %
Monolithic floor	Saving of 80-90* %

3 *Which costs need to be made to make reuse possible and how do these costs compare to those of a new element?*

This sub-question is treated in parts 6.6, 7.6, 8 and appendix D. The costs are related to the steps which are needed for reuse: stamping/supporting, material testing, sawing, and hoisting. A comparison of the costs is given in table 11.3.

Table 11.3: Costs of reused elements

Reuse of:	Costs reused compared to new
Hollow core slab floor (with struc. top. in donor build.)	30-50* % more expensive
Hollow core slab floor (without struc. top. in donor build.)	10-40* % cheaper
Monolithic floor	20-35* % cheaper

11.2. Main question

The main research question reads:

"What is the potential for reuse of structural floor elements in existing office buildings to be applied in new serial houses, considering the structural feasibility, environmental impact, and costs?"

The floors which can possibly be reused are monolithic- and hollow core slab floors. Different cases were checked in the tools and based on the results, as presented in chapter 8, the following conclusions can be drawn:

- In all cases it was structurally feasible to reuse the floors. So, the reuse potential regarding structural feasibility is big.
- The environmental impact of a reused floor is lower as that of a new floor. Thus the reuse potential regarding environmental impact is high.
- The costs comparison between a reused and a new floor strongly depends on the type of floor. It is not possible to draw one general conclusion for the reuse potential related to costs.

Based on the above stated aspects it can be concluded that the potential for reuse of structural floor elements in existing office buildings to be applied in new serial houses is promising. So…

"When you refuse to reuse, it is the world you abuse"

12 Recommendations

Based on findings in the validity, discussion, and conclusion several recommendations can be formulated. These recommendations consist out of additions which can be included in the tool and advice for future research. The different recommendations are mentioned one-by-one in the following paragraphs.

12.1. Tool development

- **Improve and validate the tools by applying them in practise**

The two tools are developed based on numerous interviews and two case studies are used in the validation process. Now, it is advised to further develop the tools in practise. When the tools are used in practise a lot of knowledge and experience can be obtained which can be used to improve the tools.

- **Widen the scope of research**

The tools are applicable to monolithic- and hollow core slab floors. The tools were originally designed for the interchange of floor elements between office buildings and serial houses. However, these floor systems are also used in other building types. Therefore the tools can also be used for other buildings.

- **Add possibilities for reuse in another function**

In the tools the possibilities and potentials regarding the reuse in the same function are examined. The elements can also be reused in another function. Perhaps reuse in another function results in more benefits regarding the environmental impact and costs, which makes it interesting to check.

12.2. Further research

- **Develop tools for other floor systems and elements**

The tools are applicable to the reuse of monolithic- and hollow core slab floors. Similar tools can be developed for other floor systems, for example TT-slab floors. It is also advised to develop reuse tools for other elements such as beams or columns or non-structural elements.

- **Translate the material flows into element flows**

Insights into material flows form the basis for reuse. Data regarding these material flows is currently material based which means the flows are expressed quantity based, e.g. as kg concrete. From a reuse standpoint it is better to know which elements are coming available. Therefore it is advised to translate the current material flows into element flows.

- **Investigate the liabilities, guarantees, and collaboration forms**

No legal aspects are treated in the tools or the report. These aspects have a mayor influence on the practical reuse potential. Therefore it is advised to look into the different legal aspects related to reuse such as liabilities and guarantees for the materials. It is also important to consider the collaboration form which is used during the execution of the project.

- **Elaborate on the dismantling/demolition process**

During the validation process with the Superlocal project, it was found that the dismantling process is more complex as was first assumed. Therefore, it is advised to thoroughly investigate this process and perhaps develop a tool which checks the possibilities for dismantling from a demolition contractor’s standpoint. This project can best be conducted in cooperation with a demolition company such as Vlasman, Markus, or Dusseldorp.

- **Do research into demountable connections**

In the reuse process the dismantled elements need to be connected to the new structure. Preferably these connections are dismountable because the elements can then be dismantled and reused again. There are currently no standard demountable connections and therefore it is recommended to develop these.

- **Develop guidelines for reuse**

Currently there is a building decree related to new construction and one related to renovation but there are no rules related to reuse. There are different guidelines for the reuse of material but there are no standards like the Eurocode. It is advised to develop these guidelines to make reuse easier.

12.3. Nebest

- **Add the different tools to the current Reusability scan of Nebest**

Two tools are developed which check the reuse potential of monolithic- and hollow core slab floors based on structural, environmental, and financial aspects. These tools are currently separate tools from the reusability scan. It is advised to incorporate these tools in the current Reusability scan of Nebest.

- **Add the potentials in the current reusability tool of Nebest**

The reusability scan results in a reusability score based on the 10R ladder. It would be nice if the tool also gives insights in the possible savings when reusing. In this way the tool can show the potentials to the building’s owner which probably will result in reuse.

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PART 4: Appendices

Tour at VBI – own figure

Appendices

A. Material flows in the Netherlands and demarcation

In this appendix the material flows in the Netherlands are examined. Based on the first part, the area defining, more in-depth studies are done into the most promising aspects found in part A1. These in-depth studies are done in parts A2 until A3. This appendix forms the basis for the research done in the main report, as is described in chapter 2.

In the different parts a division is made between different building types. This distinction is made between the following types:

Table 0.1: Building types in the Netherlands

Building types in the Netherlands	
Residential Construction	**Non-Residential Construction**
Single family houses	- Commercial Buildings
- Detached houses	- Offices
- Semi-detached houses	- Educational buildings
- Serial houses	- Care buildings
	- Shops
Apartments/multifamily houses	- Other

A demarcation is made in this appendix and the main report; Only demolition and new construction are treated in this part. Aspects concerning maintenance and rebuild are not treated, as is more elaborately explained in chapter 2.

A1. Area defining

One of the first steps in the research is to investigate the 'playing field'. Without knowing the available materials from demolitions, it is hard to find a focus. Therefore, research is done to define the building stock of the Netherlands. In most of the literature a distinction is made between housing construction (HC) and non-residential construction (NRC) (shown in table 0.1), therefore this difference is also made in this part. In the end of part A1 a conclusion will be drawn in which the two are compared. Next a recommendation is done which describes the most promising material flows and the most promising buildings on which to focus. This recommendation will be based on the research done earlier in this part. In the subsequent parts, A2-A3, an in-depth study is done into the most promising buildings and material flows.

Three different aspects per construction type are taken into consideration to define the 'playing field'. These aspects are current stock, demolition numbers, and future perspective. Using these three aspects the material flows are estimated. These material flows represent the materials which are available for reuse.

A1.1. Housing construction (HC)

There are two main types of buildings which are categorised as housing construction, namely single family houses and apartment buildings (see table 0.1). The purpose of housing construction is to create a residence. In this subsection all buildings which fall under housing construction are dealt with.

Current stock

The current stock means the number of buildings at this moment. The stock can be categorised not only by date of construction but also by type of owner. The object can either be owned by the inhabitant ('owner-occupied') or it can be rented ('rented'). In the next figure the buildings are categorised by date of construction and owner.

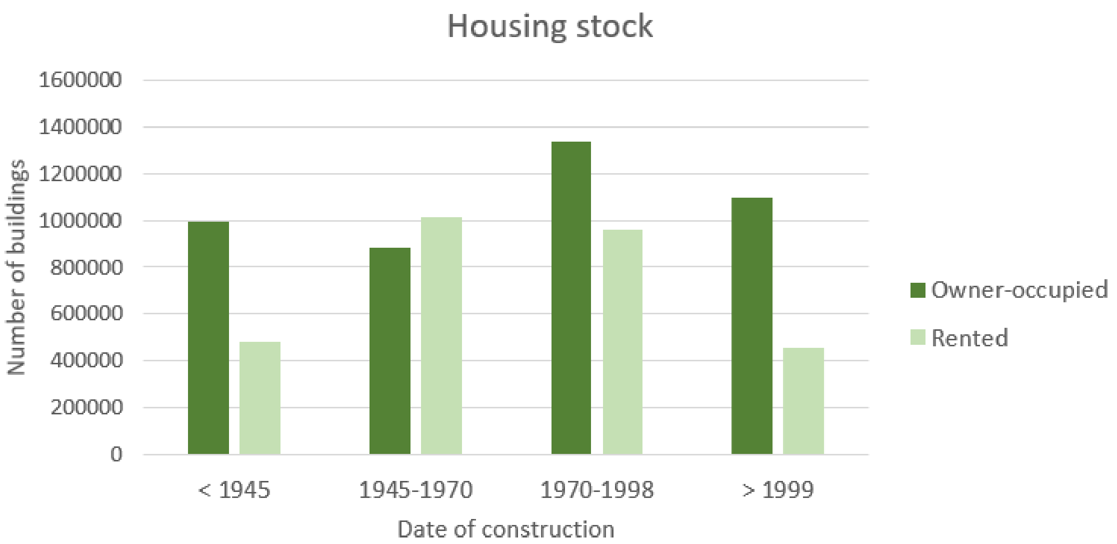


Figure 0.1: Housing stock per owner type and construction date (EIB, 2015)

As can be seen in the above shown figure the division of privately owned houses is much more evenly spread compared to the spread of rented houses. The rented houses show a significant peak between 1945 and 1998.

It is also possible to categorise the building stock only based on date of construction. When this is done a peak can be seen for houses with a date of construction between 1971 and 1980.

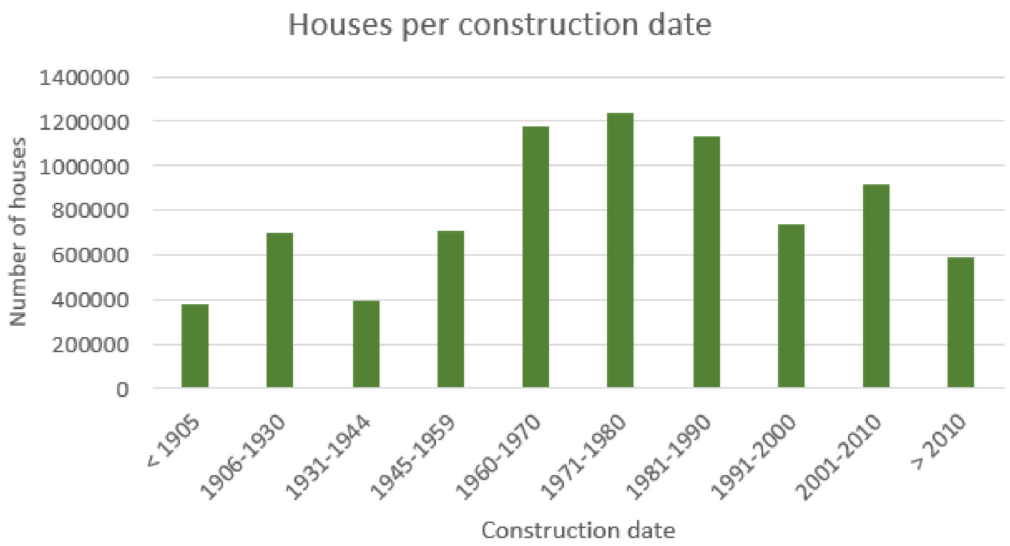


Figure 0.2: Housing construction per date (Rijksoverheid, 2020)

From the figures it can be derived that there are more than 7 million houses in total. It can also be seen that there is a great diversion in date of construction.

Demolition numbers

The next aspect which is treated are the demolition numbers. Demolition numbers state something about which materials are becoming available and the amount. The demolition numbers are the most interesting numbers to look at when taking the reuse of materials into consideration. The buildings which are being demolished are the input for your material box ('Lego box'). This box holds the elements/materials which could possibly be reused in new buildings.

In the figure below, the total area of houses which is demolished in a certain year, can be seen. When looking at the area of houses which is being demolished between 2013 and 2018 it can be seen that less area is being demolished. The trend shows a decreasing line from which it can be concluded that less houses are demolished. This can have different causes; my guess is that it is due to the rising housing demand.

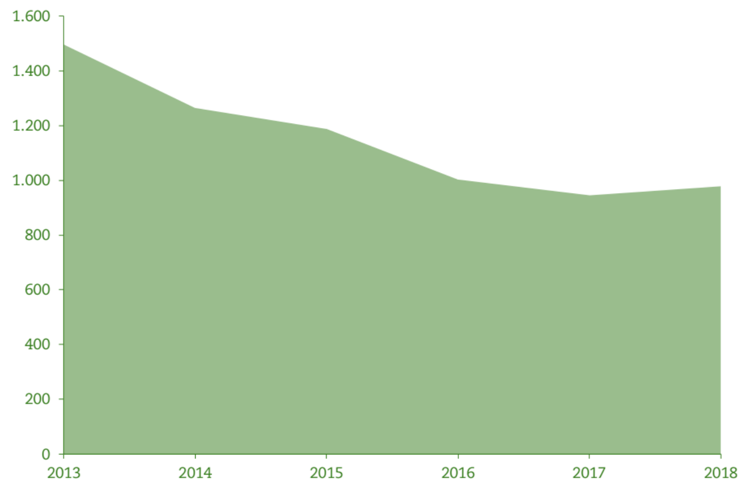


Figure 0.3: Total area of demolished houses per year in 1000 m^2 (EIB, 2019)

Next it would be interesting to see the sort of HC and the date of construction compared to the demolition numbers. In the next table the demolition numbers for different sorts of HC over different dates of construction are given.

Table 0.2: Number of demolished housed per type and construction date (EIB & Metabolic , 2022)

	< 1945	**1945-1970**	**1971-2000**	**> 2000**	**Total**
Single family	1300	3000	5000	300	5100
- Detached	300	200	100	0	700
- Semi-detached	200	300	100	0	600
- Serial	800	2500	300	300	3800
Apartments	700	3600	900	500	5700
Total	2000	6600	1400	800	10800

In the table can be seen that the demolished buildings are mostly built before 1970 and are predominantly apartment buildings and serial houses. The total amount of demolished houses (so all types combined) can also be given over the different dates of construction:

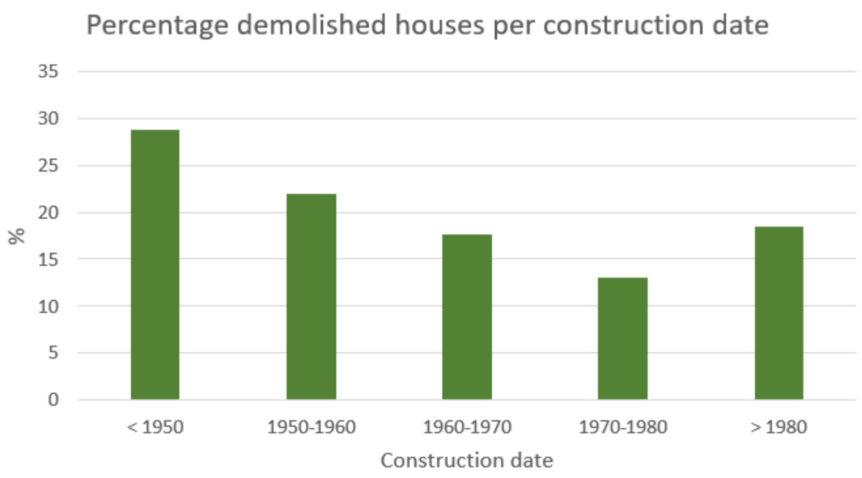


Figure 0.4: Percentage of demolished houses per construction date (EIB, 2019)

As can be seen in the figure, more than half of the buildings which are being demolished were built before 1960. The materials in these buildings can be estimated using a table in annex E of the EIB report 'Materiaalstromen, milieu-impact en energieverbruik in de woning- en utiliteitsbouw' (EIB ; Metabolic ; SGS Search, 2020). Using this table, it can be concluded that the predominant materials coming from these buildings are wood and masonry brink. These were two primarily used building materials used for housing in the period until 1960.

Future Perspective

The future perspective is based on the new construction and demolition estimates for the years 2030 and 2050. In these years the Netherlands want to use respectively 50% and 100% less primary resources as already mentioned in the problem definition. Therefore, the reuse of materials needs to be significant in this year.

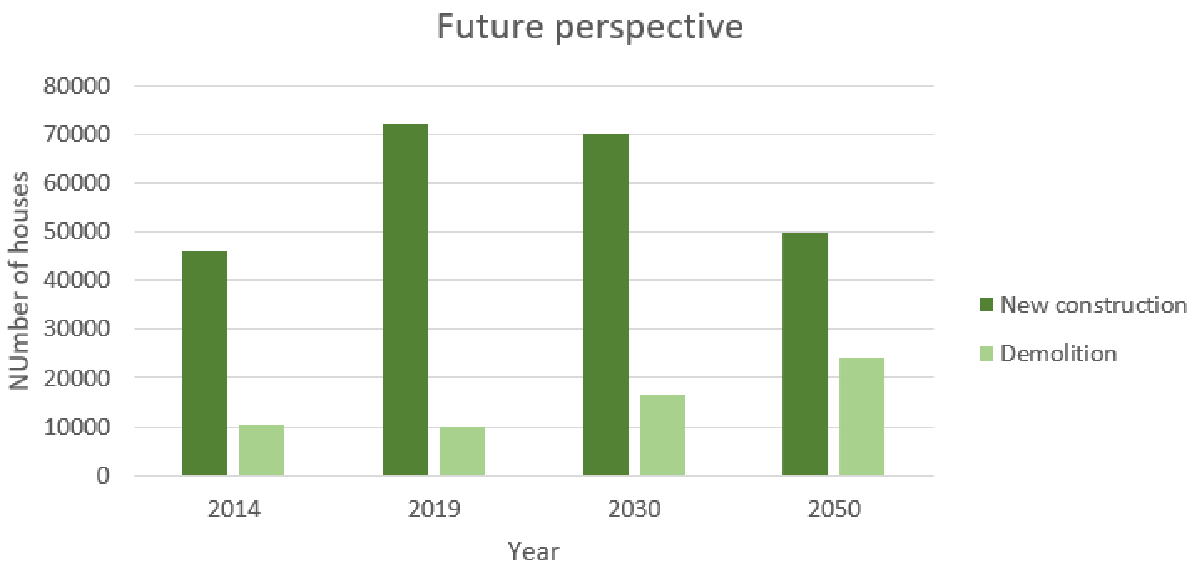


Figure 0.5: Future perspective of housing (EIB & Metabolic , 2022)

From the numbers it can be seen that there will be more new construction as demolition. Therefore, if all materials could be reused from demolition there will still not be enough to supply the demand. From the graph can also be derived that the new construction of houses will be high until 2030. The demolition of houses will only rise slightly until this year.

A1.2. Non-Residential Construction (NRC)

A non-residential construction is specified as a construction which is not inhabited. Examples of buildings which fall under NRC are office buildings and shops. In this chapter the playing field of NRC is examined.

Current Stock

The current stock means the current number of buildings, so the quantity at this moment. The current amount of NRC buildings can be categorised based on two properties: the date of construction and the category of NRC. In the following figure the NRC building stock is categorised on date of construction and category.

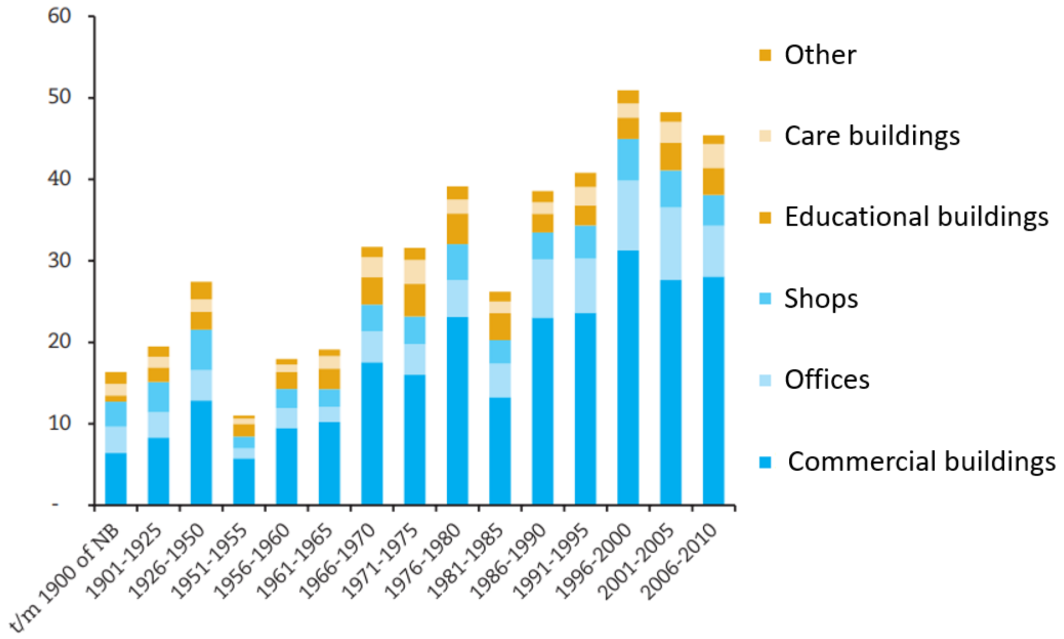


Figure 0.6: Current stock in 1,000,000 m² per type and construction date (EIB, 2015)

As can be seen in the figure the bulk of the buildings is a commercial building. The second most common category is office buildings. When looking at the number of buildings over the different dates of construction it can be seen that the majority of the buildings is built after 1966. Commercial buildings are quite a broad term and therefore this term is divided into different categories as can be seen in the following figure:

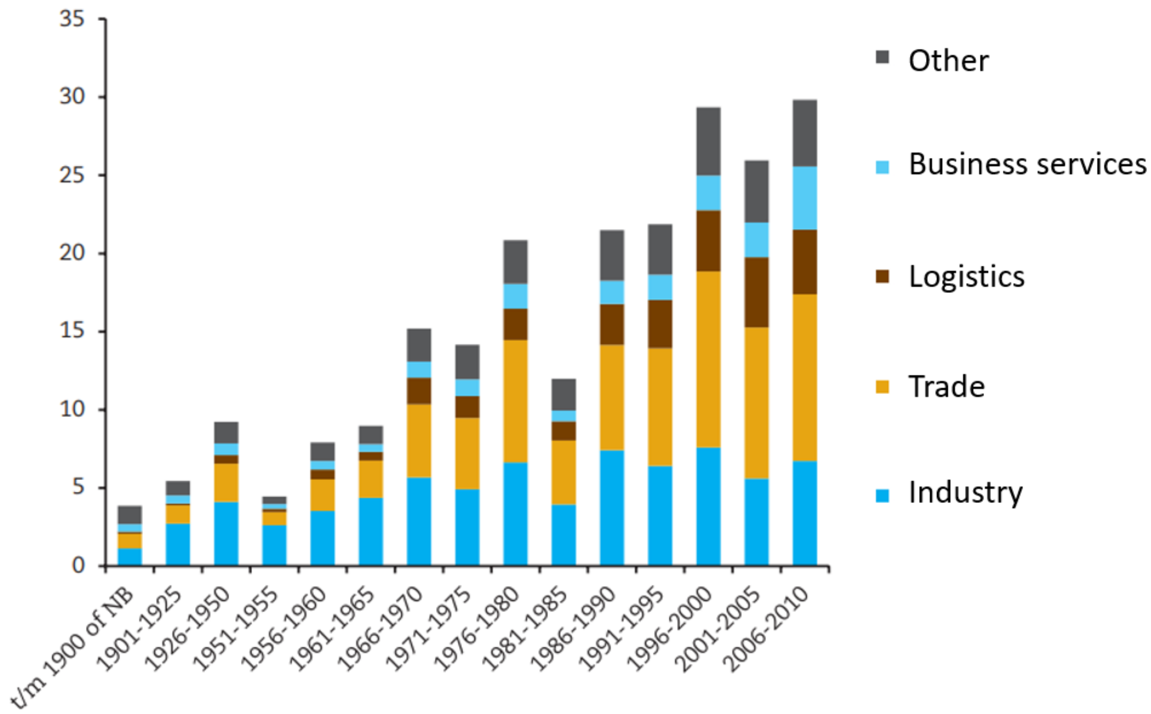


Figure 0.7: Current stock in 1,000,000 m² commercial spaces (EIB, 2015)

From this figure it can be derived that the majority of the commercial buildings is for industry purposes and for trading purposes.

Demolition Numbers

Next the demolition numbers are elaborated on. These numbers are the most interesting ones because these give an indication of the materials which are becoming available. In the next figure the total area of NRC buildings which is demolished in a certain year can be seen.

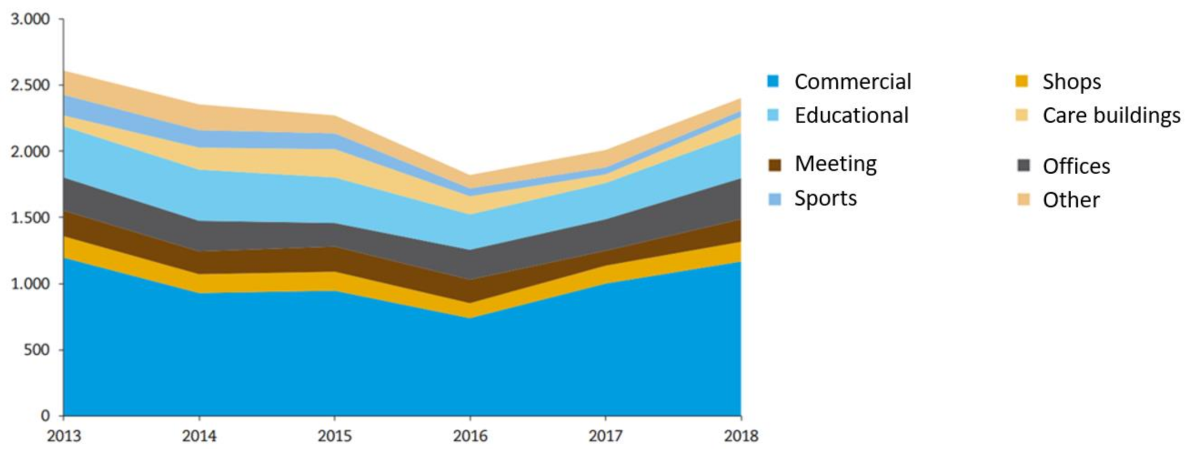


Figure 0.8: Total area NRC demolished per year in 1000 m² (EIB, 2019)

From this figure can be concluded that the amount of NRC buildings which are being demolished are rising since 2016. The majority of the buildings which are demolished are industry buildings. Office buildings and educational buildings also take up big portions. The division over the different categories can also be shown in a circular diagram:

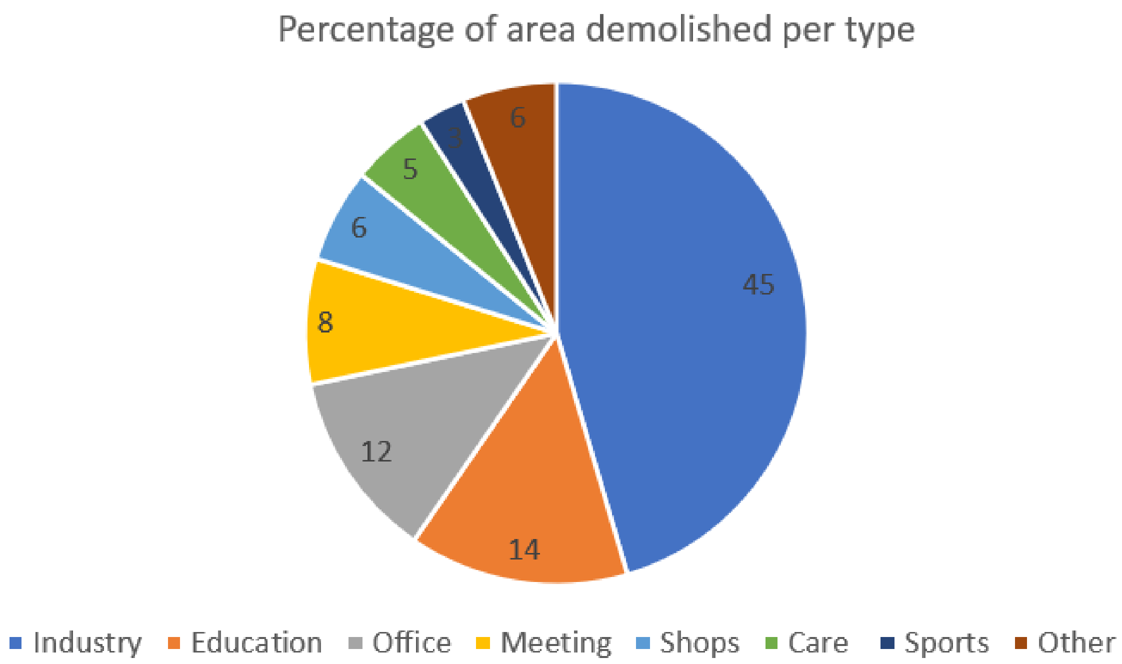


Figure 0.9: Percentage demolished per NRC type (EIB, 2019)

Next it would be interesting to see the sort of NRC and the date of construction compared to the demolition numbers. In the next table the demolition numbers for different categories of NRC over different dates of construction are given.

Table 0.3: Demolition numbers per NRC type and construction date (EIB ; Metabolic ; SGS Search, 2020)

	< 1945	1945-1970	1971-2000	> 2000	Total
Commercial	140	420	570	140	1270
Office	30	140	260	60	490
Educational	10	80	80	20	190
Care	0	20	140	80	240
Shops	50	150	110	20	330
Other	260	1190	1120	24	2910
Total	490	2000	2280	660	5430

From the table can be seen that the demolished buildings are mostly built between 1971 and 2000 and are predominantly commercial buildings. The total amount of NRC (so all categories combined) can also be given over the different dates of construction:

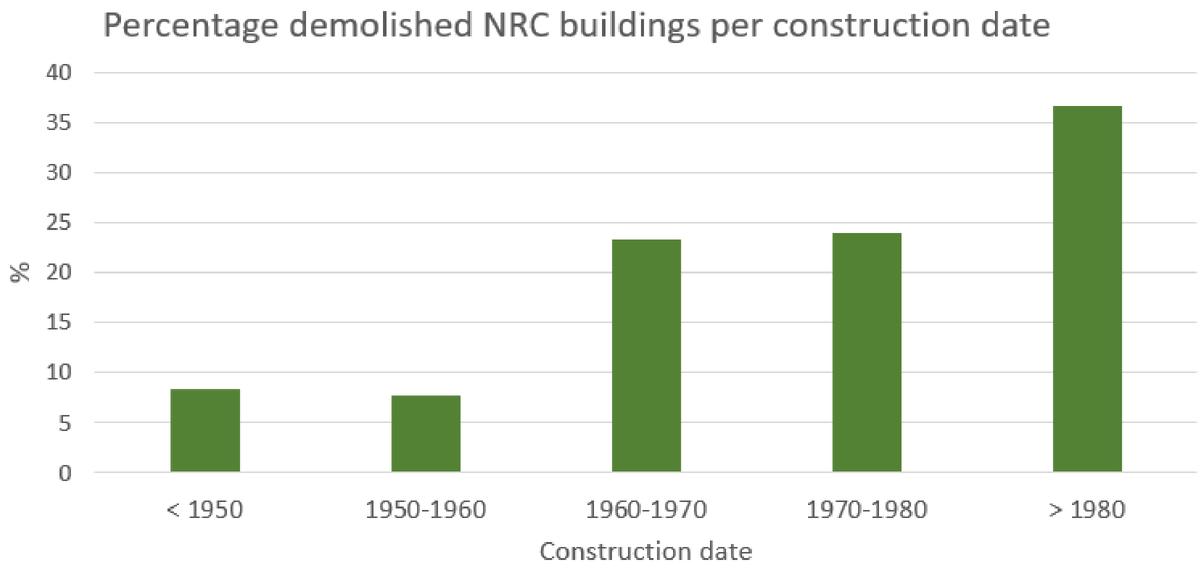


Figure 0.10: Percentage NRC demolished per construction date (EIB, 2019)

From this graph it can be derived that 60% of the demolished NRC buildings is built after 1970. The materials in these buildings can be estimated using a table in annex E of the EIB report 'Materiaalstromen, milieu-impact en energieverbruik in de woning- en utiliteitsbouw' (EIB ; Metabolic ; SGS Search, 2020). Using this table, it can be concluded that the predominant materials coming from these buildings are concrete and steel.

Future Perspective

The future perspective is based on the new construction and demolition estimates for the years 2030 and 2050. In these years the Netherlands want to use respectively 50% and 100% less primary resources as already mentioned in the problem definition. Therefore, the reuse of materials needs to be significant in this year.

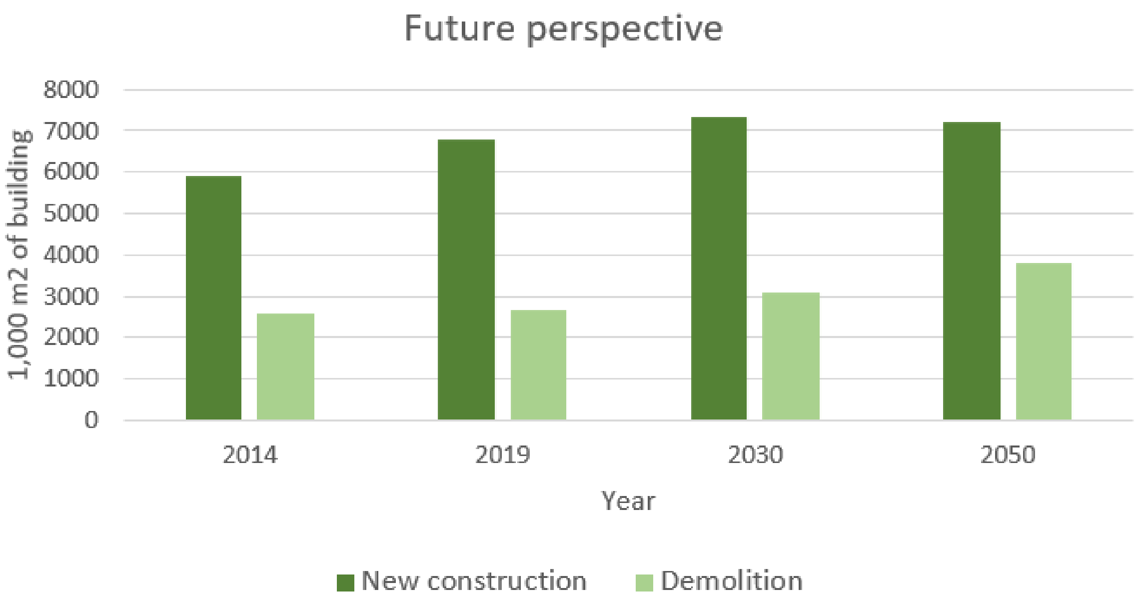


Figure 0.11: Future perspective NRC (EIB & Metabolic , 2022)

In the above shown graph can be seen that there will be more new construction as demolition. Therefore, if all materials could be reused from demolition there will still not be enough to supply the demand. The demolition will rise slightly upon the year 2050. The graph regarding the new construction flattens.

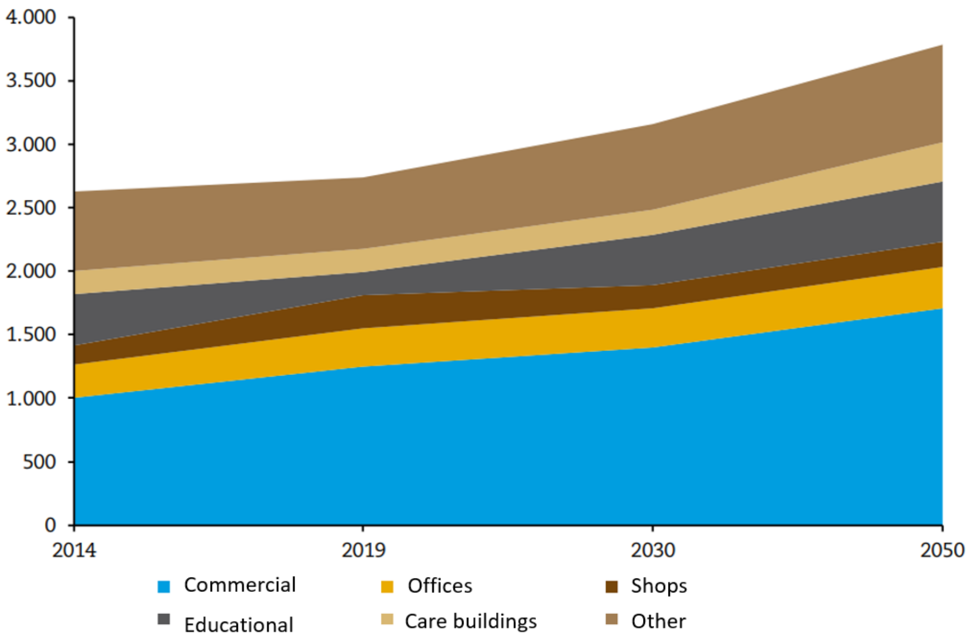


Figure 0.12: Demolition per 1000 m^2 of building per category (EIB, 2019)

As is shown in figure 0.12 the demolition of NRC is expected to stay considerable in the coming years and will even rise until the year 2050.

A1.3. Conclusions and Demarcation

Different conclusions can be drawn from the previous mentioned results. The first conclusion which can be drawn based on the current stock is that there are more HC buildings compared to NRC buildings. When comparing the demolition numbers, it can be seen that the demolition of HC is getting less over the years whereas the demolition of NRC is rising. The total area of NRC which is being demolished is also bigger compared to the area of HC which is demolished. Looking at the date of construction of the demolished buildings, it can be seen that the demolished HC buildings are a lot older compared to the demolished NRC buildings. The material usage in the HC buildings differs a lot from the materials used in NRC. In NRC mainly concrete and steel are used whereas mainly brick and wood are used in HC. The future perspective is the only aspect which is quite similar between the two building types. In both cases the newbuild is expected to be higher than the demolition.

Looking at all graphs and numbers a recommendation can be given for the building type and age which is most promising. The demolished HC buildings are a lot older than the NRC buildings. Therefore, it can be expected that the materials in NRC buildings are in a better shape. Also, the materials used in NRC are more desirable for new construction. Therefore, it is advised to focus on NRC buildings. The main two NRC buildings are offices and commercial buildings. In office buildings a lot of concrete is used, in commercial buildings mainly steel is used. Because concrete is the most needed material in new construction it is most efficient to focus on the demolition of office buildings.

On the demand side of the spectrum, the new construction, a different trend is seen. In the coming year a lot of houses need to be built. Whereas the amount of new construction of NRC buildings is quite flattened in the coming years. Therefore, it would be interesting to look at the new construction of houses on the demand side.

In the following table the conclusion of part A1 is also shown by the two red circles in the graph. In the new construction side it can be obtained that a lot of houses need to be build. The materials which are coming available from demolition are mainly coming from NRC and in particular office buildings.

In the coming two parts, part A2 and A3, a more in depth study is done into the office building stock (supply) and the new houses (demand).

	New construction			Demolition		
	2019	**2030**	**2050**	**2019**	**2030**	**2050**
Residential (amount)	**71.500**	**70.000**	**49.300**	**10.800**	**17.000**	**23.800**
Single family	43.600	33.300	23.500	5.100	8.500	13.700
Apartments	27.900	36.700	25.800	5.700	8.500	10.100
Non-Residential (1000 m2)	**6.710**	**7.380**	**7.240**	**2.740**	**3.160**	**3.780**
Commercial	4.730	4.220	4.470	1.250	1.400	1.700
Office	200	430	460	300	310	330
Care	230	460	530	180	200	310
Educational	240	580	440	190	400	470
Shops	200	210	210	260	180	200
Other	1.110	1.480	1.130	560	670	770

Figure 0.13: Overview of construction and demolition (EIB & Metabolic , 2022)

A2: Office building stock (supply)

In the previous part it was found that office buildings are the most promising building category on the supply side. In this chapter the available materials from office buildings in the Dutch building sector are examined. The available materials are estimated based on three main aspects: current stock, demolition numbers and future perspective. The inventory of materials is done from course to fine; First the Dutch building sector as a whole was examined; an elaborate explanation of this research can be read in appendix A1. Based on this prior research a demarcation was made. In this chapter the available materials coming from office buildings are studied. Based on the results of this chapter a demarcation on office buildings with a construction date between 1970 and 1990 was made for this master thesis.

A2.1. Current stock

By looking at the current building stock one can get a good impression of the current amount of materials. Office buildings represent a big portion of the total building volume in the Netherlands (see appendix A1). In the Netherlands there is approximately 47 million square meters of office building present in 2020, as can be seen in figure 0.14.

	2012 m^2	2014	2016	2018	2020
Groningen	1.250.500	1.205.000	1.164.000	1.155.000	1.148.500
Friesland	1.012.000	1.012.000	981.000	930.000	919.000
Drenthe	672.000	680.500	647.000	632.000	620.500
Overijssel	2.494.000	2.538.500	2.501.000	2.471.000	2.462.000
Gelderland	4.219.500	4.165.000	3.931.000	3.830.500	3.790.000
Utrecht	6.226.000	6.129.000	6.047.000	5.929.500	5.874.500
Flevoland	929.500	929.500	913.500	867.500	842.000
Noord-Holland	11.704.500	11.555.500	11.055.500	11.094.500	11.034.500
Zuid-Holland	13.960.500	13.831.500	13.316.000	12.717.000	12.531.000
Zeeland	476.500	476.500	471.500	490.000	487.000
Noord-Brabant	5.648.500	5.594.500	5.523.000	5.450.500	5.505.500
Limburg	2.072.500	2.115.500	2.096.500	2.091.500	2.095.500
Nederland	50.666.000	50.233.000	48.647.000	47.659.000	47.310.000

Figure 0.14: Office building stock per province (NVM Business , 2021)

From the figure can be derived that the total amount of office buildings is decreasing over time. It can be seen that the total area of office buildings is shrinking with 419,500 m^2 per year on average, for the last 8 years. An interesting and import aspect in the building stock is the construction date. Because the construction date can tell a lot about the construction method and the material usage. In figure 0.15 the construction date versus the amount of office buildings can be seen.

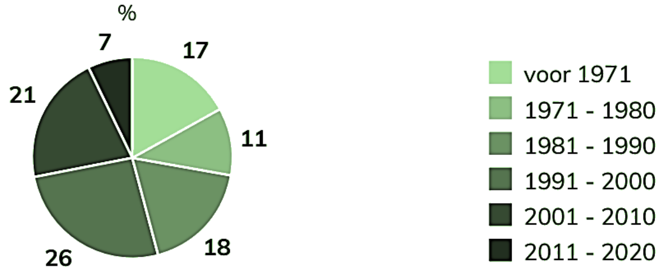


Figure 0.15: Office stock per construction date0 (NVM Business , 2021)

Using figure 0.15 it can be derived that office buildings with a construction date between 1970 and 1990 represent 29% of the total building stock. By combining the information of figure B-1 and B-2 it can be concluded that the scope of this thesis represents a building stock of approximately 0.29*47,310,000 = 13,719,900 m^2.

A2.2. Demolition numbers

As previously mentioned, the amount of office buildings is shrinking. This decreasing amount can be traced by two main processes: demolition and repurposing. The goal of this part is to find out which, and the amount of, materials which are available for a second life. Therefore, only the demolition numbers are interesting. The demolition numbers give the best possible insight into available materials. In figure 0.16 the extraction of office buildings from the stock is given.

In this figure it can be seen that mainly office buildings with construction dates between 1970 and 1990 are being demolished. From the total amount of demolished office buildings in the period between 2011 and 2020, 67% was built between 1970 and 1990 (NVM Business , 2021). According to EIB et al. (2020) 133,000 m^2 of office building with a construction date between 1971 and 2000 was demolished in 2014. In a report written by EIB et al. (2020) the material mass balance over the year 2014 is made. In this balance it can be seen that concrete has the biggest contribution to the whole. A big portion of this outgoing material flow can be retraced to the demolition of office buildings.

		herbestemming			
	sloop %	wonen	hotel	onderwijs	overig
Naar locatietype					
Centrum	23	35	31	32	35
Woonwijk	27	32	19	14	19
Bedrijventerrein	15	5	7	-	14
Kantorenwijk	33	27	43	54	28
Buitengebied	2	1	-	-	4
Naar bouwperiode					
voor 1950	9	7	11	10	17
1950-1959	4	1	1	-	5
1960-1969	15	14	8	8	1
1970-1979	33	26	15	11	22
1980-1989	34	28	19	29	14
1990-1999	4	17	31	42	15
2000-2009	1	7	14	-	25
2010 en later	-	-	1	-	1
Naar gebouwgrootte					
500-999	-	1	-	1	3
1000-2499	10	14	8	6	25
2500-4999	23	27	17	21	33
5000-9999	28	25	39	42	22
10000 en meer	39	33	36	30	17
Naar eigendom					
Huur	48	78	91	63	57
Koop	52	22	9	37	43

Figure 0.16: Demolition and repurposing of office buildings between 2011 and 2020 (NVM Business , 2021)

A2.3. Future perspective

The future is always unsure, but expectations can be made based on prior knowledge. It is for example possible to take a look at the office stock of the last years and see if a trend can be observed. In figure 0.17 the office building stock of the last ten years is shown. From this figure it can be concluded that a negative trend is present for the office building stock. The building stock is decreasing for the last ten years in a row. Based on this result it can be concluded that the office building stock will be lowering in the coming years as well. Therefore, it can be concluded that a lot of materials are coming available in the coming years.

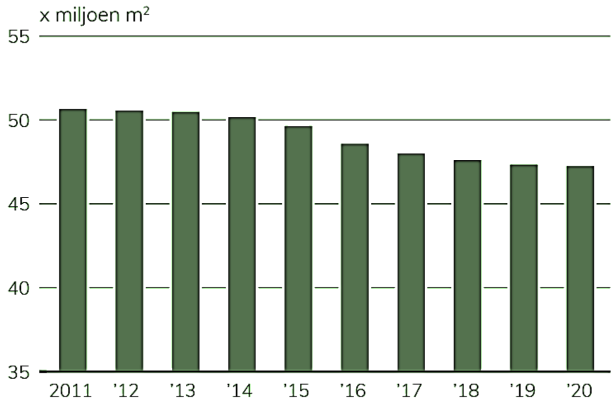


Figure 0.17: Office building stock per year (NVM Business , 2021)

Besides drawing trends it is also possible to look at prospects made by others. EIB et al. (2020) made a prediction for the year 2030. They predicted that 350,000 m^2 of office building is being demolished in 2030. This is more than double the amount demolished in 2014. Newspapers also pay attention to the office building stock. On January the 1st 2021, NOS headlined: “Big employers are cancelling office space after Corona.” (Kamphuis, 2021). In the article NOS mentions that they have spoken to the 25 biggest employers in the Netherlands. More than half of these employers indicated that they are in need of less office space because of employees working from home. The different companies, mentioned in the article, declare that they need 10 to 50% less office space after Corona.

From these different inputs it is possible to draw a conclusion regarding the future perspective of office space. All of the different inputs expect that office space will be decreasing in the coming years. Therefore, it is likely that more office buildings will get demolished. This will have as a result that more materials become available for possible reuse which shows the importance of this thesis once more.

A2.4. Building typologies

Next it is interesting to take a closer look into the materials and building techniques used to construct these office buildings with. This research is done based on a literature study. Throughout the years different structural methods are used, therefore literature dating back to this specific time period was consulted for this research.

The starting point of the research is the scope of this thesis. The scope of this thesis is made on buildings, office buildings in particular. Therefore, the research was started with buildings. According to Oosterhoff (2013) there are two types of buildings: low buildings and storey buildings. Low buildings mainly consist of hall construction; Office buildings fall in the other category, the storey buildings. Next it is interesting to see what kind of structural principals are used. In the book ‘Kracht en Vorm’ (Oosterhoff, 2013) two types of structural principles are mentioned: a wall structure and a column structure. The first structural principal is mainly used in residential construction. The second principle is the one used in office buildings and therefore we take a closer look into this principle. In a column structure the vertical load is transferred via different columns supporting the floors. The stability in these constructions is usually obtained by elevator shafts, stairs, or a core (Oosterhoff, 1990). A focus is made on office buildings dating between 1970 and 1990. During the 1970's and 1980's there was a recession. Due to this recession the amount of rented office buildings increased. In this period companies did not want to have an own building which represents their company, but they wanted a cheap office building with an open floor plan (Jong & Gunst, 1989). According to Voordt et al. (2007) a division needs to be made between two time periods namely the beginning of the seventies and the late seventies plus eighties. This division needs to be made because different structural principles are used in these different periods.

Early seventies: Point Supported Structures

In the early seventies the main structural principle used in office buildings was a point supported structure (Voordt et al., 2007). Due to the point supported structure it was favourable to have a square pattern. This square pattern without supporting beams results in weak floors in bending. Usual pattern sizes in these types of constructions are 5.4 or 7.2m (Voordt et al., 2007). This is interesting when one takes into consideration that 5.4 m is a common dimension in housing. According to Voordt et al. (2007) there are two main point supported structures used for office buildings in the early seventies:

- Point supported structure with a cantilever (figure 0.18)
- Point supported structure with an edge beam at the façade (figure 0.18)

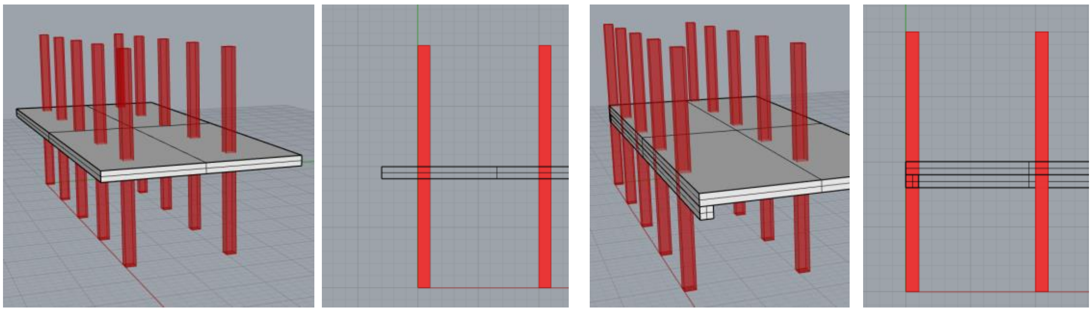


Figure 0.18: Point supported structure with a cantilever (left) and with an edge beam (right) (own figure)

The main difference in these two types is located at the edges of the floors. In the left case in figure 0.18 the floor has a cantilever over the last row of columns, in the right case there is a beam located on the edge of the floor in between the columns. The middle area in between the different columns is similar for both systems. Both systems have a two way spanning floor. This means that the floors are transferring loads in two directions towards the nearest columns. Because no beams are used in these systems it is possible to get high concentrated loads. These concentrated loads can cause punching shear, which is the main failure mechanism for point supported structures (Neenu, n.d.).

Late seventies and eighties: Line Supported Structures

In the late seventies and eighties a different structural principle was used. During this period the majority of the building had a line supported structure (Voordt, 2017). This means that the floors are not point supported by columns but beams are used. Usually these beams span perpendicular to the long side of the façade. By using beams it is possible to obtain bigger spans compared to the previously mentioned point supported structures. During the late seventies and eighties three main line supported structures were used:

- A point supported floor with cassette floor (see figure 0.19)
- A line supported structure with edge- and length beams combined with a plank floor (see figure 0.20)
- A line supported floor with a throughed suspended or hollow floor (see figure 0.21)

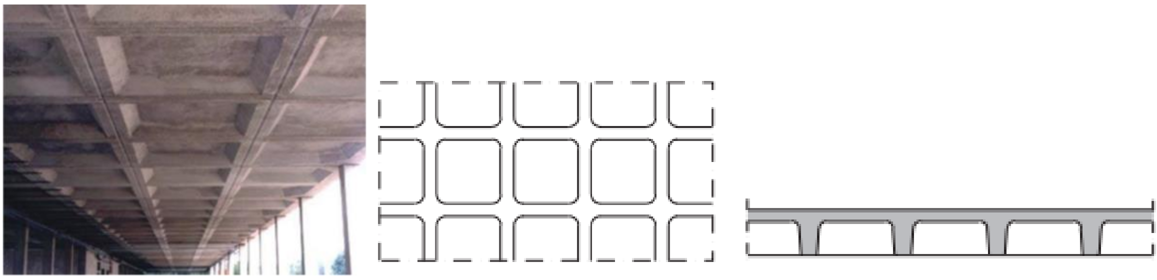


Figure 0.19: Cassette floor (Vree, Cassettevloer, n.d.) (Kamerling & Kamerling, 2004)

As can be seen in the figure the cassette floor has an interesting underside. The underside of a cassette floor has a rib shaped pattern which is obtained by placing small boxes (ca. 1 x 1 m) in the formwork during casting. In the BetonLexicon (2021) a cassette floor is specified as “an in situ floor with a rib pattern in two directions on the underside of the floor”. This special pattern is used as a weight saving measure (Kamerling & Kamerling, 2004). The lines of a cassette floor act as beams and therefore it is classified as a line supported structure. Because these ‘beams’ are spanning in two directions the floor is strong in transferring forces in two directions.

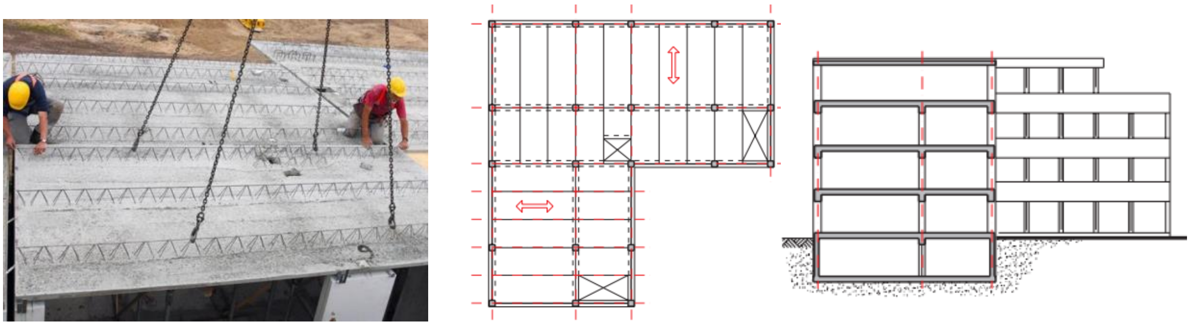


Figure 0.20: Plank floor (Olbecon, n.d.) (Kamerling & Kamerling, 2004)

A different option is a line supported structure with edge- and length beams combined with a plank floor. In this this option there are two types of beams: the edge beams and the length beams. The first beams are placed on the edges of the floors so at the facades of the building. The second beams are spanning the columns in the longitudinal direction of the building. These two different beam types and their direction can also be seen in the above shown figure. On top of these beams flat slab floors are placed. A flat slab floor consists out of two parts: a prefab bottom part with reinforcement sticking out of it and an in situ (compression) layer which is poured on top (Havebo Groep, n.d.). The in situ part is transported to the site where it is placed on the two beam types whereafter the top layer is poured on top of it during this process the floor needs to be supported.

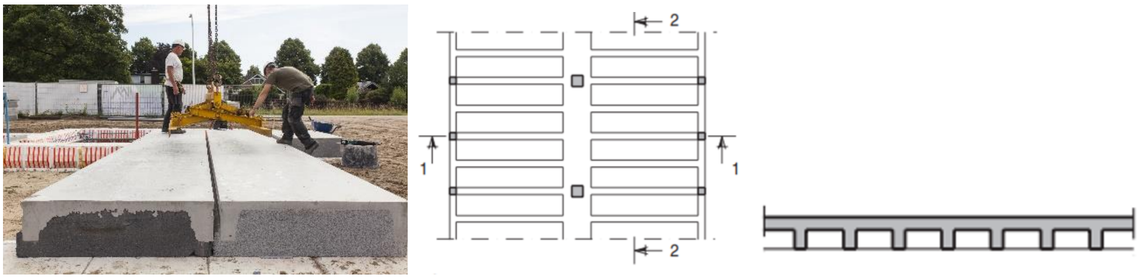


Figure 0.21: Troughed supported floor (Bruil, n.d.) (Kamerling & Kamerling, 2004)

A third option is a line supported structure with a troughed supported floor or a hollow core floor. In this structural scheme the floor is spanning in one direction. The underside of the throughed floor has line shaped thickenings which look and act as beams. This shape is used as a weight saving measure, which is similar to the cassette floor (Kamerling & Kamerling, 2004). According to the BetonLexicon (2019) a throughed supported floor is “a floor made out of prefab self-supporting elements with a flipped U shape which are connected on site using mortar joints”. This shape can also be recognised in the above shown figure. One needs to pay special attention to this floor type. This floor type is usually used as ground floors. In this master thesis the scope is made on storey floors and therefore this floor type can be left out.

During this time period it was possible that floors were pre- or post-tensioned (Voordt, 2017). This is an important aspect when one considers reuse and therefore this aspect needs to be considered.

The different systems used are also summarised in the following graph:

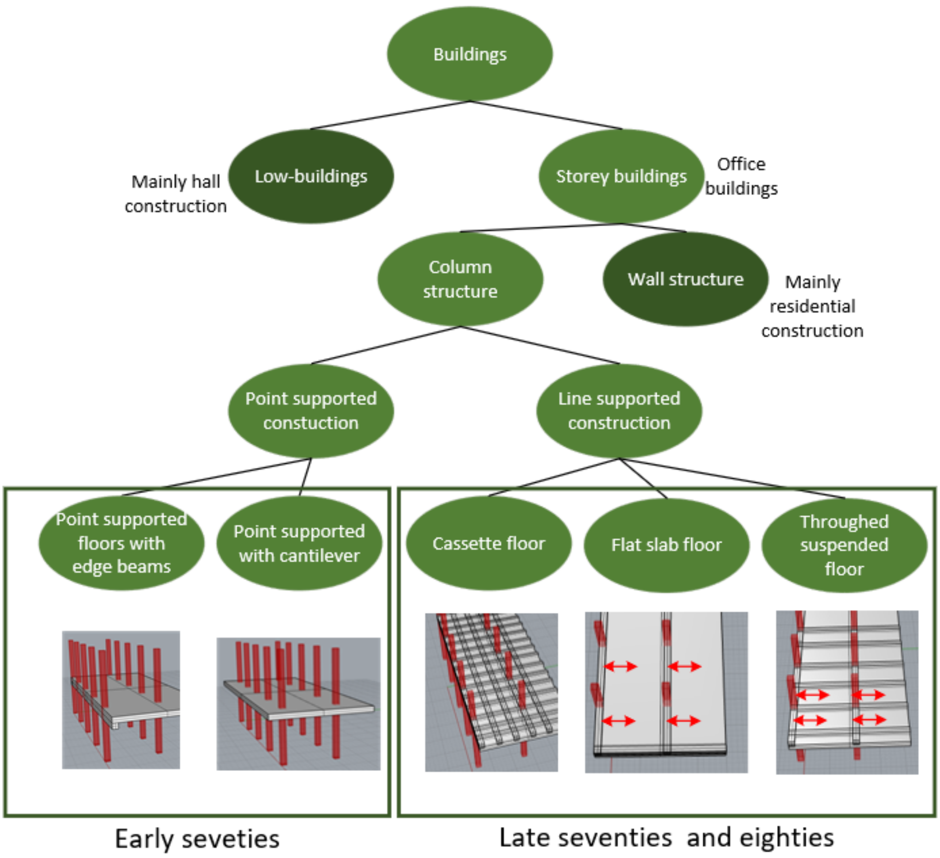


Figure 0.22: Overview of floor systems in the seventies and eighties (own figure)

A2.5. Material usage

Office buildings are storey buildings as can be read in part A2.4. Storey buildings (in the seventies and eighties) have a concrete skeleton according to Oosterhoff (1990) . In the book 'Kracht en Vorm' written by Oosterhoff in 1990 it is specified that concrete structures are usually cast in situ.

This statement is also supported by the handbook 'Prefab Beton' (Bennenk p. i., 2008). In this book the seventies and eighties are described as dark years for the prefab concrete industry. Bennenk (2008) describes: "More variation in buildings was desired in the seventies. Therefore, the prefab concrete industry had a dip in the seventies and eighties". In another book of the 'Prefab Beton' series the rise of hollow core slabs is discussed. According to Bennenk & Jongeneelen (2008) the use of hollow core slabs for small spans is rising in the 1980's.

So in this period a lot of concrete floors were used. However, there are problems with some concrete floors of certain manufacturers. In the period between 1965 and 1981 the manufacturers Kwaaitaal and Manta used calcium chloride in their concrete mixture (Perfectkeur, n.d.). They used this substance because they wanted to make sure that the concrete hardens faster. The problem with this material is that it causes concrete rot which makes the floors unsafe. Therefore, if these floors are found in buildings one needs to pay special attention to them.

Not for all column structures concrete was the main material to use. When the buildings rise more than ten storeys, the weight of concrete can add up to such high loads that concrete is not a suitable material anymore. Therefore, it is common that for buildings with more than ten storeys steel is used for the structure (Jong & Gunst, 1989).

A2.6. Floor type focus

In part A3 the element focus is discussed. Based on this part the focus is made on floor elements. As is specified in the previous paragraphs, the following flooring types are available in the office buildings with construction dates between 1970 and 1990:

- Monolithic floors
- Cassette floors
- Hollow core floors

These floors are more elaborately discussed in chapter 3 of the main report.

A3. New-build homes (demand)

In part A1 the demarcation was made on residentials buildings/houses on the new construction side (demand side). This demarcation was based on the current stock, the demolition numbers, and the future perspective for both residential and non-residential construction. In this part a closer look is taken at the new construction of houses to see which houses are the most promising to apply reused elements in. The part starts by elaborating on the future perspective of the housing market. Thereafter different housing types are treated and finally a demarcation is made on one specific housing type.

A3.1. Future perspective

The future perspective of the housing market is further elaborated on in this chapter. In the previously done research in part A1, it was found that the new construction of houses is significant in the coming years. This statement can also be confirmed when looking at different newspapers and news shows. An example is the statement done by the minister of housing (Hugo de Jonge) on the 11th of march. He stated that "there need to be 100,000 homes build every year until 2030" (Jonge, 2022). From this statement it can be concluded that a significant amount of material is needed in the coming years.

Another possible way of estimating the future of the housing market is by looking back at the housing construction of the past years. In figure 0.23 the number of new houses over the past ten years is given. In this graph somewhat of a trend can be seen from the year 2014 onwards. From 2014 to 2019 a strong rise in the amount of newly constructed houses can be seen. This strong rise flattens somewhat in 2020 but this can also be a result of the COVID-crisis. So based on the previous years it can be assumed that the amount of newly constructed houses will rise.

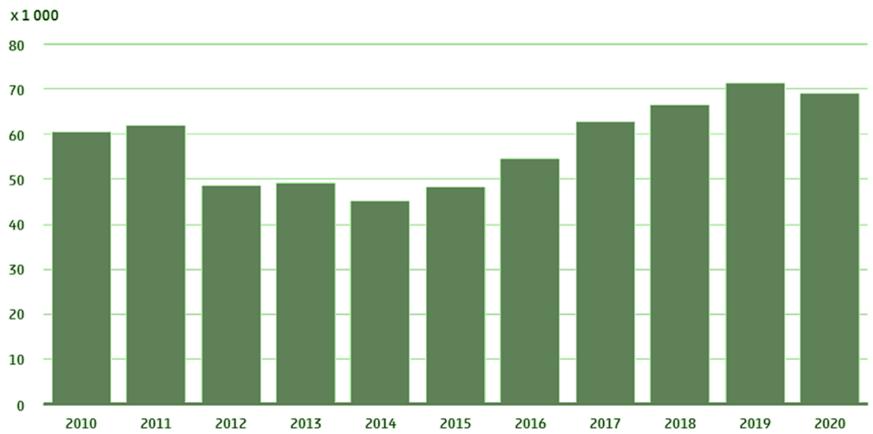


Figure 0.23: New homes over the past 10 years (CBS, 2021)

Besides the actual amount of constructed houses it is interesting to look at the amount of building permits. Building permits can be seen as a sort of forecast for the coming years. According to Sante (2021) there is usually 1.5 years difference between the building permit and the actual completion date. In figure 0.24 the amount of building permits over the last 12 years is shown. As can be seen in the graph, the building permits for the year 2021 are on a high level, even the highest level of the past 10 years. As previously mentioned there is 1.5 years difference between a permit and the final completion. So the building permits of 2021 state something about the construction for 2022 until 2024. Based on the permits, it can be concluded that a lot of houses are constructed in the coming years.

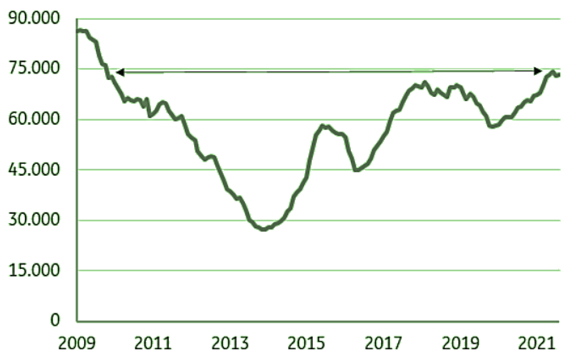


Figure 0.24: Building permits for new houses per year (Sante, 2021)

This expectation based on the amount of building permits is also supported by a forecast made by Bouwkennis (2021). This forecast was based on the economic projections made by CPB, ING, DNB, and Rabobank, which are all organisations highly involved in market prognosis. According to Bouwkennis' forecast the amount of new homes will rise in the coming years. They expect 71,500 produced houses for 2021, 72,500 houses in 2022, and around 74,500 in 2023. There are also prognosis which look further into the future. The Primos-prognosis (2020) expects that 1.24 million houses are constructed in the period between 2020 and 2035.

The last aspect which is of great importance is the vision of the Dutch government. The Dutch government presents their budget plan on a certain day, called 'Prinsjesdag'. The last 'Prinsjesdag' was on December 21st, 2021. A statement was made considering the new construction of houses in the budget plan presented in 2021. This statement stated that the Netherlands has a problem concerning living spaces. Currently there are too little houses and therefore the government made a budget of 1 billion euros to stimulate housing construction (Rijksoverheid, 2021). Therefore, it is most likely that the housing construction will rise.

A3.2. Housing types

In part A1 it was determined that the housing construction is rising in the coming years. For this thesis it is advised to make a demarcation between the different housing types. In table 0.1 the different housing types are shown. The main division is made between single-family houses and multi-family houses (apartments). In 2021 there were 7,966,331 houses in total of which 5,095,799 single-family and 2,870,532 multi-family (CBS, 2021). This research is focussed on the reuse of materials in new construction therefore it is more interesting to look at the new construction instead of the current number of houses.

The goal of the thesis is to make an impact, both on the amount of material and on the environment. Therefore the demarcation on a certain housing type is based on these two aspects.

The first aspect which is treated is the number of houses. As was previously mentioned the number of new houses is high in the coming years. The total amount of constructed houses in 2019 is shown in figure 0.25. In this figure also the amount per type of house is shown.

	Amount of residences	**Total area (1000 m2)**
Single family		9.500
- Detached	10.200	3.300
- Semi -detached	7.600	1.600
- Serial	25.800	4.600
Multi family/ Apartments	27.900	2.100
Total	**71.500**	**11.600**

Figure 0.25: New construction of houses in 2019 (EIB & Metabolic , 2022)

In the figure can be seen that the new construction of single-family houses is bigger than the construction of apartments, based both on quantity and total area. Therefore it is more interesting to focus on single-family houses. The majority of these single family houses is a serial house. So, based on the quantity of new-built houses it is advised to make a demarcation on serial houses.

The next aspect to consider is the environmental impact. In figure 0.26 the environmental impact per different housing type is stated. In this figure one can see that serial houses represent the highest MKI value of the different construction types. So based on the MKI value it is advisable to apply reused elements in serial houses.

	MKI 2019 (mil. Euro)
Single family	
- Detached	105
- Semi -detached	55
- Serial	145
Multi family/ Apartments	60

Figure 0.26: New construction of houses in 2019 (EIB & Metabolic , 2022)

A3.3. Conclusion and demarcation

In the previous paragraphs the future perspective of the housing market and the distinction between the different housing types were explained. From the future perspective sketched in A3.1. it is possible to draw the conclusion that the market for the construction of new houses will rise in the coming years. Based on the amount of new constructed housed per housing type and the MKI per housing type (as sketched in A3.2.), it can be concluded that serial houses are the most beneficial to consider for implementing reused materials. Therefore the demarcation on serial houses is made on the ‘demand’ side.

A4: Element focus

Previously the focus is made on elements coming from office buildings with a construction date between 1970 and 1990. From these elements it is chosen to only take into consideration structural elements. As mentioned in part A2, most office buildings have a column structure as a typology. The diversity of elements in a column structure is quite small. A column structure consists of the following load bearing elements (Amerongen et al., 2004):

- Columns
- Beams (if line supported)
- Floors

It is advisable to focus on one of these elements because the three different elements all have their own properties. The main objective of this thesis is to make an impact on the material usage in buildings, both in a volumetric as in an environmental way.

An interview was held with the market intelligence manager of Heidelberg Cement Group. Heidelberg Cement Group is one of the world's largest cement suppliers who operates in over 50 countries and has more than 51000 employees. In this interview a discussion was held about the volumes in the cement industry. According to predictions made by Heidelberg almost 50% of the ready mixed cement is used for floors. Columns and beams represent such small volumes that they are not included in the predictions. This assumption is also supported by the 'Betonmortelonderzoek' (2017), see the following figure:

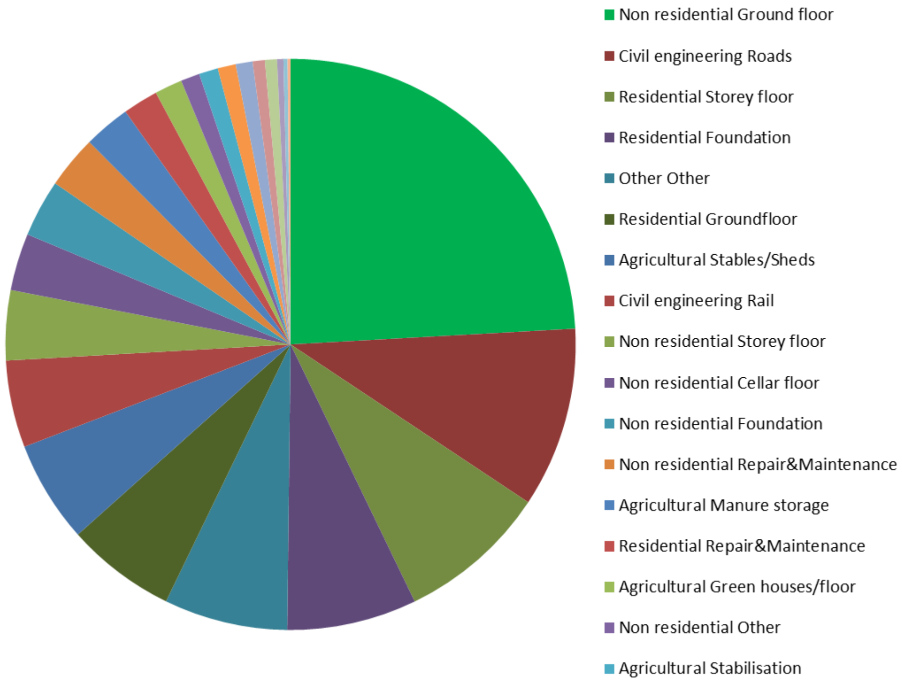


Figure 0.27: Volumes of concrete per element type (Betonmortelonderzoek 2017)

According to the figure a big portion is taken up by floors. Besides, it can be seen that beams and columns are not included in the figure because they represent too small volumes. They are included in the category 'other'. On the demand side this thesis focusses on residential storey floors. In the figure it can be seen that this portion takes up approximately 10% of the total cement industry.

Another interesting research to take into consideration, when choosing the element focus, is the EIB report about material flows (EIB & Metabolic , 2022). In this report both the mass as the MKI of different elements in the building sector (both residential and non-residential) are compared. In figure 0.28 this comparison is shown.

	Mass 2014 %	MKI 2014 %	Mass 2019 %	MKI 2019 %
Floors	34	18	28	11
Exterior walls	13	3	10	3
Ground floors	11	4	19	3
Roofs	7	7	4	3
Pile foundations	6	4	8	2
Interior walls	5	2	7	2
Exterior wall cladding	5	9	7	6
Foundations	5	3	4	3
Floor finishes	4	8	4	4
Roof finishes	3	14	3	7
Load bearing structure	3	4	1	1

Figure 0.28: Mass and environmental impact per element type (EIB & Metabolic , 2022) (adjusted)

From the figure it can be concluded that floors represent the biggest mass and the biggest MKI value. In the figure columns and beams are not mentioned separately but are treated together in the aspect load-bearing structure. This aspect represents a substantial mass of material and the MKI is also noteworthy. However, compared to the floors the values are small.

The 1-on-1 reuse as presented in this report is similar to the use of prefab elements because the elements are already fabricated and are not produced on site. It is worthwhile to take a closer look at the contractor's perspective. Cobouw, a construction journal, did research into the contractor's perspective toward prefab construction. According to this research 51% of the contractors thinks that prefab construction is vital to deal with the current housing shortages (Platschorre, 2021). During this research the contractors were also asked for which elements they think prefab construction can be applied. In this research 59% of the contractors mentioned floor elements as an element which can be applied prefabricated (Platschorre, 2021).

From the abovementioned paragraphs it can be concluded that the most interesting elements to focus on are floor elements. These elements represent a big volume of material and their contribution to the total MKI value is also big. Thirdly, it is the element of which contractors think there are big opportunities for. Therefore, the element focus in this thesis lays on floor elements.

B. Dutch Building Decree (2012)

The Dutch Building Decree (Bouwbesluit 2012) covers all rules concerning new constructions, renovations and transformations of buildings. The decree consists out of three different quality levels: new construction, existing construction, and rights acquired (Rijksdienst voor Ondernemend Nederland, 2014). The last mentioned level was added to the building decree in 2012. This quality level was introduced for the transformation of buildings (Hegeman, 2015). Before 2012 there were no rules which were applicable to transformations and therefore transformations were treated on new construction level. The reuse of elements does not have a place in the Dutch Building Decree, it is sort of in-between the three different parts. It is in a similar situation as transformations were in the period before 2012. There is no complete new construction because the elements have had a previous life in another building. But the reuse of elements cannot be categorised as a renovation or transformation either. Because, a different building is constructed using the elements, possibly even at another location. Currently several parties/initiatives (NEN, CB23 etc.) are busy with setting up new rules specifically applicable to reuse, however at moment of writing these rules are not included in the Dutch Building Decree.

In this report it is chosen to use the new construction level from the three previously mentioned levels. This quality is the highest quality level, so if the construction is safe according to this level it is also safe according to the other levels.

The scope of this thesis is made on floor elements. For floor elements there are three main aspects which should be considered according to the Dutch Building Decree. These three different elements are: fire resistance, noise resistance, and structural safety. In the following paragraphs these aspects are dealt with.

The floor elements considered are storey floors. This type of floors have less rules compared to ground floors or roofs because they are not subjected to environmental impacts.

B1. Fire resistance of floors

There are rules concerning the fire resistance of building elements. These rules are made based on the escaping time of people present in the building. They need to have a certain 'safe' time to leave the building before structural elements such as floors collapse because of fire damage (Rijksoverheid, 2012). Besides this escaping time it is important that there is the possibility to search the building for people still inside. The fire resistance of elements is given as a time in minutes. This time represents the available time there is during a fire in which people can escape the building. A time of, for example, 60 minutes means the structural elements should be able to resist the fire for 60 minutes before collapsing.

In this report the new construction of housing is examined. The needed fire resistance of floors in buildings with a residential function is given in the following figure:

Tabel 2.10.1

woonfunctie	tijdsduur van de brandwerendheid met betrekking tot bezwijken in minuten
Indien geen vloer van een verblijfsgebied hoger ligt dan 7 m boven het meetniveau	60
Indien een vloer van een verblijfsgebied hoger ligt dan 7 m en geen vloer van een verblijfsgebied hoger ligt dan 13 m boven het meetniveau	90
Indien een vloer van een verblijfsgebied hoger ligt dan 13 m boven het meetniveau	120

Figure 0.29: Fire resistance according to Bouwbesluit

As can be seen in the figure, the needed fire resistance is depended on the height of the highest floor. The needed fire resistance is bigger if the top floor is located higher from the ground. Therefore, it can be concluded that floors in serial housing have a lower limit as floors in apartment buildings because these are usually higher.

B2. Noise resistance of floors

Another important aspect which is described in the building decree is noise resistance. Different elements in the building need to have a certain noise resistance to make sure the occupants of the building do not feel sound nuisance. In this report the focus is made on storey floors in residential construction. The needed sound resistance for floors in residential construction is given in the Dutch Building Decree. According to this decree floors need to have a sound resistance of 54 to 59 dB. This is only applicable to floors which are dividing different houses. Floors separating storeys of the same house do not have sound limits.

B3. Structural safety

The third aspect specified in the Dutch Building Decree is the structural safety of elements. This aspect is the most important aspect to take into consideration whilst designing the building. The structural safety makes sure the building is buildable and will not collapse during applied loads. The structural safety is checked based on the applied loads compared to the maximum resistance of the structure. Elaborate rules are specified in the Eurocode. The focus is made on concrete structures, so the applicable Eurocode is: EN-EN 1992 - Eurocode 2.

The rules related to collapse are dealt with in the ultimate limit state and are specified by the Dutch Building Decree. There is also the serviceability limit state which states something about the capability of the element/structure in fulfilling its task. In this report floor elements are treated. The main serviceability limit concerning floors is based on the maximum deflection. For floors the maximum deflection needs to be lower than 0,004*span (Betonhuis, n.d.). However, the rules regarding the serviceability limit state are not governing design rules. These rules are no longer rules on which an element can be rejected (Rijksoverheid , 2012).

C. Material testing

Before calculations concerning reuse can be made it is important to know all parameters required. When new constructions are designed and calculated the properties are chosen by the engineer and the manufacturer or contractor makes elements according to these specifications. With reuse this principle is inverted; The element is already constructed and the engineer needs to check whether this element can be reused in a different structure as it was originally designed for. In this thesis two tools are made to check these possibilities. Both tools need information about the element to check if reuse is possible. This information can be provided by original drawings and/or calculations. However, according to different experts in the field of existing structures it is quite common that a lot of original documentation is lost/missing. When the properties cannot be found by original documentation, tests need to be conducted. These tests are even necessary if the documentation is available because the material properties can differ from the original design or the properties can have changed over time. In this chapter the necessary tests for the different parameters needed in the design tools are explained, both for the reuse of monolithic and hollow core floors.

A general explanation per test is given whereafter a sample size per test is discussed. This is a general advice and can differ case specific. Therefore it is always advised to contact a specialist to get the case specific information and sample size.

C1: Monolithic floors

The monolithic floors dealt with in this report are point supported slab floors, which are also called two-way point supported slabs. As is explained in chapter 6, it is intended to reuse parts of these floors in a similar way as a plank floor. In this way the floors become one-way slabs in the new structure. One-way slab floors can be calculated in a similar way as a beam (Braam & Lagendijk, 2011). Therefore, the information needed in the calculations is identical to that in the calculation of a beam. The needed parameters and accompanying tests are shown in the following table:

Table 0.4: Needed tests per parameter

Parameter	Needed test
Length	* aspect of new design
Width	* aspect of new design
Thickness/height	Measuring
Diameter reinforcement	Chopping
Reinforcement configuration	Concrete radar
Concrete quality/properties	Drilling cores
Reinforcement quality	Steel pulling test

C2: Hollow-core slab floors

Hollow-core slabs transfer loads in one direction in both the current as in the new design. Therefore, these elements can also be calculated as a beam. However, there are two important aspects which needs to be taken into consideration for the hollow core slabs. The first vital difference with an ordinary beam or floor is the pretensioning of reinforcement. In hollow core slabs the reinforcement is pretensioned which means the elements are prestressed. The pretensioned reinforcement is usually referred to as prestressing bars or wires. Prestressed concrete elements are calculated in a slightly different way as normal beams which needs to be taken into consideration in the tool. The second mayor difference between a ‘normal’ beam and a hollow core element is the concrete area. In hollow core elements, channels are located to lower the self-weight of the element. These openings need to be considered in the calculation by applying a modified width in the area in which the channels are placed. The needed parameters for hollow core slabs and the accompanying tests are shown in the following table:

Table 0.5: Needed tests per parameter

Parameter	Needed test
Length	* aspect of new design
Width	* aspect of new design
Thickness/height	Measuring
Hollow core design	Cutting
Diameter reinforcement	Chop open
Reinforcement configuration	Concrete radar
Concrete quality/properties	Drilling cores
Reinforcement quality	Testing steel
Prestress	Preloading

As can be derived from the table, there are more destructive tests needed on a hollow core slab. Therefore, it is advised to sacrifice a few slabs of the donor building to do testing on.

C3: Concrete radar / Ferro scan

One of the most important aspects in reinforced concrete is the reinforcement layout. Without this reinforcement layout it is not possible to calculate the strength and stiffness of the element. One method to acquire the reinforcement layout in situ is using a concrete radar/ferro scanner.

A Ferro scanner is a device which is systematically rolled over the concrete surface. The device scans the concrete using electromagnetic pulses and by doing so detects the reinforcement. Two examples of concrete radars/ferro scanners are the Proceq Profometer 5 and the Hilti ferroscanner. In figure 0.30 an image is shown of a Nebest colleague using a Hilti ferroscanner.

Figure 0.30: Usage of a concrete radar (source: Nebest)

The scanner scans the concrete and using the data obtained by this scans it is possible to make figures similar to figure 0.31 until figure 0.34. From these figures it is possible to obtain the reinforcement layout.

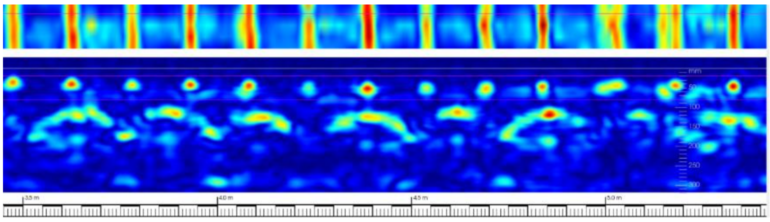


Figure 0.31: Ferro scan of hollow core element (source: Nebest)

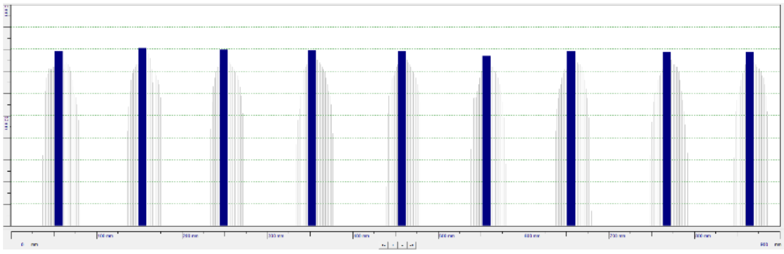


Figure 0.32: Line scan of reinforced concrete element (source: Nebest)

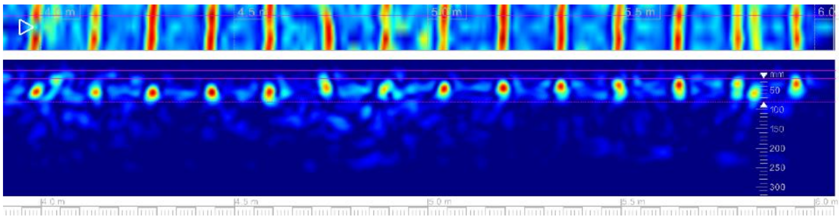


Figure 0.33: Scan of reinforced concrete element (source: Nebest)

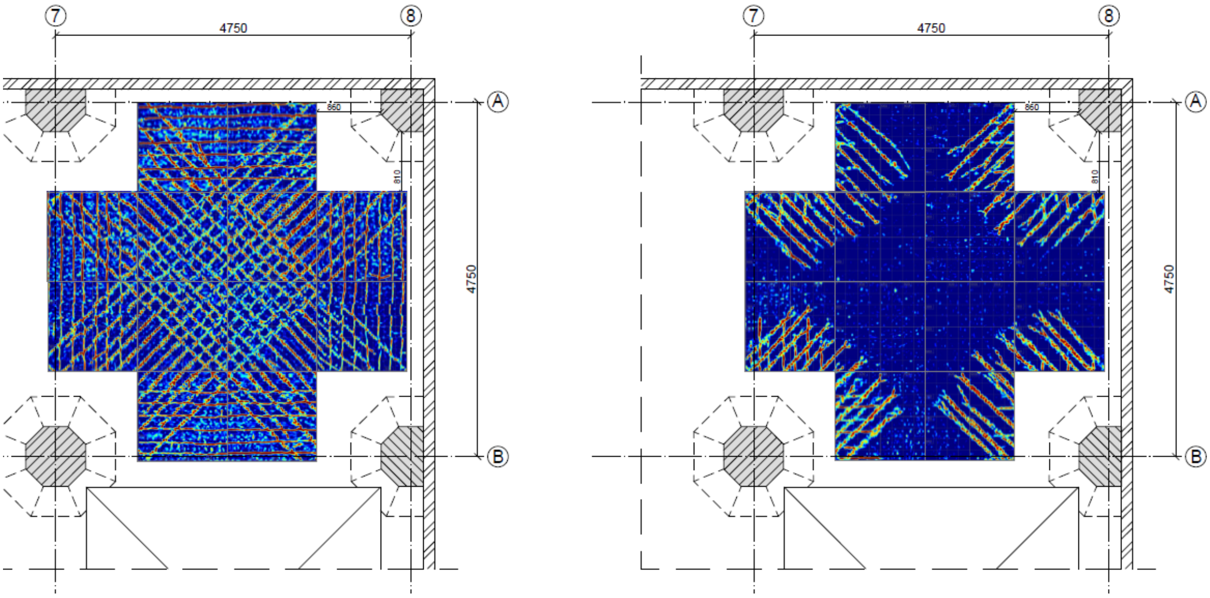


Figure 0.34: Mapping of reinforcement of the Meelfabriek in Leiden (source: Nebest)

In figure 0.31 a scan of a hollow core slab is shown. Due to the hollow cores in the element, small errors occur in the scan. In figure 0.34 a scan of a monolithic floor is shown. As can be seen in this figure, the reinforcement layout of a monolithic floor can be well mapped.

So, it is easier to map the reinforcement layout of a monolithic floor and therefore this process is less time consuming compared to mapping the reinforcement layout of a hollow core slab. But a side node needs to be added. Hollow core slabs are usually quite standardised throughout a building and therefore the sample size can be lower. A specialist at Nebest who maps reinforcement layouts on a daily basis advised the following sample sizes:

- 33% for monolithic floors
- 20 % for hollow core slab floors

The scanning of a hollow core slab takes more time but the sample size is lower. Therefore, it is assumed that the same area of floor, for both the monolithic and the hollow core floor, can be scanned on one day. According to the expert he can map 2000 m^2 of floor per day with the abovementioned sample sizes.

C4: Schmidt hammer

The concrete quality tells something about the strength properties of the concrete. Without knowing these strength properties one cannot calculate the strength of a beam or floor. A method to get an indication of the concrete quality is the Schmidt hammer test. A vital aspect which needs to be made clear is that the Schmidt hammer test gives an indicative value, this value is only an indication and cannot be used in the calculation without being verified by tests on specimens in the laboratory.

During a Schmidt hammer test a spring loaded pin hits the concrete surface. The rebound of the hammer's pin gives an estimation of the concrete surface hardness. Per measuring point this test is conducted nine times (Ermens, 2022). These nine tests are then ranked and the median of the measurements is used. This median can, using a graph, be translated to a derived concrete strength. This measurement procedure is also described in NEN-EN 12504-2. In figure 0.35 the basic steps of a Schmidt hammer test are shown.

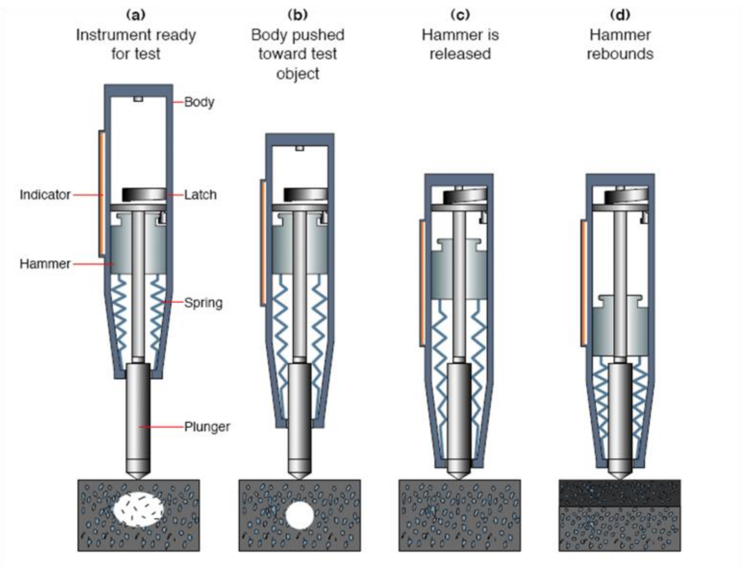


Figure 0.35: Schmidt hammer test (Civilengineering SPK, 2014)

The elements dealt in this report are floor elements which are horizontal elements. These horizontal elements are influenced by gravity and therefore the measurements of the Schmidt hammer need to be adjusted to take the influences of the gravity into account (Ermens, 2022).

Schmidt hammer tests give a fast indication. If only an indication is sufficient, Schmidt hammer test can be used. However, in this report it is chosen to not use Schmidt hammer test but actual tests on drilled cores. Different specialists at Nebest describe the shortcomings of Schmidt hammer tests and therefore they are set aside.

C5: Drilling cores for concrete properties

In calculations the exact properties of the material are needed. If the exact properties of concrete are needed it is best to take samples of the material and test these in a laboratory. For concrete the main parameters are the compressive and tensile strength. These two values can be measures by two different tests which are explained in the following two paragraphs.

Compressive strength

It is possible to get an indication of the compressive strength of concrete by doing a Schmidt hammer test, as earlier explained. If in depth knowledge is needed, cores need to be drilled from the material. These cores need to have a diameter of 100 mm and a length of approximately 100 mm (Ermens, 2022). Preferably the specimens are fully concrete without reinforcement. These cores are then cut and compressive areas are parallel polished. Thereafter the specimens can be tested in a compressive testing machine. After this test the compressive strength of the specimen can be determined based on NEN-EN 12504-1 and judged based on NEN-EN 13791. In figure 0.36 specimens of a compressive strength test are shown.

Figure 0.36: Concrete core specimens (source: Nebest)

Tensile strength

It is common to derive the tensile strength of concrete based on the splitting strength of a specimen. For this test also a core with a diameter of 100 mm and a length of circa 100 mm is needed (Ermens, 2022). The core is then shortened and the heads are parallelly grinded. It is advisable to have a dimeter vs length ratio of approximately one. The splitting tensile force is thereafter obtained by placing the specimen horizontally in a compressive testing machine. The compressive force is transferred to the element via a small strip which is the full length of the element. Due to this concentrated load the specimen will collapse in horizontal direction which tells something about the splitting force of the concrete. Based on NEN-EN 12390-6 the tensile strength of the tested specimen can be derived.

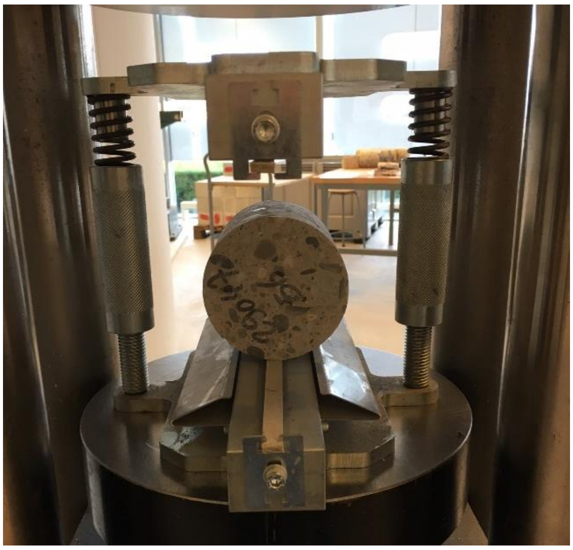


Figure 0.37: Tensile splitting force test of concrete specimen (source: Nebest)

It is possible to derive the tensile splitting strength based on a compressive strength test. Therefore, only this method is used. According to the codes, six specimens need to be taken from every relevant element. One relevant in this case can be one floor field. So as minimum, six specimens need to be taken.

The monolithic floor is poured on site by concrete coming from different truck mixers. These mixers usually have a capacity of 15 m^3, which means they can pour approximately 100 m^2 of floor. Because the concrete quality and densification of the concrete can differ per truck/batch it is advised to drill one core (and test it) per 100 m^2.

Concerning hollow core slabs it is a different story. Hollow core slabs are usually standardised throughout the building. Therefore less tests need to be conducted. As described above it is necessary to do six tests per relevant element. For hollow core slabs it is advised to sacrifice a minimum six elements from different locations in the building and drill cores from them to do the tests.

C6: Surface opening

An important detail besides the reinforcement layout is the diameter of the rebar. It is hard to obtain this diameter based on a ferro scan and therefore an extra action needs to be taken. If one wants to know the rebar diameter it is advisable to chop some concrete away to expose the rebar. In this way it is possible to verify the rebar diameter. This action does not need to take place on every location of the floor but only at a few locations. By combining the measurements on the exposed concrete with the earlier mentioned concrete radar a well-defined image of the reinforcement can be made. In figure 0.38 an image of exposed rebar is shown.

Figure 0.38: Surface opening/chopping (source: Nebest)

This chopping of concrete can be done manually but it is also possible to use water to expose the rebar. This method is called hydro demolition. In this method a highly compressed water jet sprays away the concrete and the concrete is left.

At Nebest it is common to chop the concrete away by hand. A specialist at Nebest advises to clear the rebar at two locations on each floor. In combination with the previously mentioned scans it is possible to get a good image of the reinforcement.

C7: Steel pulling test

In the calculations it is necessary to obtain the steel quality of the rebar (prestressing steel). The quality of the rebar can be measured based on a steel pulling test. For this test rebar needs to be taken from the floor and be pulled until failure in a special pulling machine. This machine measures the force required before the specimen fails and by doing so the steel quality is obtained. In figure 0.39 a steel pulling machine is shown.

Figure 0.39: Steel pulling test (source: Nebest)

The specimen in the steel pulling machine needs to have a length of 30 cm. This specimen needs to be chopped/cut from the concrete to obtain the steel quality. It is advised to do a steel pulling test for each floor.

C8: Proof loading

The best way to obtain the structural properties of a material or element is to do proof loading. During proof loading the element is loaded until failure in a similar way as it will be loaded in the new design application. Therefore the exact properties can be obtained by doing this test. The downside of this test is the loss of material. The element is loaded until failure and can thus not be reused anymore.

The material properties of a monolithic floor can well be examined based on the previously mentioned tests. However, the properties of a hollow core slab are much harder to obtain using these tests. It is for example not possible to obtain the prestressing force in the hollow core element. Therefore proof loading can be a solution for hollow core slabs of which little properties are known.

Proof loading is really case specific and therefore no further explanation is given in this report regarding proof loading. It is advised to set up a proof loading plan, matching the case, before executing it.

D. Costs

Costs are an important aspect in every project. Currently costs are one of the limiting factors of reuse. A circular way of dealing with materials is usually more expensive and therefore it is sometimes not applied (Gersen, et al., 2022). Different aspects contribute to the total price of a project. Reuse does not only result in extra costs, such as extra labour, but also savings are made on for example new materials. These different costs need to be derived and the total sum needs to be made to see whether reuse is more expansive, and if so, how much more.

One trend which is going on and could benefit the reuse world is the lowering of taxes on labour and the increase of taxes on material. By doing so the differences between reused materials and ordinary materials can be equalled. This possibility was also discussed in the online webinar of NHNEXT (North Holland Next) (2022), in the week of the circular economy. This however is a political aspect of reuse and therefore not treated in this thesis.

In this chapter different cost items of reuse are derived. Besides these costs, the price of new materials is given to make it possible to compare these costs. In this chapter only the financial figures are given. In chapter 6 and 7 these figures are used to compare the price of reuse with the new price.

D1: Price increase

The prices of construction materials have risen substantially the last few months (NOS, 2022). Therefore, to get an accurate image of the current prices, this increase needs to be incorporated in the prices. This can be done by checking the date of the source used and multiplying it with the price increase since that year. The following image shows the price index for total building costs, labour, and material. These numbers can be used to get an estimation for the current price.

Perioden	Bouwkosten totaal		Looncomponent		Materiaalcomponent	
	Prijsindex	Mutaties tov dezelfde periode vorig jaar	Prijsindex	Mutaties tov dezelfde periode vorig jaar	Prijsindex	Mutaties tov dezelfde periode vorig jaar
	2000=100	%	2000=100	%	2000=100	%
1990	.	.	.	.	82,5	.
1995	90,1	.	87,0	.	92,4	3,1
2000	100,0	3,6	100,0	2,4	100,0	4,5
2005	115,9	2,0	119,4	1,7	113,0	2,2
2010	130,8	0,6	133,8	1,9	128,4	-0,2
2015	139,8	1,9	146,0	0,9	135,4	2,5
2016	142,6	2,0	148,4	1,6	138,5	2,3
2017	145,9	2,3	151,4	2,0	143,3	3,4
2018	149,6	2,5	155,1	2,5	147,1	2,6
2019	153,8	2,8	159,2	2,6	151,5	3,0
2020	157,2	2,2	165,7	4,1	152,1	0,4
2021 januari*	160,1	2,1	167,7	2,2	155,9	1,9
2021 februari*	160,2	2,1	167,7	2,2	156,0	2,0
2021 maart*	160,6	2,4	168,4	2,6	156,2	2,1
2021 april*	161,8	3,6	168,4	2,6	158,5	4,6
2021 mei*	162,9	4,4	168,4	2,5	160,7	6,2
2021 juni*	164,2	5,2	168,4	2,4	163,2	7,9
2021 juli*	166,1	5,4	168,4	0,8	166,9	10,1
2021 augustus*	165,9	5,0	166,6	-0,2	168,0	10,2
2021 september*	166,2	5,4	166,6	-0,2	168,7	11,1
2021 oktober*	167,0	6,0	166,2	-0,5	170,5	12,5
2021 november*	167,2	6,0	166,2	-0,5	170,9	12,5
2021 december*	167,5	5,3	166,2	-1,4	171,6	12,1
2021*	164,2	4,4	167,4	1,0	163,9	7,8
2022 januari*	173,0	8,0	173,2	3,3	175,8	12,7
2022 februari*	173,7	8,4	173,2	3,3	177,1	13,5
2022 maart*	176,9	10,2	173,3	2,9	183,2	17,3

Figure 0.40: Price increase (CBS Statline, 2022)

The graph can be read the following: if one wants to know the current labour price and has a source that tells labour was €50 an hour in 2010, one can multiply 50 by 175,3/133,8 = 1,308. So, the estimated current labour price, based on this source, is 50*1,308 = €65 per hour.

D2: New hollow core floor

The costs of new hollow core floors are dealt in this section. The costs of hollow core floors are estimated on three different sources. These sources and corresponding costs are given first, thereafter these costs are compared and a final price is given.

In the concrete building structures reader (CIE3340/CIE4281, 2016) indications are given for the costs of different floor systems. In the reader the costs of hollow core slabs are given. These prices are given for the year 2014 so they need to be multiplied by a factor as explained in section D1. The costs of hollow core slabs are:

- Floor thickness 200 mm, approx. €45-55/m^2 x (176,9/139,8) = €63/m^2
- Floor thickness 260 mm, approx. €65-75/m^2 x (176,9/139,8) = €89/m^2
- Floor thickness 320 mm, approx. €65-75/m^2 x (176,9/139,8) = €89/m^2

Besides the building structures reader there are other sources which are giving cost estimations. For example the bouwkosten.nl website. On this website current construction price estimations are given. This website gives the following costs for hollow core slabs (Bouwkosten.nl, 2022):

- Floor thickness 150 mm, €49,10/m^2
- Floor thickness 200 mm, €52,57/m^2
- Floor thickness 260 mm, €61,17/m^2

Next another website is consulted. This website is made to give advice for offers and does this by stating current target prices for different construction materials. The website gives the following costs for hollow core floors (Offerteadviseur , 2022):

- Floor thickness 280 mm, €88,50/m^2
- Floor thickness 300 mm, €91,50/m^2

Different prices and thicknesses are stated above. To compare the different sources one thickness needs to be chosen, this thickness is 260mm because this is a common one for the different sources. In the following table a comparison is made between the different prices stated and the average of these prices is given.

Table 0.6: Price index for new hollow core floor

Source	Price index (260 mm)
Building Structures reader	€89/m^2
Bouwkosten	€61,17/m^2
Offerteadviseur	€88,50/m^2
Average	**€80/m^2**

So based on these three sources it can be derived that the costs of a hollow core floor are approximately €80/m^2.

D3: New plank floor

In this section the costs for plank floor are treated. The costs of plank floors are estimated on three different sources. These sources and corresponding costs are given first, thereafter these costs are compared and a final price is given.

First the building structures reader (CIE3340/CIE4281, 2016) is consulted. In this reader price estimations for different floor systems are given, including plank floors. The price estimations made in this reader are for the reference year 2014, therefore these prices need to be multiplied by a certain factor as is explained in section D1. The costs of plank floors are:

- Floor thickness 150 mm, approx. €75-85/m^2 x (176,9/139,8) = €101/m^2
- Floor thickness 200 mm, approx. €85-95/m^2 x (176,9/139,8) = €114/m^2
- Floor thickness 250 mm, approx. €95-105/m^2 x (176,9/139,8) = €127/m^2

Besides the building structures reader there are other sources which are giving cost estimations. For example the bouwkosten.nl website. On this website current construction price estimations are given. This website gives the following costs for plank floors (Bouwkosten.nl, 2022):

- Floor thickness 170 mm, €68,30/m^2
- Floor thickness 200 mm, €75,60/m^2

Next another website is consulted. This website is made to give advice for offers and does this by stating current target prices for different construction materials. The website gives the following prices for plank floors (Offerteadviseur , 2022):

- Floor thickness 150 mm, €127,50/m^2
- Floor thickness 180 mm, €132,50/m^2
- Floor thickness 200 mm, €140/m^2
-

Different prices and thicknesses are stated above. To compare the different sources one thickness needs to be chosen, this thickness is 200 mm because this is a common one for the different sources. In the following table a comparison is made between the different prices stated and the average of these prices is given.

Table 0.7: Price index new plank floor

Source	Price index (200 mm)
Building Structures reader	€114/m^2
Bouwkosten	€75,60/m^2
Offerteadviseur	€140/m^2
Average	**€111/m^2**

So based on these three sources it can be derived that the costs of a plank floor are approximately €111/m^2. Comparing this to the cost of a hollow core floor (section D2) one can see that a plank floor is considerably more expensive.

D4: Sawing

Sawing is an important process during the dismantling of a building. This sawing is needed if the joint between different concrete elements is made with mortar or concrete. In figure 0.41 the sawing of a concrete slab into different elements is shown.

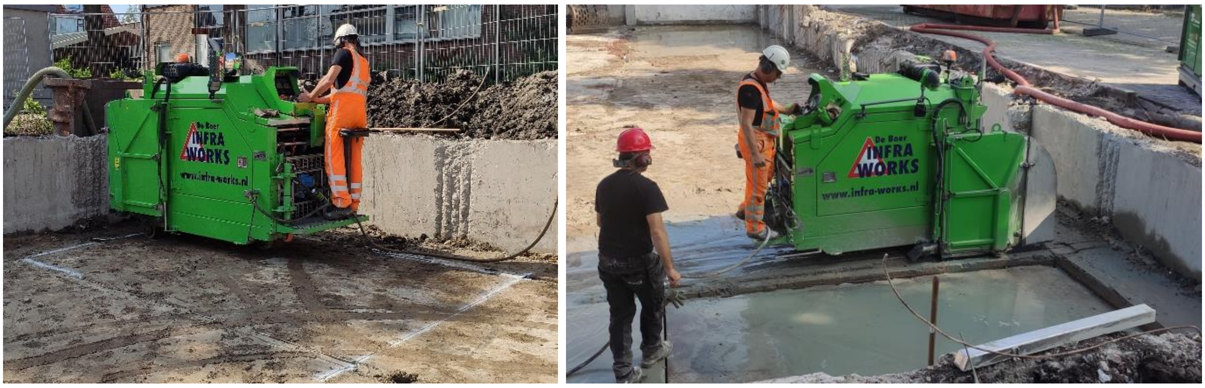


Figure 0.41: Sawing of concrete (Lenears, 2022)

This sawing is seen as a costly procedure and therefore it is important that these costs are charted. The costs for sawing are estimated based on different sources. The price mentioned per different source is first stated. Thereafter the average of all of these prices is taken as a target price.

The first source which is used is a quotation by Lek Sloopwerken for the dismantling of the A67 viaduct in the ‘Closing The Loop Project’ (Lek Sloopwerken , 2021). In this quotation the following price was used for sawing:

- Sawing of concrete: €70/ m^1

Next a website is used for the price indication of sawing. The website Sloop-Gigant is used in this case. The website states the following price for concrete sawing (Sloop Gigant , 2020):

- Sawing of concrete: €1,82/cm/ m^1

This price is a price per centimetre thickness, therefore a reference thickness needs to be chosen to compute the average sawing price. In this report a reference thickness of 300 mm is chosen based on the findings in chapter 3. Thus the price of concrete sawing, according to this source, is €54,60/m1.

Thirdly another website is consulted to compute the sawing price. The website is called Sloop concurrent and gives up-to-date prices for demolition related processes. According to the website, the price of sawing in a concrete floor is (Sloop Concurrent , 2022):

- Sawing of concrete: €2,10/cm/ m^1

This price is also a price per centimetre thickness, so the abovementioned reference thickness needs to be applied in this price. The price according to Sloop Concurrent, for the reference thickness, is: €63/ m^1.

Now there are three different price estimations for the sawing of concrete, based on three different sources. In the following table these prices are compared and an average price is calculated.

Table 0.8: Sawing prices

Source	Price index (200 mm)
Quotation of Lek Sloopwerken	€70/ m^1
Sloop Gigant	€54,60/ m^1
Sloop Concurrent	€63/ m^1
Average	**€65,50/ m^1**

So, the price of concrete sawing is estimated to be €65,50/ m^1.

D5: Stamping/supporting

It is possible that the floor elements need support during sawing because they otherwise would fall. Supporting of floors is usually done using stamps. In this chapter the costs of stamping a floor are examined based on different sources and an average target price is given grounded on this data.

The first source, which is used to derive the costs of stamping, is the Bouwkosten website. This website gives current estimated costs for construction materials and processes involved. The estimated costs for stamping a concrete storey floor are:

- Stamping: €6,22/m^2

Secondly a report of Bouwformatie (Houwaard, 2008) is used. This report dates back to 2008 and therefore an adjustment in the price needs to be done as explained in section D1. The price according to the report is:

- Stamping: €7,55/m^2 x (176,9/130,8) = €10,21/m^2

Now the average of these two prices can be computed. In the following table the prices according to the different sources are stated and the average is calculated:

Table 0.9: Stamping/supporting prices

Source	Price index (200 mm)
Bouwkosten	€6,22/m^2
Bouwformatie	€10,21/m^2
Average	**€8,22/m^2**

So, the price of stamping is estimated to be €8,22/m^2.

D6: Hoisting

It takes 0.24 hours to hoist and move one floor element (Bouwkosten, 2022). It is assumed that a 100 ton crane is used in this process. The values used in the calculation of the environmental impact are also applicable to a 100 ton crane.

The costs of a crane are usually made up out of transport costs, labour costs and renting costs. In the pricelist of JNS Bouw & Montage the transport price and renting price are given. The transport costs are €247.5 and the price per hour rent is €165 (JNS Bouw & Montage , 2022).

The labour costs of a crane operator differ between €37,50 and €75 (Grondverzet.nu, n.d.). In this report the average of these values is used, so it is assumed that the crane operator costs €56.25.

Thus the total price per day is equal to: 165*8 + 247.5 + 56.25*8 = €2017.5. In a day it is possible to hoist approximately 33 (=8/0.24) elements. Therefore the costs of hoisting one element are approximated to be €61.14.

D7: Traditional demolition

Traditional demolition is also a costly process. It is less labour and time intensive as circular demolition so, it is less expensive as circular demolition. However, it still is a costly activity. On the Bouwkosten website an estimation is given on how much traditional demolition of certain floor types cost (Bouwkosten , 2022). The following prices are found:

- Hollow core floor, thickness 260 mm (< 500 m^2): €58,35/m^2
- Hollow core floor, thickness 260 mm (> 500 m^2): €51,70/m^2
- Plank floor, thickness 200 mm (< 500 m^2): €45,10/m^2
- Plank floor, thickness 200 mm (> 500 m^2): €42,45/m^2

So on average the costs of traditional demolition of hollow core floors are €55,03/m^2 and €43,78/m^2 for plank floors.

D8: Testing

The different tests mentioned in appendix C all have different costs. In this chapter the costs per test are stated. In part C1 and C2 the needed tests and accompanying costs for respectively the reuse of monolithic and hollow core slab floors are given.

The costs given in this chapter are approximations and can differ per case. These approximations are made based on different interviews with material specialists at Nebest. It is advised to contact Nebest or another consultancy firm if an actual price is desired.

Mapping the reinforcement layout (ferro scan/concrete radar)

As is specified in appendix C it is possible to map around 2000 m2 of floor a day. The price of a specialist/inspector including equipment is approximately €1480 a day. So the mapping of the reinforcement layout costs approximately 1480/2000 = €0.74/m^2.

This value is an approximated value because the actual price depends strongly on the amount of floor area. If, for example, only 1 m^2 of floor needs to be mapped. The price will be much higher than the abovementioned €0.74.

Drilling cores

In appendix C can be read that it is advised to drill one core every 100 m^2 of monolithic floor. Regarding hollow core slabs it is advised to drill six specimens throughout the building.

Inspectors of Nebest do the drilling in duo's and can do 24 cores a day which results in an approximated price of €63 per core.

This is again an approximated value and can differ strongly on the amount of cores because the prices are usually calculated per day.

Testing cores

The testing of cores is done in Nebest's own laboratory. The price of one test is approximated to be €70.

Surface opening/chopping

The opening up (uncovering) of the reinforcement is usually done by hand, as mentioned in appendix C. Therefore the time required strongly depends on the skill of the specialist/inspector but also on the case. On average it is possible to expose the rebar on seven locations in one day. Which means that the chopping of concrete on one location costs approximately €175.

Steel pulling test

Before a steel pulling test can be done, a part of rebar needs to be freed from the concrete. A more elaborate explanation of this process is given in appendix C. The freeing of steel is done by hand in a similar process as the chopping. Therefore a similar price, of €175 per chop, can be used. The test itself costs around €70. So the combined costs of a steel pulling test can be approximated on €245.

Proof loading

Proof loading gives the best insights on the actual properties of the element/materials, as also mentioned in appendix C. However, regarding costs, it is hard to approximate a value because it is really case specific.

In this report the costs of proof loading are not mentioned because it is not possible to estimate it. If one wants to know the actual costs it is advised to set up a proof loading plan for the actual case and get offers from different specialised firms.

E. Environmental Impact

In this chapter the environmental impact of floor elements is examined based on a Life Cycle Assessment (LCA). The environmental impact shows the burden which a product has on the environment. In the coming years, society needs to lower the burden on the environment significantly to make sure the earth stays liveable. The reuse of materials is a practise which can lower that burden immediately, unlike new materials which take development time.

The chapter starts by explaining the LCA, which is a way to examine the environmental costs of a product over its lifetime. Thereafter the boundary conditions, used in this report to compute the environmental impact, are explained. In the end the methodology used in chapter 6 and 7 is clarified.

E1. Life Cycle Assessment (LCA)

A Life Cycle Assessment (LCA) is a way to quantify the environmental impact of a certain product. In a LCA all aspects of a product's life are treated. Therefore it is vital to start by defining the lifecycle of a product. Different models are used in an LCA, the three most common ones are: Cradle to Gate, Cradle to Grave, and Cradle to Cradle. As can be seen in figure 0.42, Cradle to Cradle covers the most aspects and is the most circular one.

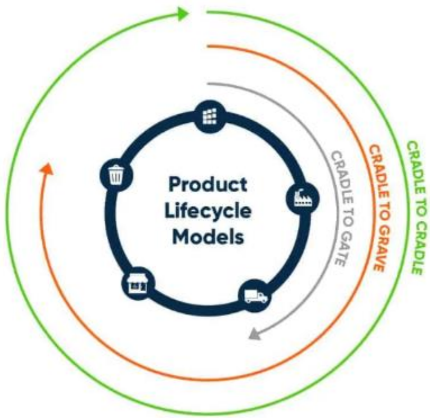


Figure 0.42: Product lifecycle models (Ecochain, n.d.)

In NEN-EN 15978-1 the sustainability of structures is treated and LCA's are explained. In this standard four stages with different substages are distinguished in the building assessment, which are (NMD):

- A: Production and Construction stage
    - A1-A3: Production
    - A4: Transport
    - A5: Construction
- B: Use stage
    - B1: Usage
    - B2: Maintenance
    - B3: Reparations
    - B4: Replacement
    - B5: Renovation
- C: End of life stage
    - C1: Deconstruction/demolition
    - C2: Transport
    - C3: Waste treatment
    - C4: Waste disposal
- D: Beyond the life cycle (Recovery, Reuse, Recycling)
    - Benefits and loads beyond the system boundary

In the National Environmental Database (NMD), Economic Product Declarations (EPD's) are recorded which give the environmental impact of different products on some of the abovementioned stages. The stages which are included in the EPD's on the NMD are: A1-3, A4, C3, C4, and D.

The procedure of conducting a LCA is divided into four different steps which are shown in figure 0.43. In the following subparagraphs these steps are explained.

Figure 0.43: Four steps of a LCA (Ecochain, n.d.)

1. *Goal and scope*

The first step in almost all analyses is to define the goal and the scope of research, this is similar in an LCA. It starts by checking the type of object/element of which it is desired to conduct an LCA. Thereafter, the boundaries of research need to be defined. Aspects to take into consideration are the four different life cycle stages and the different impact categories. In chapter 2 the goal and scope for this report are explained.

2. *Life Cycle Inventory*

The following step is the Life cycle Inventory. In this step the environmental inputs and outputs concerning the product are gathered. In the previous step, the goal and scope definition, the boundaries of the LCA are set. The data collected is collected in between these boundaries. The Life Cycle Inventory can be seen as the data collecting part of the research. A graphical interpretation of a Life Cycle Inventory is given in figure 0.44.

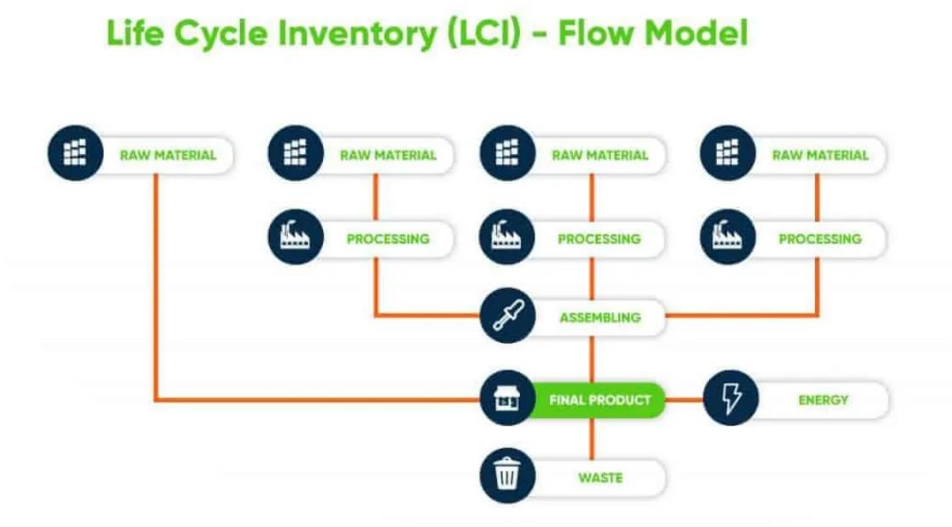


Figure 0.44: Life cycle inventory (Ecochain, n.d.)

As can be seen in the figure, all steps concerning the product need to be treated which makes the process time consuming. Luckily there are Economic Product Declarations (EPD) for the most common products. These EPD's can substitute parts of the LCI.

3. Impact assessment

After the LCI is made the impact assessment needs to be done. In this assessment the LCI data is linked to the different impact categories. In this way the different aspects of the LCI are monetized to make it possible to compare and add them. This monetization is done with standard values for the different environmental impact categories. This value represents the burden on the environment. The monetary value stands for the costs that need to be made to remove the pollution from the environment again. When EPD's are used the impact assessment is usually already done.

4. Interpretation

The last step of the LCA is the interpretation of results. In this step it can be concluded which inputs have a high impact and which life stages contribute the most to the environmental costs of the product. The interpretation of the environmental costs as computed in chapter 6 and 7 is done in the conclusion (chapter 11).

E2. Boundary conditions and assumptions

It is important to set clear boundary conditions for the LCA. Starting, by setting up the goal and scope of the LCA as mentioned previously. In the end it is desired to compare the LCA of a new element with that of an old one and therefore it is vital that the same boundary conditions and assumptions are used for the different LCA's. The used boundary conditions and assumptions are mentioned one-by-one whereafter a reasoning is given for the set condition/assumption.

- Concerning the levels mentioned in E1, only levels A1-3 are used in the LCA's computed in this report.

Level A1-3 is about the production process of the product. This production process is the main difference between a new floor element and a reused one. A new floor has an environmental impact during production which is treated in the EPD values mentioned for levels A1-3. A reused floor element does not have these values but has another 'production process'. The production process of a reused floor element is the dismantling of the element from the original construction and the adjustment of it to make it fit in the new construction. These handlings have an environmental impact which can be seen as the production process of the reused element. Therefore, these two processes can be compared and conclusions can be drawn based on them. The environmental impact for stage A4, the transportation to the construction site, can be similar for both the new and the reused element and strongly depend on the location of the construction site. Therefore, this stage is left out. According to Poppa et al. (2016) structural elements have little environmental impact during their use phase. Therefore, this stage is excluded from this report. The last stage, stage D, can be similar for the reused and the new element and it is uncertain what happens with them beyond the life cycle. Therefore this stage is also not treated.

- The results of the LCA's are only used to compare the new elements with the reused elements.

Because not all aspects are included in the LCA's of the new and the reused floor elements it is only possible to compare these two to one another and not to environmental data of other floor elements which have different stages incorporated in the LCA.

- The life cycle is set at 50 years.

According to the NEN-EN 1990 (2019) the design service life of residential buildings is 50 years. This period is chosen as the life cycle in the LCA's. For both the reused and the new elements it is possible that they are reused after these 50 years. This period is disregarded in this report.

- The residual lifespan of the reused element is minimum 50 years.

The floor elements are inspected before they are reused. There are also different tests conducted on them. Based on this inspection and the different tests, the residual life span is estimated. If the element has a residual lifespan of less than 50 years, it is disregarded. Therefore, all elements which are reusable have a minimum residual lifespan of 50 years.

- In the LCA's, conducted in this report, 11 impact categories are treated. These categories are:
  - GWP = Global Warming Potential
  - ODP = Ozone layer Depletion Potential
  - HTP = Human Toxicity Potential
  - FAETP = Freshwater Aquatic Eco-toxicity Potential
  - MAETP = Marine Aquatic Eco-Toxicity Potential
  - TETP = Terrestrial Eco-Toxicity Potential
  - POCP = Photochemical Oxidation Potential
  - AP = Acidification Potential
  - EP = Eutrophication Potential
  - ADP = Abiotic Depletion Potential – fossil fuel
  - ADP = Abiotic Depletion Potential – nonfuel compounds

There are currently more impact categories (19) stated in the Eurocode. Sometimes there are also less impact categories used in an LCA. However, in this report it is chosen to use these 11, because these are the ones specified in the National Environmental Database (NMD). This database is used to collect the EPD's of the different products and therefore the same impact categories as in the database are used in the LCA's conducted in this report.

- The residual environmental impact of the material of the to be reused elements is set on €0, -.

The elements have already 'paid their price' (burden) in their previous life in the donor building. Therefore, this price does not have to be paid in the new construction. The price which needs to be paid in the new construction is only related to the changes/adjustments which need to be made to the element. These aspects are incorporated for the reused elements in this report.

- The reference date of the environmental data is set at 17-06-2022.

On the 17th of June all environmental data was downloaded from the National Environmental Database (NMD). The data on this website may change over time and therefore the data need to set when one wants to make comparisons.

- The environmental data of category 3 products on the National Environmental Database (NMD) is lowered by 30% in this report.

There are three different categories on the National Environmental Database (NMD); Category 1 is data supplied by the producer; Category 2 is supplied by an organisation (collection of companies); And category 3 is generic data from the NMD. The last one is open source data whereas the other ones are not (fully) public. Therefore, it is desirable to use category 3 data as a researcher. However, category 3 data is increased by 30% to take into account different deviations. In this report, level 3 data is lowered by 30%, to make the data suitable.

- The environmental impact of possible tests is disregarded.

It is possible that tests need to be conducted to obtain the material properties of the elements. These tests are described in appendix C. The environmental impact of these tests is hard to assess and most likely insignificant. Therefore, the environmental impact of the different tests is disregarded.

E3. Methodology used in the report

In this report the environmental impact of both reused and new elements is examined and compared. This is done within the abovementioned boundary conditions and using the mentioned assumptions. The different floors have different environmental impacts. An elaborate explanation for the environmental impact of hollow core slabs is given in chapter 6. A similar explanation for the reuse of monolithic floors is stated in chapter 7.

F. Force distribution and reinforcement layout of monolithic floors

Monolithic floors refer to two way continuous flat slabs which are poured in situ. These floors are commonly used in office buildings and transfer loads in two directions. In this report a tool is developed which checks if a monolithic floor can be cut into pieces and reused as a storey floor in a serial house. Besides the structural aspects, the environmental impact and the costs involved are examined in this tool.

To make reuse possible the floors need to be cut into different pieces. Before these cuts are made, it is necessary to have insights in the reinforcement layout of the floor. In this appendix the guidelines dating back to the original construction period (1970-1990) are examined. Before these guidelines are treated some general information about the force distribution of monolithic floors is given

F1: Force distribution

As described above, monolithic floors are transferring forces in two directions. This makes that it is a lot harder to calculate the forces in the floor compared to a slab transferring loads in one direction. The monolithic floors applied in office buildings, built between 1970 and 1990, are usually point supported (see appendix A) which means there are no beams supporting the floor. However, according to Ham & Lukovic (2020) parts of the floor act as if there are beams located. The parts in between the columns act as fictitious/hidden beams.

A way to calculate the forces in a two way slab is using the strip method. With this method the slab is divided into column strips and middle strips as shown in figure 0.45.

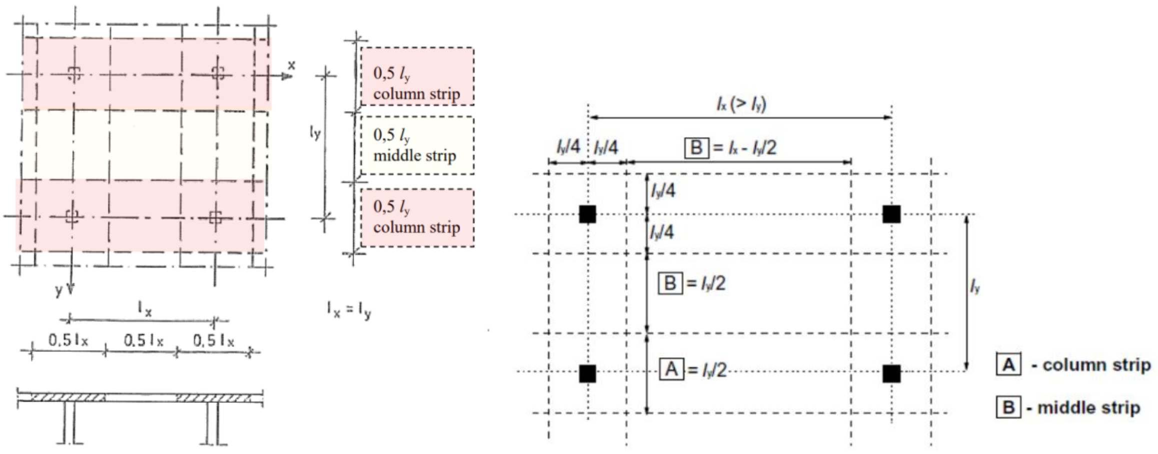


Figure 0.45: Left: strip method according to NEN6720 (Ham & Lukovic, 2020). Right: Strip method according to NEN-EN1992-1-1

These column strips are the parts which act as fictious beams. Uniformly distributed loads applied on the floor transfer from a middle strip to a column strip and from a column strip to the columns. So, these column strips can be seen as a sort of beams. The total applied load is taken by the column strips and the middle strips combined. Therefore the sum of forces in these two strips need to add up to

100%. In the NEN-EN 1992-1-1 a simplified division of the bending moments over the column- and middle strips is given, as shown in figure 0.46.

	Negative moments	Positive moments
Column Strip	60 - 80%	50 - 70%
Middle Strip	40 - 20%	50 - 30%
Note: Total negative and positive moments to be resisted by the column and middle strips together should always add up to 100%.		

Figure 0.46: Bending moment in strips (NEN-EN1992-1-1)

From this table and the abovementioned reasoning it can be concluded that the middle strips take up less loads/forces as the column strips. This means that it is possible that these parts have less reinforcement as a result.

The forces in the floor can also be modelled using a Finite Element Model (FEM). A FEM analysis is not done in this research however there are several videos available in which two way flat slabs are modelled. For this part a video made by 'Creative Engineering Center' was consulted (2020). In this video a two way flat slab was modelled in the program CSI Safe, which is a program specialised in the design of floor systems. In this program the floor is also calculated based on the strip method. The floor is divided into column- and middle strips and the bending moments on the different locations are calculated. The bending moments are calculated in two directions, M11 and M22, as is shown in figure 0.47.

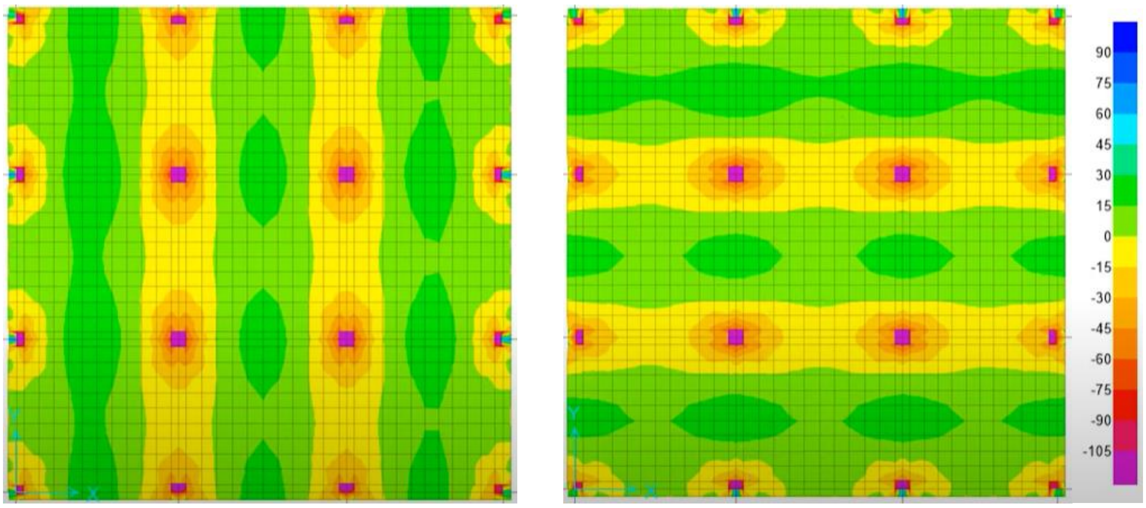


Figure 0.47: Bending moments M11 (left) and M22 (right) in a monolithic slab (Creative Engineering Center, 2020)

In this figure it can clearly be seen that there are upward bending moments (hogging) near the supports (and in some parts of the column strips) and there are downward bending moments (sagging) in the middle strips of the slab. Therefore, it can be concluded that the parts near the columns are governing for the top reinforcement and the parts in the middle strips are governing for the bottom reinforcement.

According to different experts, monolithic floors are usually reinforced using reinforcement nets which are applied in the top and bottom part of the slab as respectively top and bottom reinforcement. Therefore, it is most likely that the floors have the same reinforcement over the area.

Near the supports, high shear forces occur. Therefore, it is presumable that stirrups are used on these locations to cope with these high shear forces. In the middle of the floor no/little shear forces are present. Thus, the application of stirrups is no necessity at these locations.

F2: VB1974 – guideline

The floors, dealt with in this report, are constructed between 1970 and 1990. In this time period different codes, as currently, were used to design/dimension floors with. In this time period the main guideline/code related to the design of reinforced concrete was the VB1974/1984 which was published between 1974 and 1983 (Gijsbers, 2012).

Accompanying these codes there were different design graphs and tables which were used in practise. Graphs and tables which related to the design of flat slab floors were the GTB1974 (GTB = Graphs and Tables for Concrete). In the GTB1974 handholds for the dimensioning of different slab designs were given. The slabs which are treated in this report are two way continuous slabs, which are type III-2 up to III-5 in the GTB1974. The different types are shown in figure 0.48.

For these types of slabs, bending moment graphs and tables are given in the code. The graphs and tables, related to a type III-2 plate, are given on the next page. A type III-2 plate is related to the middle part of the continuous flat slab as is shown in figure 0.48.

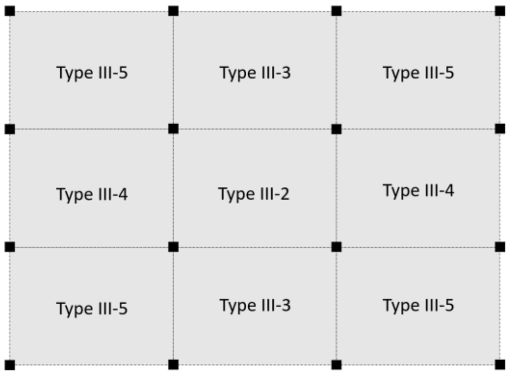


Figure 0.48: Plate types (own figure)

From the graphs and table, shown on the next page, a similar conclusion can be drawn as was done in part F1. In the graphs and table it can be seen that there are upward bending moments located near the columns and downward bending moments at the middle parts. Therefore, the governing reinforcement in the middle part is the bottom reinforcement and the top reinforcement is governing near the columns.

The design graphs for the different types are quite similar shape-wise. The difference between the different types lies on the values of the bending moments.

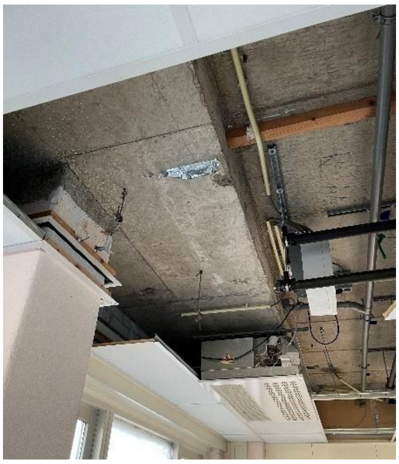


Figure 0.49: Strengthening of strips (own figure)

The modelling as explained in part F1 and the original and current codes, all give similar results related to the force distribution in the monolithic floors; There are upward bending moment near the columns and downward bending moments in the middle parts. Therefore it can be advised to conduct test both near the column and in the middle to see if the same reinforcement is used and what the dimensions and layout are throughout the floor.

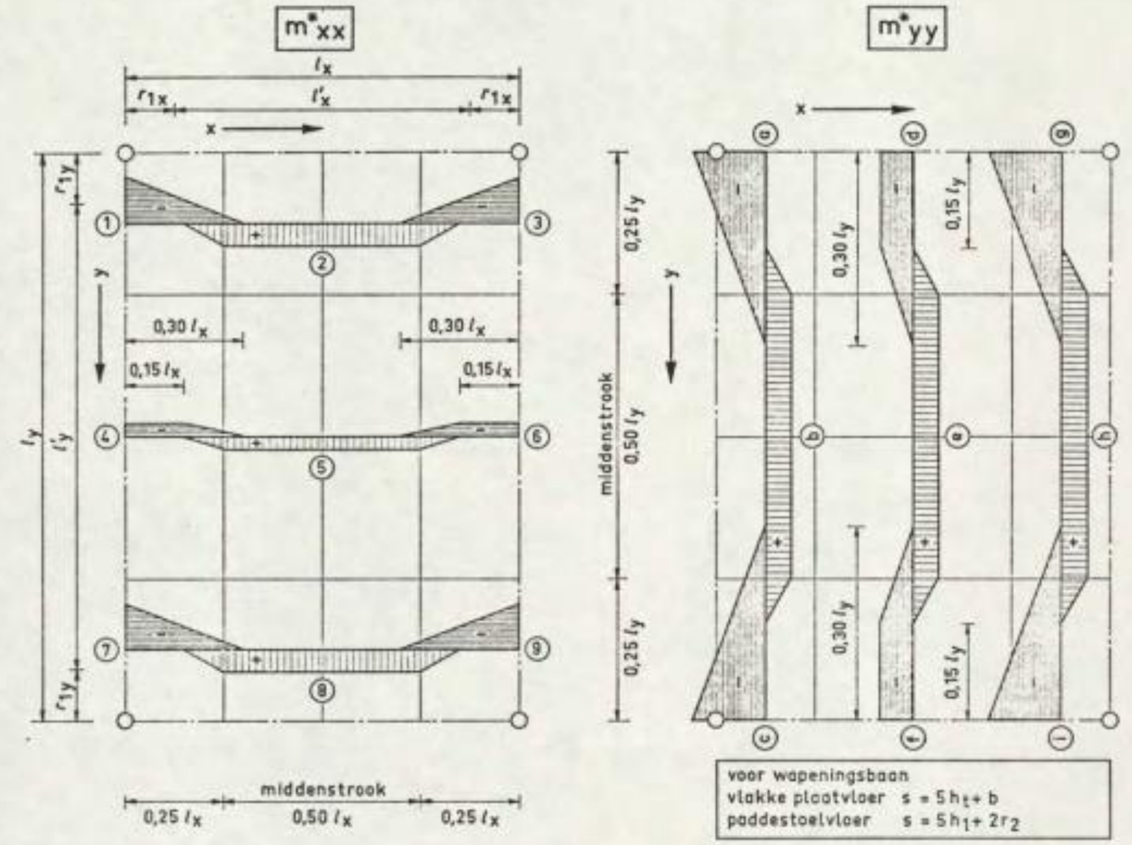
There is the possibility that column strips are locally strengthened. An example of a situation where this was the case was found during a location visit in Alkmaar of which a photograph is shown in figure 0.49.

GTB 1974 – 14.16

platen • **plaat III – 2**

Wapeningsmomenten per lengte onder gelijkmatig verdeelde belasting

geschematiseerd verloop van wapeningsmomenten



coëfficiënten voor wapeningsmomenten																			[illegible]
	$m^*_{xx} = 0{,}001\, ql_x^2 \times$									$m^*_{yy} = 0{,}001\, ql_x^2 \times$									
l_y/l_x	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f	g	h	i	
1,0	−132	+54	−132	−40	+34	−40	−132	+54	−132	−132	+54	−132	−40	+34	−40	−132	+54	−132	5,8
1,2	−140	+61	−140	−34	+30	−34	−140	+61	−140	−180	+69	−180	−67	+53	−67	−180	+69	−180	8,8
1,4	−146	+67	−146	−28	+25	−28	−146	+67	−146	−235	+89	−235	−102	+77	−102	−235	+89	−235	13,8
1,6	−151	+73	−151	−22	+21	−22	−151	+73	−151	−296	+112	−296	−145	+104	−145	−296	+112	−296	21,1
1,8	−155	+78	−155	−18	+17	−18	−155	+78	−155	−363	+140	−363	−195	+134	−195	−363	+140	−363	31,8
2,0	−159	+81	−159	−14	+14	−14	−159	+81	−159	−437	+171	−437	−251	+167	−251	−437	+171	−437	46,6
2,5	−164	+88	−164	−7	+7	−7	−164	+88	−164	−650	+265	−650	−425	+263	−425	−650	+265	−650	107,8
3,0	−166	+92	−166	−4	+4	−4	−166	+92	−166	−902	+380	−902	−644	+380	−644	−902	+380	−902	217,9

Figure 0.50: Design tables VB1974

G. Solutions for ductwork and cables

The new application of the reused floor elements is in serial housing. In houses there are several installations which result in cables and ductwork. This ductwork/cables needs to be placed throughout the building. Currently it is common to apply ductwork and cables in the structural floor layer (Groot, 2022). However, this is not desired from a reuse standpoint. As is described in chapter 4, the lifespan of the structural layer (floor) and the service layer (ducts) is different. Therefore, it is advisable to keep these two layers separated. It is also not advisable to implement ductwork/cables in the floors because this limits the possibilities of further reuse. Besides, it also results in a less adaptive building.

Therefore, there is chosen to separate the structural reused floors and the ductwork/cables. However, the ductwork and cables still need to be placed in the building. In this chapter different possible methods to do so, and their pros and cons, are given. No choice between the different options is made because the desired option strongly depends on the case and the contractor's and/or architect's preferences.

G1: Foam concrete

The first option to locate ductwork and cables in the building is by using a foam concrete topping as is shown in figure 0.51. This is a special kind of concrete which consists for a minimum of 20% out of air (volume) (Propump Engineering , n.d.). Due to this high amount of air the density gets a lot lower compared to normal concrete. The density of foam concrete differs between 300 kg/m^3 and 1200 kg/m^3 which is a lot lower as the 2400 kg/m^3 which is the normal density of concrete (The constructor , n.d.)

Figure 0.51: Pouring of foam concrete (Loon, 2021)

In the concrete mixtures used for foam concrete a much higher cement content is used of between 350 kg/m^3 and 1200 kg/m^3 (Propump Engineering , n.d.). This higher content is needed because the concrete strength is lowered significantly by the air in the mixture. The strength of foam concrete usually varies between 0.5 MPa and 12 MPa (Propump Engineering , n.d.). This strength is enough for the floor to cope with stresses coming from for example a person walking on heels.

The advantages of foam concrete are the low density which results in a minimum extra floor load applied on the structural layer. Besides the low self-weight the material is really well capable of filling all voids in between the different cables and ducts because it is really well flowable during pouring. This property also makes the material really easy to execute and relatively cheap. The last advantage is the load spreading property of the material. Foam concrete spreads the loads over a big area.

The main two disadvantages are the environmental impact of the floor and the fact ducts cannot be accessed anymore. Foam concrete has a high cement ratio. Cement is the biggest contributor to the total environmental impact of concrete. Therefore, it can be concluded that the environmental impact of foam concrete is high. Besides this impact, the ducts are not accessible and it is hard to reuse the structural floor elements because of the wet connection.

In conclusion this option can be specified as an easy and cheap solution, however it is not an advised option based on circularity.

G2: Computer floor / floating top floor

Another possibility is to make a floating floor on top of the structural floor. In this floor all ductwork and cables can be placed. This floating top floor would be similar to a computer floor.

A computer floor is floor which is placed on top of the structural floor and has an open space in which the different cables and ducts can be located. This principle is usually applied in big office spaces and are used to hide the different cables. An image of a computer floor is given in figure 0.52.

Figure 0.52: Computer floor (System floor technics, n.d.)

A similar floor can be used in housing to locate the different cables and ductwork in. The biggest space needs to be freed for the ducts related to ventilation. These ducts have a height of approximately 70 mm (CIE3340/CIE4281, 2016).

The main advantage of using a computer floor would be the flexibility of design. By implementing this floor type it is always possible to reach and adjust the ducts and cables. This also gives a big potential for reuse. Besides this flexibility the computer floor is an easy and lightweight option.

The main disadvantage is the extra height of the floor. Due to this extra height, more façade is needed which results in a more expensive building. Another potential downside of a computer floor could be the acoustics. Due to the air in between the structural floor and the computer floor it could be possible that the floor acts as a sound box which could lead to nuisance. The last disadvantage is that no floor heating can be used in combination with a computer floor.

G3: Lowered ceiling

Both of the abovementioned options consist out of a layer which is places on top of the floor. This solution is located at the other side of the floor, the bottom. In office buildings this is a common option which is used to locate ductwork and cables. The solution is the implementation of a lowered ceiling. This is a construction which is hanging from the roof where all ducts and cables are placed behind. An example of a lowered ceiling is shown in figure 0.53.

Figure 0.53: Lowered ceiling (own figure)

The main advantage of this option is the flexibility in the design, the favourable price, and the low weight. This option is also the option which was most likely applied in the original application of the to be reused elements. Therefore this option would be easy to reimplement in the new design.

The main disadvantage is the location of the ducts in relation to the functions. Because the ducts are placed below the floor, holes need to be made in the structural floor on locations where the ducts/cables are needed. This results in holes in the floor elements which weakens them and makes them less appropriate for further reuse. Another disadvantage is the look of a lowered ceiling. Usually a lowered ceiling has a certain appearance which is not desired in housing.

H. Structural calculations

H1. Stability

Stability is an important aspect of a building. When a building is stable it can cope with the applied horizontal forces without falling down or encountering big deformations (sway). This report deals with the reuse of floor elements in the new construction of serial housing. Serial houses are constructed in a row and are all attached to one another. Regarding the stability of serial houses an assumption is made. It is assumed that one house by itself needs to be stable without the help of the adjacent houses.

There is no case treated in this report, therefore a standardised serial house is used in the stability calculations. RVO (a governmental organisation) has made 33 reference buildings which represent the 'standard' buildings in the Netherlands (Loos, 2017). One of these buildings is a serial house as shown in the left part of figure 0.54.

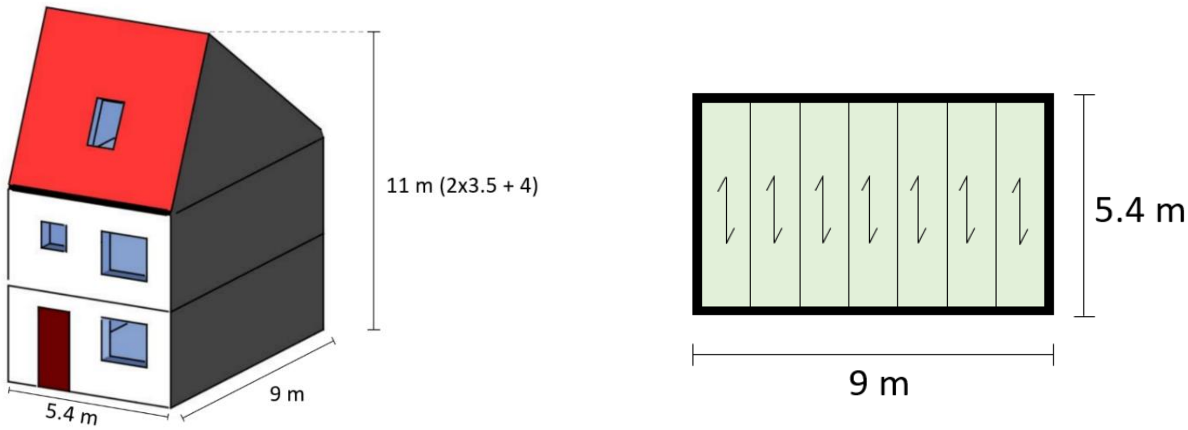


Figure 0.54: Reference building (left) (Loos, 2017) and floor placement (right) (own figure)

This standard building is a middle house in a row of serial houses. There are also corner houses in the row however the majority of the houses is a middle one. Therefore this one is considered. The standard dimensions of a serial house can be seen in the figure. The reused storey floors used in the serial house are applied spanning in width direction as is shown in the right part of figure 0.54. This is both the case for the reused hollow core slab elements and the monolithic elements.

The stabilizing elements need to stabilize the building during horizontal induced forces. These horizontal forces can be a result of: wind, earthquakes, and imperfections. In the stability calculation done in this chapter only wind forces are considered. Horizontal forces caused by earthquakes or imperfections are not treated. The horizontal forces due to wind can be quantified based on design tables according to the Eurocode. These wind forces depend on the height of the building and the location at which the building is situated. The reference building has a total height of 11 meters and it can be located everywhere in the Netherlands. Therefore, the location with the highest wind forces is considered in the calculations, area I coastal. The wind force which needs to be considered at a height of 11 meters on this location is 1.61 kN/m^2 (Es & Pasterkamp, 2014). This wind force is the force acting on the top of the building, the wind force is lower near the base of the building. In the stability calculation done in this chapter the maximum wind force (at 11 m height) is applied on the full height of the building which will result in an overestimation of the applied forces. The wind force is a horizontal force which needs to travel from the facades via the floor to the stabilizing elements, the walls. The floors need to act as a stiff disk to make this possible (Velthorst, 2007).

In the calculation it is assumed that the roof does not act as a stabilizing element. Therefore, the horizontal force on the top floor (#2) is the governing one as illustrated in figure 0.55.

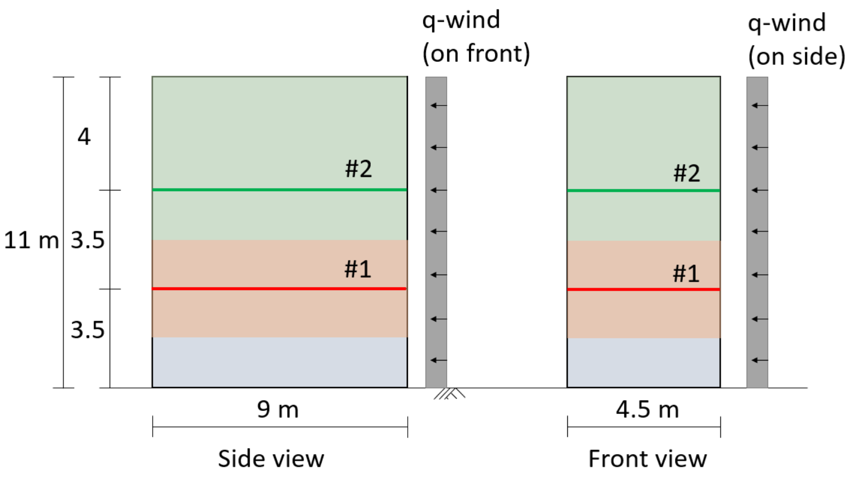


Figure 0.55: Horizontal loads applied due to wind (own figure)

The horizontal force on this floor can be calculated by multiplying the area, which is transferred to the floor, by the wind force. The wind force applied to the floor is given in the following figure:

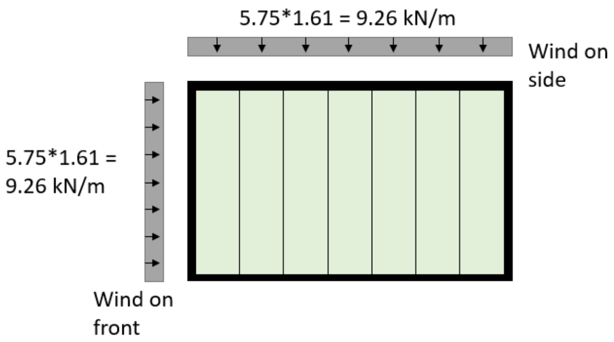


Figure 0.56: Horizontal loads applied due to wind (own figure)

The stabilizing elements in the building are the exterior walls. It is assumed that these walls have the capacity to cope with the induced forces related to stability. In an ordinary house, with new floors, the walls are also acting as stabilizing elements. Therefore, these walls are assumed to be capable of coping with the forces and thus calculations related to the walls are disregarded.

The walls are similar at both sides. Therefore, the centre of gravity corresponds with the middle of the building which results in even load spread between the two walls.

Wind applied on the front side of the building results in loads applied to the side of the floor elements. The elements are connected to stabilising walls on both sides and have strength in this plane. Therefore, the floor elements can act as a stiff disk in this direction. This results in a situation in which the elements are capable of transferring the horizontal forces to the stabilizing walls.

The governing situation is the one with wind applied on the side of the building. In this situation the biggest forces are applied. The force needs to be transferred from one floor element to another, to reach the stabilising elements. Thus the floor needs to act as a stiff disk in this direction. The forces in the floor are shown in figure 0.57.

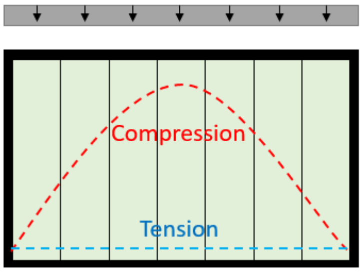


Figure 0.57: Forces in the floor due to wind (own figure based on: (CIE3340/CIE4281, 2016))

The tension forces at the end of the floor can be taken by the stabilising wall in the other direction. The compression forces in the floor are taken by the elements itself. The elements are made of concrete which is really capable of coping with compressive forces. Therefore, these forces are not a problem for the floor.

The elements need to be able to transfer shear forces between each other to make disk action possible. Usually this disk action is obtained by adding a structural layer (compression layer) to the top of the floor. However, this layer makes the floor a lot harder to dismantle which lowers the reuse potentials for the future. Therefore, it is desired to not apply this layer.

The gaps in between the different elements are filled with mortar to make a flat floor surface. This mortar does not affect the reuse potential (by much) because it can easily be removed when reuse is desired. Besides, this mortar is needed to obtain a flat floor without openings. According to Pasterkamp (2018) these joints have the capacity to transfer a shear stress of 0.1 N/mm^2. This statement was also backed during a meeting with several experts of VBI. So, if the shear stresses due to the wind force stay below this limit, the floor can have enough diaphragm action without a structural topping.

The maximum applied shear forces in the floor due to wind are:

$$V_{ED} = \frac{1}{2} * L * q = \frac{1}{2} * 9.26 * 9 = 41.67 kN$$

This shear force can be transferred into the applied shear stress by diving the force over the area at which it applied. For this example a floor thickness of 200 mm is assumed. According to chapter 4 this thickness is around the lower bound of the used floor thicknesses. It is assumable that the floor is thicker as this 200 mm. If the floor is thicker the resulting shear stresses are lower. Therefore, if the floor succeeds with a thickness of 200 mm, it will also succeed for bigger thicknesses.

The applied shear stresses are:

$$v_{ed} = \frac{V_{ED}}{b * h} = \frac{41.67 * 10^3}{200 * 5400} = 0.039 N / mm^2 < 0.1 N / mm^2$$

Thus the applied shear stresses are below the limit. Therefore, it can be concluded that the floor has enough disk action to cope with the wind forces. This means the stability of the system is granted without the application of a structural topping to the floor. The only measure which needs to be taken is the filling of the joints between the elements. As mentioned previously, this is not only needed for stability but also from a more general architectural standpoint.

H2. Monolithic floors

The most important aspect for constructions is the structural safety of a structure. If a structure is not structurally safe, collapse may occur. Therefore, it is vital to check the reused floor elements for the Ultimate Limit State (ULS). Besides collapsing it is possible that a structure does not operate as intended. This aspect is covered in the Serviceability Limit State (SLS) (Paik & Thayamballi, 2009). Floors are susceptible for deflection and therefore the SLS is usually governing (Hordijk & Lagendijk, 2018). In this part the ULS and SLS checks are explained. These checks are automated in the tool of which screenshot are shown in chapter 8. By automating these calculations it is possible to change parameters and obtain results rapidly.

Before the ULS and SLS are treated the structural system is explained. After the ULS and SLS are treated the stability of the system is addressed.

H2.1. Structural system

In the original application the floors were used as two way point supported slabs, which are described in appendix F. In the new design the floor elements are applied simply supported as is shown in figure 0.58.

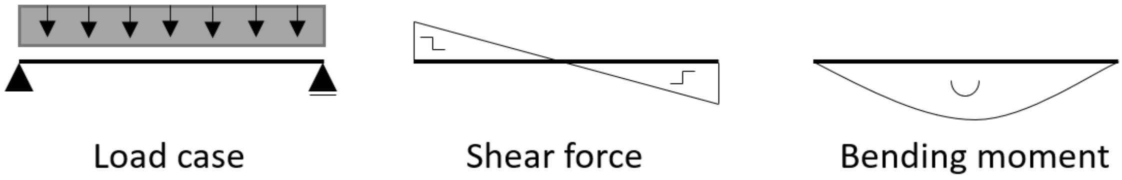


Figure 0.58: Load case, shear force graph, and bending moment graph (own figure)

As can be seen in the figure, simply supported structures do not have support bending moments which is both an advantage as a disadvantage. The floor elements near the supports do not have to take up bending moments but in the middle of the span the bending moments are bigger.

According to Braam & Lagendijk (2011): a simply supported reinforced concrete floor element can be calculated as a reinforced concrete beam with a width of 1 meter.

Now that we know in which structural scheme the floor elements are applied, it is possible to derive the appropriate formulas to do the ULS and SLS checks necessary.

H2.2. Input parameters

Different input parameters are needed in the structural calculation. These parameters can be obtained in three different ways:

- Reading them from original drawings*
- Conducting different tests as described in appendix C
- Estimating them by rules of thumb**

* It is uncommon in practise that all original drawings are still available. Besides, it is not certain that the original drawings state all parameters and that these parameters are actually applied. Therefore, this method to obtain the parameters will be uncommon.

** This is mainly an option in an early phase of a project in which only a feasibility study is conducted.

If the elements are being reused it is always necessary to validate the parameters by testing. Therefore, the costs of testing are always added to the total costs, as described in appendix D.

The different input parameters which are needed in the calculation are shown in the following figure. In the tool some parameters can be chosen by a dropdown menu to make sure that they are entered in the right format.

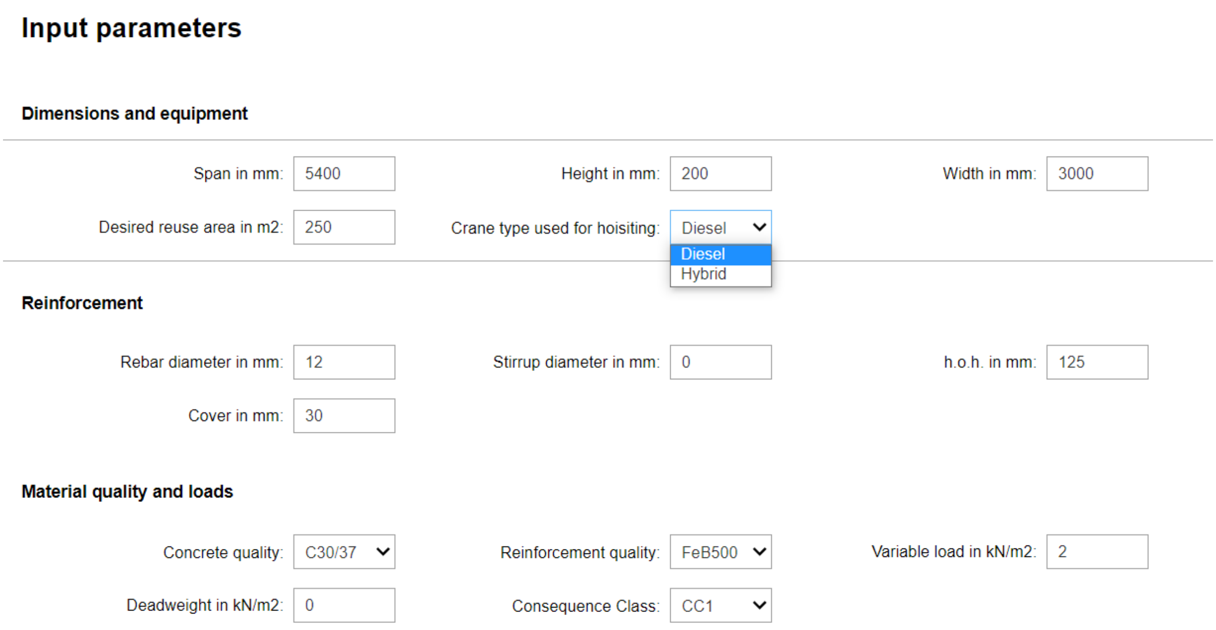


Figure 0.59: Input parameters in the tool (screenshot)

H2.3. Cross-section- and material properties

From the input parameters different cross-section properties and material properties can be calculated. The cross-section properties calculated and the used formulas are:

- $d = h - c - ø_{str} - \frac{1}{2} ø_r$
- $Ac = h * b$

Some cross-section properties are also calculated in the following paragraphs.

The material properties are traced from an Excel-file which holds all material properties as specified in the Eurocode. These properties are for example the E-modulus and the strength properties of the material.

H2.4. Loads

The loads on the structure can be divided in permanent- and variable loads. The permanent loads are:

- *Self-weight* $= h * 24$ *[kN/m²]*
- *Dead-weight [kN/m²]*

The variable load is prescribed by the Eurocode and is given as a force over an area:

- *Variable load [kN/m²]*

With these loads the load combinations for the SLS and ULS can be computed the following:

- *SLS load = 1,0 * total permanent load + 1,0 * total variable loads*
- *ULS load = (1,35 * total permanent load + 1,5 * total variable loads) * K_{FI}*

  K_{FI} = factor for the Consequence Class

Using these loads it is possible to compute the forces in the structural element. As described earlier the structural system is simply supported. Therefore, forget-me-nots can be used to compute the design forces:

- $M_{Ed} = \frac{1}{8} * q * l^2$
- $V_{Ed} = \frac{1}{2} * q * l$

These forces are used in the ULS and SLS checks.

H2.5 Ultimate Limit State (ULS)

In the Ultimate Limit State it is checked whether the structure can take up the applied forces on itself without collapsing. The three possible forces in a structure are: bending moments (M), shear forces (V), and normal forces (N). Normal forces may occur due to disk action of the floor which is related to the stability of the building (explained in H1). Because the application of the floor elements is in serial housing it is assumed that normal forces due to disk action are rather small. Therefore, only the bending moment resistance and the shear resistance are checked.

Bending moment resistance

First the bending moment resistance of the cross-section is calculated. When a cross-section is loaded in pure bending, as is the case in the structural system of the floors, three characteristic bending moments can be characterised. These bending moments are: the cracking moment, yielding moment, and the failure bending moment. The latter is treated in this part, the other bending moments are dealt in part H2.6. At the ultimate bending moment the reinforcement steel has already yielded and the concrete strain is equal to ε_{cu3} which equals 3.5 ‰. The height of the concrete compressive zone is equal to X_u. The stress and strain diagram of the cross-section at the ultimate bending moment are given in figure 0.60.

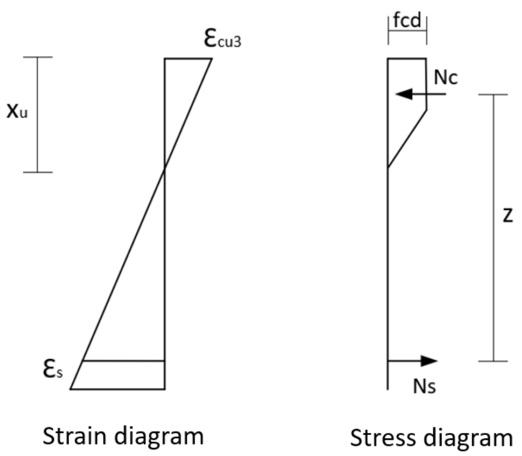


Figure 0.60: Stress- and strain diagram (own figure)

Only an external bending moment is applied to the cross-section. Therefore, the forces in the cross-section need to make horizontal equilibrium. This holds that the compressive force in the concrete

(Nc) needs to be equal to the tensile force in the reinforcement steel (Ns). These forces are calculated the following:

- $N_s = A_s * f_{yd}$
- $N_c = \alpha * x_u * f_{cd} * b$

In the formula of Nc a factor α is used. This factor is the surface factor of the geometry. For rectangular cross-sections with a concrete strength class lower or equal to C50/60, α equals 0.75 (Braam & Walraven, 2019). The only unknown in the equation is the height of the concrete compressive zone, X_u, which therefore can be calculated. Now it is possible to compute the bending moment resistance of the cross-section. This is done by computing the bending moment in the point Nc (Braam & Lagendijk, 2011):

- $M_{rd} = A_s * f_{yd} * z$

In which z is the internal lever arm of the cross-section. Z can be calculated the following:

- $z = d - \beta * x_u$

In the formula for the internal lever arm (z) a factor β is used. This factor is the centre of gravity factor (Braam & Walraven, 2019). This factor is used to compute the centre of gravity of the concrete compressive zone and thus the point at which Nc is attached.

Now the bending moment resistance is known, it is possible to check whether the cross-section can take up the applied load without failure. This is usually done by doing an unity check (UC). This unity check is calculated in the tool.

Shear resistance

Shear force is the force acting perpendicular to the floors plane. The force wants to push one part of the element upwards and the other part downwards (↑ ↓). In reinforced concrete it is common to apply stirrups to cope with these shear forces. However, in the monolithic floors which are being reused, it is possible that no stirrups are located (see appendix F). Therefore, only the shear force capacity of concrete is calculated. This shear force capacity is usually calculated using an elaborate calculation because the shear force distribution is complex. But the NEN-EN 1992-1-1 also specifies a safe lower bound value of the shear resistance (Braam & Lagendijk, 2011):

- $v_{rd,c} = v_{\min} = 0.0035 * k^{3/2} \sqrt{f_{ck}}$ with: $k = 1 + \sqrt{\frac{200}{d}} \leq 2.0$

Using this formula it is possible to calculate the shear resistance of the concrete without shear reinforcement. The total shear capacity is calculated the following:

- $V_{rd,c} = v_{rd,c} * b * d = v_{\min} * b * d$

When the capacity is known it is possible to check whether the concrete can cope with the applied shear force, which is usually done by computing an UC value. This unity check is done in the tool.

It is possible that there is no shear reinforcement located in the reused floor element. In the calculation explained above it is checked whether the element can cope with the shear forces without having shear reinforcement. So, if the element passes the calculation it can cope with the shear forces.

However, this does not mean that no shear reinforcement needs to be applied. The NEN-EN 1992-1-1 specifies a minimum amount of shear reinforcement in part 9.2.2. But there is a sidenote which needs to be made; In NEN-EN 1992-1-1 part 6.2.1.4 it is specified that the minimum amount of shear reinforcement does not have to be applied in plate like elements such as massive floor elements. The reused floor elements fall under this exception and therefore the elements do not need to have a minimum amount of shear reinforcement. So, concerning shear forces, the elements are safe if they pass the UC as described above.

H2.6. Serviceability Limit State (SLS)

The SLS is about the functioning of the structure. In the SLS the structure is calculated as if it is in normal use. According to the NEN-EN 1992-1-1 three aspects need to be checked in the Serviceability Limit States, which are:

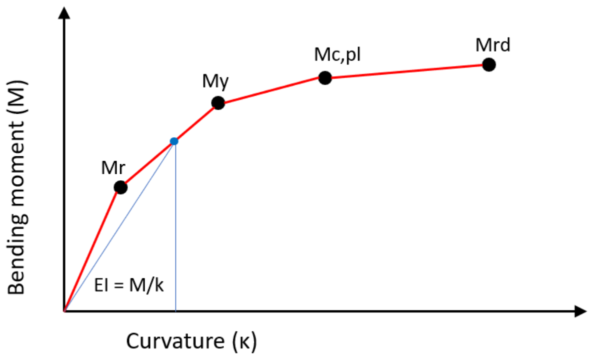
- Stress limitation
- Deflection control
- Crack control

Stress limitation means that the compressive stress shall be limited. This to avoid cracks from forming and to minimize creep. Cracks can influence the durability of the concrete because they lower the concrete cover locally. The floor elements, dealt with in this report, originate from office buildings and are reused in serial housing. The environmental class in which the concrete is situated is a class X0 (or XC1) which means that the concrete is not highly vulnerable for corrosion. Therefore, the durability of the structure is most likely not the limiting factor. If the floor elements are well checked on cracks, before reusing them, problems regarding stress limitation are not prone to happen. Therefore, stress limitation is not dealt with in the tool and not further elaborated on in this report.

In the following paragraph the other two SLS aspects, deflection and crack width, are elaborated on. Besides these checks it is also desirable that the structure 'warns' before failure. This means that the structure shows signs of failure, such as cracks or big deflections, before it collapses. When the cracking bending moment is lower than the failure bending moment the structure will give these signs. In the following paragraphs the M-κ diagram is derived. In this diagram it can easily be seen if the cracking bending moment is lower as the ultimate bending moment which means that the structure warns before failure.

Deflection

In the SLS the deflection of an element is calculated and it is checked whether this deflection satisfies the maximum deflection as specified in the Eurocode. The floor elements are made from reinforced concrete. Reinforced concrete is a combination of steel and concrete and therefore the bending stiffness (EI) of the cross-section is not easy to compute. The bending stiffness of reinforced concrete depends on the applied bending moment on the cross-section (Braam & Lagendijk, 2011). It is possible to derive the bending stiffness at SLS from the M-κ diagram of the cross-section as shown in figure 0.61. Therefore the M-κ diagram is first constructed whereafter the deflection is calculated and compared to the maximum deflection.



$$EI = \frac{M}{\kappa}$$

Figure 0.61: M-k diagram (own figure based on: CTB2220)

The M-κ diagram is constructed by computing the four characteristic bending moments and drawing straight lines in between. The four characteristic bending moments are:

- Mr = cracking bending moment. At this bending moment the first cracks in the materials start to show.
- My = yielding bending moment. At this bending moment the reinforcement steel start to yield.
- Mc,pl = 'stuikomemt'. At this bending moment the concrete start to have plastic deformation
- Mrd = failure bending moment. At this bending moment the cross-section fails.

These four bending moments are calculated whereafter the M-κ diagram is established. Using this M-κ diagram the bending stiffness (EI) of the cross-section at the SLS load case is derived and the deflection is calculated.

<u>Cracking moment</u>

The first point on the M-κ diagram is the bending moment at which cracks start to form. At this location the tensile stresses in the concrete are equal to the tensile strength of the concrete: $\sigma_{ct} = fctm$. From this point onwards the reinforcement steel will be activated and takes up the tensile forces in the cross-section. Therefore the bending stiffness of the cross-section, untill Mr is reached, is equal to that of a not reinforced cross-section: $EI = Ec * \frac{1}{12} * b * h^3$ (the steel is not activated). Because the cross-section is composed of more than one material a factor needs to be introduced which is the ratio between the different E-moduli of the materials. This ratio is αe:

- $\alpha e = \dfrac{E_s}{E_c}$ with: $E_c = \dfrac{f_{cd}}{1.75 * 10^{-3}}$

Now using this ratio it is possible to compute the kwadratic-surface-moment which is used to compute the height of the compressive zone x. This is done the following:

- $A_c = h * b$
- $As = \alpha e * \pi * \text{ø}_r^{\,2} * \#bars$
- $xc = h / 2$
- $xs = h - d$
- $x_{uncracked} = \dfrac{\Sigma Ai * xi}{\Sigma Ai}$

Next the mass moment of inertia can be calculated: $I_0 = \Sigma(I_{self} + I_{steiner})$ and EI computed using the E-modulus of concrete (Ec). Now the cracking moment Mr can be calculated:

- $Mr = f_{ctm} * W = f_{ctm} * \frac{I_0}{z_{under}}$ with $z_{under} = h - x_{uncracked}$

The last step is to compute the accopanying curvature using $\kappa_r = \frac{Mr}{EI_0}$ and the first point on the graph is known.

<u>Yielding moment</u>

The following point at the graph is the yielding point. At this point, the stress in the steel is equal to the yielding stress: $\sigma_s = f_{yd}$.

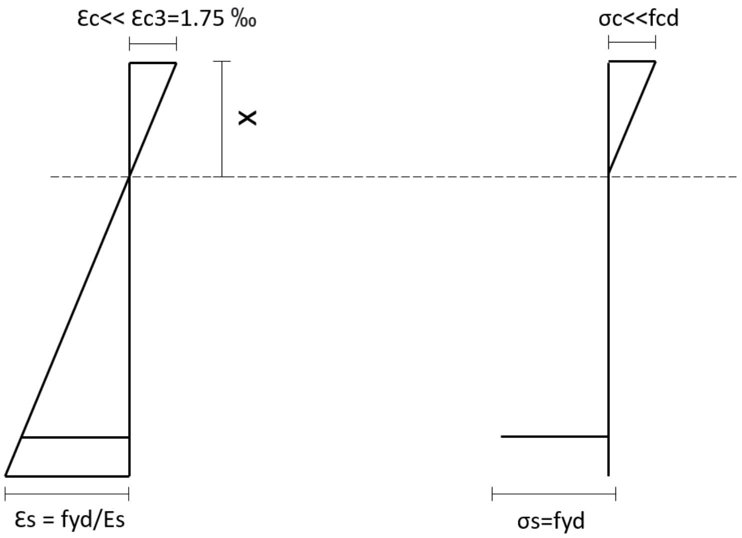


Figure 0.62: Stress strain diagram (own figure)

Based on the above shown stress and strain diagrams, the following formulas can be derived (Braam & Lagendijk, 2011):

- $\varepsilon_c = \frac{x}{d-x} * \varepsilon_s$
- $\sigma_c = \varepsilon_c * Ec = \frac{x}{d-x} * \frac{\sigma_s}{\alpha e}$

As long as $\varepsilon_c < 1.75‰$ (needs to be checked in the end) there is horizontal equilibrium in the cross-section which holds:

- $Nc = Ns$ which means: $\frac{1}{2} * b * x * \sigma_c = As * \sigma_s$

The height of the compressive zone (x) is the only unknown in this equation and can therefore be calculated. Using this height and the known steel stress fyd, the strain in the concrete can be calculated:

- $\varepsilon_s = \varepsilon_{sy} = \frac{fyd}{Es}$
- $\varepsilon_c = \frac{x}{d-x} * \varepsilon_s$

Using the strains and the height of the compressive zone it is possible to calculate the curvature and the yielding bending moment:

- $\kappa_y = \frac{\varepsilon_c + \varepsilon_s}{d}$
- $My = As * fyd * (d - \frac{1}{3} * x)$

With the curvature and the yielding bending moment the bending stiffness of the material can be found:

- $(EI)_y = \frac{My}{\kappa_y}$

Now the second point of the graph is known.

Plastic deformation concrete (betonstuik)

The next point on the graph is the point at which plastic deformation of the concrete occurs. This means that the strain in the concrete is equal to $\varepsilon_{c3} = 1.75‰$. At this situation the shape of the stress-strain diagrams is similar as in figure 0.62. However, the strain in the reinforcement steel is bigger, the strain in the concrete is 1.75 ‰ and the stress in the concrete is equal to fcd. There is still horizontal equilibrium in the cross-section, which means:

- $Nc = Ns$ which holds: $\frac{1}{2} * b * x * \sigma_c = As * \sigma_s$

The height of the compressive zone (x) is the only unknown in this equation and can therefore be calculated. Using this height it is possible to compute the steel strain:

- $\varepsilon_s = \frac{x}{d-x} * \varepsilon_c$

Now both the steel strain and the concrete strain are known, it is possible to calculate the associated curvature and bending moment:

- $\kappa_{c,pl} = \frac{\varepsilon_{c3} + \varepsilon_s}{d}$
- $M_{c,pl} = As * fyd * (d - \frac{1}{3} * x)$

With the curvature and the bending moment the bending stiffness (EI) can be calculated:

- $(EI)_{c,pl} = \frac{M_{c,pl}}{\kappa_{c,pl}}$

This results in the third point on the graph.

Bending moment resistance

The last point of the graph is the bending moment resistance. At this point the structure fails due to the applied bending moment. The strain in the concrete is equal to the maximum strain of concrete: $\varepsilon_{cu3} = 3.5‰$. Based on the horizontal equilibrium the height of the compressive zone can be calculated:

- $\alpha * b * x_u * f_{cd} = A_s * f_{yd}$

Using this height the steel strain can be calculated:

- $\varepsilon_s = \frac{d - xu}{xu} * \varepsilon_{cu3}$

Now the strains and the height of the concrete compressive zone (xu) are known the curvature and bending moment at failure can be calculated:

- $\kappa_{Rd} = \frac{\varepsilon_{cu3} + \varepsilon_s}{d}$
- $M_{Rd} = A_s * f_{yd} * z$ with: $z = d - \beta * x_u$

Finally the bending stiffness at failure is known: $(EI)_{Rd} = \frac{M_{Rd}}{\kappa_{Rd}}$

This gives the fourth and final point on the graph.

Thus all points of the M-κ diagram are known and the graph can be plotted, as shown in figure 0.63. From this graph the bending moment stiffness at SLS moment can be derived.

```
Bending stiffness EI equals 4664.206658830374 kNm2.
```

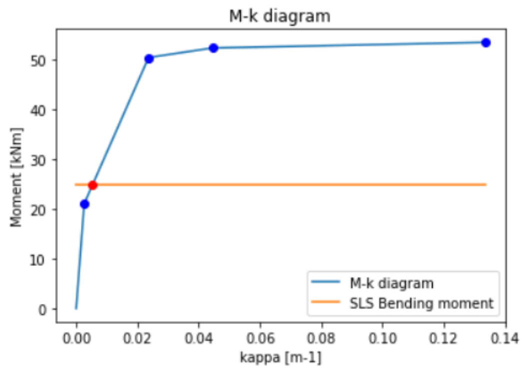


Figure 0.63: M-k diagram (screenshot)

Using this bending stiffness and a forget-me-not the deflection at SLS load can be calculated. This deflection can be compared to the maximum deflection for floors (w<0.004*L), as is specified by the Eurocode. The check on deflection is done in the tool.

Crack control

In the SLS check on crack control it is checked whether the formed cracks are below the maximum crack width. The maximum crack width is a parameter to ensure the durability of the concrete. If the maximum crack width is exceeded, it is likely that damage occurs to the rebar. The maximum crack width is prescribed based on the environmental class the concrete is surrounded in. The floor elements originate from office buildings and are reused as storey floors in residential buildings. Therefore the environmental class of the concrete does not change. The environmental class of the concrete is class X0 (or XC1). NEN-EN 1992-1-1 table 7.1N gives a maximum crack width, for reinforced concrete in a class X0 or XC1 environment, of 0.4 mm. According to the Eurocode this width is not governing based on durability but on aesthetics.

Before the maximum crack width in the new situation is calculated something needs to be mentioned about cracks which may have formed in the previous life of the element. In the previous application of the element (in the office building) it is most likely that cracks have occurred. Therefore, it is necessary that the element is examined and cracks are measured before the element is reused. The tool only calculates newly formed cracks and therefore the already formed cracks need to be measured before the element can get a second life.

The maximum crack width of the concrete can be calculated using the following formula (Braam & Lukovic, 2017):

- $$w_{\max} = \frac{1}{2} * \frac{fctm}{\tau bm} * \frac{Ø}{\rho_{p,eff}} * \frac{1}{Es} * (\sigma_s - \alpha * \sigma_{sr} + \beta * \varepsilon_{cs} * Es)$$

With: $\rho_{s,eff} = \dfrac{As}{b * h_{c,eff}}$

The cross-section is loaded in bending which means:

- $$h_{c,eff} = 2,5 * (h - d) \leq (h - x) / 3$$

The height of the concrete compressive zone is calculated using:

- $$x = (-\alpha e * \rho + \sqrt{(\alpha e * \rho)^2 + 2 * \alpha e * \rho}) * d$$ with: $\rho = \dfrac{As}{b * d}$ and $\alpha e = \dfrac{Es}{Ec}$

The maximum steel stress in the crack formation stage can be calculated the following, for cross-sections loaded in bending:

- $$\sigma_{sr} = \frac{M_{crack}}{z * As}$$

The steel stress at SLS bending moment can be calculated as:

- $$\sigma_s = \frac{M_{SLS}}{z * As}$$

It is assumed that the concrete does not have shrinkage anymore. This because the concrete is already of a considerable age. So, the shrinkage component, ε_{cs}, is assumed to be 0.

The factors α and τ_{bm} depend on the condition. In figure 0.64 these factors for different conditions are given:

	crack formation stage	stabilized cracking stage
Short term loading	α = 0,5 (0,6) β = 0 τ_{bm} = 2,0 f_{ctm}	α = 0,5(0,6) β = 0 τ_{bm} = 2,0 f_{ctm}
long term or dynamic loading	α = 0,5 (0,6) β = 0 τ_{bm} = 1,6 f_{ctm}	α = 0,3 (0,4) β = 1 τ_{bm} = 2,0 f_{ctm}

Figure 0.64: Parameters based on load condition (Braam & Lukovic, 2017)

Now all factors in the equation are known and the maximum crack width can be calculated. This calculation is done in the tool.

H3. Hollow core floors

The structural safety is of great importance. If the structure does not satisfy the requirements it is possible that the structure fails which could result in damage to persons or objects. Therefore the structural feasibility can be seen as a dealbreaker aspect in the design. When the structural feasibility cannot be proved the structure cannot be built. In this case it does not make sense to calculate the other aspects regarding the environmental impact and costs.

In this part the ULS - and SLS checks are explained. These different tests are all automated in the tool as is shown in chapter 7. In this part a similar approach is applied as used in part H2. First the structural system and the input parameters are explained. Thereafter the checks in the ULS and SLS are done.

H3.1. Structural system and loads

In the original application, the elements were simply supported on both sides and transferred loads in one direction. The structural system in the new (reused) application is similar to the one in the original situation. The slabs are supported on both sides by walls and transfer loads in one direction (length direction). The structural scheme is similar to the one shown in figure 0.58. Therefore similar formulas for the applied loads, as described in H2.4, can be used in this part.

It is possible that a structural topping is applied on top of the floor element. In the donor building this structural layer is used as a compression layer. This layer needs to be sawn in between the elements to free the elements. In the new application it is assumed that the structural topping does not add any strength. This assumption is made because it is unknown how strong the bond between the element and the topping is. In the calculations the topping is calculated as a dead weight on top of the floor. If the element does not meet the structural requirements, it is possible to see if the element would pass if the strength of the topping is taken into consideration. In this case the bond between the topping and the element needs to be derived from tests. This process is not described in this report.

H3.2. Input parameters

The input parameters, needed in the different calculations, are shown in figure 0.65. In this figure it can be seen that different properties regarding the prestressing are needed. It is possible to calculate slab elements with 3 different layers of prestressing. This option is made in the tool because it is possible that three layers of prestressing reinforcement are present in the elements. For different input parameters dropdown menus are given to make sure the info is presented in the right format.

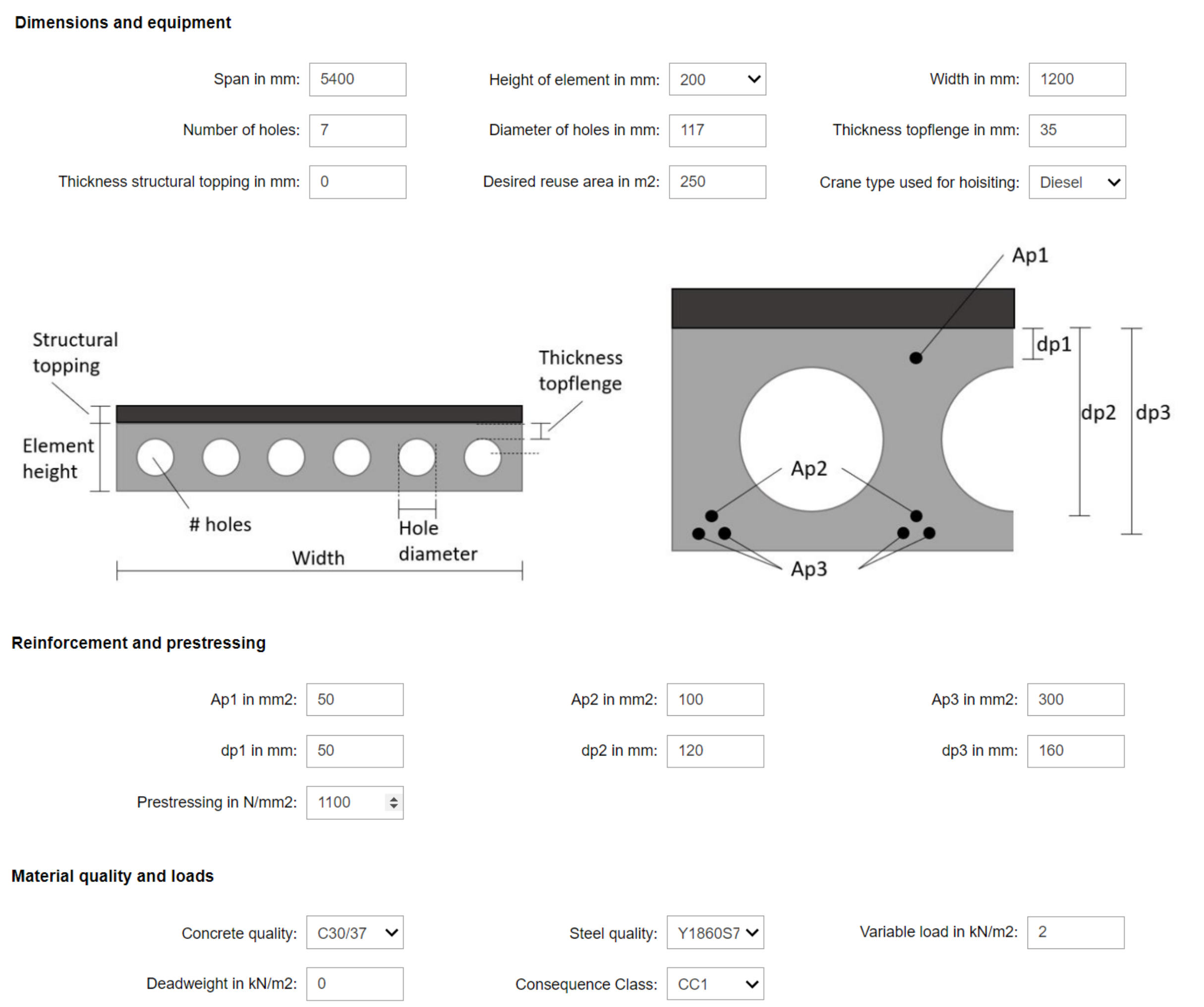


Figure 0.65: Input parameters (screenshot)

The input parameters can be obtained via three different ways. These three approaches are similar to those explained in H2.2.

H3.3. Cross-section – and material properties

Several cross-section properties are needed in the different calculations. The needed properties related to the cross-section layout are: concrete area, mass moment of inertia, and first moment. These tree properties can be calculated using respectively the following three formulas (Braam & Walraven, 2019):

$$Ac = b*h - \frac{1}{4}*\pi*d^2*\#holes$$

$$Ic = \frac{1}{12}*b*h^3 - \frac{\pi}{4}*r^4*\#holes$$

$$S = \frac{b*h}{2}*\frac{h}{4} - \frac{1}{2}*\pi*r^2*\frac{4*r}{3*\pi}*\#holes$$

The different material properties are taken from an Excel-file. In this Excel file all properties of different materials are given based on the Eurocode. This is similar to the tool for monolithic floors.

An important aspect concerning the prestressing, is the amount of prestressing losses. The elements originate from office buildings with a construction date between 1970 and 1990. This means the elements are already 30 to 50 years old. The prestressing force has decreased over this time period due to different prestressing losses such as shrinkage, creep, and relaxation (Braam & Walraven, 2019). The exact prestressing losses can be calculated using an elaborate calculation. However, in the calculations done in this report the total amount of prestressing losses is estimated. It is estimated that the total prestressing losses are 20%. This value is derived from 3 sources: a lecture about prestressed concrete by the Avans technical school (2021), the book prestressed concrete by Braam & Walraven (2019), and the lectures of the CIE4160 course by Sandra Nunes (2021). This value was also backed during the interview with the experts of VBI. They use this value to calculate the strength of the element at a time of 50 years from manufacturing.

H3.4. Ultimate Limit State (ULS)

The ultimate limit state is related to the strength of the structure. The structure needs to be able to cope with the applied forces. In these parts the bending moment capacity and the shear resistance of the cross-section are checked. The checks related to the applied normal forces are disregarded. The floor elements are applied in serial housing which means that they only need to have little disk action as explained in appendix H1. Therefore it can be assumed that normal forces in the floors are rather small and will not cause problems.

Bending moment resistance

The bending moment resistance of a prestressed cross-section can be found based on the stress-strain diagram of the cross-section. This stress-strain diagram is given in figure 0.66.

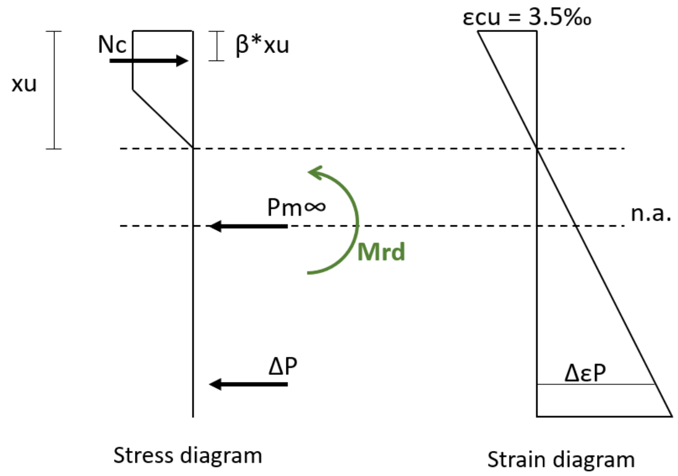


Figure 0.66: Stress strain diagram (own figure)

In the aboveshown figure only one stress and strain are given related to the prestressing strands. However, it is possible to indicate three layers of prestressing reinforcement in the input parameters. For these three layers an equivalent prestressing is assumed in the cross-section. The stress and strain related to this equivalent prestressing is shown in figure 0.66.

Another assumption is made regarding the neutral axis (n.a.) of the cross-section. It is assumed that the neutral axis is located on a level of height over two (half height). This assumption is made based on different cross-sections found online of which the level of the neutral axis was known.

The cross-section is stable which implies that the forces need to make horizontal equilibrium. The forces present are:

- Nc = concrete compressive force
- Pm∞ = prestressing force
- ΔP = increase of prestressing force

From these three forces two are unkown: Nc and ΔP. Both of these forces are dependend on the height of the concrete compressive zone xu. So there is one equations and one unknown which can be solved. In a rectangular cross-section the concrete compressive force can be caluclated the following:

$$Nc = \alpha * fcd * xu * b$$

However, in this chapter hollow core slabs are treated which have a rectangular cross-section but there are holes in it. Therefore it is not possible to use a standard value for alpha as was the case in the calculation of the monolithic floors. The concrete compressive force is equal to the area of xu multiplied by the concrete stress. The area of xu is dependent on the widht. The widt of the cross-section is different over the height. The maximum width is located at the top of the cross-section and is b=1200 mm. In the middle of the cross-section the holes are located which results in the lowest width of $bw = b - \#holes * holedia$. In the calculations for the concrete compressive force, Nc, it is assumed that the holes are square. In the bottom of figure 0.67 this assumption is shown. In the top part of the figure the actual situation is shown. This assumption results in less concrete area which result in a weaker cross-section and is thus an underestimation of the capacity.

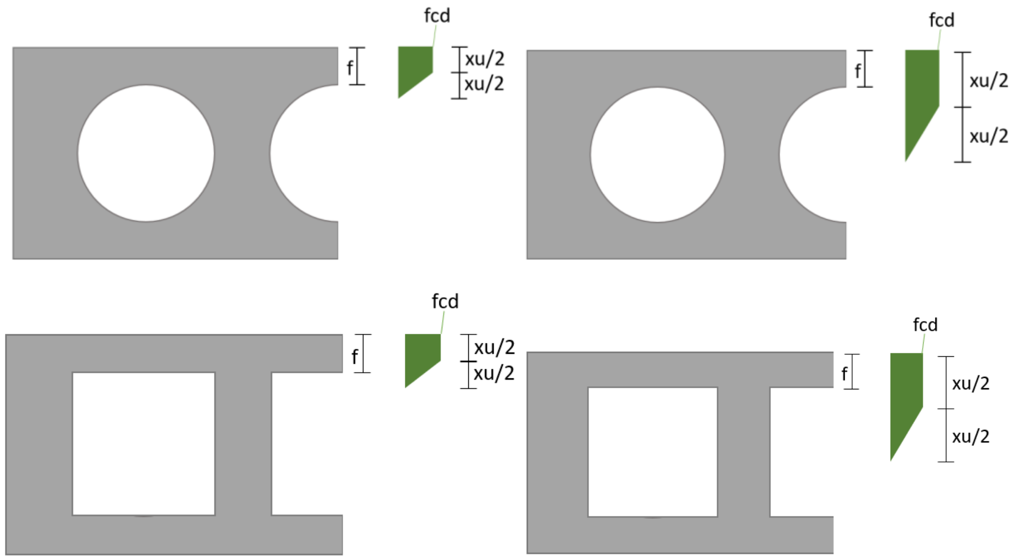


Figure 0.67: Stresses in cross-section, actual case in top and assumed in bottom (own figure)

In the figure it can be seen that the force is assumed to be bi-linear. This assumption is also made in the book 'constructieleer in gewapend beton' (Braam C. , 2012) and the lectures of the CIE4160 course (Nunes, 2021). Based on the figures a function is made in Python which calculates the value of Nc. A screenshot of the script is sown in figure 0.68.

```
def NCfunc(xu):
    if xu/2 < f and xu > f:
        NC = xu/2*fcd*width+(f-xu/2)*fcd/(xu/2)*(xu-f)*width+(f-xu/2)*(fcd-fcd/(xu/2)*(xu-f))*0.5*width+0.5*(xu-f)*fcd/(xu/2)*(xu
    if xu <= f:
        NC = 0.75*fcd*xu*width
    if xu/2 > f:
        NC = f*fcd*width + (xu/2-f)*fcd*bw + xu/2*fcd*0.5*bw
    return NC
```

Figure 0.68: NC function in Python (screenshot)

Next the increase in prestressing force can be calculated. The increase in prestressing force can be calculated based on the strain diagram. This calculation is also done in Python and shown in figure 0.69.

```
def ΔPfunc(xu):
    Δεp = (dptot-xu)/xu*Ɛcu3
    εptot = σpinf/Ep+ Δεp
    eps = fpd/Ep
    σp = fpd + ((εptot-eps)/(εud - eps)) * (fpk/1.1 - fpd)
    ΔP = σp*Aptot - pminf
    return ΔP
```

Figure 0.69: Delta P function in Python (screenshot)

Both forces are dependent on the height of the concrete compressive zone xu and it is known that there needs to be horizontal equilibrium in the cross-section. Thus the following equation needs to be met:

$$Nc = \Delta P + Pm\infty$$

This equation has as only unknown the height of the concrete compressive zone and therefore this height can be calculated. The height of the concrete compressive zone is calculated in the tool using an iterative process. When the height is known the forces NC and ΔP can be calculated.

Next the bending moment resistance of the cross-section can be calculated. The bending moment resistance can be calculated by taking the sum of bending moments around the point at which Nc is applied. This force is located on a distance β*xu from the top of the cross-section. The value for β is 0.39 for rectangular cross-sections however this standard value can not be used due to the holes in the hollow core element. Beta is related to the center of the force Nc. The value for β is caluclated in the tool based on geometry. The code of this calculation is shown in figure 0.70.

```
def Betafunc(xu):
    if xu/2 < f:
        A = fcd*xu/2*width
        B = (f-xu/2)*(fcd/(xu/2)*(xu-f)) * width
        C = (fcd - (fcd/(xu/2)*(xu-f)))*(f-xu/2) * 0.5 * width
        D = (fcd/(xu/2)*(xu-f)) * (xu-f)* 0.5 * bw
        beta = (A*0.5*xu/2 + B*(xu/2 + (f-xu/2)/2) + C*(xu/2+(f-xu/2)/3) + D*(f+(xu-f)/3))/(A+B+C+D)
        β = beta/xu
    if xu/2 > f:
        A = fcd*f*width
        B = fcd * (xu/2-f)* bw
        C = fcd*xu/2*0.5*bw
        beta = (A*0.5*f+B*((xu/2-f)*0.5+f)+C*(xu/2+xu/6))/ (A+B+C)
        β = beta/xu
    return β
```

Figure 0.70: Code to calculate Beta (screenshot)

Now all values are known and the value of the bending moment resistance can be calculated. This bending moment resistance can be compared to see whether the cross-section is strong enough to cope with the applied forces. An important note needs to be added to the applied bending moment. The bending moment due to the eccentricity of the prestressing needs to be taken into consideration in the applied bending moment. Thus the applied bending moment has a part related to the applied forces on top of the floor and a part related to the eccentricity of the prestressing. The unity check on bending moment resistance is done in the tool as can be seen in part **Fout! Verwijzingsbron niet gevonden.**.

Shear resistance

It is uncommon to apply stirrups in hollow core slabs. Therefore, the shear resistance without shear reinforcement is checked. In new applications there is usually a minimum amount of shear reinforcement for reinforced/prestressed concrete elements. However according to NEN-EN1992-1-1 part 6.1.4. this minimum amount of shear reinforcement does not have to be applied in plate like elements such as hollow core elements.

The shear resistance of the cross-section is dependent on whether the cross-section is cracked. In this part both the shear resistance of the cracked and the uncracked zone are checked. The shear resistance of the uncracked zone is related to the tensile splitting force according to the Eurocode. In the tool the maximum applied shear force is checked with both the resistance in the cracked and the uncracked zone.

Cracked zone

The shear resistance of simply supported prestressed elements without shear reinforcement, which are cracked due to bending moments, can be calculated using the following formula (NEN-EN1992-1-1 part 6.2.2.2.):

$$V_{Rd,c} = [C_{Rd,c} * k * (100\rho_l * f_{ck})^{1/3} + k_1 * \sigma_{cp}] * b_w * d$$

This shear reinforcement has a minimum value of vmin:

$$v_{rd,c} = v_{\min} = 0.0035 * k^{3/2}\sqrt{f_{ck}}$$ with: $k = 1 + \sqrt{\frac{200}{d}} \leq 2.0$

In the calculation done it is chosen to use the minimum value of the shear reinforcement because it is likely that the cross-section will satisfy the needed shear resistance due to the line supports. If the minimum value does not pass it is possible to check whether the actual shear resistance meets the requirements.

The shear resistance of the cross-section is checked for the smallest width of the cross-section. The check is done using an unity check.

$$V_{Rd,c} = v_{rd,c} * bw * d = v_{\min} * bw * d$$ with: $bw = b - \#holes * holedia$

Uncracked zone

In parts which are uncracked under bending the shear resistance needs to be limited by the tensile splitting force of the concrete. In this case the following formula needs to be used (NEN-EN1992-1-1 part 6.2.2.2.):

$$V_{Rd,c} = \frac{I * bw}{S} * \sqrt{(f_{ctd})^2 + \alpha_l * \sigma_{cp} * f_{ctd}}$$ Where: $\alpha_l = l_x / l_{pt2} \leq 1.0$

In the calculations an assumption is made regarding the value of α_l. It is assumed that α_l = 0.5. Different calculations were checked and from these calculations the assumed value is derived.

This tensile splitting force is checked with the applied shear force in the cross-section with the execution of a unity check (UC). If the cross-section does not satisfy with the assumed value of α_l, it is advised to do a separate calculation for this parameter. It can be possible that the cross-section passes with this adjusted value.

H3.5. Serviceability Limit State (SLS)

In the servicabilyt limit state it is checked whether the structure functions as desired. In this state the loads applied are similar to those which are present during normal use. Accroding to the Eurocode there are three differnet checks related to te SLS:

- Stress limitation
- Deflection control
- Crack control

Stress limitation is usually predomently an issue during the first period of the structural elements. This apsect involves the cracking of the concrete which could result in durability issues. Stress limitation is probably not an isue for the floor elements treated in this report as is more eleborately explained in H2. Thererfore, checks related to stress limitation are disregarded.

The other two aspects are delfection and crack control. Both of these aspects are related to the cracking bending moment of the cross-section. In the calculation of the deflection, the bending stiffness of the cross-section (EI) is needed. This value depends on whether the cross-section is cracked or not. Aspects related to crack control are also depended on the cracking bending moment. Therefore, first the cracking bending moment is adressed.

Cracking bending moment

The cracking bending moment is the bending moment at which the first cracks are formed. It marks the start of the crack formation stage in the M-k diagram. The cracking bending moment can be calculated using the following formula (Braam C. , 2012):

$$M_{cr} = (f_{ctm} + \sigma_{pm,\infty})W_o$$

Where: $W = \frac{I}{z}$ $\qquad f_{ctm} = 0.30 * f_{ck}^{2/3} (\leq C50/60)$ $\qquad \sigma_{pm,\infty} = \frac{P_{m,\infty}}{A_c}$

Using these formulas it is possible to calculate the cracking bending moment. This process is automated in the tool which makes it possible to check different possibilities by the click of a button. The cracking bending moments for several cross-sections and loads were computed in the tool. It was found that the applied bending moment is 'always' lower as the cracking bending moment (with realistic values). Therefore, it can be concluded that the cross-section stays uncracked. This has two consequences: there is no need to control the cracks because they are not formed, and it is possible to calculate the deflection using the E-modulus of uncracked concrete.

Deflection

As explained in the previous paragraph it is possible to use the E-modulus of uncracked concrete to calculate the deflection of the floor element. The total deflection of the cross-section consists out of two parts: a part related to the uniformly distributed load (↓), and as a result of the prestressing forces applied to the bottom of the cross-section (↑). The total deflection due to the prestressing and the applied load can be calculated using the following formula (Avans Hogeschool , 2021):

$$w_{tot} = w_q + w_p = \frac{5}{384} * \frac{q * L^4}{E_c * I} + 2 * \frac{M_p * L^2}{16 * E_c * I}$$ with: $M_p = P_{m,\infty} * e_p$

This formula is derived from different standard forget-me-nots. Using this formula it is possible to calculate the total deflection of the cross-section under loading. This total deflection can be checked with the maximum allowable deflection of $w_{\max} = 0.004 * L$. In the tool it is checked if the deflections stay below this limit. The original upward deflection due to the original prestressing or the possible downward bending moment due to creep are not considered in the tool.