Circularity potential in building adaptation projects and building demolition projects

Thesis

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Circularity potential in building adaptation projects and building demolition projects

A tool to measure what the circularity potential of a building adaptation project or building demolition project is.

A thesis submitted to Delft University of Technology for the degree of Master of Science in Architecture, Urbanism and Building Sciences

By

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P5 Report

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Colophon

Circularity potential in building adaptation projects and building demolition projects
A tool to measure what the circularity potential of a building is, and how circularity can be applied

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´´In the end, the term ´circularity´ may just be one way to make us aware that we need a more encompassing, integrated and restorative sustainability path that includes people as much as technology and nature´´

~ Michiel Schwartz

Preface

This graduation thesis revolves around circularity in the built environment, specifically focussed on building adaptation projects and building demolition projects. The accommodating theme is 'Circular-adaptable real estate reuse to react to societal changes' for the master track Management in the Built Environment at the University of Technology in Delft.

This report contains a research into the complexity of circularity in the built environment, how it can be measured and how it can be applied. In this research, a tool has been developed which helps to identify what the circularity potential of building adaptation projects and building demolition projects is.

The reason I chose to follow the Management in the Built Environment master track is because of my interest in the real estate market. More specifically, the question on how to satisfy demands in the real estate market through looking for opportunities within the existing building stock has interested me increasingly in the last years. Lately I have always found it very interesting how demands for real estate keep increasing, while there are also many vacancies in the existing building stock. Something in this paradoxical issue intrigued me to have my thesis be focussed around a subject regarding opportunities in existing building stock. Furthermore, circularity in the built environment also plays a large role in this thesis. For myself, I was always a bit unclear and a bit sceptical on the opportunities regarding circularity in the built environment. Hence, I wanted to delve deeper in this subject as well, to find out where the complexities lie and how they can potentially be approached and solved.

I would like to thank my supervisors from the Delft University of Technology; Vincent Gruis and Hilde Remoy. Your knowledge and expertise surrounding the subject of my thesis has truly helped a lot in defining my research. Your feedback, support and enthusiasm throughout the whole process has been affecting and inspired me to continue improving and learning about more aspects around the topic than I could have imagined at the beginning.

I would also like to thank Marjolijn Versteegden and Robbin Schinkel at Arcadis. You helped me with getting into contact with so many interesting contacts within Arcadis and outside of Arcadis. This truly helped to elevate the research to the next level. Furthermore, you were always supportive of my progress and willing to help wherever this was possible.

Lastly, I would like to thank everyone who participated in this research, either through exploratory interviews, in depth interviews, project visits or simulation tests.

I hope you enjoy reading this report as much as I enjoyed researching!

Berend Langenberg
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Abstract

On the real estate market, there will always be a demand for newly constructed real estate. Demand and supply are never quite in balance, meaning that the construction of new real estate will always exist. However, looking for opportunities to satisfy the demand with the existing building stock is often forgotten or neglected. 87% of the needed buildings in 2050 have already been built (Wilkinson & Remoy, 2017). This is why building adaptation is so important. Concepts such as circularity, renovation and adaptive reuse are very important in the real estate market. When real estate is constructed circularly, it is 'modular and flexible by design where resource loops are closed and human well-being is promoted' (Leising et al., 2018). Therefore, building adaptation is a circular measure, and building demolition can and should be done circularly as well. Building adaptation and circular demolition are central in this research. Adaptive reuse is part of building adaptation, and means a major change to an existing building with alterations of both the building itself and the function it accommodates, so across-use adaptation (Wilkinson, 2014). Renovation is similar to adaptive reuse, only the function stays the same, so within-use adaptation (Wilkinson, 2014). These concepts all focus on using the existing building stock to satisfy demands, rather than to construct new buildings. Functional, technical, cultural, legal and location factors have been thoroughly mapped out in previous literature to establish what makes a building suitable for transformation or renovation (Ginelli, 2016). However, circularity potential and ways on how to determine circularity potential in building adaptation projects and demolition projects have not been clearly mapped out yet. With circularity becoming increasingly popular because of future goals that need to be met, it becomes important that clear ways to map out circularity potential in such projects are developed. This research fills in this research gap by creating a tool which gives a circularity potential score to existing buildings which will either be adapted or demolished, and shows which circularity measures can be taken. Furthermore, the tool will give indications on potential CO_2 emission savings by applying circular strategies. Because there is no one way to approach this, instead of a main research question, a main research aim has been set up: *To develop a tool which measures and identifies what the circularity potential of building adaptation projects and building demolition projects is.* This tool is originally inspired by the conversion potential meter, developed by (Geraedts et al., 2018). Further on in the research, many extra tools and frameworks inspired the final result of the tool; the Circularity Potential Meter.

Keywords: Building adaptation, demolition, circularity, built environment, tool

Executive summary

Introduction

On the real estate market, there will always be a demand for newly constructed real estate. Demand and supply are never quite in balance, meaning that the construction of new real estate will always exist. Solutions to satisfy the demands on the real estate market are often sought by constructing new real estate. However, even though 87% of the needed buildings in 2050 have already been built, the already existing building stock is often overlooked when trying to satisfy demands. (Wilkinson & Remoy, 2017). This is where building adaptation and circular demolition in the built environment comes into play. With building adaptation, renovation and transformation projects of existing buildings are meant. Circular demolition looks at ways to dismantle buildings while retrieving as many resources as possible for potential future reuse.

Within the built environment, circularity is also becoming increasingly more popular. Circularity in the built environment can be defined in many ways. For this research, the 10R Framework by potting et al. (2017) is used to define circularity and will be explained further in a later section of this report. Circularity, building adaptation projects and building demolition projects form the main concepts of this report, which also leads to the main research goal:

'To develop a tool which measures and identifies what the circularity potential of building adaptation projects and demolition projects is'

This main research goal is based on the fact that circularity in the built environment is becoming increasingly popular. However, currently there is still confusion around what circularity in the built environment exactly is, and how it can be applied (Lacy & Rutqvist, 2015). In many cases, 'Lack of awareness, knowledge and experiences with the Circular Economy' is seen as one of the main barriers of applying the circular frameworks in practice (Çetin et al., 2021).

The developed tool will eliminate these barriers by combining multiple frameworks into one tool. This will illustrate how these circular frameworks are connected to each other and will therefore clarify what circularity in the built environment is and how it can be applied. A circularity potential 'score' for building adaptation projects and building demolition projects will result out of the tool, also indicating potential CO_2 emission savings when circular strategies are applied.

Methodology

The main research aim of this report will be achieved through qualitative research. Literature research is the main method used to gather sufficient background information about the main concepts. Empirical research is done to gain more insight in how this works out in practice. Simulation tests, in depth interviews, exploratory interviews and project visits have been conducted. The main body of empirical research comes from the exploratory interviews. This method was chosen because of the low threshold it has to set up an exploratory interview, therefore making it easier to come into contact with more experts.

Main takeaways

In order to develop the tool which identifies what the circularity potential in building adaptation projects and building demolition projects is, it became evident that a good understanding of factors which determine circularity potential is essential. In order to gain this understanding, it is crucial to

know which factors there exist which influence this circularity potential in the first place, and to which elements these factors even apply.

The NL SFB list is an official categorization system of building elements. The list consists out of nine categories, each consisting out of a list of building elements. For developing the tool, this list has proven to be very useful, because it shows which building elements a building consists of, therefore showing to which building elements circular strategies can be applied.

The possible circular strategies which can be applied are retrieved from the 10R Framework by Potting et al. (2017). This framework shows 10 circular strategies, rated from R0 (most circular strategy), to R9 (least circular strategy). It provides a good basis to establish an understanding what exactly circularity is.

To determine which 'R' strategy will be applied, it became clear that the disassembly potential and condition of building elements must be determined. To measure potential CO2 emissions savings, the materials and the amounts of these materials must be determined. With this information, CO2 emission savings calculations can be made.

Frameworks

10R Framework

The 10R framework plays a big part in this research, as it is the main tool which describes possible circular strategies. The 10R framework originally is not developed for the built environment specifically. However, it can be applied to the building industry. The 10R framework shows 10 circular strategies (R0-R9), where R0 is the highest circularity level and R9 is the lowest circularity level (Potting et al., 2017). In this research, it became clear that the 10R framework is already used repeatedly in practice, either adapted 1 on 1, or with its own variation. The 10R framework is actually a valid model to make circularity clearer regarding the application of circularity in the construction sector. In practice, the following definitions are given to the 10 R's, when applied in the built environment:
R0, Refuse: Refuse/prevent loss of value
R1, Reduce: Use less resources
R2, Redesign: Redesign with a circular mindset
R3, Reuse: 1 on 1 reuse (2nd hand). Dismount element, transport for direct reuse
R4, Repair: Maintenance and repairs. Dismount element, transport, repair before reuse
R5, Refurbish: Fix up product. Dismount element, transport, fix up / modernise product before reuse
R6, Remanufacture: create a new product from 2nd hand products. Dismount element, transport and apply product in element with the same function.
R7, Repurpose: Reuse the product for something else. Dismount element, transport and apply product in element with different function.
R8, Recycle high value: Reuse resources.
R9, Recycle low value: downcycle resource.
R10, Recover: Energy recovery

NL SFB

The NL SFB list is used to determine to which building elements circular strategies can be applied. As mentioned in the main takeaways, it is crucial to understand all building elements to which the circular strategies from the 10R framework apply. This is where the NL SFB list is used. The NL SFB list is a list which categorizes buildings into building elements (BNA, 2005). In the tool developed in this research, the building elements in the NL SFB list will be tested on their disassembly potential and condition.

Based on these two factors, an 'R score' from the 10R framework is determined. Furthermore, when the materials and the amounts of the materials are known for the building elements in the NL SFB list, the tool makes calculations for potential CO2 emission savings.

Disassembly potential

Disassembly potential is a crucial factor when it comes to the circularity potential of building elements. With the disassembly potential, the ease in which a building element can be disassembled is meant is meant (van Vliet et al., 2021). When the disassembly potential of a building element is good, it does not have to be (partially) demolished in order to re-use it in a new project, making the circularity potential better. The same goes the other way around. When the disassembly potential of a building element is bad, it has to be (partially) demolished. Therefore, it cannot be reused 1 on 1 and has to be repaired, refurbished or even recycled for parts. As can be seen on the 10R framework, repairing, refurbishing and recycling score a lower level of circularity, therefore decreasing the circularity potential.

Condition (NEN 2767)

The NEN 2767 condition measurement is an effective way to objectively measure what the condition of building elements are. The building elements used in this method are also from the NL SFB list, which makes it that these two frameworks work together nicely. The condition of the building elements is based on three aspects, which are 'Flaw', 'Intensity', and 'Scale'. Based on these aspects, a condition score of 1 to 6 can be given to the building elements. The condition of a building element influences the circularity potential of this element. When the condition is very good, it could be reused, but when the condition is very bad and beyond repairing, it might have to be recycled or recovered.

Construction Material Pyramid

The last framework integrated in the developed tool in this research is the Construction Material Pyramid, by CINARK (CINARK, 2021). This framework shows the amount of CO2 emissions in kilograms produced when one cubic meter of this material is created. Therefore, this framework can be used to calculate the CO2 emission savings when building elements are reused in a new project, as these elements do not have to be created from scratch again. Based on this, the tool calculates an estimation on potential CO2 emission savings when building elements are reused in building adaptation projects or building demolition projects.

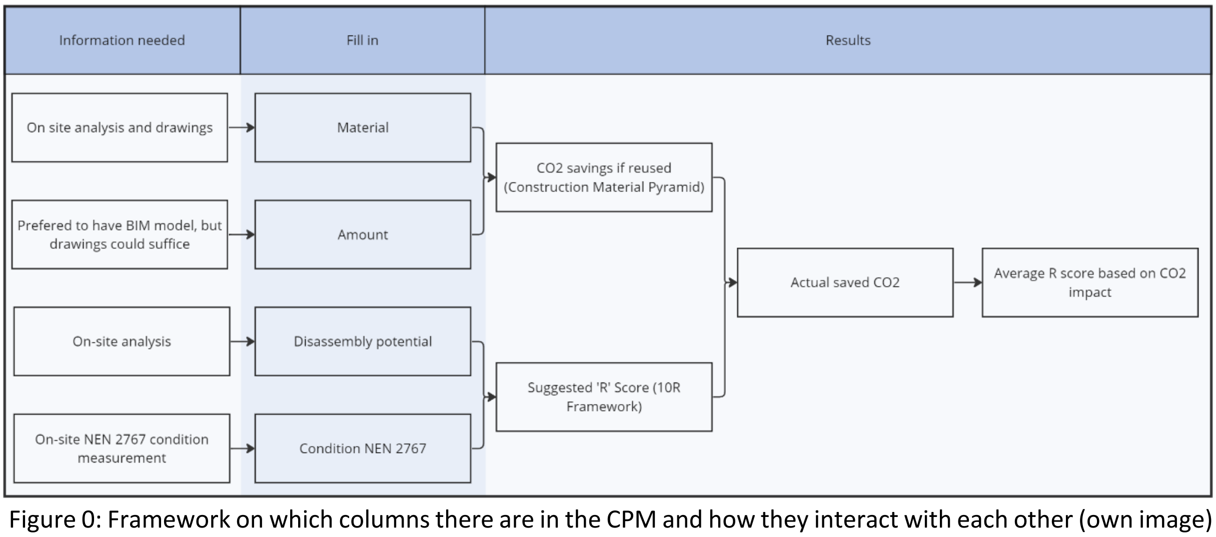

Figure 0: Framework on which columns there are in the CPM and how they interact with each other (own image)

Figure 0 shows how the explained tools and frameworks are connected. Furthermore, the image shows which cells in the tool will have to be filled in, which information you need in order to fill in the cells, and what the results given by the tool are. As can be seen, for each of the NL SFB building elements, the material, amount, disassembly potential and condition NEN 2767 has to be filled in. Based on this CO2 emission savings will be calculated, and a suggestion for an 'R score' will be provided by the tool. Based on the 'R score' provided by the tool, a correction on the CO2 emission savings is made. Then, based on the corrected CO2 emission savings, an average weighted 'R score' is calculated.

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1. Introduction

1.1 Introduction

1.1.1 The Built Environment

The built environment is a critical sector in many aspects, such as its influence on economy, society and natural environment (Çetin et al., 2021). Regarding environment, it is estimated that the construction sector is responsible for roughly 37% of global energy-related emissions (Hamilton & Kennard, 2022). Because of this large influence, the construction sector also has the potential to come with initiatives to diminish emissions on a large scale (Goldstein et al., 2013). Often, the solution is sought in constructing new buildings with high sustainability standards. However, adaptation and adaptive reuse of the existing building stock is essential, as 87% of the needed buildings in 2050 have already been built (S. J. Wilkinson & Remoy, 2017). That is why adaptive reuse and renovation are a good way to diminish emissions in the construction sector (Remøy, 2014b). Throughout this research, adaptive reuse projects (transformation projects) and renovation projects will be described as 'building adaptation projects'.

Another way to diminish the emissions in the construction sector is by adapting to a circular economy (Benachio et al., 2020). The concept of circular economy has been embraced as an approach for minimising resource inputs and outputs by introducing cyclic principles (Çetin et al., 2021). These cyclic principles consist of for instance the recovery of building waste after a building has been demolished, through material reuse and recycling. This, in its turn, reduces energy consumption and has environmental benefits such as waste reduction (Assefa & Ambler, 2017). Therefore, approaching demolition projects with circularity principles in mind, is crucial to diminish emissions as well. There are many definitions of what exactly a circular economy is, but all definitions include key words such as 'life cycle approach', 'reuse' (of materials and buildings) and recycle (Çetin et al., 2021). Aseffa & Ambler (2017), describe it as 'an economy that ideally eliminates wastes while maintaining the added value in products in a closed loop'. Recently, building adaptability and adaptation have been understood as key concepts that fit with the principles of the circular economy and a circular built environment (Ness & Xing, 2017). Circular-adaptable real estate fits well in such a circular economy. Circular-adaptable real estate is the adaptation of obsolete and/or vacant buildings, while also incorporating circularity (Hamida et al., 2022). It implies that major parts of the original building, such as the structure, are retained, while other parts of the building are replaced and upgraded to suit new standards and changing requirements (Bullen, 2007). It contributes to the sustainability goals by reusing the existing building stock and breathing new life into it.

1.1.2 Adaptive reuse

This research will go further into depth about circularity within the construction sector, and building adaptation projects of vacant and/or obsolete buildings, and demolition projects. Vacancy and obsolescence are related to each other in the sense that obsolescence is caused by vacancy and vacancy is also caused by obsolescence. Obsolescence is defined as 'the loss of ability of an item to perform satisfactorily due to changes in performance requirements' (ISO), 2011), which according to Muldoon-Smith, (2016), can be indicated by high levels of vacancy. Obsolescence means that a building has aged in a sense that it cannot house its function in a proper manor anymore. When the functional lifetime has been reached, the building will eventually become vacant. Vacant and/or obsolete buildings are therefore very much connected to building adaptation and demolition projects (Armstrong et al., 2021). Building adaptation tackles vacancy, which therefore tackles building obsolescence as well.

1.1.3 Circularity

Next to building adaptation, applying circularity principles is crucial in order to reduce CO_2 emissions as well. One way to explain circularity is by the 10R model by (Kirchherr et al., 2017) (Potting et al., 2017). This model shows 10 R's regarding circularity from R0, 'Refuse', to R9, 'Recover', where R0 is the best way to apply circularity, and R9 is the least circular intervention you can take. In other words, this model shows which circular measures can be taken in projects, and grades them in how effective they are. These circular measures from the R ladder, are based on two crucial factors, which are the disassembly potential of elements and the condition of the elements (Többen & Opdenakker, 2022). This will be further explained in chapter 2.3.7 and 2.3.8.

1.1.4 Tools

In the past, tools have been developed which measure circularity potential or adaptive reuse potential. One of the tools which measures adaptive reuse potential is called the Transformation Potential Meter (TPM), by Geraedts et al., (2018). This tool originally inspired this research to develop a similar tool which measures the circularity potential of adaptation projects and demolition projects. During research, other tools used in practice were discovered as well (Appendix A, Company L 21st of March, Person PP 11th of April), further inspiring this research to develop an independent tool solely focussed on measuring circularity potential. The tools which inspired this research will be shortly explained here, and will be further elaborated on in chapter 2.5.

Transformation Potential Meter (TPM)

The TPM works with 6 steps (step 0 to step 5) (table 1). Step 0 is a market scan to appraise the supply and demand of both offices and housing. Should the market be suitable, you can pursue to step 1. Step 1 is a quick scan including veto criteria. These are 8 crucial criteria, meaning that if one of these criteria is not met, the building is not suitable for transformation. Step 2 is a more in dept scan after step 1 is successfully finished. It includes feasibility scans regarding both the context of the building and of the building itself. In total there are 23 and 28 criteria respectively which the building can score points on from a scale from 1 (good) to 3 (bad). Step 3 determines the transformation class, which is based on the scores gathered from step 2. The lower the score, the better the transformation potential (table 2). Step 4 and 5 are optional and go further into dept about the financial feasibility of the project and the risk assessment checklist. The TPM will be further explained in chapter 2.5.1.

Transformation potential meter			
Step	**Action**	**Level**	**Outcome**
Step 0	Inventory market supply of unoccupied offices	Stock	Location of unoccupied offices
Step 1	Quick Scan: initial appraisal	Location	Selection or rejection of offices for further
	of unoccupied offices using veto criteria	Building	study; GO / NO GO decision
Step 2	Feasibility scan: further appraisal	Location	Judgement about transformation potential
	using gradual criteria	Building	of office building
Step 3	Determination of transformation class	Location	Indicates transformation potential on 5-point
		Building	scale from very good to NO GO
Further analysis (optional, and may be performed in reverse order if so desired):			
Step 4	Financial feasibility scan using design	Building	Indicates financial/economic feasibility
	sketch and cost-benefit analysis		
Step 5	Risk assessment checklist	Location	Highlights areas of concern in
		Building	transformation plan

Table 1: Step 0 – step 5 TPM (Geraedts et al., 2018)

STEP 3: DETERMINATION OF TRANSFORMATION CLASS OF OFFICE BUILDING			
Transformation score Location + Building = 0 - 40	Transformation class 1: Excellent transformability	Total Score A + B:	
Transformation score Location + Building = 41 - 80	Transformation class 2: Transformable	laximum Score Location + Building	
Transformation score Location + Building = 81 - 120	Transformation class 3: Limited transformability	= 115 + 84 =	199
Transformation score Location + Building = 121-160	Transformation class 4: Very poor transformability		
Transformation score Location + Building = 161-199	Transformation class 5: Not transformable	RANSFORMATION CLASS:	

Table 2: Determination of transformation class of office building (Geraedts et al., 2018)

The TPM was developed in 2007 and requirements have changed since then. Therefore, the TPM was updated to a newer version in 2018. Circularity only gained popularity over the last decade (Benachio et al., 2020), but most of the previous research and the TPM do not include these factors of circularity in the determination on whether to take on a project or not. That is why this research will look further into the role that circularity factors play in building adaptation projects and demolition projects.

Material Passport

For this research, a project visit was organized with a company who make material passports of buildings which will either be renovated in the near future, or which will be demolished in the foreseeable future (Appendix A, Company L, 21st of March) . In the case of this project visit, a material passport was being made for a building in Tilburg, for which the future was not clear yet. It was not clear whether the building would still be there in 5 years or in 25 years. Nonetheless, a material passport had to be made, on the instructions of the municipality.

For making this material passport, 2 people would walk around the building, establishing many details within the building. This was done with a tool, controlled via a tablet. Of all the elements in the building, ranging from window frames and doorframes, to the main structure of the building, certain specifics had to be filled in in the tool. First the element would be looked up in the NL SFB database. The fact that the NL SFB database was also used in this tool shows that this list is very suitable for building categorization. Once the correct element was selected, material had to be filled in, its category, its technical quality, its aesthetic quality and the disassembly potential had to be registered. From this project visit, useful information was gathered on what works well and what does not work as well. This will be further explained in chapter 2.5.2.

Arcadis tool

Arcadis has also developed a tool regarding circularity. There was a tender for circular demolition via Arcadis, for which they invited five companies who could send their plan of approach for the project. In order for the companies to send this plan of approach, Arcadis set up the tool, which the companies had to fill in (Appendix, Person PP, 11th of April).

The goal of this tool is not to visualize what the circular potential of the project is, but for the companies to show how they are going to demolish the building in a circular way, and why they should win the tender. For this, Arcadis already delivers information about the building, which are the layers of Brand, the element/product, the material/type, the amount and unit and the impact of the component. The companies had to fill in which 'R' from the 10R framework that they were going to apply on the product and explain why and what the risks were for them. Based on this, a circular score was given and the achievability was determined. This tool will be further explained in chapter 2.5.3.

1.2 Research problem

Over the last years, a paradigm shift has been occurring in the construction industry, with the adaption of a circular economy model. Aims are made to keep building materials in a closed loop in order to reduce waste generation and therefore reduce the use of virgin materials (Benachio et al., 2020). However, even though this shift is supposedly taking place, for many developers there is still a lot of confusion around the circular economy principles and how to apply them in the built environment (Lacy & Rutqvist, 2015). Research by Cetin et al (2021) even shows that 'lack of awareness, knowledge and experiences with CE' is one of the biggest barriers when implementing circularity in the built environment. Furthermore, even though building adaptation contributes to the circular economy principles as well, stakeholders only weakly recognize its correlation to the circularity framework (Ikiz Kaya et al., 2021). This shows that for a large part, applying circularity in the built environment are mostly aims, and are not actually being applied enough yet, partly because of the confusion on how to achieve this. With climate problems becoming more pressing and with arrangements from the Paris accords closing, the process of implementing circular economy elements needs to go faster.

1.3 Research gap

Based on the research problem, a research gap can be identified. Currently, there are no easy or straight forward ways to identify circular strategies which actually can be taken, and what factors or aspects these strategies could be based on. Therefore, this research aims to fill in this research gap by developing a tool which can be applied in building adaptation projects and demolition projects. The tool will show which circularity strategies can be taken, based on the 10R model, and will give suggestions on why these steps are taken, based on disassembly potential and condition of elements. To identify which elements of a building these circularity steps can be taken on, the NL SFB list is used. The NL SFB list is an official categorization of a building in all its elements. Furthermore, the tool will provide a score in the end which shows what the circularity potential is for the building and its current components. This way, the tool can easily be used by anyone to check how they can contribute to applying circular economy measures. Because this tool will not become the only tool to measure what circularity potential is, it is difficult to set up a main research question that will be answered. This is because the result of this research, the tool, is not the only possible answer. Therefore, instead of setting up a main research question, this research has a main research aim which will be aimed to be achieved by developing the tool.

1.4 Research questions

1.4.1 Research aim

The main research aim that comes out of this is:
To develop a tool which measures and identifies what the circularity potential of building adaptation projects and building demolition projects is.

1.4.2 Research questions to achieve the research aim

To achieve the research aim, the following questions will be answered:

- **SQ1:** What is building adaptation and demolition?
- **SQ2:** What is circularity/circular economy and how can it be applied in the built environment?
- **SQ3:** To which building elements can circularity in the built environment be applied?
- **SQ4:** Which tools/frameworks already exist to measure the adaptation potential and circularity potential of a building?
- **SQ5:** What choices (possibilities) are added to the decision-making process when you add circular approaches to the question about how to adapt or demolish a building?
- **SQ6:** Who are the users of the Circularity Potential Meter and what are their viewpoints on the usability, benefits and complications regarding the tool?

1.5 Conceptual model and Research design

1.5.1 Conceptual model

Based on the determined research aim and research questions and the desired outcome of the research, the following conceptual model can be set up (figure 1). On the left, the types of projects involved in the research are shown. Here it can be seen that demolition projects and building adaptation projects are the main focus of the research when it comes to types of projects, where building adaptation projects can be divided into adaptive reuse projects and renovation projects. Then, in order to eventually come to a circularity potential score of these types of projects, it is crucial that they are categorized into components. This is shown in the conceptual model by the NL SFB norm, which categorizes buildings into elements and components. These elements and components are then judged by their disassembly potential and condition, which are two crucial factors to determine the circularity potential of the respective elements. This circularity potential is then graded by both the 10R model, by potting et al. (2017) and kirchherr et al. (2017) and by the CO2 impact it has if elements are reused. The Circularity Potential Meter 2023 tool shows what the circularity potential of a building is, based on the combination of the NL SFB norm, disassembly potential, condition according to the NEN 2767 norm, the 10R model and CO2 impact.

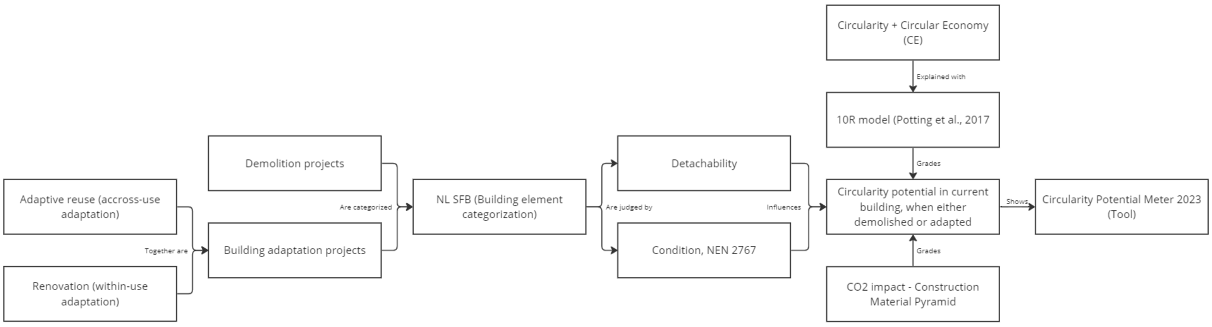


Figure 1: Conceptual model (Own image)

1.5.2 Research design

The research design that comes out of the research questions is as followed (figure 2).
Sub questions 1, 2 and 3 will mostly be answered in P2 and are largely based on literature research. Even though the basis for the answers for these questions was set in P2, throughout the whole graduation period, knowledge was added to each chapter. In P3 and P4, the empirical part of the research is conducted. Through interviews, project visits and simulation tests, sub questions 4, 5 and 6 were answered. These were all mandatory in order to develop the tool for this research.

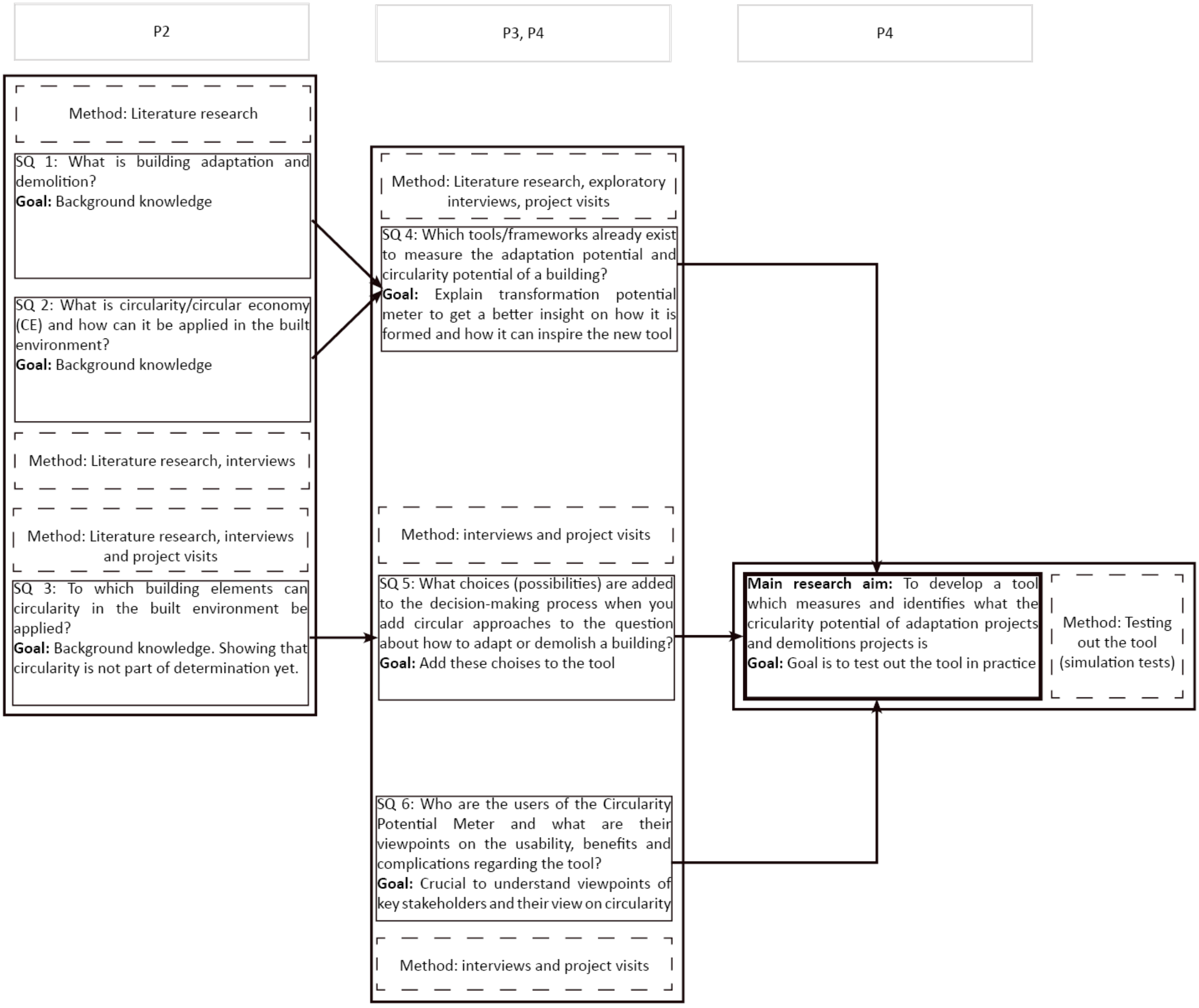


Figure 2: Research design (Own image)

1.6 Research method

The research methods used in this paper are mostly qualitative. Literature research is the main tool used to gather sufficient background information about the subjects. Building adaptation, circularity, determining factors for building adaptation up until this point and current tools will all be researched via literature research. Based on this, SQ5 can be answered, which shows the added possibilities that circularity can bring.

Empirical research is done to gain more insight in how this works out in practice. Simulation tests, in depth interviews, exploratory interviews and project visits will form the basis of the empirical research. They will provide the information about the extent to which circularity is applied now in transformation, how this is measured, and which stakeholders are involved in this process.

The in depth interviews will be conducted in a semi-structured way. Semi-structure interviews are useful to address 'how' and 'why' questions from the perspective of experience. Furthermore, semi-structured interviews are flexible and give space for improvisation during the interview. The interviewee can take the lead, which the interviewer can respond to (Low, 2013). This particular type of interviewing is useful for this research because circularity is still a research area which needs to explored more and is very complex.

These interviews will be conducted with employees of Arcadis, with stakeholders involved in the disassembly process of buildings and with stakeholders involved in circularity in the construction industry. In total, 4 in depth interviews were conducted.

The exploratory interviews will be held with employees of Arcadis and with stakeholders involved in circularity, disassembly potential, condition measurements based on the NEN 2767 norms. These exploratory interviews are essential to this research because of the iterative process in which the intended tool will be developed. Because of these interviews, the tool can be discussed with professionals in the field, to see what their view on it is. These interviews are easy and low threshold for the interviewees, meaning that it is easier to set them up and conduct them. Therefore, a larger amount of professionals can be reached, improving the quality of the research. Furthermore, because of these interviews, new lines to other professionals can be connected, improving the amount of stakeholders from different fields who contributed in the research. In total, 41 exploratory interviews were conducted, spreading out over 9 different companies.

Project visits will also be organized in this research. In total there will be four project visits. One project visit will be with a circular demolition company, to see to what degree circularity can be applied when demolishing in a circular way. The next project visit will be the creation of a material passport within a building that will be demolished in the future. Another project visit will be to an old apartment complex from 1960, which will be checked on its circular potential when it will be demolished in a few months. This apartment building is already uninhabitable, so the tenants are no longer living here. The last project visit will be a project where a condition measurement will be done according to the NEN 2767 norm. All these project visits will help greatly to further develop the tool within this research.

Furthermore, a simulation test will be conducted, where the tool is tested out in practice. This is with a project which is going to be demolished in a circular way, by the same company mentioned in the project visit (Appendix A, Person PP, 21st of April). This project will be used to test out the tool, and to see where the use cases of the tool lie. Furthermore, the tool will also be tested by other professionals in the field. The apartment complex from 1960 will be inserted in the tool by the professional who guided the project visit.

Regarding the Data Management Plan, the following important factors are important. Transcripts of interviews, contact data of participants and signed consent forms will be stored at the Project Storage of the TU Delft. This will only be accessible by the project team, consisting of myself, Vincent Gruis, Hilde Remoy and Marjolijn Versteegden (thesis mentors). The data will be stored for 10 years or more, which is in accordance with the TU Delft Research Data Framework Policy. When conducting interviews, informed consent will have to be signed by the interviewee before the start of the interview. This is to make sure the data is reusable in future researches and that the data is FAIR (Findable, Accessible, Interoperable, Reusable) (Wilkinson et al., 2016). At the end of the research, the data will be accessible via the TU Delft Repository.

When doing research, it is also important that it is done ethically. The core principles of ethical research, according to (Chan, 2021), are the following:

- Do no harm (but also do some good). Doing no harm means that personal data is not leaked and nobody in the research has felt uncomfortable. Furthermore, by adding to the body of knowledge of circularity in the construction industry, this study aims to 'do some good'.
- Confidentiality, strongly related with 'doing no harm'.

- Informed consent. This means making sure that the participants involved are involved willingly and with full consent of using the data gathered in the interview.
- Reliability, validity and (mis)representation of data. Reliability is achieved by making the research repeatable. This is achieved by structuring the conceptual model, making sure that the literature research is structured and repeatable. Validity is achieved by interviewing stakeholders from different perspectives and making sure that bias and emotion do not drown out the essence.
- Data protection (data management). Prevention of data loss is crucial when it comes to data protection. It shows quality and professionalism and it has a recognition impact

1.7 Research output

The goal of this research is to design and test out a circularity potential tool, which can be used on building adaptation projects and demolition. This tool is inspired by tools such as the 'Transformation Potential Meter', developed by Geraedts & van der Voordt in 2007, the material passport tool, and the Arcadis tool. The tool will be called the Circularity Potential Meter and will be developed by implementing the 10R model on circularity by Potting et al. (2017) and kirchherr et al. (2017), the NL SFB norm, disassembly potential, NEN 2767 and CO2 impact. The tool will show on which aspects of the building and to what degree circularity principles can be applied. The tool will be tested and developed, and based on simulation studies and interviews, the tool will be refined and improved over time.

1.8 Planning

Figure 3 shows the current planning for this research. It is divided into 5 blocks, each representing P1 through P5 respectively. P2 and P4 are crucial GO/NO GO moments during the graduation process, where presentations have to be given and reports have to be handed in. If the P4 result is GO, you can officially graduate at the end of P5. P1 and P3 are less crucial deadlines, which are there mostly to have a progress update.

At the moment of writing (20-06-2023), P1, P2, P3 and P4 are finished. The P5 report has been handed in. The GO/NO GO presentation for P4 was on the 30th of May, which resulted in a GO. In P1, a list of 7 points needed to be finished, which are now included in this report. P2 is a long period where a lot progress has been made. A large part of the literature research has been conducted and a first version of the Circularity Potential Meter was developed. Several topic adjustments took place and an internship company was found at Arcadis. P3 is also a long period in which a lot of progress has been made, especially regarding empirical research. Interviews play a large part in this. In total, 2 in depth interviews, and 41 exploratory interviews have been held. Furthermore, 4 project visits took place, in which local interviews were conducted as well. The Circularity Potential Meter was developed further, and many improvements were made.

At the end of P3, most of the empirical research has been conducted. At the end of P4, this empirical research has been written out in the report, and the tool is fully developed and the first official version has been tested out by a professional in the field. In P4, no more than 2 parties were found willing to test out the tool in a simulation. The results of these simulations have been applied in the research in the form of redeveloping the tool to make it more user friendly. The time up to P4 has been filled in by writing out the empirical research and by writing out the test results from simulation studies. Furthermore, a concrete answer to all research questions has been formulated.

After the ‘GO’ result from P4, there was a period of one month working up until P5. In this one month, the final refinements in the Circularity Potential Meter have been made. Furthermore, two more exploratory interviews were organized aimed to gain an understanding of how stakeholders such as architects would react to the results provided by the CPM. The CPM has been passed on to these persons and will form an inspiration for tools they are working on themselves. A page on the Arcadis Sharpoint has also been made, making the research available to all colleagues within Arcadis. Lastly, the P5 report has been overhauled to have a more clean lay-out and the P5 presentation has been made. On the 27th of June, 2023, the P5 presentation will take place.

In the end, most of the research has gone according to planning. A few deviations took place during P2 when the topic was adjusted, and it took a bit longer than expected to find an internship company. The actual empirical research has been more productive than planned. The amount of exploratory interviews and project visits that were held exceeded expectations, and therefore greatly contributed to the research. In the end, the graduation process has been fluent, without major setbacks.

Working up to P1								
36	37	38	39	40	41	42	43	44
							Deadline	Present
1. Research problem								
2. Research gap								
3. Research questions								
4. Research design								
5. Research method								
6. Find and read literature								
7. Make a planning								

Working up to P2												
45	46	47	48	49	50	51	52	1	2	3	4	5
				1,2,3,4						5, 6		Present
1. Reach out to companies for cases and internship												
2. Literature research, finish reading sources												
3. Become an expert at the tool as it is now												
4. Answer first 5 research questions												
5. Do research with the existing tool and the WIP tool at cases I got from companies												
6. Do empirical research at companies regarding stakeholders												

Working up to P3											
6	7	8	9	10	11	12	13	14	15	16	17
					1,2,3,4						Present
1. Do research and interviews at companies regarding stakeholders *1											
2. Do research with existing tool and WIP tool at project visits and cases I got trhough Arcadis *2											
3. Start answering SQ 6 and 7											
4. finish and refine literature research for SQ 1-5											

Working up to P4				
18	19	20	21	22
				Present
1. New tool finished				
2. Answer SQ 6 and SQ 7				
3. Answer main question by testing out tool				
4. Write out new research				

Working up to P5			
23	24	25	26
1			Present
1. Finishing touches			

Figure 3: Concrete planning (Own image)

2. Literature research and empirical research

Based on the conceptual model, building adaptation, demolition and circularity are the key concepts within this study. To be able to eventually achieve the main research goal, these key concepts need to be elaborated and understood clearly. They form the basis of knowledge needed in order to conduct the research in the end.

2.1 Building adaptation

2.1.1 Defining adaptive reuse and renovation

To understand what adaptive reuse and renovation are, it is first important to know what adaptation is, or in this case, building adaptation. The word 'adaptation' comes from the Latin words 'ad' (to) and 'aptare' (fit) (S. Wilkinson, 2014). How the word is used nowadays the definition includes 'change of use', maximum 'retention' of the original structure of the building and its fabric and improving its condition in order to extend the useful life. In the book 'Sustainable building adaptation: innovations in decision-making' (2014), Sara J. Wilkinson lists the following terms which exist in a 'unhappy confusion' which means that they have similar or the same meanings: renovation, adaptive reuse, refurbishment, remodelling, reinstatement, retrofitting, conversion, transformation, rehabilitation, modernisation, re-lifing, restoration and recycling. For example, renovation and refurbishment are very similar in the fact that the end product is in a better condition. However, for renovation this is more in a state of repair, while refurbishment is more to polish up or rub up. Conversion or transformation are different than this in the fact that the end product now also has a different function.

This leads to the difference between 'within use' and 'across use'. Building adaptation occurs in both cases but they don't mean the same thing. An office can undergo an adaptation but still be used as an office (within use). However, when the function of the office would change to, for example, a residential function, it is called 'across use'. So when a building is adapted, it can mean all the different mentioned words. A definition which encompasses all definitions correctly is stated by (Douglas, 2006): 'any work to a building over and above maintenance to change its capacity, function or performance, in other words, any intervention to adjust, reuse, or upgrade a building to suit new conditions or requirements.' For this study specifically, renovation projects and transformation/conversion projects are studied. The verbs 'to transform' and 'to convert' will be used interchangeably throughout this study, and are thus considered synonyms. Because renovation and transformation are important in this study, 'within-use adaptation' and 'across-use' adaptation are central.

Now that the definition of building adaptation has been established, the definition of adaptive reuse and renovation specifically can be researched. Adaptive reuse is defined as a major change of a building with alterations of both the building itself and the function it accommodates, so across-use building adaptation. Typically the drivers to choose for adaptive reuse and renovation are social, economic and environmental (Remøy, 2014a). With the social driver, the preservation of an area through building adaptation is meant. When an area consists of many vacant buildings, the area can become desolate and unappealing to go to. So building adaptation can give the area a more renewed appeal, preventing desolation and promoting people to stay in this area or travel to it by public transport as well. Economic drivers for building adaptation are the fact that the value of the converted buildings increases. Studies in Hong Kong showed a value increase of 9,8% compared to the un-refurbished version of the building (Chau et al., 2003). Environmental drivers are drivers which are seen as a vital part of sustainability developments. Applying building adaptation can contribute to sustainability and climate change through mitigation of CO_2 emissions ((Bullen & Love, 2010). Environmental drivers are the main drivers in Australia for building adaptation (Wilkinson & Remøy, 2021).

A main reason for building adaptation is obsolescence. With this, the becoming obsolete of a building is meant. Without obsolescence, there is no adaptation (Remøy, 2014a). The causes for such functional obsolescence are societal, economic and technological changes. Because of these changes, the building becomes longer suitable to accommodate the original intended functions. Vacancy can therefore be a result of obsolescence, but vacancy and obsolescence are not the same. Social and economic decay are the perceived problems of obsolescence, because of the abandoned and badly maintained appearance of these buildings. Vandalism and graffiti and illegal occupancy are big risks that come along with long-term vacancies. Typically, the risks for investors can be spread by having a large variety in the portfolio. This way, the issue of depreciation of the building is only dealt with when selling the building. However, owners of long-term vacant buildings suffer from a lack of income. Furthermore, high vacancy rates indirectly harm investors because of the negative impact it has on the market. Obsolescence should be avoided, because the consequences for owners and investors are generally negative. Building adaptation is not only a suitable solution for this, but also contributes to a more sustainably achieved building stock (Remøy, 2014a).

2.1.2 Lifespan and obsolescence

Building adaptation takes place when a building becomes obsolete and/or vacant. This obsolescence and vacancy is strongly related to the lifespan of a building. The lifespan of a building is seen as a cyclical process, according to the life cycle perspective on buildings. During the initial phases (initiative, briefing, design and construction processes), the building is created. During the cyclical lifespan, use and operation alternate with adaptations. Obsolescence may be indicated when a building is assessed on its future usability in certain stages. Technical obsolescence (related to technical lifespan), functional obsolescence (related to functional lifetime) and economic obsolescence (related to economic lifespan) may occur when the future usability of the building is assessed. All lifespans are explained by (Remøy, 2014a).

The technical lifespan is defined by the technical state by the building in question. If the technical and physical demands that are demanded for the building to function well are still in met, the building is still within its technical lifespan. This length of time can be extended by maintaining and operating the building well. With maintenance, the repairs of the building are meant, which ensure or restore the original functionality of the building. Measures which improve the initial technical quality of the building are not included in this maintenance, because it is no longer part of the original functionality.

The functional lifespan is the period of time during which a real estate object can still provide the original intended function demanded by the user. This includes functionality of use, aesthetic, social legal and environmental aspects. When the building limits the use, the functional lifespan is ended. When the functional lifespan ends, a choice has to be made regarding the future of the building. Often, building adaptation is the preferred option here. This way, the building continues its lifespan, with either the same function, or with a different function.

The economic lifespan is the period of time during which the real estate object generates more income than costs. When the present value of all the future incomes is higher than the present value of all future costs, the building is still in its economic lifespan. The income and costs that a building can create depend on the price, quality, competition in the market and the maintenance costs. When an owner can no longer see the possibility to generate more income than costs, the economic lifespan ends.

These three types of lifespan are interrelated. For example, if the functional lifespan has ended, this usually implies that the economic lifespan also ends. If the functional lifespan ends, it is not possible to find a tenant for the building, which means the building can no longer generate income to cover the costs. The end of the functional lifespan may be caused by the end of the technical lifespan; however, it is often the case that a building is still in a technically good condition when the end of the functional lifespan has been reached.

2.1.3 Options to deal with structurally vacant buildings

When a building is vacant, the owner has multiple options on coping with this vacancy: consolidation, adaptation or upgrading, demolition and new construction and conversion (table 3). Consolidation is often the preferred option, which is to leave the building empty and wait for better times to take action (Remøy, 2014c). This option is often chosen because it is the easiest option. Furthermore, the actual owners of the building often do not actually fully understand the other available options that there are, like for example renovation. Renovation is another option for coping with structural vacancy. Renovation means that the building remains with the same function, however it can mean that the building is renovated for another building in the same market segments. When there are high levels of vacancies in the market, renovation might not provide a significant positive effect and the costs might actually turn out higher.

Demolition and new construction is another intervention which an owner can choose from. A new building is created which is more suitable for future use. However, this option takes up a lot of time and money and could be a waste of resources if the vacant office building in question is still in a good technical state. A study conducted by Assefa & Ambler (2017) studied the options of demolishing and rebuilding and converting a building. The study compared the environmental impact that both options had in 7 different aspects, which are fossil fuel consumption, global warming potential, acidification potential, human health criteria, eutrophication potential, ozone depletion potential and smog potential. The results of the study were significant in the fact that in six out of the seven aspects, a 20% to 41% reduction was discovered (Assefa & Ambler, 2017). In theory, this makes a strong case for building adaptation over building demolition. However, in these cases, there was no intention to demolish the buildings in the most circular manor. Circular demolition, in which the main goal is to reuse as much as possible could result in different results (Appendix A, Person M, Monday 27th of February).

Another way to deal with structural vacancy in offices is mothballing. This means temporarily allowing use for housing to avoid illegal occupation. This option might precede the other mentioned options and can also be seen as part of consolidation. Furthermore, taking this step might cause extra damages to the building, increasing repair costs before renting the building out again.

Lastly, conversion is an option to deal with the structural vacancies. This option can be difficult to do successfully because the future market value of the building which now accommodates a new function must be higher than for the current function. However, when it does work out successfully, advantages are that the location has been used durably, income has been less disrupted compared to redevelopment and social, financial and sustainable factors are higher (Remøy, 2014c).

The table below shows an overview of the benefits and drawbacks of each of the options.

Option	Benefits	Drawbacks
Maintain in current state (consolidate)	Preserves the property Sustains existing use Ensures ongoing service and lifespan	Requires maintenance costs though no incomes are generated
New tenancy – better study of the market	Find a suitable tenant, may ensure ongoing beneficial use of the property	May be time consuming to find a user for a structurally vacant building; requires maintenance, refurbishment or incentives
Mothball	Minimises running costs, such as cleaning, heating and lighting	Costly to keep safe and secure; vulnerable to vandalism and squatting, dust and dirt accumulation and dampness in the building; no rental income
Anti-squat	Minimises running costs, secures the building against squatting and vandalism	Exposed to wear and tear, inhabitation may influence possible tenancy negatively
Dispose	Realises asset/site value, reduces management and operating costs	Loss of potentially useful asset, price may not correspond to book value
Demolition and new building	New building tailored to meet users preferences	Disruptive and expensive, delay of income, location characteristics cannot be influenced
Adapt and renovate	Enhances the physical and economic characteristics of the building, delays deterioration and obsolescence, reduces the likelihood of redundancy, sustains the building's long-term beneficial use	Disruptive and expensive, extended lifespan is unlikely to be as great as a new building, upgraded performance cannot wholly match that of a new building, location characteristics cannot be influenced
Convert	Enhances and alters the physical and economic characteristics of the building, prevents deterioration and obsolescence, sustains the building's long-term beneficial use, sustains social coherence in the area	Disruptive and expensive, market uncertainty, location characteristics may not suit new function, building costs may be out of control, new rental function may not be the core business of the owner

Table 3: Options to cope with vacancy (Remøy, 2014a)

2.2 Building demolition

2.2.1 Construction and demolition waste

Building demolition in itself is a clear concept. However the building waste treatment is where discussions regarding circularity and sustainability come into play, and where a lot of research still needs to be done. With building demolition, large quantities of construction and demolition waste are generated. This waste typically comes in substantial generated volumes, and therefore there will be large quantities of embodied resources. This makes this waste stream an important focus of current European policies (Gálvez-Martos et al., 2018). Reducing generated waste from these projects, minimising transport impacts and maximising re-use and recycling are key principles to reduce environmental impact of building demolition projects. This can be achieved by improving the quality of secondary materials, and by optimising the environmental performance of treatment methods. (Gálvez-Martos et al., 2018).

As mentioned before, construction and demolition waste (CDW) contributes to roughly 37% of the total amount of waste generated in the world (Hamilton & Kennard, 2022). This waste may consist for roughly 85% out of concrete, ceramics and masonry (Ponnada & P, 2015). The general aim is to reduce this as much as possible by applying principles such as reusing and recycling. In practice, companies that are focussed on circular demolition are increasing in popularity. However, circular demolition is still difficult because generally, buildings that are demolished in this time, have been built centuries ago. Back then, buildings weren´t generally constructed with a mindset that is has to be possible to be demolished in a circular manor. Buildings back then were not constructed demountable, and the materials that were used were generally not thought of to be reused or recycled (Appendix A, Person LL, 24th of March). However, recently, the awareness regarding these principles of demountability and material reusability are growing in popularity and therefore applied more often. In chapter 2.3, circularity will be thoroughly researched, and circularity in building demolition will be discussed further.

2.2.2 Answer to sub question 1

The first question that needed to be answered to achieve the research aim is 'What is building adaptation and demolition?'. To summarise, building adaptation is a collective word, which encompasses many definitions. These definitions are renovation, adaptive reuse, refurbishment, remodelling, reinstatement, retrofitting, conversion, transformation, rehabilitation, modernisation, re-lifing, restoration and recycling. All these definitions are similar but not identical. Therefore, building adaptation is the overarching word that describes all these definitions. However, a distinction has to be made between 'within use' and 'across use' adaptation. For within use adaptation, the function of the building stays the same, where across use adaptation changes the function of the building. The most common interventions within these definitions are renovation, and adaptive reuse respectively, and will form the main focus of this research. Building adaptation is based on building obsolescence and building lifespan.

Another way to deal with structurally vacant buildings, next to building adaptation, is building demolition. Building demolition in itself is a clear concept, however, building waste treatment is where a large impact can be had. This is where a circular economy can have a big influence.

2.3 Circular economy

2.3.1 Defining circularity

A circular economy (CE) has been defined many times. When speaking of a circular economy in general, the Dutch Ministry of Infrastructure and the Environment describes it as ´an economic system based on the reusability of products and product components, recycling of materials, and on conservation of natural resources while pursuing the creation of added value in every link of the system´ (Potting et al., 2017). However, this is just one of many definitions that have been given to a circular economy. There is a large conceptual confusion about the circular economy, which is illustrated well by a literature review conducted by (Kirchherr et al., 2023), which resulted in 221 definitions of the concept. Some of these definitions were also specified towards the built environment.

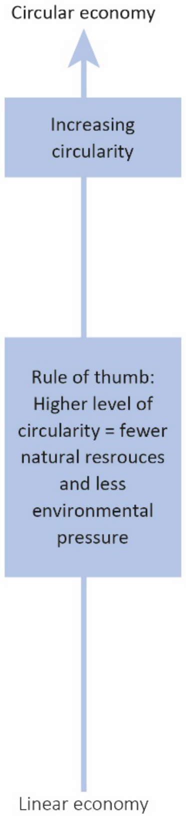
In a research done by Sultan Cetin, Vincent Gruis and Ad Straub (2021), these definitions are analysed and compared. Pomponi & Moncaster (2017), explained the CE in regards to circular buildings as followed: 'a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles'. This definition does not cover the full meaning of CE because the actual CE principles it mentions are not explained further.

Another definition done by (Leising et al., 2018) defines the CE more extensively: ''A lifecycle approach that optimizes the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank''. What becomes clear in this definition is that the emphasis is on the material life cycle. A non-academic actor EMF described a circular built environment as ''modular and flexible by design where resource loops are closed and human well-being is promoted'' (Çetin et al., 2021). Furthermore another definition for circular construction is presented: '' … the development, use and reuse of buildings, areas and infrastructure without unnecessarily exhausting natural resources, polluting the living environment, and affecting ecosystems. Construction in a way that is economically sound and contributes to the well-being of humans and animals. Here and there, now and later''. These definitions give an understanding of what exactly the circular economy in the built environment entails. For the sake of this research, the definition by the EMF is most accurate, because it emphasizes on both modular and flexible design, and resource life cycles. This definition is also in line with information gathered from interviews with Person A and Person F on the 26th of January and the 2nd of February respectively (Appendix A).

2.3.2 Circularity frameworks

For the actual implementation of the CE, there are multiple frameworks. The 10R framework by (Potting et al., 2017) and (Kirchherr et al., 2017) and the ReSOLVE framework by the EMF (Ellen MacArthur Foundation, 2015) are two frameworks which define what a circular economy can entail. They will be described here.

The framework developed by Potting et al. (2017) and Kirchherr et al. (2017) is called the 10R framework, and measures the progress of the CE transition we currently have (figure 4). This progress is measured based on 10 R's in which R9 is the least circular intervention and R0 is the most circular intervention. Using these 10 R's, it can be analysed to what extent developments are circular



Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intesive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of materials with energy recovery

Figure 4: 10R framework (Potting et al., 2017) (Kirchherr et al., 2017)

As a baseline it can be concluded that more circularity is better for the environment (Potting et al., 2017). However, this does not always have to be the case. Achieving circularity is a goal, meaning that circularity itself is not a means. Circularity can be achieved by applying the 10 R's. Smarter product use and manufacture is the best way to achieve this (figure 4). These interventions directly influence the amount of resources that are used and needed. It is generally seen as better than extending a lifespan

of a product and its parts. This is because this product is being used for the same product function or more users being served by one product (strategy with high circularity). Recycling and recovering come after this and have the lowest priority in a circular economy. This is because the materials are no longer available to be applied in other products.
An important notion hereby is that more circularity does not have to mean a more sustainable production chain in every way. For example, for products to be reused, they often have to be processed which can cost more fossil fuels than actually remaking the product from scratch. This for example mostly the case when recycling contaminated materials. Furthermore, car sharing can reduce the amount of cars that are needed, but it might also motivate people without a car in the beginning to actually take the car now (Potting et al., 2017).

The ReSOLVE framework by the EMF (Ellen MacArthur Foundation, 2015) is based on three key principles which the circular economy rests on:

- Preserve and enhance natural capital
- Optimise resource yields
- Foster system effectiveness by revealing and designing out negative externalities

These three principles can be translated into a set of six business actions, which are the ReSOLVE actions: Regenerate, Share, Optimise, Loop, Virtualise and Exchange. In general, the ReSOLVE framework is not specifically designed to be applied to the built environment. They mostly resemble major circular business opportunities for businesses. However, they can also be translated to circular principles within the built environment. For example, the 'share' strategy can be applied to reuse reclaimed building products. Furthermore, assets such as cars and office spaces can be shared as well. The 'optimise' strategy can also be applied, for example when aiming to increase the performance of buildings during the design phase.

For this research and for creating the circularity potential tool, the R framework by (Potting et al., 2017) and (Kirchherr et al., 2017) will be used. This is because the R framework shows a ranking in different circular strategies, and can therefore help to define scores when analysing buildings on their circularity potential. The ReSOLVE strategy, however, will also be used to gather a better understanding of how the 10R framework can be applied.

2.3.3 Circularity in the built environment

The Netherlands is one of the first countries to set government-wide goals to achieve a fully circular economy by 2050. In order to reach these targets, the Dutch government has set goals to become at least 50% circular in the built environment by 2030 (Ikiz Kaya et al., 2021). This means that steps to become more circular have to be made in the built environment as well. When speaking of circularity in the built environment, in general, the management of construction and demolition waste for resource recovery is meant. The reuse, recycle and recovery of materials or components and keeping a closed loop is the main standpoint in this (Ghaffar et al., 2020).

In the construction sector in the Netherlands, already 95% of the construction waste is being recycled or reused (Schut et al., 2015). In this aspect, the Netherlands serve as an example to the rest of the world. In an industry which generates roughly 39% of all generated waste in the world, this is a very important result (Hamilton & Kennard, 2022). Even though this appears to be very circular, in reality, this does not mean circularity yet. This is because this building waste cannot be recycled to be of the same quality as it was originally. For example, the waste concrete can be reused, but not in buildings anymore because of reduced quality. It can only be reused as for example road foundation (Schut et al., 2015). Achieving circularity comes from materials having multiple life cycles, remaining of the same quality. This percentage is actually only roughly 6% (Haas et al., 2015). This shows that there is a mismatch between policies, political goals, and actual results.

In order for the built environment to become circular, buildings should be considered as a material bank, where valuable materials are ‘stored’ for the time being (Ghaffar et al., 2020). Smart design and circular value chains are ways to achieve this and are crucial in order for the construction sector to reduce their waste output. The ‘end-of-life’ perception should be replaced by business models which include reducing, reusing, recycling, and recovering materials. In this, reducing and reusing should be aimed towards the most, because they don’t require (much) extra energy in order to be reintroduced in the chain. However, recycling is attractive in certain scenarios. From an economic perspective, the yielded product must be competitive in relation to cost, quality and quantity of virgin materials. This also means that recycling can be encouraged when virgin materials are taxed more. Furthermore, recycled materials are a better option in regions where access to raw materials and land filling sites is limited (Tam & Tam, 2006).

What is mentioned above, does not cover all the R’s from the framework of Potting et al. (2017) and Kirchherr et al. (2017). The R framework mostly applies to a product industry, but can also be applied more to the construction industry as well. This regards particularly the pre-use phase-related strategies, which are refuse, rethink and reduce. Not much literature research has been devoted to find out how these factors can be applied strongly in the construction industry, in order to achieve a circular economy. Furthermore, repair, which includes maintenance and is part of the use-phase of the building, remanufacture and repurpose can be applied in the construction industry as well. Keeping all R’s in mind is crucial to achieve the most circularity as possible (Çetin et al., 2021). However, as the word ‘adaptive reuse’ suggests, reuse is the most crucial R in this framework. Even though not much literature has been devoted to applying the R framework in practice, via empirical research in the form of project visits, the application of the R framework in demolition projects has been researched.

As mentioned above here, the 10R framework originally is not developed for the built environment specifically. However, it can be applied to the building industry. In this research, it became clear that the 10R framework is already used repeatedly, either adapted 1 on 1, or with its own variation (Appendix A, Person LL, Company D, Person M, Person WW, Company K, Person FF). In the research problem of this research, it is stated that for many organizations, circularity is a goal to achieve. However, there is still confusion in the industry regarding what exactly circularity in the built environment means, and how it can be applied. The 10R model is actually a very strong model to make circularity more clear regarding the application of circularity in the construction sector. This research involves empirical research in the form of project visits, where a project visit of a circular demolition company was conducted (Appendix A, Company D, 27th of February) . They specialize in circular demolition and also apply the 10R model for their projects.
They describe the 10 R´s as follows:

- R0, Refuse: Refuse/prevent loss of value
- R1, Reduce: Use less resources
- R2, Redesign: Redesign with a circular mindset
- R3, Reuse: 1 on 1 reuse (2nd hand). Dismount element, transport for direct reuse
- R4, Repair: Maintenance and repairs. Dismount element, transport, repair before reuse
- R5, Refurbish: Fix up product. Dismount element, transport, fix up / modernise product before reuse
- R6, Remanufacture: create a new product from 2nd hand products. Dismount element, transport and apply product in element with the same function.

- R7, Repurpose: Reuse the product for something else. Dismount element, transport and apply product in element with different function.
- R8, Recycle high value: Reuse resources.
- R9, Recycle low value: downcycle resource.
- R10, Recover: Energy recovery

This model can be applied to all elements in a building, but when looking at the existing building stock and their potential adaptation projects or demolition projects, R3-R10 apply. However, in order to apply this model to these elements within buildings, it needs to be clear what type of elements exist in buildings. Currently, there are multiple ways to identify elements within buildings. They NL SFB list, the Layers of Brand and a demarcation list (demarcatielijst) are examples of ways to categorize building elements. These will be explained further in chapter 2.4.

2.3.4 Applying circularity principles in the built environment

Circular design in in the construction industry has been clearly formulated with the ReSOLVE framework (Ellen MacArthur Foundation, 2015). The following principles can and should be applied in order to achieve circularity (Schut et al., 2015):

- Low-material design
- Modular design
- Adaptive design
- Design for deconstruction
- Design for recycling / cradle to cradle > upcycling
- Recycle for (circular) design
- Material passports

The principle of low-material design is that using less material also leads to less use of raw materials, and therefore also causes less waste and environmental effects. In case of buildings, this does not always have to be the case, because less materials, also lead to less energy efficiency. Low-material design is strongly related to waste flows of both construction waste and demolition waste. The most effective way to limit on site waste is to use prefabricated building elements. In building adaptation projects, this still hardly happens, even though the abilities of the suppliers to deliver customized elements is high. Furthermore, because of prefab materials it would be possible to accurately sort the created wasteflows at the construction site.

Modular design can drastically improve the technical lifespan of a building. Building sections can be replaced rapidly and efficiently as 'modules'. Furthermore, repairs and maintenance can be done off-site. In modular design, an optimum life is assumed for parts of the building, like the structure, exterior walls and roofs, insulation and energy systems. These can easily be replaced or repaired by reinstalling a new module.

With adaptive design, a building can adopt a multiple of functions during its lifetime. The foundation and skeleton of the building are supposed to be able to fulfil multiple functions. In an adaptable building, the layout, fitting and technology used can change radically. There can be tension between low-material design and adaptive design. In an interview with Person A, from Company A, this was mentioned to be the key principle of circularity in the built environment (Appendix A, 26th of January)

Design for deconstruction means that the building can be disassembled at the end of its lifespan. The materials which come out of this building can then be refurbished and reused in other projects.

Currently, hardly any projects are designed for deconstruction, so brute force is the only way to deconstruct a building. Materials are therefore hardly reusable.

Design for recycling / cradle to cradle are strongly related to design for deconstruction. This is because cradle to cradle does not only mean reuse of the materials, it also means reuse of materials in the long term. This is connected to upcycling, which means that the material use should be at least of the same quality as in the original product. In order to make this work, design for deconstruction is therefore essential.

Recycle for (circular) design is related to material flows. Materials have to be able to be reused for the same function more than one time. For this to be possible, significant technological improvements in the recycling industry have to be made to be able to deliver the same quality product for multiple times. Currently, projects for bricks and concrete are running to make this possible. This will be operational within a couple of years.

Material passports show which materials and how much of these materials have been used in building projects. This is a very helpful tool to be able to discover which products and materials in a building can be reused or recycled after deconstruction. Currently, this is discovered through manual investigation of a building (Appendix A, Company L, 21st of March) . However, more often than not, more information is necessary. Building Information Models (BIM) are rapidly developing to include this information in current buildings. However, the greatest challenge of the material passport is to find a way how to store and keep the information accessible for the 50 to 100 years lifespan of a building.

As can be seen the last four aspects are deeply related to the circularity potential that can be found in existing projects, and are therefore deeply related to the 10R framework as well, specifically R3-R10. The first three aspects are also related to circularity, but mostly look at how it can be applied in new built projects, and therefore apply less to the scope of this research.

Hamida et al., (2022) has also done extensive research about the application of circularity in the built environment, but specified it towards building adaptability. They identified ten descriptions of applying circularity in building adaptation projects. These ten descriptions of circular building adaptability are:

- Configuration flexibility: the possibility to reconfigure the floorplan of a building without needing external resources. Options to achieve this can be demountable or movable components.
- Product dismantlability: the possibility to dismount components of a building without damaging the building or generating waste off of it. The components can be used elsewhere.
- Asset multi-usability: the possibility to add multiple different functions in a building, for example by creating multi-purpose spaces, but also by adding shared facilities.
- Design regularity: the possibility to bring regularity in the spatial configuration of the building, so that the facility can be used for other purposes should it be transformed.
- Functional convertibility: the possibility for the building to accommodate multiple functions, while keeping its value and prolonging its lifespan. For this, modular or mixed use-design is essential.
- Material reversability: possibility to provide, use and reuse building materials as efficient as possible. Using second hand materials, creating material passports and collaborating with the Construction and Waste industry is crucial for this.

- Building maintainability: possibility to maintain performance of the building and to maintain the usefulness of the building. This can be done by smart technologies, helping with the operation phase of the building. Furthermore, proactive maintenance and procuring service of building components are part of this as well.
- Resource recovery: possibility to regenerate the resources consumed in the building, to reduce the use of new material and energy. Renewable energy, natural ventilation and natural lighting are ways to achieve this.
- Volume scalability: possibility to increase the size of the building both vertically and horizontally, while eliminating waste generation.
- Asset refit-ability: possibility to add state of the art technology and products in the building

As can be seen, both researches by (Schut et al., 2015) and (Hamida et al., 2022) show similarities, but also extend each other. Their definitions of application of circularity in the built environment will partially be used for setting up the circularity potential tool. The partial use in setting up the circularity potential tool has to do with the fact that the scope of this research is based on the current built stock and adaptation and demolition projects. Therefore, product dismantlability, material reversability and resource recovery are the most important aspects from the research by Hamida et al. (2022), to be applied in the tool

2.3.5 Barriers and enablers regarding circularity in the built environment
Barriers and enablers for applying circularity in the built environment have been identified many times and have been categorized in different ways. This section uses an extensive research done by Cetin, Gruis & Straub conducted in 2021 (Çetin et al., 2021), which categorizes barriers of implementing circularity in the built environment in the following categories: Social and cultural barriers, organisational barriers, financial barriers, sectoral barriers, technical and technological barriers and regulatory barriers. The enablers are categorized in the same way. Table 4 shows all the identified barriers and enablers. Something to note for this study is that it applies to social housing associations. Nonetheless it still gives a good indication of the type of barriers and opportunities there can be regarding the implementation of circularity in the built environment.

Category	Barriers and eEnablers	Min	Max	Mean	Std dev	Mean Category
Barriers						
Social and Cultural Barriers	Lack of awareness, knowledge and experience with the CE	2	5	3.84	0.87	3.27
	Resistance from stakeholders	2	5	3.42	0.94	
	Tenant preference for new building products	2	4	3.32	0.8	
	Lack of willingness to collaborate across the supply chain	1	4	3.26	0.85	
	Lack of consumer (tenant) awareness and interest	1	4	2.53	0.88	
Organisational Barriers	Giving higher priority to other issues, e.g., energy transition	3	5	4.11	0.72	3.62
	Operating in a linear system	2	5	3.68	0.8	
	Limited top management commitment and support for circularity	1	5	3.58	1.23	
	Lack of time and human resources	2	5	3.47	0.99	
	Insufficient technical training and education on circularity	1	5	3.26	1.02	
Financial Barriers	High purchasing costs of new circular materials	3	5	4	0.46	3.8
	High purchasing costs of recycled materials	2	5	3.95	0.69	
	Unclear business case	2	5	3.95	0.94	
	High upfront investment costs	3	5	3.89	0.72	
	High costs for collecting, dismantling, urban mining	2	5	3.84	0.59	
	Limited funding for circular projects	1	4	3.16	0.93	
Sectoral Barriers	Conservative and uncooperative nature of building industry	2	5	3.79	0.95	3.42
	Lack of standardisation	2	5	3.68	0.86	
	Uncertainty in building end-of-life issues	2	5	3.42	0.82	
	Long product life-cycles	1	5	3.37	1.13	
	Poor partnership formation with supply chain	2	5	3.26	1.07	
	Complexity of buildings	2	5	3	0.92	
Technical and Technological Barriers	Lack of an information exchange system	2	5	3.68	0.86	3.5
	Lack of circular design guidelines	2	5	3.53	0.82	
	Lack of relevant tools for material reuse	2	4	3.47	0.68	
	High costs of implementing new technologies	2	5	3.32	0.8	
Regulatory Barriers	Circularity is not effectively integrated in regulations	2	5	3.68	0.8	3.51
	Limited circular procurement	2	5	3.68	0.8	
	Uncertainty regarding future legislation	2	5	3.42	0.82	
	Lack of global consensus on CE	2	5	3.26	0.91	
Enablers						
Social and Cultural Enablers	Leadership	3	5	4.21	0.61	3.84
	Collaborating with other social housing organizations	3	5	4.05	0.6	
	Circular economy training, education and workshops	2	5	3.84	0.67	
	Social awareness and shifting tenant preferences	3	5	3.79	0.61	
	Awareness raising events	3	4	3.32	0.46	
Organisational Enablers	Commitment and support from the top management	3	5	4.58	0.59	4.09
	High priority on circularity within the organisation	2	5	3.95	0.89	
	Collaboration of internal teams	2	5	3.74	0.64	
Financial Enablers	Clear business case for CE	3	5	4.05	0.83	3.91
	Lower costs for circular materials	3	5	4.05	0.6	
	Financial incentives to use secondary materials	2	5	3.84	0.93	
	Lower costs for collecting, dismantling, urban mining	2	5	3.84	0.87	
	Sufficient funding for circular projects	2	5	3.79	0.83	
Sectoral Enablers	R&D and innovation	3	5	4.05	0.69	3.99
	Best practice case studies	3	5	4	0.56	
	Better collaboration with sector parties	3	5	3.95	0.6	
	Development of standards	2	5	3.95	0.83	
Technical and Technological Enablers	Development of enabling technologies	3	5	3.95	0.6	3.87
	Development of tools and guidelines	2	5	3.84	0.74	
	Development of digital marketplaces for secondary material	2	5	3.84	0.93	
	Development of circular procurement systems	2	5	3.84	0.81	
Regulatory Enablers	Incentives for CE	2	5	4.11	0.72	3.96
	Circular economy legislation	3	5	4.05	0.69	
	Policy support	3	5	3.95	0.51	
	Waste management directives	2	5	3.95	0.83	
	Global agreement on circular economy	2	5	3.74	0.85	

Table 4: Barriers and enablers for implementing circularity in the built environment (Çetin et al., 2021)

The numbers behind the barriers and enablers show the significance of the factors. Their study was conducted with multiple social housing associations, who were presented with this exact list of barriers and enablers. They were asked to rank them based on how significant they are, 1 meaning not significant at all, and 5 meaning very significant. That is why the 'mean' number shows a good indicator on how significant the barrier or enabler actually is.

What is interesting is that one of the most significant barriers is the ´lack of awareness, knowledge and experience with the CE´. This is part of the research problem which this research addresses. The tool developed in this research shows the connection between condition and disassembly potential, and the 10R framework. Therefore, this research makes clear which steps regarding circularity can be taken, and also what their influence is on CO_2 emissions, which will be described in chapter 2.3.6. Creating more knowledge and awareness about the CE can also contribute in dealing with other barriers. This is because it is now more clear what exactly it is and how it can be applied. Willingness to apply it and clear business cases can therefore also be a result. It also creates more awareness on which aspects make applying circular principles more easy. This educates on how future projects can be constructed in a way which is more suitable for applying circular principles more easily.
The tool can also help to make it insightful which materials, components and elements will be retrieved from the adaptation and demolition projects. These can then be placed on marketplaces, or used directly in new projects.

This is just a selection of barriers and enablers which this research can contribute to resolve. One can therefore see how, in general, a bigger awareness and more knowledge regarding CE can solve many problems regarding barriers and enablers. The Circularity Potential Meter aims to fill in this gap.

2.3.6 Materials, quantity and CO2

One result from adapting to a circular economy is reduced CO_2 emissions. The CO_2 emissions can be reduced by applying the different R´s in the 10R framework. This means that when building components are reused directly, CO_2 emissions are diminished because these components do not have to be produced from scratch, with virgin resources (Kralj & Markic, 2008). The amount of CO_2 emissions saved is therefore closely related to the type of materials that are reused, the amount of the material that is being reused and the specific R that is applied to these materials. Different materials emit different amounts of CO_2 in their production process, making certain materials more preferable to use than others.

In order to calculate what the CO_2 impact is of applying the 10R framework on specific amounts of construction material pyramid can be used (figure 5) (Beim & CINARK, 2021). The values shown in this framework are often used in practice to calculate the CO_2 emission savings (Appendix A, Company D, Person Z). This pyramid allows you to compare different kinds of materials and material categories. This pyramid shows exactly which materials there are and what their Global Warming Potential (GWP) is. This GWP is shown in kg CO_2 / m^3, which means the CO_2 emissions per cubic meter produced of the related material. On the basis of the Environmental Product Declarations (EPD), the Construction Material Pyramid shows the impact of relevant building materials for the building phases A1 – A3. These phases are the beginning stages of construction, which means until the material is on the construction site. This means that transportation of the material is also included.

What is important to realize is that the CO_2 impact in adaptation or demolition projects strongly relates to the applied R of the component. One can imagine that 1 on 1 reuse of components has a bigger CO_2 impact regarding saving emissions, compared to recycling. If a component is reused 1 on 1, the maximum amount of CO_2 emissions is saved, because no new production process has to be applied (Kralj & Markic, 2008). However, this is not the case for the different R's that follow. It is difficult to make a precise calculation on how much of a percentage of CO_2 emission savings is lost when getting lower on the 10R framework. Every project is unique and transport costs, repair costs, recycling costs etc. will vary. Therefore, this research will apply rough assumptions to give an indication and to show that applying R3 saves more CO2 emissions than R9. The following assumptions are used in this research:

- R3, Reuse: 100%
- R4, Repair: 90%
- R5, Refurbish: 80%
- R6, Remanufacture: 70%
- R7, Repurpose: 60%
- R8, Recycle: 50%
- R9, Recover: 40%

Steps of 10% are applied based on research done by Vefago & Avellaneda (2013). Their research shows that, compared to reuse, recycling is somewhere between 33% and 66% worse regarding CO2 emissions. Therefore, this research applies 50% for R8, and the steps in between are of 10% each. Recover still saves CO2 emissions, because it creates energy from materials that did not have to specifically be created in order to create the energy.

Figure (5): Construction Material Pyramid (Beim & CINARK, 2021)

2.3.7 Condition according to NEN 2767

In chapter 2.3.6, CO2 emissions were discussed. In order to determine how much CO2 emissions can be saved, it is crucial to know which R from the 10R framework is applied. What was discovered in the research done by Hamida et al., (2022) and Ellen MacArthur Foundation, (2015) with their ReSOLVE framework is that when it comes to circularity in adaptation projects and demolition projects, condition and disassembly potential of components and materials are crucial. This is also confirmed by interviews and conversations held in practice (Appendix A, Person F 2nd of February, Person X 28th of February, Person Y 3rd of March, Person CC 7th of April, Person H 7th of March). This sub chapter will go further into depth about condition, and chapter 2.3.8 will go more into depth about disassembly potential.

The condition of materials and components has a large influence on the reusability of this particular material or component (Vefago & Avellaneda, 2013). One way to identify the condition of these products is through the NEN 2767 norm. The NEN 2767 describes a method to determine the technical state of building elements by judging it in an objective and sensible manor. The fundamentals of this method are the registration of flaws/shortcomings (gebreken), and their characteristics. This list of flaws (gebrekenlijst) are all predetermined and show all the possibilities that building elements can have, the respective seriousness (ernst) of the flaw, and, if applicable, the intensity (intensiteit) of the flaw. Furthermore, the scale of the flaw also impacts the condition. This scale (omvang) is based on a certain percentage of the building element which contains the flaw.

The reason that the NEN 2767 norm is used in this research is because of the fact that it is a very objective way to determine conditions of elements. The conditions 1 through 6 form a clear parameter on which R scores in the R10 model can be based. An elaborate explanation of the NEN 2767 norm follows.

As mentioned, the NEN 2767 norm gives condition scores to building elements based on objective factors. These condition scores can be 1 through 6, where 1 is the best condition that an element can have, and 6 is the worst condition.

1. Excellent condition (uitstekende conditie)
2. Good condition (goede conditie)
3. Reasonable condition (redelijke conditie)
4. Moderate condition (matige conditie)
5. Bad condition (slechte conditie)
6. Very bad condition (zeer slechte conditie

The determination method of these conditions is based on seriousness, intensity and scale. The seriousness of the flaw determines which matrix has to be used for the determination of the condition score of a building element. The following matrix exists for the category 'seriousness' (table 5):

Seriousness	Explanation	Example
Very serious flaw	Causes derogation of the function of the building element	Wood rot, tear in concrete
Serious flaw	Causes degradation of the building element without directly harming the functionality	Erosion, flaw that leads to leakage
Minor flaw	Does not cause derogation of the functionality of the building element	Discolouration

Table 5: Division seriousness (NEN 2767)

For the 'scale' of the flaw, the following division is used (table 6):

Scale	Percentage	Description
Scale 1	< 2%	The flaw occurs incidentally
Scale 2	2% - 10%	The flaw occurs locally
Scale 3	10% - 30%	The flaw occurs regularly
Scale 4	30% - 70%	The flaw occurs considerably
Scale 5	> 70%	The flaw occurs in general

Table 6: Division scale (NEN 2767)

For the ‘intensity’ of the flaw, the following division is used (table 7):

Intensity score	Name	Explanation
Intensity 1	Beginning phase	The flaw is generally hardly visible and occurs shallow
Intensity 2	Advanced phase	The flaw is clearly visible on the surface
Intensity 3	End phase	The flaw is very clearly visible, irreversible and can barely increase in severity

Table 7: Division intensity (NEN 2767)

These 3 matrixes together of ‘seriousness’ (ernst), ‘Scale’ (omvang) and ‘intensity (intensiteit), results in 1 comprised matrix which predetermines the condition of building elements (table 8).

Condition score NEN 2767-1:2017 (and further)

Flaw	**Intensity**	**Scale** < 2% incidentally	2 - 10% locally	10 - 30% regularly	30 - 70% considerably	> 70% regularly
Minor flaw	Beginning	1	1	1	1	2
	Advanced	1	1	1	2	3
	End	1	1	2	3	4
Serious flaw	Beginning	1	1	1	2	3
	Advanced	1	1	2	3	4
	End	1	2	3	4	5
Very serious flaw	Beginning	1	1	2	3	4
	Advanced	1	2	3	4	5
	End	2	3	4	5	6

Table 8: Condition score matrix (NEN 2767)

This matrix can be applied to all building elements in a building. These building elements are according to the NL SFB element code, which will be further described in chapter 2.4.2. All these building elements have a specified predetermined list of potential flaws. These can be found in the NEN 2767 part 2 norm, which shows the complete flaw list (gebrekenlijst). This list is too large to include here.

The condition measurements of building elements are very objective and there is not a lot of room for personal interpretation. This is why it is good to use it in this research.

In practice, the NEN 2767 norm does come with considerations to keep in mind. For example, a building element can have a very serious flaw, but when it only occurs incidental, it can still score a condition score of '2'. These limitations came forward in many conversations during research and have to be kept in mind (Appendix A, Person R 2nd of March, Person OO 13th of April, Company N 18th of April, Person Y 3rd of March, Person MM 31st of March).

2.3.8 Disassembly potential

In a circular economy, product and material reuse is key. It considers products at the end of their useful life not as waste, but as sources of raw materials that you can reuse. Because buildings are fixed objects, made up of a quantity of different products and materials attached to each other, reuse of materials is not self-evident. This also explains why disassembly potential is such a key concept within the circular economy. The extent to which elements can be disassembled based on the connections they have between each other, determines the degree of disassembly potential. Retainment of function and high-quality reuse after this disassembly are the main goals. A literal definition of disassembly potential is the following: 'The disassembly potential of a building is the degree to which objects can be disassembled at all scales without compromising the function of the object or surrounding object' (van Vliet et al., 2021). With objects, all materials, products, elements etc independent of a certain scale are meant.

There are multiple ways to determine what the disassembly potential of objects is. One of the developed ways, and also inspiring the used way in this research, is developed by Company B in collaboration with W/E adviseurs and DGBC (van Vliet et al., 2021) (Appendix A, Person F, 2nd of February). Their method is an elaborate way to express the detachability potential in a number from 0.1 – 1. 1 is perfect disassembly potential, for example a magnetic connection, and 0.1 is the worst disassembly potential, which can be glue for example. This number is based on connection type, connection accessibility, independency and geometry of product edge. Within this method, the connection with the 10R framework is made as well. A better disassembly potential leads to a better chance to apply R3, 1 on 1 reuse. Furthermore, a better disassembly potential also contributes to adaptability of a building, because objects and elements can easily be replaced. Maintenance also becomes more accessible with increased disassembly potential.

The report mentions that, should you wish to integrate this measuring methods in existing sustainability tools, the disassembly potential index should be a benchmark used to determine the disassembly potential for a building in its totality. This shows that disassembly potential is a crucial aspect in circularity in order to determine what the circularity potential of a building in its totality could be. Even though this method is very elaborate and well thought out, it will not be used in its exact form within this research. However, the grading system will be used to express the disassembly potential in three simple classes: 'good' (goed), 'average' (matig), 'bad' (slecht). By expressing the disassembly potential in these 3 grades, and by applying the 6 possible conditions determined by the NEN 2767 method, 18 different combinations of these two are possible. These 18 combinations can then be expressed in the respective R's in the 10R framework. This will be further explained in chapter 3.1.8.

The reason that 'good', 'average' and 'bad' are the options in the method used in this research is because it roughly relates to the possible results in the disassembly potential method. For two of the four factors mentioned (independency and geometry of product edge), there are three options as well:

1.00, 0.4 and 0.1. The other two options (connection type and connection accessibility), show a gradual division of 1.00, 0.80, 0.60, 0.40 and 0.1. With this in mind, the division chosen in this research is applied. Furthermore, this method is used in practice as well, for a project which will be circularly demolished, to word a simpler and more easily understandable disassembly potential. This shows that this method is applied in practice, and that it worked in an understandable way as well (Appendix A, Person H 7th of March, Person PP 11th of April).

2.3.9 Answer sub question 2

As can be read, circularity is a broad concept where many factors come into play. A definition by EMF, ''modular and flexible by design where resource loops are closed and human well-being is promoted'' is the definition that fits within this research. The problem statement of this research is that even though there is a supposed paradigm shift taking place, for many developers there is still a lot of confusion around the circular economy principles and how to apply them in the built environment (Lacy & Rutqvist, 2015). The 10R Framework by Potting et al. (2017) (Kirchherr et al., 2017) is a framework that defines 10 circular steps which can be taken, and grades them by how good these interventions are. Even though this framework is originally not created specifically for the built environment, it is applied often, and the definitions of each 'R' have been adjusted to be suitable for the built environment. This framework is useful to clarify what circularity in the built environment means, but because circularity is such a broad word, this framework does not include all factors concerning circularity. Low-material design, modular design, adaptive design, design for deconstruction, design for recycling / cradle to cradle, recycle for (circular) design and material passports are all interventions which can be taken in the built environment, to achieve circularity. For the scope of this research, the focus is put on building adaptation and demolition, meaning that circular construction will not be included in this research. For applying circularity to building adaptation projects and demolition projects, the 10R framework is crucial. Furthermore, the materials and the amount of these materials that have to be processed in these projects are important to calculate the potential CO2 emissions savings can be made. The construction material pyramid is a useful tool to use for this. Lastly, the NEN 2767 condition and disassembly potential of building elements are crucial to be identified, in order to apply the 10R framework to the building adaptation projects and demolition projects.

2.4 Building elements

In order to determine what the circularity potential of a building is, it is important to determine what elements there are in a building. The categorization of a building into elements makes it so that circularity potential scores can be applied to these specific elements, creating a complete analysis. There are multiple methods to categorize buildings into elements. The following methods will be explained in this chapter: Brand Layers, NL SFB and the demarcation list.

2.4.1 Brand layers

Buildings and all their components have life cycles. Based on the lifecycles of layers of a building, determinations and choices regarding the 10R framework can be taken. The Building Life Cycle Theory by (Brand, 1994) explains six layers of a building in which change can take place. These layers are the 6 s´s: Site, Structure, Skin, Services, Space Plan and Stuff. Every layer has its own lifecycle (figure 6).

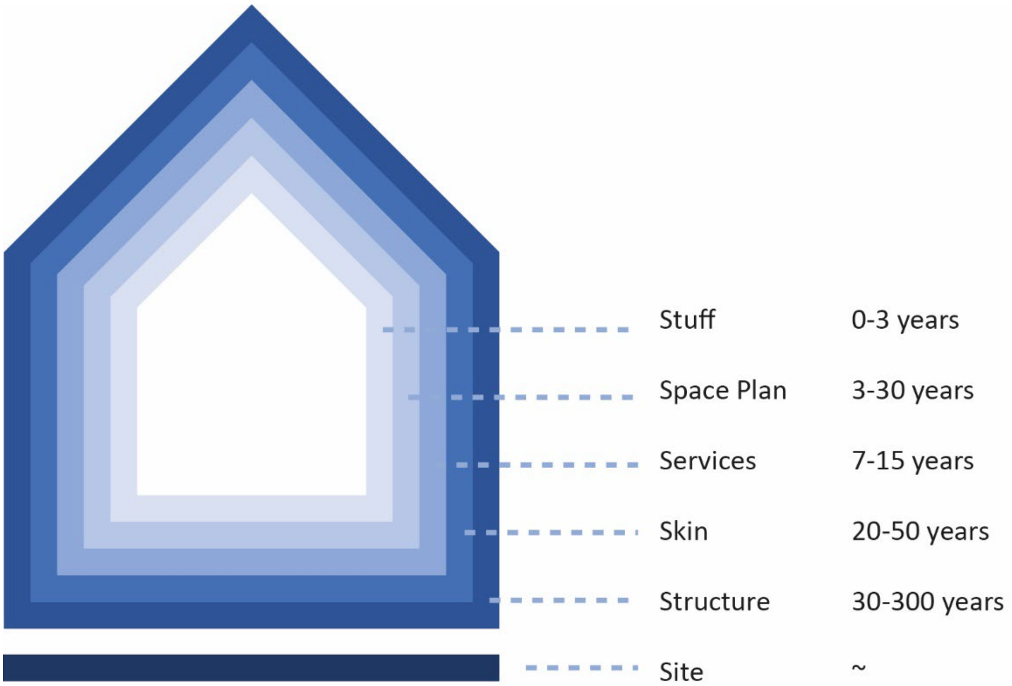


Figure 6: Building Life Cycle Theory (Brand, 1994)

This division of layers provides a good insight into a building and which components should and could be replaced in a certain timeframe. This helps to determine which circularity principles, for example based on the 10R model, can be implemented in adapting these layers in their certain timeframe.
Within the building lifecycle, changes occur. (Douglas, 2006) adopted a five-stage cycle in this. The first cycle was labelled 'birth' and resembles a new function and new user in the accommodation. 'Expansion' is the second stage and resembles new needed requirements within the accommodation and new services and a new layout are introduced. 'Maturity' is the third stage and resembles the discussion whether the current function can be maintained in the building, or whether the building can no longer fulfil the current needs. Stage four is 'redundancy' and resembles the becoming vacant or obsolete of the building due to changes in for example sources of power, societal cultural values and market needs. 'Rebirth' or 'demolition' are the final stage, where the decision between building adaptation or rebuilding has to be made. Building adaptation can take place at every stage after 'birth', according to (Douglas, 2006).

The disassembly potential study by van Vliet et al., (2021), also refers to the layers of Brand. This is because the disassembly potential is not relevant to all products in a building. The layers of Brand help to identify which products disassembly potential should be applied to. In their study it only refers to the layers: space plan, services, skin and structure. Skin and stuff are not included in their measurement method. One of the characteristics of the Layers of Brand is that products have different life spans. Structural products usually last for the entire lifetime of a building. The other layers however do not last the whole lifetime of the building. For these products specifically it is very important to be produced for disassembly. In this research, and concerning the Circularity Potential Meter that will be set up in it, 'Stuff' will be included as a layer where disassembly potential is shown. This is because of one of the project visits conducted in this research. This project visit showed a circular demolition company, which attached a lot of value to the existing stuff that was in the building, and showed the great potential that reusing this stuff could have (Appendix A, Company D, 27th of February).

2.4.2 NL SFB

The NL SFB list is another way to categorize a building into elements and layers (BNA, 2005). SFB is the abbreviation from the Swedish committee 'Samarbetskommittén för Byggnadsfragor' which translates roughly to 'joint working committee on construction issues'. This committee set up the original version in the year 1947. This document eventually became an internationally used method to categorize buildings.

The NL SFB list consists of 5 different tables which are (BNA, 2005):

- Table 0: Spatial services, which consists of the coding for the to be built surroundings at the to be created spaces
- Table 1: Functional building elements, which consists of the coding for the functional building elements of the to be built services
- Table 2: Construction methods, which consists of the to be applied construction methods
- Table 3: Construction resources. Which consists of the coding for the to be applied (building)materials
- Table 4: Activities, features and characteristics, which consists of the coding for the to be organized preparation and building process.

For this research, table 1 is most important because it shows all the elements in a building to which condition and disassembly potential can be applied to. Table 1 is often used in practice when it comes to circularity (Appendix A, Company D 27th of February, COMPANY G 24th of March, Company N 18th of April). Furthermore, the NL SFB list is also used in the NEN 2767 norm. Therefore, these two methods connect well with each other, and can therefore also be applied in unison in this research.

Table 1 is shown in the later versions of the Circularity Potential Meter (chapter 3.1.3 – 3.1.8), showing the categorization with 1 number after the comma. The list also expands to much more specific elements, going to up to 4 numbers behind the comma. For this research, this is too specific, and it will become too time consuming to use the tool.

2.4.3 Demarcation

A demarcation list is a list with building technical or installation technical instances which apply to buildings. In this demarcation list, arrangements are made regarding whose responsibility the maintenance is for certain elements within the buildings. This means that these lists are also building specific, and thus, differ per project. This is why this method cannot be used in this research. The Circularity Potential Meter is supposed to be able to be applied to all building adaptation and demolition projects. Therefore, the NL SFB method suits this research better.

2.4.4 Answer sub question 3

As mentioned, in order to apply circular measures in building adaptation and demolition projects, it is important to know to what building elements these measures can be applied. This research identified three categorisation methods for buildings to which the circularity frameworks can be coupled. These are the layers of Brand, the NL SFB list and a demarcation list. The layers of Brand divide a building is six layers, which are site, structure, skin, services, space plan and stuff (the six s's), and couples these to a certain lifespan. The NL SFB list is an official categorization method used to categorize buildings into specific building elements. A demarcation list has the same principle as the NL SFB list, but is specified for each building. Each building has their own demarcation list. For this research specifically, the NL SFB list suits best, because it can be applied to all buildings, and it combines well with the NEN 2767 norm and disassembly potential methods.

2.5 Existing tools

2.5.1 Transformation Potential Meter (TPM)

As mentioned in the introduction, there is a tool that already exists, which measures the transformation potential for offices to a housing accommodation. However, this tool does not take into consideration what the circularity potential of such a conversion is. As of right now, this means that the circularity potential is not seen as a crucial factor that influences the final decision-making in projects.

To be able to set up a similar tool like the Transformation Potential Meter (TPM) but then to measure the circularity potential, it is important to understand how the TPM is set up, in order to inspire the setup of the new Circularity Potential Meter. The TPM is set up in 6 steps, step 0 to step 5.

Step 0: Inventory of supply at city, district or portfolio level
Before deciding to transform a vacant office building into housing, it is first important to determine whether the market suits this. An inventory is needed of the market supply of office buildings in a specific city, municipality, area or portfolio. Furthermore, this market supply needs to have been vacant for a certain amount of time or may be expected to become vacant in the near future.

Step 1: Quick Scan; first impression, evaluation based on veto criteria
Step 1 is a quick scan of the most important factors which determine whether or not to take on the conversion project. There are 10 so called 'veto criteria', meaning that if any one of these criteria is not met, the project will receive a NO GO. The veto criteria are divided in Criteria for market, stakeholders, location and building level and they apply to all target groups. Table 5 shows the criteria in step 1. Because this step can be completed with little research, this is a very effective step in order to quickly determine whether to pursue with the project or not.

Step 2: Feasibility scan based on gradual criteria
If the results of step 1 indicate a GO (all criteria were answered 'yes'), a feasibility scan can be conducted, which goes further into detail about the conversion potential with more gradual criteria. These criteria alone do not cause a GO or NO GO but the amount of criteria that are met in total influences the eventual outcome.

The feasibility scan is divided into location level and building level. At location level, the factors are divided into 7 main criteria, which are subdivided into functional aspects, cultural aspects and legal aspects. These, in their turn are subdivided into 23 sub-criteria. The feasibility scan at building level contains 14 main criteria, which are subdivided in functional aspects, cultural aspects, technical aspects and legal aspects. These, in their turn are subdivided into 29 sub-criteria. Every criteria that is met with a 'yes' improves the overall score of the building, therefore increasing the potential to be converted. These are added up, the higher the result is, the better.

Step 3: determination of the conversion potential class
Step 3 is an easy step to complete, once the complete checklist from step 2 has been filled in. It consists out of determining what the score is that the building receives regarding its conversion potential. This is determined as followed: the maximum achievable score is 202 points. This is scored if all criteria are answered with ' yes'. By multiplying the amount of yes's from the location level by 5, and multiplying the amount of yes's from the building level by 3, a score of 202 is reached. This difference in multiplier is to show that location factors weigh a more significant role in the final decision making than the building factors.

Based on this score, the building can be placed in classes 1 through 5. Class 1 (score lower than 40) means that there is no transformation potential, and class 5 (score higher than 160) means that there is excellent transformation potential. This score is there to show an indication of what the conversion potential of the building is, but it does not define the final decision.

If, after the first three steps, the conversion class is 4 or 5, the analysis can be continued by two additional steps. These steps are to study the financial feasibility of the conversion project (step 4) and conducting a risk assessment for further planning (step 5). Depending on the nature of the project involved and the developer of the project, step 5 may come before step 4.

Step 4: Financial feasibility scan
The financial feasibility scan is there to give an indication of the viability of the conversion project. It is not a detailed calculation yet. The financial feasibility depends among other things on the condition of the building, (land) acquisition cost, the level of renovation that is required, the finishing and comfort level of the housing, the number of (extra) dwelling units that can be created in the building and the project yield by rental income and/or sales prices (Gelinck, 2013).

For transformation projects, it is difficult to have standard numbers on what the costs can be. Every project is unique, which means that the state of the building may differ in every project. Furthermore, size, location, shape, materials etc. all vary per project, meaning that it becomes virtually impossible to set standard numbers for costs.

Step 5: Risk assessment checklist with possible solutions
Step five consists of a risk assessment, where potential risks and ways to mitigate these risks are analysed. These risk assessment also exist both on building level and on location level. Complete lists of what these risks are and possible solutions have already been created in previous researches done by R. Geraedts, D.J.M. van der Voort and H. Remoy (2018).

In its basis, this tool helps to design the Circularity Potential Meter. The way it is set up makes it so that a quick scan of a building can be made, and through a scoring system, it can quickly be determined how suitable the building is for transformation. This will form the basis for the Circularity Potential Meter as well.
Where it differs from the Circularity Potential Meter, is the fact that the TPM looks at certain building requirements which need to be met, and it regards aspects. The CPM does not look at building requirements to be able to house another function. It looks specifically at building materials and components to measure how well they are suited for reuse. The financial feasibility scan and the risk assessment checklist also don't correspond to the scope of this research. However, a follow up on how applying circularity principles can influence the possible feasibility of a project is an interesting topic to move further on.

2.5.2 Material passport

For this research, a project visit was organized with a company who make material passports of buildings which will either be renovated in the near future, or which will be demolished in the foreseeable future (Appendix A, Company L, 21st of March) . In the case of this project visit, a material passport was being made for a building in Tilburg, for which the future was not clear yet. It was not clear whether the building would still be there in 5 years or in 25 years. Nonetheless, a material passport had to be made, on the instructions of the municipality.

For making this material passport, 2 people would walk around the building, establishing many details within the building. This was done with a tool, controlled via a tablet. From all the elements in the building, ranging from window frames and doorframes, to the main structure of the building, certain specifics had to be filled in in the tool. First the element would be looked up in the NL SFB database. The fact that the NL SFB database was also used in this tool shows that this list is very suitable for building categorization. Once the correct element was selected, material had to be filled in, its category, its technical quality, its aesthetic quality and the disassembly potential had to be registered. What can be seen is that this has many aspects which will be added to the CPM as well. However, different options will be given for each category:

- With category, in a way, the 10R framework is used. However, options that their tool gives for this are not the 10 R's, but they are options such as 'herbruikbaar' (reusable). The CPM will apply the 10R framework concretely, meaning that an objective score can be given.
- With technical quality, options such as 'good', 'bad' or 'average' were used. In contrast to the CPM, where the NEN 2767 score will be applied, this is less objective, but easier to fill in.
- With aesthetic quality, options such as 'user traces' were given. This aesthetic quality is not concretely used in the CPM.
- For disassembly potential, the types of connections were given, so options such as 'bolted', 'frazed' etc. This is only part of the disassembly potential method developed by DGBC, and also does not always provide the full story of the element. This is more or less in between the method used in the CPM and in the DGBC developed method.

From this project visit, useful information was gathered on what works well and what does not work as well. Some of the categories used in their tool, will also be used in the CPM, just with different options to fill in.

2.5.3 Arcadis tool

Arcadis has also developed a tool regarding circularity (Appendix A, Person WW, 20th of April). There was a tender for circular demolition via Arcadis, for which they invited five companies who could send their plan of approach for the project. In order for the companies to send this plan of approach, Arcadis set up the tool, which the companies had to fill in.

The goal of this tool is not to visualize what the circular potential of the project is, but for the companies to show how they are going to demolish the building in a circular way, and why they should win the tender. For this, Arcadis already delivers information about the building, which are the layers of Brand, the element/product, the material/type, the amount and unit and the impact of the component. The companies had to fill in which 'R' they were going to apply on the product and explain why and what the risks were for them. Based on this, a circular score was given and the achievability was determined.

To compare it to the tool developed in this research, the following remarks can be made:

- Instead of the NL SFB list, the demarcation list for this specific tender was used. This can be done because the tool is only used for this project. However, it cannot be used for other project because of this.
- The tool developed by Arcadis does not have the goal to show what the circular potential of the project is. It is used for circular demolition companies to share their circular viewpoint on the project.
- A scan regarding disassembly potential and amount of material and components had already been done prior to sending out the tender.

What is interesting to see is that even though the tools have both been developed separately, there are many aspects of circularity which are applied in both models.

2.5.4 Answer sub question 4

Sub question 4 is 'Which tools/frameworks already exist to measure the adaptation potential and circularity potential of a building?'. What has become clear is that there are many tools and frameworks that are in some form related to measuring circularity potential. Even though many tools and frameworks have been covered in this literature research, there are undoubtedly more frameworks that haven't been discussed in this research. The following list summarizes which tools and frameworks have been discussed, and are added in the tool developed in this research:

- 10R framework
- Construction Material Pyramid
- NEN 2767 norm
- Disassembly potential
- Brand Layers
- NL SFB list

The reason that these are added to the developed tool in this research have been discussed in the respective chapters themselves, but will be briefly summarized here. The 10R framework has been added to the tool because it includes a grading system and it gives a clear idea of what circularity is, and which steps can be taken to achieve circularity. The Material Pyramid is added because it has a great variety of materials for which the Embodied CO2 amounts are calculated. This adds an extra significant layer to the tool, because it helps to identify which circular measures in specific projects have the greatest impact. The NEN 2767 norm has been added to the tool because this method helps to determine the condition of a building element as objectively as possible. This helps to diminish subjective influences in the results of the tool. Furthermore, the NEN 2767 also makes use of the NL SFB list, which is also added to the tool. Lastly, because the NEN 2767 norm has 6 different grades, it works well in combination with the 3 possibilities of the disassembly potential, given in the tool. Disassembly potential is crucial when determining the circularity potential of building elements, and is therefore added in the tool. Furthermore, as mentioned, in combination with the NEN 2767 norm, it works well to determine which circular measures can be taken. The Brand Layers are added to the tool because this is one way to categorize buildings into layers. Conclusions can be drawn from identifying which layers have the greatest potential circular impact. Furthermore, because the Brand layers work with a lifecycle principle, it can be identified approximately how long building elements can continue to be used within new projects. Lastly, the NL SFB list is also added to the tool. This list categorizes buildings into building elements in a very objective manor. The list can be applied to every existing building, making it useful to implement in a tool such as the Circularity Potential Meter. Furthermore, the NL SFB list is also used in the NEN 2767 norm. It is useful that it identifies which building elements there are in buildings, and therefore to which building elements the circular principles can be applied.

Other tools and frameworks discussed in this research which are not added 1 on 1 in the developed tool, but did inspire the final version are:

- ReSOLVE framework
- Demarcation list
- Transformation Potential Meter
- Material Passport tool
- Arcadis tool

The ReSOLVE framework has not been added to the tool because it achieves a similar goal as the 10R framework, only without it having a ranking system. However, the ReSOLVE framework did help to gather a better understanding of circularity in the built environment in general. The demarcation list inspired the tool for a categorization system of buildings, but was replaced by the NL SFB list because this list can be applied to all buildings. A demarcation list is building specific, and can therefore not be integrated in a tool which is meant to be applied to all buildings. The Transformation Potential Meter was one of the first tools to inspire this research, and similar principles were integrated in earlier versions of the Circularity Potential Meter. However, as research progressed and more information was gathered about circularity, the tool further developed to its own version where most aspects do not overlap with the Transformation Potential Meter any more. The Material Passport tool and the Arcadis tool are both tools where overlap with the Circularity Potential Meter was found. However, they were not inspired by each other, but rather confirmed that certain aspects of circularity are crucial to implement in these sorts of tools.

3. Results

3.1: Circularity Potential Meter (CPM)

This chapter will go through the process of developing the tool, briefly explaining all 8 versions which came before the final version of the tool. The final version will be explained extensively, whilst with the other versions, mostly the process of development will be explained. The images are meant to showcase the progress between each version. They are not the complete list, but they rather show how every version has added columns and how every version is restructured to become more user friendly. The fact that the images cannot be read in the later versions, shows that the tool became more extensive as time progressed.

3.1.1 First version of the tool

The first version of the tool (table 8) was developed solely based on the literature research which had been done up until that point. The Transformation Potential Meter formed the main inspiration for the way that it was structured. This could be seen in the four different aspects it was categorized in, the gradual criterion, the data source column and the fact that the gradual criterion were 'yes' or 'no' questions. Furthermore, next to measuring what the circularity potential in the building itself was, steps to construct circular were also given in this version. In total, there were four columns in this version:

- Aspect
- Gradual Criterion
- Data source
- Assessment

The main reason that this tool was further developed was because the tool was meant to be a quick scan, however, the questions asked in this version were very difficult questions to answer.

Aspect	Potential in building itself (building/location specific) Gradual Criterion	Data source	Assessment Yes	No
Functional			Yes	No
	1 Are there redevelopment projects (nearby) to gather materials/components from to use in this project?		x	
	2 Are there best practice cases of similar projects where circularity principles were applied?		x	
	3 Can selective deconstruction be applied (refuse)		x	
Stakeholders				
	4 Can there be a cooperation with stakeholders who work gather/sell/buy materials from this project?		x	
	5 Can local skills/techniques/knowledge be used?		x	
Technical				
	6 Are reusable/recyclable materials used in the current existing building?		x	
	7 If 'yes' at previous question, can these materials be reused/recycled in this project or other projects?		x	
	8 Is there a material passport of the intended redevelopment project?		x	
	9 Can the building system be reused?		x	
	10 Is proper waste management possible?		x	
	11 Is the building built modular?		x	
	12 Is the building built demountable?		x	
Legal				
	13 Does local municipality have circularity goals in the construction industry?		x	
	14 Have subsidies been given out for projects with circularity goals?		x	
	15 Is there a possibility to receive subsidies for circularity goals?		x	
	Steps to take to construct circular			
	16 Can/will the new building be built modular?		x	
	17 Can/will the new building be built demountable?		x	
	18 In the new building, can/will materials with a good life cycle potential be used?		x	
	19 Can/will a material passport be made for the new building?		x	
	20 Can/will energy efficient measures used?		x	
	21 Contributed to ecosystems preservation and regeneration		x	
	22 Contributed to reducing construction/management waste and landfill		x	
	23 Are cultural values preserved?		x	
		Total	23	0

Table 9: First version of Circularity Potential Meter (own image)

3.1.2 Second version of the tool

The second version of the CPM (table 10) consisted of 3 parts: circularity potential in the building itself (building specific), 'other' circularity potential measures, and steps to construct circular. This way, the circularity potential of the projects would be tested on several different scales. However, because this second version was mostly based on literature research, and not much research from practice had been done, this version would come to change a lot in future versions. In the end, this second version did not fit the scope of the research well. The parts 'other' and 'steps to construct circular' are not part of the scope of this research and were therefore removed in later versions of the tool. This version is the last version where these two parts were still integrated. This is not to say that circularity potential is not influenced by these parts. However, for building adaptation projects and for demolition projects, these play less of a role.

What was added in this version was the Layers of Brand categorization method and the 10R framework. This way, the first version where buildings could be graded was developed. The reason for adding the layers of Brand to the tool was to bring a structure to the tool where the building could be categorized in elements. These building elements would then be graded based on the 10R framework. The building elements shown in each of the Brand layers were not found in any particular list, but were added by walking through the Architecture faculty and noticing what building elements there exist.

Aspect	Potential in building itself (building/location specific) Gradual criterion	Averages and total	R0-R9	Which R?	Why?
Site					
	1 Ground		0	Refuse	No groundwork needs to be done (no decontamination)
		Avarage R Site	0		
Structure					
	2 Foundation		3	Reuse	Good condition
	3 Load bearing structure		3	Reuse	Good condition
	4 Facade (if structural)		x	x	
		Avarage R Structure	3		
Skin					
	5 Window frames		5	Refurbish	Rust removal
	6 Windows		8	Recycle	Too low quality to reuse
	7 Insulation		7	Repurpose	Can be used elseware but not high quality enough for this project
	8 Facade material (if non-structural)		3	Reuse	Facade material is wooden slabs, can be reused
	9 Water proof layering		7	Repurpose	Good condition but not suitable for this project
		Avarage R Skin	6		
Services					
	10 Communications wiring		9	Recover	Outdated and bad condition
	11 Electrical wiring		9	Recover	Outdated and bad condition
	12 Lighting		3	Reuse	Lighting has rustic character and can be reused/revived in new project
	13 Plumbing		8	Recycle	Outdated and bad condition
	14 Sprinkler system		3	Reuse	Piping is still in good condition and can be reused in new project
	15 Heating system		5	Refurbish	Mostly radiators are used, these can be refurbished and reused
	16 Ventilating system		8	Recycle	Too much rust on ventilation canals to be wort it to refurbish
	17 Air conditioning		8	Recycle	Too much rust on ventilation canals to be wort it to refurbish
	18 Elevators		3	Reuse	Very good condition, seriously consider reusing this!
	19 Escelators		9	Recover	Outdated and bad condition
		Avarage R Services	6,5		
Space Plan					
	20 Walls		3	Reuse	In good condition in general, however, remove some for flexible floorplan
	21 Ceilings		5	refurbish	Remove molds
	22 Floors		3	Reuse	Good condition
	23 Doors		4	Repair	Pretty good condition, needs some repairs, can also be repurposed
		Avarage R Space Plan	3,75		
Stuff					
	24 Furniture		5	Refurbish	Left over furniture can be refurbished and then reused to keep character
	25 Kitchen		5	Refurbish	Leftover kitchens can be refurbished
	26 Chairs		5	Refurbish	Needs some refurbishments but can be reused then
	27 Desks		5	Refurbish	Needs some refurbishments but can be reused then
		Avarage R Stuff	5		
		Total average R	4,04166667		
	Other		Yes	No	
	28 Are there best practice cases of similar projects where circularity principles were applied?		x		Look at project (x)! They were really inventive with bio based materials
	29 Can selective deconstruction be applied (refuse)		x		Garage section can be kept as it is!
	30 Is there a material passport of the intended redevelopment project?			x	
	31 Is the building built modular?			x	
	32 Is the building built demountable?			x	
	33 Does local municipality have circularity goals in the construction industry?		x		They specifically mentioned their goals in their reports
	34 Have subsidies been given out for projects with circularity goals?			x	
	35 Is there a possibility to receive subsidies for circularity goals?		x		Convince municipality to act on their goals
		Total other	4	4	
	Steps to construct circular		Yes	No	
	36 Low material design		x		
	37 Modular design			x	
	38 Adaptive design		x		
	39 Design for deconstruction		x		
	40 Design for recycling / cradle to cradle > upcycling potential		x		
	41 Recycle for circular design		x		
	42 Create material passport		x		
	43 Use of energy efficien measures		x		
		Total circular measures taken	7	1	
x		Total	11	5	

Table 10: Second version of circularity potential meter (own image)

3.1.3 Third version of the tool

The third version of the tool was developed during the internship, where the first research in practice was conducted and implemented (Appendix A, Company D, 27th of February). The NL SFB list was now included in the tool, but still categorized through the Layers of Brand methodology. Furthermore, only a selection of the NL SFB list was actually implemented, and did not contain the proper numbering. This version looks similar to the previous version. The reason why the NL SFB list was added was because of the project visit that was done on the 27th of February. This is the first time that this list had come up in the research, and seeing as a building categorization system was a vital part of the research, the NL SFB list was immediately implemented. Furthermore, because the intent of the tool was to keep the scan as concise as possible, not the complete NL SFB list was implemented. Only the categories perceived as vital were implemented. The layers of Brand still functioned as a main categorization as well, because this was the first time the NL SFB list was introduced, and I did not feel confident to completely discard the Brand layers yet as a categorization system.

Aspect	Potential in building itself (building/location specific) Gradual criterion	Averages and total	R0-R9	Which R?	Why?
Site					
	1 Soil condition		0	Refuse	No groundwork needs to be done (no decontamination)
	2 Ground facilities				
	3 Build-up				
	4 Fences / enclosure				
	5 Terrain finishes				
	6 Terrain, mechenical engineering				
	7 Terrain, electro technical				
	8 Terrain design				
		Avarage R Site	0		
Structure					
	9 Ground floor, structural		3	Reuse	Good condition
	10 Foundation constructions		3	Reuse	Good condition
	11 Column foundations		x	x	
	12 Outside facade structural				
	13 Inner wall structural				
	14 Floors, structural				
	15 Roof, structural				
	16 Main structure				
		Avarage R Structure	3		
Skin					
	17 Outside facade, not structural		5	Refurbish	Rust removal
	18 Roof, not structural		8	Recycle	Too low quality to reuse
	19 Facade, Opening, not filled		7	Repurpose	Can be used elseware but not high quality enough for this project
	20 Facade, Opening filled with window and window frame		3	Reuse	Facade material is wooden slabs, can be reused
	21 Facade, Opening filled with door and door frame		7	Repurpose	Good condition but not suitable for this project
	22 Roof, opening, not filled				
	23 Roof, opening filled with window and window frame				
	24 Prefab components				
		Avarage R Skin	6		
Services					
	25 Heat generation		9	Recover	Outdated and bad condition
	26 Drainage systems		9	Recover	Outdated and bad condition
	27 Water systems		3	Reuse	Lighting has rustic character and can be reused/revived in new project
	28 Gas systems		8	Recycle	Outdated and bad condition
	29 Cold generation		3	Reuse	Piping is still in good condition and can be reused in new project
	30 Heat distribution		5	Refurbish	Mostly radiators are used, these can be refurbished and reused
	31 Air treatment systems		8	Recycle	Too much rust on ventilation canals to be wort it to refurbish
	32 Climate and plumbing systems		8	Recycle	Too much rust on ventilation canals to be wort it to refurbish
	33 Cetral electrical systems		3	Reuse	Very good condition, seriously consider reusing this!
	34 Power systems		9	Recover	Outdated and bad condition
	35 Lighting systems				
	36 Communications systems				
	37 Safety systems				
	38 Transport systems				
	39 Building management systems				

Table 11: Third version of circularity potential meter (own image)

3.1.4 Fourth version of the tool

The fourth version was a much further developed version of the tool. Most of the developments were based on a conversation had on a meeting with Person X (Appendix A, 28th of February). In this version, the Brand layers did not form the main categorization anymore, but rather had their separate categorization in the second column. The reason behind this was based on the conversation from the 28th of February. The NL SFB system is more elaborate than the layers of Brand and is used in practice often as an official categorization system for buildings. The reason that the layers of Brand are still left in is because it is still interesting to analyse which Brand layers have the highest impact when it comes to preventing CO_2 emissions through reuse.

The main categorization was now fully based on the NL SFB list, however, the proper numbering was not included in this list yet, with the idea of keeping the list shorter and more concise. Furthermore, the column 'amount' and 'unit' were added and the column 'condition' was added. The reasons for these additions are the fact that knowing the amount of material that comes from these types of projects helps to calculate CO_2 emission savings. This was mostly discussed with Person C, who also introduced me to the Construction Material Pyramid (Appendix A, 1st of March). Furthermore, condition of building elements plays a large role in reusability of these elements, and should therefore be included in the tool. Person H and Person X were adamant on the fact that condition of building elements plays this large role, which makes sense (Appendix A, 28th of February, 3rd of March). For the 'condition' column, the NEN 2767 norm was not implemented yet, because at this point I was not introduced to this method yet. Lastly, the 10R framework was implemented in the form of a matrix, which was suggested by Person X and confirmed to be applied this way in practice as well by Company D (Appendix, 3rd of March). This way, it is possible to show the percentage of a building element to which a certain 'R' score applies. The fourth version of the tool was the first version where the focus was really on the circularity potential in the building itself, and the categories 'other' and 'ways to construct circular' started to become less important. They were no longer in the focus of this study.

		Potential in building itself (building/location specific)								Refuse	Rethink	Reduce	Re-use	Repair	Refurbish	Remanufacture	Repurpose	Recycle	Recover
Aspect	**Brand layer**	**Gradual criterion**	**Amount**	**Unit**	**Condition**	**Average R and total**	**R0-R9**	**Which R?**	**Remarks/why?**	**R0**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**
Substructure																			
	Site	1 Soil condition	3000	m3			4	Repair	No groundwork needs to be done (no decontamination)					100%					
	Structure	2 Ground floor, structural	1000	m2			3	Re-use					100%						
	Space plan	3 Ground floor, not-structural	1000	m2			3	Re-use					100%						
	Structure	4 Foundation constructions	100	pcs			5	Refurbish							100%				
	Structure	5 Column foundations	100	pcs			6	Remanufacture								100%			
						Avarage R Substructure	4,2												
Above ground structure																			
	Skin	6 Outside facade, not-structural	720	m2			3	Re-use	Good condition				100%						
	Structure	7 Outside facade, structural	0	m2			3	Re-use	Good condition				100%						
	Structure	8 Inner wall, structural	300	m2			1	Rethink			100%								
	Space plan	9 Inner wall, not-structural	1000	m2			2	Reduce				100%							
	Structure	10 Floors, structural	800	m2			3	Re-use					100%						
	Space plan	11 Floors, not-structural	200	m2			3	Re-use					100%						
	Space plan	12 Stairs and slopes	10	pcs			4	Repair						100%					
	structure	13 Roof, structural	360	m2			5	Refurbish							100%				
	Skin	14 Roof, not-structural	0	m2			5	Refurbish							100%				
	Structure	15 Main structure	500	pcs			4	Repair	250 colums and 250 beams					100%					
						Avarage R Above ground structure	3,3												
Top structure																			
	Skin	16 Facade, opening, not filled	0	pcs			5	Refurbish	Rust removal						100%				
	Skin	17 Facade, opening, filled with window and window frame	100	pcs			8	Recycle	Too low quality to reuse									100%	
	Skin	18 Facade, opening, filled with door and door frame	10	pcs			7	Repurpose	Can be used elseware but not high quality enough for this project								100%		
	Space plan	19 Inner wall, opening, not filled	50	pcs			3	Re-use	Facade material is wooden slabs, can be reused				100%						
	Space plan	# Inner wall, opening, filled with window and window frame	100	pcs			7	Repurpose	Good condition but not suitable for this project								100%		
	Space plan	21 Inner wall, opening, filled with door and door frame	100	pcs			6	Remanufacture								100%			
	Space plan	# Floor opening	5	pcs			6	Remanufacture								100%			
	Skin	# Roof, opening, not filled	0	pcs			5	Refurbish							100%				
	Skin	# Roof, opening, filled with window and window frame	10	pcs			5	Refurbish							100%				
	Skin	25 Prefab components	100	pcs			5	Refurbish							100%				
						Avarage R Top structure	5,7												
Finishes																			
	Space plan	# Facade finishes	720	m2			3	Re-use	Outdated and bad condition				100%						
	Space plan	27 Inner wall finishes	1300	m2			3	Re-use	Outdated and bad condition				100%						
	Space plan	# Floor finishes	1000	m2			3	Re-use	Lighting has rustic character and can be reused/revived in new project				100%						
	Space plan	# Stairs and slopes finishes	100	m2			4	Repair	Outdated and bad condition					100%					
	Space plan	# Ceiling finishes	300	m2			5	Refurbish	Piping is still in good condition and can be reused in new project						100%				
	Space plan	31 Roof finishes	100	m2			5	Refurbish	Mostly radiators are used, these can be refurbished and reused						100%				
						Avarage R Finishes	3,8												
Mechanical installations																			
	Services	# Heat generation	100	pcs			3	Re-use	In good condition in general, however, remove some for flexible floorplan				100%						
	Services	# Drainage systems	1000	m			5	Refurbish	Remove molds						100%				
	Services	# Water systems	500	m			3	Re-use	Good condition				100%						
	Services	35 Gas systems	100	m			4	Repair	Pretty good condition, needs some repairs, can also be repurposed					100%					
	Services	# Cold generations	0	m			5	Refurbish							100%				
	Services	37 Heat distribution	10000	m			5	Refurbish							100%				
	Services	# Air treatment systems	1000	m			5	Refurbish							100%				
	Services	# Climate and plumbing systems	0	m			8	Recycle										100%	
						Avarage R Mechanical installations	4,8												
Electrical Installations																			
	Services	# Central electrical systems					8	Recycle	Left over furniture can be refurbished and then reused to keep character									100%	
	Services	41 Power systems					8	Recycle	Leftover kitchens can be refurbished									100%	
	Services	# Lighting systems					5	Refurbish	Needs some refurbishments but can be reused then						100%				
	Services	# Communications systems					3	Re-use	Needs some refurbishments but can be reused then				100%						
	Services	# Safety systems					3	Re-use					100%						
	Services	45 Transport systems					5	Refurbish							100%				
	Services	# Building management systems					6	Remanufacture								100%			
						Avarage R Electrical installations	5,4												
Fixed design																			
	Stuff	47 Ballustrades and handrails					3	Re-use	No groundwork needs to be done (no decontamination)				100%						
	Stuff	# Traffic facilities					3	Re-use					100%						
	Stuff	# User facilities					5	Refurbish							100%				
	Stuff	50 Kitchen facilities					5	Refurbish							100%				
	Stuff	51 Sanitary facilities					5	Refurbish							100%				
	Stuff	52 Maintenance facilities					5	Refurbish							100%				
	Stuff	53 Storage facilities					5	Refurbish							100%				
						Avarage R Fixed design	4,4												
Non-fixed inventory																			
	Stuff	54 Traffic inventory					5	Refurbish	Good condition						100%				
	Stuff	55 Users inventory					5	Refurbish	Good condition						100%				
	Stuff	56 Kitchen inventory					5	Refurbish							100%				

Table 12: Fourth version of circularity potential meter (own image)

3.1.5 Fifth version of the tool

In this version, the proper numbering, and therefore the complete NL SFB list was added. This is because the realization had come that in order to have a complete and sufficient analysis regarding circularity potential, it should be possible to grade all building elements present in a building. Depending on the intentions for a project, each building element can be more valuable than another, so all building elements should be included in the tool. Furthermore, based conversations with Person H (Appendix A, 27th of March), disassembly potential, CO_2 impact and the NEN 2767 were also added to the tool. The reasons behind this are the fact that disassembly potential plays a large role in reusability of the building element, and therefore in the circularity potential. CO_2 impact is an interesting statistic where the impact on the environment can easily be visualized in the tool. Lastly, the NEN 2767 norm is included because this is a very objective way to grade building elements on their condition, therefore decreasing the subjectivity element of reusability.

		Potential in building itself (building/location specific)										Refuse	Rethink	Reduce	Re-use	Repair	Refurbish	Remanufacture	Repurpose	Recycle	Recover
Aspect	**Brand layer**	**Gradual criterion**	**Amoun**	**Unit**	**Condition**	**Impact**	**Losmaakbaarhe**	**Average R and total**	**R0-R9**	**Which R?**	**Remarks/why?**	**R0**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**
Substructure																					
	Site	11.1 Soil condition, ground	3000	m3					4	Repair	No groundwork needs to be done (no decontamination)					100%					
	Structure	11.2 Soil condition, water	1000	m2					3	Re-use					100%						
	Space plan	13.1 Ground floor, not-structural	1000	m2					3	Re-use					100%						
	Structure	13.2 Ground floor, structural	100	pcs					5	Refurbish							100%				
	Structure	16.1 Foundation constructions, feet and beams	100	pcs					6	Remanufactur								100%			
		16.2 Foundation constructions, retaining walls																			
		17.1 Column foundations, not pile driven																			
		17.2 Column foundations, pile driven																			
								Avarage R Substructure	4,2												
Above ground structure																					
	Skin	21.1 Outside facade, not-structural	720	m2					3	Re-use	Good condition				100%						
	Structure	21.2 Outside facade, structural	0	m2					3	Re-use	Good condition				100%						
	Structure	22.1 Inner wall, not-structural	300	m2					1	Rethink			100%								
	Space plan	22.2 Inner wall, structural	1000	m2					2	Reduce				100%							
	Structure	23.1 Floors, not-structural	800	m2					3	Re-use					100%						
	Space plan	23.2 Floors, structural	200	m2					3	Re-use					100%						
	Space plan	24.1 Stairs and slopes, stairs	10	pcs					4	Repair						100%					
	structure	24.2 Stairs and slopes, slopes	360	m2					5	Refurbish							100%				
	Skin	24.3 Stairs and slopes, ladders and climbing irons	0	m2					5	Refurbish							100%				
	Structure	27.1 Roofs, not-structural	500	pcs					4	Repair	250 colums and 250 beams					100%					
		27.2 Roofs, structural																			
		28.1 Main structure, column and beams																			
		28.2 Main structure, walls and floors																			
		28.3 Main structure, spatial units																			
								Avarage R Above ground structure	3,3												
Top structure																					
	Skin	31.1 Facade, opening, not filled	0	pcs					5	Refurbish	Rust removal						100%				
	Skin	31.2 Facade, opening, filled with window and window frame	100	pcs					8	Recycle	Too low quality to reuse									100%	
	Skin	31.3 Facade, opening, filled with door and door frame	10	pcs					7	Repurpose	Can be used elseware but not high quality enough for this project								100%		
	Space plan	31.4 Facade, opening, filled with sliding doors/windows and frames	50	pcs					3	Re-use	Facade material is wooden slabs, can be reused				100%						
	Space plan	32.1 Inner wall, opening, not filled	100	pcs					7	Repurpose	Good condition but not suitable for this project								100%		
	Space plan	32.2 Inner wall, opening, filled with window and window frame	100	pcs					6	Remanufactur								100%			
	Space plan	32.3 Inner wall, opening, filled with door and door frame	5	pcs					6	Remanufactur								100%			
	Skin	32.4 Inner wall, opening, filled with sliding doors/windows and frames	0	pcs					5	Refurbish							100%				
	Skin	33.1 Floor opening, not filled	10	pcs					5	Refurbish							100%				
	Skin	33.2 Floor opening, filled	100	pcs					5	Refurbish							100%				
		34.1 Ballustrades and handrails, ballustrades																			
		34.2 Ballustrades and handrails, handrails																			
		37.1 Roof, opening, not filled																			
		37.2 Roof, opening, filled with window and window frame																			
		38.1 Prefab components																			
								Avarage R Top structure	5,7												
Finishes																					
	Space plan	41.1 Facade finishes	720	m2					3	Re-use	Outdated and bad condition				100%						
	Space plan	42.1 Inner wall finishes	1300	m2					3	Re-use	Outdated and bad condition				100%						
	Space plan	43.1 Floor finishes, raised	1000	m2					3	Re-use	Lighting has rustic character and can be reused/revived in new project				100%						
	Space plan	43.2 Floor finishes, not raised	100	m2					4	Repair	Outdated and bad condition					100%					
	Space plan	44.1 Stairs and slopes finishes, stairs finishes	300	m2					5	Refurbish	Piping is still in good condition and can be reused in new project						100%				
	Space plan	44.2 Stairs and slopes finishes, slopes finishes	100	m2					5	Refurbish	Mostly radiators are used, these can be refurbished and reused						100%				
		45.1 Ceiling finishes, lowered ceiling																			
		45.2 Ceiling finishes, not lowered																			
		47.1 Roof finishes, finishes																			
		47.2 Roof finishes, coating																			
		48.1 Finishes, complete package																			
								Avarage R Finishes	3,8												
Mechanical installations																					
	Services	51.1 Heat generation, local	100	pcs					3	Re-use	In good condition in general, however, remove some for flexible floorplan				100%						
	Services	51.2 Heat generation, central	1000	m					5	Refurbish	Remove molds						100%				
	Services	51.3 Heat generation, provided heat	500	m					3	Re-use	Good condition				100%						
	Services	51.4 Heat generation, central services for combined generation and provision of he	100	m					4	Repair	Pretty good condition, needs some repairs, can also be repurposed					100%					
	Services	51.5 Heat generation, special cases	0	m					5	Refurbish							100%				
	Services	52.1 Drainage systems, rainwater	10000	m					5	Refurbish							100%				
	Services	52.2 Drainage systems, fecies	1000	m					5	Refurbish							100%				
	Services	52.3 Drainage systems, waste water	0	m					8	Recycle										100%	
		52.4 Drainage systems, combined																			
		52.5 Drainage systems, special cases																			
		52.6 Drainage systems, waste																			
		53.1 Water, drinking water transport																			
		53.2 Water, heated tapwater, generation and transport																			
		53.3 Water, services for grey water																			

Table 13: Fifth version of circularity potential meter (own image)

3.1.6 Sixth – Eighth version of the tool

These three versions had relatively minor changes compared to the previous versions. The only added column was the column where an explanation for the NEN 2767 could be given. This is now possible in case a condition score needs to be nuanced. In rare cases, NEN 2767 condition scores can be deceiving, so in this case it can be useful to write remarks to explain why a certain condition score is given. This was suggested by a professional in the field regarding the NEN 2767 condition measurements (Appendix A, 3rd of March, Person Y) The bigger changes took place in making the tool more user friendly. Therefore, the columns were restructured so that the order in which you fill in the tool is more logical. Furthermore, 'average R' scores are now based on the amount of cells that are filled in. The unit in which you specify the amounts of a certain building element can now be selected through a drop down menu, showing the units that are also used in the actual NL SFB list. Another added function is that the 'R' score is now based on an average that is filled in in the 10R framework matrix. Lastly, a Dutch translation and an English translation of the tool were developed. All these changes were implemented based on my own testing of the tool on hypothetical buildings. I noticed the tool could be finetuned a lot when testing it out on hypothetical cases, which is why I implemented the changes for quality of life. The tool is now much more structured and easy to follow.

		Circulaire potentie van het gebouw			Zie toelichtingen tab	NEN 2767		Refuse	Rethink	Reduce	Re-use	Repair	Refurbish	Remanufacture	Repurpose	Recycle	Recover			
Aspect, NL SFB	**Brand lagen**	**Gebouwelementen specifiek**	**Hoeveelhe**	**eenheid**	**Losmaakbaarh**	**Conditie**	**Gebaseerd op, korte uitleg:**	**R0**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R0-R9**	**Opmerkingen/waarom?**	**CO2 Impact**
Funderingen																				
	Site	11.1 Bodemvoorzieningen, grond		m3														0		
	Site	11.2 Bodemvoorzieningen, water		m3														0		
	Space plan	13.1 Vloeren op grondslag, niet constructief		m2														0		
	Structure	13.2 Vloeren op grondslag, constructief		m2														0		
	Structure	16.1 funderingsconstructies; voeten en balken		m1														0		
	Structure	16.2 funderingsconstructies; keerwanden		m1														0		
	Structure	17.1 paalfunderingen; niet geheid		Units														0		
	Structure	17.2 paalfunderingen; geheid		Units														0		
			0														Gem. R	######		
Ruwbouw								**R0**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**			
	Skin	21.1 buitenwanden; niet constructief		m2														0		
	Structure	21.2 buitenwanden; constructief		m2														0		
	Space plan	22.1 binnenwanden; niet constructief		m2														0		
	Structure	22.2 binnenwanden; constructief		m2														0		
	Space plan	23.1 vloeren; niet constructief		m2														0		
	Structure	23.2 vloeren; constructief		m2														0		
	Space plan	24.1 trappen en hellingen; trappen		m2														0		
	Space plan	24.2 trappen en hellingen; hellingen		m2														0		
	Space plan	24.3 trappen en hellingen; ladders en klimijzers		m1														0		
	Skin	27.1 daken; niet constructief		m2														0		
	Structure	27.2 daken; constructief		m2														0		
	Structure	28.1 hoofddraagconstructies; kolommen en liggers		m1														0		
	Structure	28.2 hoofddraagconstructies; wanden en vloeren		m2														0		
	Structure	28.3 hoofddraagconstructies; ruimte-eenheden		m2														0		
			0														Gem. R	######		
Afbouw								**R0**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**			
	Skin	31.1 buitenwandopeningen; niet gevuld		m2														0		
	Skin	31.2 buitenwandopeningen; gevuld met ramen		m2														0		
	Skin	31.3 buitenwandopeningen; gevuld met deuren		m2														0		
	Skin	31.4 buitenwandopeningen; gevuld met puien		m2														0		
	Space plan	32.1 binnenwandopeningen; niet gevuld		m2														0		
	Space plan	32.2 binnenwandopeningen; gevuld met ramen		m2														0		
	Space plan	32.3 binnenwandopeningen; gevuld met deuren		m2														0		
	Space plan	32.4 binnenwandopeningen; gevuld met puien		m2														0		
	Skin	33.1 vloeropeningen; niet gevuld		m2														0		
	Skin	33.2 vloeropeningen; gevuld		m2														0		
	Stuff	34.1 balustrades en leuningen; balustrades		m1														0		
	Stuff	34.2 balustrades en leuningen; leuningen		m1														0		
	Skin	37.1 dakopeningen; niet gevuld		m2														0		
	Skin	37.2 dakopeningen; gevuld		m2														0		
	Skin	38.1 inbouwpakketten		m2														0		
			0														Gem. R	######		
Afwerkingen								**R0**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**			
	Space plan	41.1 buitenwandafwerkingen		m2														0		
	Space plan	42.1 binnenwandafwerkingen		m2														0		
	Space plan	43.1 vloerafwerkingen; verhoogd		m2														0		
	Space plan	43.2 vloerafwerkingen; niet verhoogd		m2														0		
	Space plan	44.1 trap- en hellingafwerkingen; trapafwerkingen		m2														0		
	Space plan	44.2 trap- en hellingafwerkingen; hellingafwerkingen		m2														0		
	Space plan	45.1 plafondafwerkingen; verlaagd		m2														0		
	Space plan	45.2 plafondafwerkingen; niet verlaagd		m2														0		
	Space plan	47.1 dakafwerkingen; afwerkingen		m2														0		
	Space plan	47.2 dakafwerkingen; bekledingen		m2														0		
	Space plan	48.1 afwerkingspakketten		m2														0		
			0														Gem. R	######		
Installaties, werktuigbouwkundig								**R0**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**			
	Services	51.1 warmte-opwekking; lokaal		Units														0		
	Services	51.2 warmte-opwekking; centraal		Units														0		
	Services	51.3 warmte-opwekking; toegeleverde warmte		kW														0		
	Services	51.4 warmte-opwekking; warmte-krachtkoppeling		kW														0		
	Services	51.5 warmte-opwekking; bijzonder		kW														0		
	Services	52.1 afvoeren; regenwater		m1														0		
	Services	52.2 afvoeren; fecaliën		m1														0		
	Services	52.3 afvoeren; afvalwater		m1														0		
	Services	52.4 afvoeren; gecombineerd		m1														0		
	Services	52.5 afvoeren; speciaal		Units														0		
	Services	52.6 afvoeren; vast vuil		m1														0		
	Services	53.1 water; drinkwater		m1														0		
	Services	53.2 water; verwarmd tapwater		Units														0		

Table 14: Eighth version of circularity potential meter (own image)

3.1.7 Ninth version of the tool

The ninth version of the tool is much further developed than the previous version. This was mostly based on a conversation held with Person CC (Appendix A, 7th of April). This person thoroughly discussed the tool and suggested that it had to be more automated. The tool should already give suggestions by itself, based on data you fill in. When developing the tool, this was not something I considered. However, when discussing with Person CC, it became clear why this is necessary. Before this version, the CO2 calculations had to be done manually, increasing labour drastically to fill in the tool. Person CC mentioned that no one would fill in this column if they had to calculate everything themselves. Furthermore, simply filling in disassembly potential, condition and the 10R framework yourself can be an option, but there should also be an automated way which makes it way faster to fill in the tool. Therefore, the automation of the combination of disassembly potential and condition, resulting in an ´R´ score, was a very valuable suggestion, which was then added to the tool as well.

This version added the ‘material’ column, which contains a list of materials for which the embodied carbon emissions are known. This column, combined with the ‘+/- M3’ column, will give an estimate of the amount of embodied carbon emissions which can be saved by reusing these materials. Furthermore, the ‘disassembly potential’ (losmaakbaarheid) column now has a drop down menu of 3 options ‘good’, ‘average’ and ‘bad’, which was suggested by Person H on the 7th of March (appendix A), and the condition column now has the drop down menu for the options 1 through 6. The combination of these two columns now give a suggestion for which ‘R’ from the 10R framework can be implemented. This thoroughly improved the product of this research, because through this automation, it is now much less labour intensive to fill in the tool.

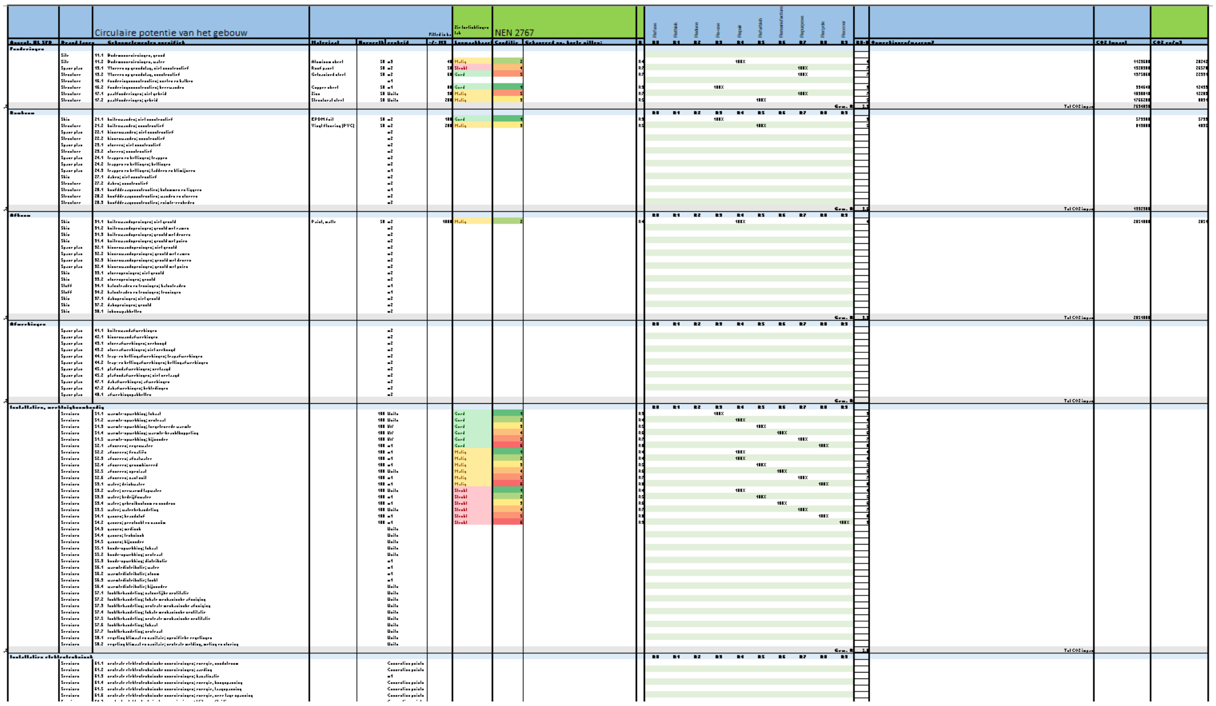


Table 16: Ninth version of circularity potential meter (own image)

3.1.8 Tenth (last) version of the tool

In between the first version of the tool and the last version of the tool, there are many different versions. The last version, as it is right now, is the 10th version of the tool. The most recent version of the tool has been developed thoroughly since the first version of the CPM. Based on literature research and empirical research, many columns have been added. This sub chapter will go over all the columns of the last version of the tool, explain why they were added, and what their influence is on the results. It is similar to a short summary of the literature research and empirical research explained before, because this all influences the result of the tool. At the end of this chapter, a conceptual scheme is developed to show in which order the tool should be filled in, what the needed information for this is, and what possible results are from the tool.

The following columns are part of the tool and discussed in this sub chapter (table 17):

- Sub categories of NL SFB list
- Brand layers
- Specific building elements, based on NL SFB list
- Material
- Amount and unit
- Amount in Cubic meters (m3)
- Disassembly potential
- Condition (based on NEN 2767 norm)

- ‘R’ score based on disassembly potential and condition
- 10R framework matrix
- Average ‘R’ score based on matrix
- ‘R’ score based on CO2 emissions
- CO2 impact if reused
- CO2 impact based on ‘R’ score

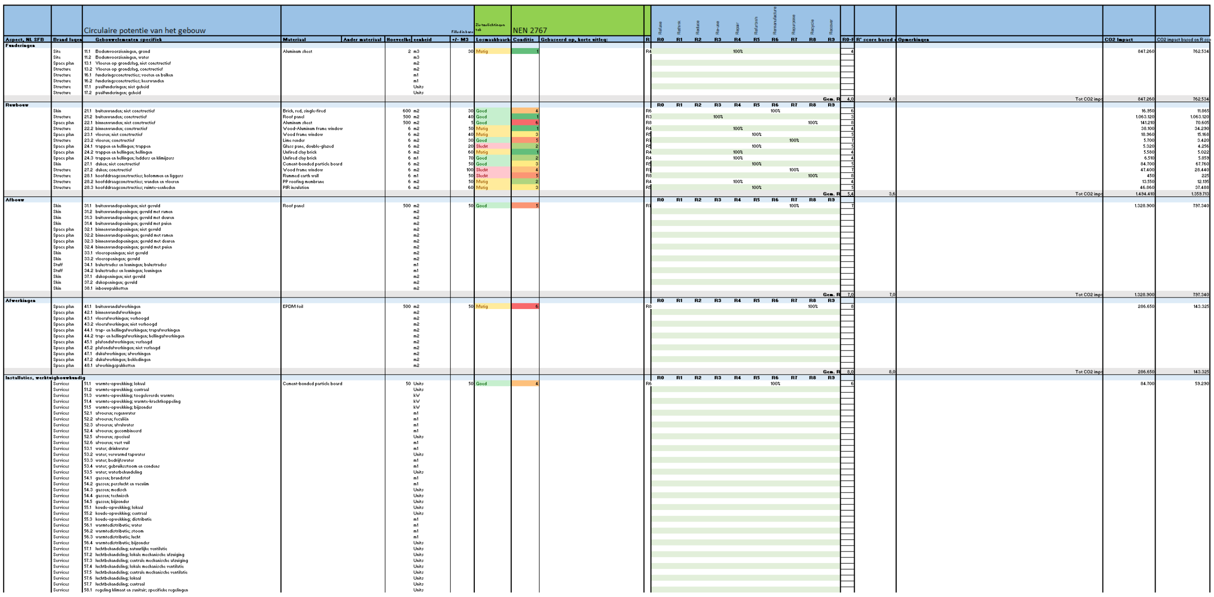


Table 17: Tenth version of circularity potential meter (own image)

Sub categories of NL SFB list

In chapter 2.4.2, explaining about NL SFB, it was already mentioned that the detail to which this would be integrated would be with 1 number behind the comma. However, these building elements are also divided into nine sub categories. These are the following:

- Ground, substructure (funderingen)
- Structure primary elements, carcass (ruwbouw)
- Secondary elements, openings (afbouw)
- Finishes (afwerkingen)
- Services, mainly mechanical (installaties, werktuigbouwkundig)
- Services, mainly electrical (installaties, elektrotechnisch)
- Facilities (vaste voorzieningen)
- Fittings (losse inventaris)
- Ground facilities (terrein)

There are multiple reasons why this categorization is also applied in the tool. First of all, it is simply part of the NL SFB categorization system so it makes sense in that way. It also gives structure to the tool and makes it easier to read and fill in. The main reason, however, is that interesting conclusions can come from it. Every sub category will receive an ‘average R’ score based on all the specific building elements that got this score. Based on this, and based on the CO2 impact, the different sub categories can be compared. It can be seen per sub category how well they score, what the reuse potential is, and based on this, decisions can be made.

Brand layers
In the first versions, the Brand layer system was used for the sub categorization of building elements. However, because this categorization system is mostly focussed around the lifetime of the layers, building elements are hard to categorize in this way, the NL SFB method was chosen in the end. The reason why it is still in the tool is because of the fact that, in practice, everyone knows about this categorization system, and it is still used often for other purposes as well. When an ‘R’ score has been given to a certain building element, conclusions can also be taken based on the Brand layer that this element is in. The ‘R’ score might be good, but when according to the Brand layers, the end of its lifecycle is near, this ‘R’ score could be reviewed further. The reason that it does not directly influence the R result is because of the fact that lifecycle can be influenced by many factors. A product can be in a very bad state even though it is still in early stages of its lifecycle, purely because of other factors surrounding the element. This works the other way around as well. The brand layers could still be integrated in presenting the numbers, to show that it could be kept in mind when reviewing the results.

Specific building elements, NL SFB list
This column shows all the building elements presented in the NL SFB list, based on 1 number behind the comma. Because the tool has to be filled in with relative simplicity, in order to make it a relatively quick scan of a building, the list does not specify in elements with 2 numbers behind the comma. This way, the list would contain over 1000 elements to be filled in, making it too time consuming.

Material
The material that a certain building element is made of is important for multiple reasons. First of all, the material that the element is made of has a certain value of CO2 emissions it produced to be created in the first place. Therefore, by applying the 10R framework to this building element, a certain amount of CO2 emissions can be saved, because the element might not have to be created from scratch again. Furthermore, the material that the building element is made out of can also influence the ‘R’ score in general. Some materials are better recyclable than other materials. However, because there is no easy way to implement this for every existing material, this will have to be judged separately.
In the ‘material’ column in the tool, a drop down menu is given, showing a list of materials for which it is known what the CO2 emission is when the material newly created. This is the list shown in the Construction Material Pyramid in chapter 2.3.6. Based on the selected material and the amount of the material that is in the project, a CO2 saving will be calculated in the CPM. If the building element is made out of a material which is not in the list, it is possible to type in the material yourself. However, no CO2 calculations will be made in this case.

Amount and unit
The amount and unit shows how much of a certain building element there is in the building. This is important to realize because the amount of product there is in the building influences the amount of CO2 that can be saved. Because not every building element can be measured in cubic meters, the unit can be chosen for each building element via a drop down menu. Only if the amount of the material can be measured in cubic meters, a CO2 saving calculation can be made. The amount of cubic meters can be filled in in the next column.

Amount in cubic meters
As mentioned, this column can be filled in with the amount of cubic meters of a certain material that there is in the building. The amount of a specific material in cubic meters on which the 10R framework will be applied, can result in the amount of CO2 emissions saved. Based on just site visit and floorplans, the amount of a specific material in cubic meters that there are in a building can be difficult to

calculate. Therefore, in practice, quick BIM models are made, in which mostly the architectural elements are integrated (Appendix A, Person PP, 11th of April). From these BIM models, the amount of each material can easily be retrieved, and inserted in the model. The bulk of materials is usually included in the BIM models, so the potential CO2 savings that come out of this will also form the bulk of the total amount. Installations and products that belong in the 'stuff' category from the brand layers are usually not included in the BIM models. The amount of these specific elements can however still be included in the model, but no CO2 calculations will then be made. Should this be whished, these calculations can be made separately, if the results are thought to be potentially significant.

Disassembly potential

The disassembly potential has already been covered in chapter 2.3.8. In practice, it is considered to be very important when it comes to circularity potential (Appendix A, Person F 2nd of February, Person H 7th of March, Person CC 7th of April). The easier an element can be disassembled, the higher the reuse potential of this element is. In the CPM, disassembly potential can be categorized in 'good', 'average' and 'bad'. This is then coupled with the NEN 2767 condition, which is 1 to 6, to calculate an 'R' score based on the 10R framework. The explanation for the disassembly options is as follows:

- Good: high disassembly potential, the materials, products and elements are easy to disassemble, without a large time investment. There will be no damage caused to the element and surrounding elements.
- Average: average disassembly potential, the materials, products and elements are difficult to remove without causing damage to the harvested components and surrounding components, or the components require a significant time investment to be disassembled.
- Bad: bad disassembly potential, the materials, products and elements cannot be removed without causing damage to the harvested components and surrounding components.

These categories are based on a model used in practice by Arcadis, to analyse building components regarding their disassembly potential (Appendix A, Person H, 7th of March).

Condition, NEN 2767

The condition measurement based on the NEN 2767 norm has been covered in chapter 2.3.7. As mentioned, the condition, coupled with the disassembly potential, will give a suggestion for the 'R' score. Because the condition score might not always give the full story of the building element, there is a second column where a brief explanation for the score can be given, should this be necessary.

'R' score based on disassembly potential and NEN 2767 norm

This column shows the suggested 'R' score, based on the disassembly potential and the condition. Because there are three options for the disassembly potential, and six options for the conditions, there are a total of 18 combinations for these two columns. Every combination has their own respective 'R' score, which are as follows:

- Disassembly potential: good, condition: 1 -> R3
- Disassembly potential: good, condition: 2 -> R4
- Disassembly potential: good, condition: 3 -> R5
- Disassembly potential: good, condition: 4 -> R6
- Disassembly potential: good, condition: 5 -> R7
- Disassembly potential: good, condition: 6 -> R8
- Disassembly potential: average, condition: 1 -> R4
- Disassembly potential: average, condition: 2 -> R4
- Disassembly potential: average, condition: 3 -> R5
- Disassembly potential: average, condition: 4 -> R6

- Disassembly potential: average, condition: 5 -> R7
- Disassembly potential: average, condition: 6 -> R8
- Disassembly potential: bad, condition: 1 -> R4
- Disassembly potential: bad, condition: 2 -> R5
- Disassembly potential: bad, condition: 3 -> R6
- Disassembly potential: bad, condition: 4 -> R7
- Disassembly potential: bad, condition: 5 -> R8
- Disassembly potential: bad, condition: 6 -> R9

These scores were given based on discussions with circularity experts within Arcadis (Appendix A, Person OO 13th of April, Person H 25th of April). There is room for personal interpretation of the results. The suggested 'R' score will be automatically generated, but can be overwritten should this be desired. Reasons for overwriting the suggested 'R' score can be because of the influence of material or brand layers, which are now not included in the automatic calculation. Product lifetime and material can influence the reusability or recyclability of the building elements in question.

10R Framework matrix

This matrix shows the percentage of the building element to which the in the previous column 'R' score they apply. Because of this, the model will automatically suggest that 100% of the building element applies to the in the previous column generated 'R' score. Because this does not automatically have to be the case, this matrix can also be overruled manually, by filling in what the actual division of the 10R framework is for the particular building element. This matrix is integrated in the model so that the model can be applied to any building, no matter the scale. The method of dividing the 10R framework into a matrix has also already been applied in practice by other companies who focus on circular demolition (Appendix A, Company D, 27th of February).

Average 'R' score based on the matrix

Based on the matrix in the previous columns, an average R score is calculated for each building element that is in the building. For example, when 20% of a building element is R3, and 80% of a building element is R4, the 'average R' for this element would be: 20% * 3 + 80% * 4 = 3,8. Clearly this is not an actual existing 'R' in the 10R framework, however, it is supposed to give an idea of the outcome for the building element in question. Furthermore, when all elements are filled in, all these elements will have an 'average R' score. Summing all these scores will give an 'average R' score for the whole category from the NL SFB list. This way, an overview can be created of all 'average R' scores for the nine NL SFB categories, which can give a quick impression on the circularity potential of a building. A total average R score based on all nine categories is also calculated, but should always be carefully checked whether this is a realistic outcome.

This 'Average R' column is one of the main outcomes that this tool gives, to give an idea of what the actual circularity potential of a building is. It is supposed to give a quick impression of the circularity potential of a building, because the average R, combined with the amount of potential CO2 savings can influence decision making.

'R' score based on CO2 emissions

The 'R' score based on CO2 emissions accounts for the impact that the circular interventions have, based on their CO2 impact. The reason that this function is included in the tool is because the results might otherwise indicate an unrealistic image. For example, the average 'R' score between R3 and R7 is R5. However, if the CO2 impact for the R3 score is much higher, this score should weigh more in the calculation for the average 'R' score.

CO2 impact based on 'R' score

This column shows how much CO2 emission can be spared based on the material that the building element is made of, the related CO2 savings per cubic meters (m3) and the 'R' score that is given to the building element. The CO2 impact will be calculated based on the 'R' score that is calculated and the percentage number that is coupled to this. In chapter 2.3.6, these percentages were given:

- R3, Reuse: 100%
- R4, Repair: 90%
- R5, Refurbish: 80%
- R6, Remanufacture: 70%
- R7, Repurpose: 60%
- R8, Recycle: 50%
- R9, Recover: 40%

The explanation for these numbers is also given in chapter 2.3.6. The CO2 equivalent in the next column is based on the construction material pyramid.

3.1.9 Manual for using the tool

There is also a manual which explains how the tool works exactly. It shows a step by step guide on how the tool must be filled in, and which results will come out of it. The manual is added as an appendix to this document, which can be found in Appendix B.

3.1.10 Column interaction framework

The framework in figure 7 was developed to illustrate how the columns interact with each other:

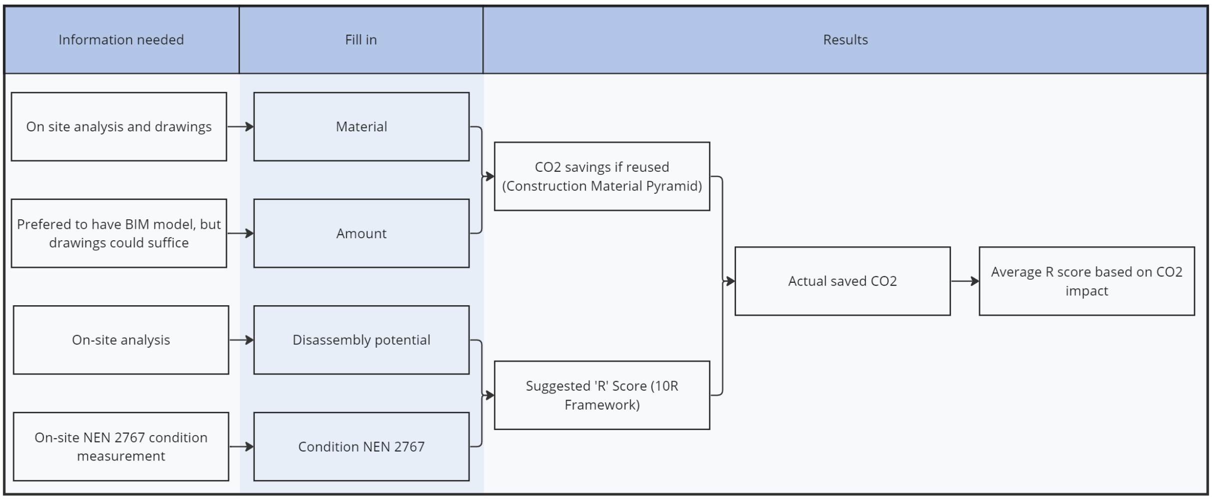


Figure 7: Framework on which columns there are in the CPM and how they interact with each other (own image)

This image shows which cells need to be filled in, which information is needed for them, and what the results are from the filled in cells.

3.1.10 How to determine which R to use

The determination of whether or how a material or component can be reused is difficult and can be interpreted differently by individuals (Park & Chertow, 2014). In general, a material becomes waste not just because of its physical and/or chemical characteristics, but also because of the mismatch between supply and demand. This is because waste is not gathered based on demand, as opposed to virgin materials, which are gathered based on demand (Baumgärtner, 2004). This is also confirmed in other theories regarding reusability factors by (van de Minkelis, 2020). He describes 5 reusability factors which are: product choices, design choices, project management, type of demolition company and the sales market.

Product choices

When choosing products which can potentially be reused or recycled, there are certain aspects that need to be checked. The material which it is made of and its characteristics are firstly important. ‘How fragile is the material?’, ‘Can it be recycled and serve as the same product or as another product?’ and ‘Based on weight, can the material be retrieved by hand?’ are examples of questions you need to ask. Furthermore shape and measurements are important to determine the ease of implementation elsewhere.

Design choices

Design choices are based on how and where the product is attached. This heavily impacts the retrievability of the material or component. When a component is attached nine stories high and the connection is complicated, retrieving the component can be dangerous and time consuming, and therefore not be worthwhile.

Project management

Project management incorporates factors such as planning and budget. When materials are retrieved and they are not suitable for reuse at the same project, they have to be stored and sold. Storing retrieved materials costs time, money and space. The amount of time a material can be stored differs per project, and can certainly influence the decision on whether to actually store the material, or to get rid of it. When there is only 2 months to sell the materials, it might be risky to store them, especially when the materials cannot be used on the location itself.

Type of demolition company

Compared to the other mentioned factors, the demolition company plays a less predictable role. However, the type of demolition company also influences the decision for reuse. The company might, for example, not have a storage department nearby, which eliminates the option store potentially reusable components all together.

Sales market

The sales market can be divided into B2B market (business-to-business) and B2C market (business-to-consumer). When the B2B market is not interested in taking over the gathered materials, for example because the other business does not see potential in profitably selling the materials further, the B2C market can be an option. However, because the materials gathered from the projects often come in large quantities, the supply of resources is, more often than not, too large for the B2C market. Furthermore, due to inconsistencies in supply and demand, it is difficult for contractors to rely on these markets and buy materials this way. The applicability and regulation can also cause complications regarding this subject.

These five aspects always need to be kept in mind when deciding on the circularity potential of a building. However, for this research specifically, the building components themselves have are the significant factor. External factors are left out of the question, but can be researched further in future research. Product choices and design choices are the main components in deciding the ‘R’ score.

3.1.11 Answer sub question 5

From the literature and empirical research conducted in this report, many choices regarding circularity in the built environment have been identified. If developing a circular adaptation project is your goal, or if your goal is to demolish a building as circularly as possible, it has to be identified which circular measures can be taken on what elements. Furthermore, it is also important to identify how much embodied carbon emissions can be saved through these circular interventions. The framework in figure 7 illustrates well what the choices and possibilities are in the decision-making process when circular approaches are added to the question on how or why to adapt or demolish a building. In order to identify which 'R' score can be given to building elements and what the potential CO2 savings are in the project, it is important to know what materials are used in the project and what the amounts of these materials are in the project. Furthermore, disassembly potential of these elements and the NEN 2767 condition of these elements needs to be researched and identified. In order to acquire this data, on site analysis and analysis of drawings of the buildings has to be done. Furthermore, it is recommended to create a schematic version of a BIM model in order to identify the amounts of materials present in the building. Lastly, a specialized NEN 2767 condition measurement has to be conducted.

3.2 Use of the tool

3.2.1 Users

The CPM, developed in this research, will be used as a tool for inspections on a circular level. One could think of maintenance inspectors, who could be hired to carry out this specific research. Based on conversations held with Person LL, who provides similar consults regarding circularity, (Appendix A, Company G, 10th of May), the CPM showed potential. Most of the feedback was regarding adding functions that could make the CPM more user friendly and smooth to use. Person LL is a circular potential inspector. The inspectors generally work for consultancy companies. However, the tool is also meant to be straightforward to fill in, and can therefore be filled in by anyone who has basic knowledge about architecture and the to be scanned building in the form of drawings or BIM models.

When the consultancy companies carry out this research with the CPM, they do it in collaboration with other stakeholders. This collaboration can be with key stakeholders within the design and build process of a project. The client or contractor can both benefit from the results of the CPM scan. For example, when a client wants to adapt or demolish a building, they can hire the consultancy firm to make a scan with the CPM, and based on the results that come out of this, the client can make requests or deals with the contractor. Furthermore, when a client does not choose to have this scan carried out, a contractor can choose to do this, to see if there is circular potential in the project that they are going to be carrying out. Money and CO2 emissions and building materials and components could be saved based on the outcomes of the scan.

A designer can also be inspired based on the results of the scan. For example, when the scan shows many building components that can be reused 1 on 1, the designer can keep this in mind and base their design on this. This is already seen in practice as well. Circular demolition companies inspect which materials or components can be reused, pass on this information to the architecture firm, and within this collaboration, a whole new project is created with reused materials and components (Appendix A, Company D, 27th of February). This tool will therefore help in creating more awareness regarding circularity, and it will make it clear which steps can be taken, based on disassembly potential, condition, material and lifecycles. This is the essence of what circularity means in the built environment, and will therefore help in making it clear for stakeholders what circularity means exactly. In a conversation with an architect (Appendix A, Company F, 16th of June), the CPM was received with enthusiasm. The way in which it is designed to be simple to fill in was seen as a very positive aspect.

3.2.2 Portfolio

Because the CPM can be a relatively quick scan of the circularity potential of an adaptation or demolition project, the scan can be applied relatively quickly to a large portfolio of buildings. Something that came to mind in an exploratory interview was that this would be a good use for this tool (Appendix A, Person MM, 31st of march). When a large portfolio of buildings is scanned in a relatively short timeframe, a comparison between projects can be made. The portfolio would show in an instant where large or small CO2 emission savings can be made and where good or bad 'R' scores are shown. Therefore, this portfolio mechanic is also integrated in the tool, and looks as follows (table 18):

	R fundering	R Ruwbouw	R Afbouw	R Afwerkingen	R Installaties, werktuigbouwkundig	R installaties elektrotechnisch	R Vaste voorzieningen	R Losse inventaris	R Terrein	Totaal
Gebouw 1	4,0	3,6	7,0	8,0	6,0	4,0	3,0	3,0	5,0	4,4
CO2 impact	762.534	1.359.713	797.340	143.325	59.290	3.973.950	122.090	5.650	183.448	7.407.340
Gebouw 2										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 3										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 4										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 5										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 6										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 7										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 8										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 9										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 10										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 11										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 12										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 13										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 14										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 15										
CO2 impact	0	0	0	0	0	0	0	0	0	0

Table 18: Portfolio comparison between buildings (own image)

As can be seen, in this case 15 buildings can be compared. They show the 'average R' score for each NL SFB category, and they show how much CO2 will be saved for each of these 'R' scores in each of the categories. Furthermore, on the right side, the total of the 'average R' scores and CO2 savings is shown as well. This way, in one quick view, multiple buildings can be scanned and compared on their circularity potential.

3.2.3 Answer sub question 6

Sub question six is: "Who are the users of the Circularity Potential Meter and what are their viewpoints on the usability, benefits and complications regarding the tool?". In this research, the following users were identified: consultancy companies, clients, contractors, designer (companies) and demolition companies. This is not to say that these are the only users who can potentially benefit from using the tool. What was generally perceived as a benefit is the fact that the CPM has been set up in a way that it is easy to make the scan. Quick scans regarding circularity potential and potential CO2 emission savings can be made, so that decisions can be made based on these results. This can also be identified by the fact that the portfolio tab has been introduced, so that many buildings can be compared.

Complications were found in the fact that the results that come out of the tool are largely indicative, and always have to be reconsidered when actually moving forward with a project. Furthermore, the usability regarding user friendliness can be improved upon.

4. Conclusion

Circularity in the built environment is a broad topic where many factors come into play. With circularity becoming increasingly popular because of future goals that need to be met, it becomes important that clear ways to map out circularity potential in projects are developed. This research specifically focusses on building adaptation projects and demolition projects, where the aim is to develop a tool which can identify what the circularity potential in such projects are. In order to achieve this research aim, six sub questions were set up. These sub questions identified what exactly building adaptation projects and demolition projects are, and what circularity in the built environment is. Furthermore, building element categorization systems were identified and existing tools that map out similar potentials within adaptation projects and demolition projects were researched. Lastly, stakeholder involvement and the choices regarding circularity they make and can make were identified.

By researching these topics and finding answers on these sub questions, the main research aim '*To develop a tool which measures and identifies what the circularity potential of building adaptation projects and building demolition projects is*' could be achieved.

Through literature research and empirical research in the form of exploratory interviews, in depth interviews and project visits, several important elements regarding circularity in building adaptation and building demolition projects were identified. Disassembly potential of building elements and the condition of these building elements are important when it comes to the reusability of these elements. Furthermore, the materials that these elements are made of play an important role as well. This is because the type of material that the building element is made out of, also determines the amount of CO_2 emissions that can be saved when it is reused. Therefore, the three factors, disassembly potential, condition (according to the NEN 2767 norm) and material of the building element were all added in the tool.

The way in which the saved embodied carbon emissions are determined is through the Construction Material Pyramid, by Beim & CINARK (2022). This tool has a large list of materials for which the embodied carbon emissions per cubic meter are determined when the material is created. Therefore, when these elements are reused in projects, these emissions are spared. The materials do not have to be newly created. In order to then determine what the circularity potential is of the building elements, the three factors need to be accounted for, and be explained. For this, the 10R framework by Potting et al. (2017) and Kirchherr et al. (2017) is used. This framework 'grades' all circularity measures with a score, where R0 is the best score and R9 is the worst score.

In order to combine the three crucial factors and the 10R framework, it is important to know to which building elements these factors apply. For this, the NL SFB list is used. This is an official categorization system, which categorizes building elements into 9 different sections. These sections are then divided into specific building elements to which all discussed frameworks can be applied. In the developed tool, for all building elements, the material, the amount, the disassembly potential and the condition can be filled in. Based on these factors, the tool will determine what the circularity potential for each building element is and for each NL SFB category is, in the form of an 'R' score from the 10R framework. Furthermore, the saved CO_2 emissions are automatically calculated, based on these 'R' scores. Because the saved CO_2 emissions show what the impact of certain measures can mean, this impact is also calculated through to also account for importance of these certain measures.
Through literature research, exploratory interviews, project visits and simulation tests, the tool was developed. Therefore, the main research aim of this report was achieved.

The first research question that needed to be answered to achieve the research aim is 'What is building adaptation and demolition?'. To summarise, building adaptation is a collective word, which encompasses many definitions. These definitions are renovation, adaptive reuse, refurbishment, remodelling, reinstatement, retrofitting, conversion, transformation, rehabilitation, modernisation, re-lifing, restoration and recycling. All these definitions are similar but not identical. Therefore, building adaptation is the overarching word that describes all these definitions. However, a distinction has to be made between 'within use' and 'across use' adaptation. For within use adaptation, the function of the building stays the same, where across use adaptation changes the function of the building. The most common interventions within these definitions are renovation, and adaptive reuse respectively, and will form the main focus of this research. Building adaptation is based on building obsolescence and building lifespan.
Another way to deal with structurally vacant buildings, next to building adaptation, is building demolition. Building demolition in itself is a clear concept, however, building waste treatment is where a large impact can be had. This is where a circular economy can have a big influence.

The second research question is there to establish an understanding about circularity in the built environment. Circularity is a broad concept where many factors come into play. A definition by EMF, ''modular and flexible by design where resource loops are closed and human well-being is promoted'' is the definition that fits within this research. The problem statement of this research is that even though there is a supposed paradigm shift taking place, for many developers there is still a lot of confusion around the circular economy principles and how to apply them in the built environment (Lacy & Rutqvist, 2015). The 10R Framework by Potting et al. (2017) (Kirchherr et al., 2017) is a framework that defines 10 circular strategies which can be taken, and grades them by how good these interventions are. For applying circularity to building adaptation projects and demolition projects, the 10R framework is crucial. Furthermore, the materials and the amount of these materials that have to be processed in these projects are important to calculate the potential CO_2 emissions savings can be made. The construction material pyramid is a useful tool to use for this. Lastly, the NEN 2767 condition and disassembly potential of building elements are crucial to be identified, in order to apply the 10R framework to the building adaptation projects and demolition projects.

The third research question regards building elements to which circular strategies can be applied. This research identified three categorisation methods for buildings to which the circularity frameworks can be coupled. These are the layers of Brand, the NL SFB list and a demarcation list. The layers of Brand divide a building is six layers, which are site, structure, skin, services, space plan and stuff (the six s's), and couples these to a certain lifespan. The NL SFB list is an official categorization method used to categorize buildings into specific building elements. A demarcation list has the same principle as the NL SFB list, but is specific for each building. Each building has their own demarcation list. For this research specifically, the NL SFB list suits best, because it can be applied to all buildings, and it combines well with the NEN 2767 norm and disassembly potential methods.

The fourth research question is 'Which tools/frameworks already exist to measure the adaptation potential and circularity potential of a building?'. What has become clear is that there are many tools and frameworks that are in some form related to measuring circularity potential. Even though many tools and frameworks have been covered in this literature research, there are undoubtedly more frameworks that haven't been discussed in this research. The following list summarizes which tools and frameworks have been discussed, and are added in the tool developed in this research:

- 10R framework
- Construction Material Pyramid

- NEN 2767 norm
- Disassembly potential
- Brand Layers
- NL SFB list

Other tools and frameworks discussed in this research which are not added 1 on 1 in the developed tool, but did inspire the final version are:

- ReSOLVE framework
- Demarcation list
- Transformation Potential Meter
- Material Passport tool
- Arcadis tool

The fifth research question is about added choices regarding circularity in the built environment. From the literature and empirical research conducted in this report, many choices regarding circularity in the built environment have been identified. If developing a circular adaptation project is your goal, or if your goal is to demolish a building as circularly as possible, it has to be identified which circular measures can be taken on what elements. Furthermore, it is also important to identify how much embodied carbon emissions can be saved through these circular interventions. The framework in figure 7 illustrates well what the choices and possibilities are in the decision-making process when circular approaches are added to the question on how or why to adapt or demolish a building.

The sixth and last research questions regards the users of the Circularity Potential Meter and their viewpoints of the tool. The users of the Circularity Potential Meter are consultancy companies, clients, contractors or architects. Consultancy companies can for example offer the service of doing the Circularity potential scan for the other mentioned users. The decision-making process of clients, contractors and architects will be influenced based on the results that come out of the tool. The simplicity of the way that the tool has been set up has been received positively by the mentioned users. It should not be too time consuming to make the scan.

By finding an answer to the six research questions, the main research aim could be achieved. The Circularity Potential Meter has been developed by doing this research and has been received positively by users in the field.

5. Discussion

When it comes to circularity in the built environment, there are many factors to be considered. Therefore, it is important to realize that the tool that was developed in this research can always be extended. The tool was developed in roughly 3 months in which it is difficult to grasp the full concept of circularity potential in building adaptation and building demolition projects.

The applicability of the tool in practice is something that has to be researched further. Because it took time to develop the tool, there was not much time left to test the tool out in practice. The tool has been tested out twice, in which the main concern resulted to be user convenience. Testing out the tool more often would have resulted in the possibility to add these points of feedback to the tool, to make it more user friendly.

Furthermore, when it comes to the tool itself, it has to be mentioned that the results from it are indicative and suggestive. The tool is meant to serve as a relatively quick scan to determine what the circularity potential is. In reality there are too many factors which play into the results that are achieved at the end of such projects. Therefore, it has to be kept in mind that when the tool is filled in, the results that come out of it are indicative. External factors such as storage for materials, transport of the materials and the market for the materials play a role in results regarding circularity as well. However, because the scope of this research is to identify what the circularity potential of a building is, specifically for all the building elements present in the building, these factors are not taken into account in the tool. When it comes to materials of building elements, there are some factors that need to be addressed as well. The construction material pyramid used in this research, does not contain data for every building material in the world. Therefore, it can occur that a material is used in a building for which the CO2 values are unknown. When this is the case, impact of certain measures cannot be calculated and could give a wrong image on the circularity potential of a project. Furthermore, not every 'R' score can be applicable to every type of material, meaning that the suggested 'R' score from the tool always has to be reconsidered when looking at the type of material that the building element is made of.

For further research, it can be interesting to take the tool as it is now, and to immediately start working on testing it out more in practice. Furthermore, there will always be extra factors regarding circularity that can influence the score of the circularity potential. More research into the influence of these factors and ways on how to add these factors to the tool can be interesting as well. It should be noted that the CPM has been passed on to professionals at the University of Technology Delft, who are working on designing a circularity tool as well. They are passionate and inspired by the CPM and will use it to further develop their own research. Furthermore, the CPM has also been passed on to an architecture firm, where they will further discuss the tool with their colleagues, and apply it to one of their projects. However, this opportunity came late in the process, so the results have not been processed in this research.

6. Reflection

This research is conducted as a graduation thesis for the master track Management in the Built Environment (MBE) of the Master Architecture, Urbanism & Building Sciences (AUBS) at the Delft University of Technology. The master track Management in the Built Environment looks at the connection between people and real estate. The specific theme related to this research is theme 1 'Circular and adaptable property and real estate development'. The supervision theme members are mostly related to the Real Estate Management (REM) course, which focuses on the ongoing process of aligning the built environment and the needs of users.

The relationship between my graduation topic and the theme of the graduation lab (theme 1) can be found in the emphasis on circularity and adaptable property. The focus of this research is very much aligned with this theme, as the main concepts of this research are circularity, building adaptation and building demolition. Regarding the master track specifically, the connection between people and real estate can really be found in the fact that many individuals and companies and their viewpoints regarding circularity were included in this research. Circularity is a complex construct when it is applied in the built environment, and the connection between people and real estate regarding this theme is evident.

Relevance

Because of pressing climate goals that are set in 2030 and 2050, developing a circular economy is becoming increasingly more crucial. Because the built environment is responsible for a large part of the total CO2 emissions, circularity in the built environment must be embraced and adapted to as well. In order to do this, it has to become clear what circularity in the built environment means, what strategies can be applied, and what factors these strategies are based on. From a scientific standpoint, it is critical to sketch out what these strategies are, and how they can be applied.

Methodology

Regarding methodology, a variety of research methods were used. At the start of my research, I was convinced that semi structured in depth interviews would be the main research method to gather empirical data. Because I was developing a tool, discussing circularity, building adaptation and circular demolition with professionals in the field felt like the right approach. However, as soon as I started my internship at Arcadis and conducted my first two in depth interviews, I realized that this was not the right way to do my empirical research. The interviews took long to set up and required a lot of preparation, as well as the need to transcribe and code. I realized that developing the tool meant an iterative process. Discussing the tool with professionals with different viewpoints is how the tool should be further developed.

This is when I started arranging exploratory interviews. These interviews were low threshold conversations where I could get to know colleagues within Arcadis and they could get to know what my graduation thesis is about. By presenting my tool as I was developing it, interesting discussions could start to take place and new connections with other people were often a result from the conversations. Because of the low threshold to set up such a meeting, it was possible to speak to many different professionals, resulting in interesting discussions.

A drawback of this research method was that these conversations would not be recorded. The meetings were mostly set up to get introduced to each other and to discuss about our professions. Therefore, all these meetings were organised in person and not recorded. This meant that I had to keep up a log with all the meetings I had, where I typed out the main discussed ideas. These were short summaries, resulting in the fact that coding and looking for connections between conversations was difficult. Keeping up with the log was an enjoyable and useful experience however. The log can be found in Appendix A, and is referred to many times in the research.

Another important research method were project visits. In total I had four project visits where I could join a company for a morning or afternoon where I could ask all my questions regarding the project. These project visits were very useful to this research but had the same drawbacks in that the conversations were not recorded. After a project visit was done, I would write down the main takeaways right after, it is difficult to remember a complete conversation that took place over multiple hours. The connections that came out of this were very useful as well.

The last research method used were simulation tests. This is an underrepresented part of the research. The reason for this is that developing the tool was an iterative process, where early versions were not suitable for use in practice yet. Later versions were suitable, but by that time it was difficult to find volunteers who were willing to test out the tool in practice. In the end, it was tested out in practice once. However, the tool has also been passed on to enthusiastic professionals at the TU Delft and at an architecture firm, where they will find inspiration in the tool and apply it to their own field of research.

Personal reflection

P1 and P2 mainly consisted of literature research. Over the course of this period, my topic was adjusted multiple times, which made the process less smooth than I expected. In P1, I was convinced that the topic that I had come up with was final and specific. However, when the literature research actually started in P2, I realized that the task at hand was overwhelming. There are so many articles written about circularity and building adaptation, that it becomes difficult to filter through it. Finding literature which specified in the topic that I had come up with in P1 was difficult, resulting in the several adjustments to the eventual topic.

The course started out with weekly meetings. These were helpful to stay motivated to come up with new material every week. Furthermore, the feedback provided by the supervisors and also knowing the progress of other students helped to continue moving forward. What I ended up with at the P2 presentation was a first version of my tool. At this point, I was proud of what I had achieved and felt confident for the future research.

The first weeks after P2 were hectic. A lot work went into P2 and it felt like a small break was needed, however, the internship at Arcadis started right away. It is difficult to start out at such a large organization when you do not know your colleagues yet. Progress was slow because at this point I was still trying to set up in depth interviews. After meetings with my mentors at Arcadis and after conversations with my parents, I decided to simply start messaging many colleagues at Arcadis to get to know each other. This is when my research started moving forward again. From this point onwards, the research went smoothly. Every week I had multiple meetings and project visits planned and I could easily fill my time at Arcadis. My mentors at Arcadis were very helpful and supportive, as well as my mentors at the TU Delft. The complete experience for P3 and P4 at Arcadis were pleasant.

Value and transferability

The societal value of this research is in the fact that there is now an easy and concrete way to determine the circularity potential of adaptation and demolition projects. Furthermore, because of the many existing frameworks regarding circularity, combined into one tool, it becomes more clear to stakeholders which factors concern around circularity. The confusion on what circularity is exactly and how it can be applied will be cleared up more. The results are very transferable but also suitable for future research. External factors can be included in the tool as well, and further testing of the tool in practice can definitely add to the value of this research. I am happy that I could pass on the developed tool to enthusiastic professionals at the TU Delft and an architecture firm. They will continue working with it and let it inspire them to further develop their own tools.

7. References

Armstrong, G., Soebarto, V., & Zuo, J. (2021). Vacancy Visual Analytics Method: Evaluating adaptive reuse as an urban regeneration strategy through understanding vacancy. *Cities*, *115*, 103220. https://doi.org/10.1016/j.cities.2021.103220

Assefa, G., & Ambler, C. (2017). To demolish or not to demolish: Life cycle consideration of repurposing buildings. *Sustainable Cities and Society*, *28*, 146–153. https://doi.org/10.1016/j.scs.2016.09.011

Baumgärtner, S. (2004). Price ambivalence of secondary resources: joint production, limits to substitution, and costly disposal. *Resources, Conservation and Recycling*, *43*(1), 95–117. https://doi.org/10.1016/J.RESCONREC.2004.04.013

Beim, A., & CINARK. (2021). *The Construction Material Pyramid*. Https://Materialepyramiden.Dk/#.

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

BNA. (2005). *NL/SfB-tabellen - inclusief gereviseerd elementenmethode '91*.

Brand, S. (1994). *How buildings learn: What happens after they're built?* (1st ed., Vol. 1). Penguin.

Bullen, P. A. (2007). Adaptive reuse and sustainability of commercial buildings. *Facilities*, *25*(1–2), 20–31. https://doi.org/10.1108/02632770710716911

Bullen, P. A., & Love, P. E. D. (2010). The rhetoric of adaptive reuse or reality of demolition: Views from the field. *Cities*, *27*(4), 215–224. https://doi.org/10.1016/j.cities.2009.12.005

Çetin, S., Gruis, V., & Straub, A. (2021). Towards circular social housing: An exploration of practices, barriers, and enablers. *Sustainability (Switzerland)*, *13*(4), 1–24. https://doi.org/10.3390/su13042100

Chan, P. (2021). *Doing Research Ethics: Problems, Principles and Process [Slides]*.

Chau, K. W., Wong, S. K., Leung, A. Y. T., & Yiu, C. Y. (2003). Estimating the value enhancement effects of refurbishment. *Facilities*, *21*(1/2), 13–19. https://doi.org/10.1108/02632770310460504/FULL/XML

Douglas, J. (2006). *Building Adaptation* (2nd ed., Vol. 1). Routledge. https://doi.org/10.4324/9780080458519

Ellen MacArthur Foundation. (2015). *Delivering the Circular Economy: A Toolkit for Policymakers*. Https://Ellenmacarthurfoundation.Org/a-Toolkit-for-Policymakers.

Gálvez-Martos, J. L., Styles, D., Schoenberger, H., & Zeschmar-Lahl, B. (2018). Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling*, *136*, 166–178. https://doi.org/10.1016/J.RESCONREC.2018.04.016

Geraedts, R., van der Voordt, T., & Remøy, H. (2018). Conversion Potential Assessment Tool. In S. Wilkinson & H. Remøy (Eds.), *Building urban resilience through conversion adaptation* (pp. 1–18). Blackwell Wiley.

Ghaffar, S. H., Burman, M., & Braimah, N. (2020). Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. *Journal of Cleaner Production*, *244*, 118710. https://doi.org/10.1016/J.JCLEPRO.2019.118710

Ginelli, E. (2016). *Sustainability and Innovation for the Future ADAPTIVE REUSE OF VACANT OFFICE BUILDINGS IN MILAN*. http://www.abc.polimi.it

Goldstein, B. P., Herbøl, M., & Figueroa, M. J. (2013). Gaps in tools assessing the energy implications of renovation versus rebuilding decisions. *Current Opinion in Environmental Sustainability*, *5*(2), 244–250. https://doi.org/10.1016/J.COSUST.2013.03.005

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. https://doi.org/10.1111/JIEC.12244

Hamida, M. B., Jylhä, T., Remøy, H., & Gruis, V. (2022). Circular building adaptability and its determinants – A literature review. *International Journal of Building Pathology and Adaptation*. https://doi.org/10.1108/IJBPA-11-2021-0150

Hamilton, I., & Kennard, H. (2022). *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*.

Ikiz Kaya, D., Dane, G., Pintossi, N., & Koot, C. A. M. (2021). Subjective circularity performance analysis of adaptive heritage reuse practices in the Netherlands. *Sustainable Cities and Society*, *70*. https://doi.org/10.1016/j.scs.2021.102869

International Organization for Standardization (ISO). (2011). *Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing. ISO Standard No. 15686*. https://www.iso.org/standard/61148.html

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. *Resources, Conservation and Recycling*, *194*, 107001. https://doi.org/10.1016/j.resconrec.2023.107001

Kralj, D., & Markic, M. (2008). Building Materials Reuse and Recycle. *WSEAS Transactions on Environment and Development*, *4*(5), 409–418.

Lacy, P., & Rutqvist, J. (2015). *Waste to Wealth*. Palgrave Macmillan UK. https://doi.org/10.1057/9781137530707

Leising, E., Quist, J., & Bocken, N. (2018). Circular Economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, *176*, 976–989. https://doi.org/10.1016/J.JCLEPRO.2017.12.010

Low, J. (2013). Unstructured and semi-structured interviews in health research. In *Researching health: Qualitative, quantitative and mixed methods* (1st ed., Vol. 2, pp. 87–105).

Muldoon-Smith, K. (2016). *An Investigation into the Nature, Scale and Location of Secondary Commercial Office Vacancy in the UK and an Appraisal of the Various Strategies and Opportunities for its Management and Amelioration*. Northumbria Institution.

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Park, J. Y., & Chertow, M. R. (2014). Establishing and testing the "reuse potential" indicator for managing wastes as resources. *Journal of Environmental Management*, *137*, 45–53. https://doi.org/10.1016/J.JENVMAN.2013.11.053

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/J.JCLEPRO.2016.12.055

Ponnada, M. R., & P, K. (2015). Construction and Demolition Waste Management – A Review. *International Journal of Advanced Science and Technology*, *84*, 19–46. https://doi.org/10.14257/ijast.2015.84.03

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring Innovation in the Product Chain*.

Remøy, H. (2014a). Building Obsolescence and Reuse. In S. J. Wilkinson, H. Remøy, & C. Langston (Eds.), *Sustainable building adaptation: innovations in decision-making* (pp. 95–120). Wiley Blackwell.

Remøy, H. (2014b). Examples of Successful Adaptive Reuse. In S. J. Wilkinson, H. Remøy, & C. Langston (Eds.), *Sustainable Building Adaption: Innovations in Decision-making* (pp. 135–158). Wiley Blackwell.

Remøy, H. (2014c). Reuse versus Demolition. In S. J. Wilkinson, H. Remøy, & C. Langston (Eds.), *Sustainable Building Adaption: Innovations in Decision-making* (pp. 121–134). Wiley Blackwell.

Schut, E., Grielaard, M., & Mesman, M. (2015). *Circular economy in the Dutch construction sector A perspective for the market and government Status Final*.

Tam, V. W. Y., & Tam, C. M. (2006). A review on the viable technology for construction waste recycling. *Resources, Conservation and Recycling*, *47*(3), 209–221. https://doi.org/10.1016/J.RESCONREC.2005.12.002

Többen, J., & Opdenakker, R. (2022). Developing a Framework to Integrate Circularity into Construction Projects. *Sustainability*, *14*(9), 5136. https://doi.org/10.3390/su14095136

van de Minkelis, H. (2020). *Assessing the Market Potential of Second-hand building Products*. Delft University of Technology (TU Delft).

van Vliet, M., van Grinsven, J., & Teunizen, J. (2021). *Circular Buildings - a measurement method for disassembly potential 2.0*.

Vefago, L. H. M., & Avellaneda, J. (2013). Recycling concepts and the index of recyclability for building materials. *Resources, Conservation and Recycling*, *72*, 127–135. https://doi.org/10.1016/j.resconrec.2012.12.015

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., … Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 160018. https://doi.org/10.1038/sdata.2016.18

Wilkinson, S. (2014). Defining Adaptation. In S. J. Wilkinson, H. Remøy, & C. Langston (Eds.), *Sustainable Building Adaptation: Innovations in Decision-making* (pp. 3–17). Wiley Blackwell.

Wilkinson, S. J., & Remoy, H. (2017). Adaptive reuse of Sydney offices and sustainability. *Sustainable Buildings*, *2*, 6. https://doi.org/10.1051/sbuild/2017002

Wilkinson, S., & Remøy, H. (2021). Sustainability and within use office building adaptations: A comparison of Dutch and Australian practices. *17th Annual Pacific Rim Real Estate Society (PRESS) Conference*, 1–11.

8. Appendix

8.1 Appendix A, Log

Thursday 26th of January

Interview with **Person A**, from Company A. Was a very interesting interview. Their vision of what circularity in adaptation projects is is as follows: they aim to make flexible buildings, which are not designed for one specific function, but are suitable for all functions. For more details, check the transcript.

Wednesday 1st of February:

Introduction day at Arcadis. Got to know a lot of other associates and met my mentors at Arcadis. **Person B and Person C** are my mentors and gave me a tour through the building. Furthermore, they introduced me to a lot of colleagues and we planned in that we have a meeting to catch up every Wednesday. I was also introduced to **Person D and Person E**. We arranged that we would meet on Monday the 6th of February. However this got rearranged to Wednesday the 8th of February.

Thursday 2nd of February

Interview with **Person F**, from **Company B**. Person F explained a lot about their way to indicate what the circularity potential of projects is. They work a lot with disassembly potential, but also specify materials and amounts. They have a very big database when it comes to materials and components, and this database shows for each of these materials and components what their values are regarding building circularity index (BCI) and disassembly potential. Extremely interesting interview, for more details, check the transcript!

Wednesday 8th of February:

Me and **Person E** had a meeting planned on this day to get to know each other, but also to discuss potential project visits for my graduation plan. **Person E** is a commercial manager in the division ´Buildings´ at Arcadis. Person E is focussed on tenders and how these can be sourced and won. Person E is also involved in the TCL project, which is the Technology Centre Land in Leusden. This is a project of the Defence in the Netherlands, located in Leusden.

Technology Centre Land (TCL), Leusden:

- Defence
- Architect: Dik van Wageningen
- Constructor: Royal Haskoning
- Materials: Mick Hendriks

Person E reached out to **Person G (Company C)** on the 16th of february, to find out if I could possibly join for a tour through this project, to test out the tool that I am developing for my graduation project. After a long wait, I reached out myself on the 7th of march to Marc to see if there was any progress in this request. This resulted in the fact that a project visit is unfortunately not possible because of classified status of Defense projects, and the fact that my research would not add much for them.

Furthermore, Person E suggested the Baanbrekers project, which would be done in collaboration with BAM. I received documents for this (TN353633 – SF02 Aankondiging van een opdracht), showing the Tender of this project. Unfortunately, this project is not yet in a stage where it can be beneficial for my research.

Lastly, Person E mentioned a project which was replacing newbuild in Den Haag, including demolition specifications. **I still need to contact Person H and Person E for this.**

I also had a catch up meeting with Person B on this day. Not much extra came out of this.

Thursday 9th of February:
Weekly catch up meeting with **Person C**. Person C sent me a bunch of reference projects and names which I could contact. Check teams chat to see what came out of this.

Friday 17th of February:
Me and **Person I** had a meeting planned on this day to get to know each other. We talked about the TCL project because Dirk was also involved in this project. Furthermore, Dirk shared a document (BIjlage 14.11 Duurzaamheidseisen TCL), which shows a circularity score given by Company B, using their BCI tool and other tools. This is a very useful document for my personal graduation research.

Monday 20th of February
Person J and I had a meeting planned this day to get to know each other. Person J is from the Constructive department and also project manager and team leader. Our conversation was very fruitful. We talked about projects where circularity was a prominent factor. Mentioned projects were:

- Above ground parking garage, ASML parkeergarage P10
- Lumiere, renovation of a timber factory
- City Farm Rembrandtpark, high involvement of Person J and Person P

Regarding the City Farm there was a lot to discuss. Person K is writing demolition specifications to see if elements, components and materials can be reused in a circular manor. **I can ask Person K about the approach that they are taking to write these specifications.** VBI is a kanaalplaatvloer (hollow-core slab floor) deliverer and thinks about sustainability a lot too **(VBI)**. **Person L** is involved with VBI and can be approached to see whether there are any kanaalplaatvloeren available.

The most fruitful topic we talked about was **Company D**, which is a company which demolishes buildings in a circular manor. In other words, they disassemble buildings. Person J did not have any contacts at Company D himself, but recommended that I would just simply give them a call to see whether they could help me any further. So on the 21st of February I called Company D to explain them about my interests in circularity, and whether they had any projects running that I could visit. They told me that this was an interesting request and they would get back to me within the week. I feel like I got lucky, because on the same day, I got a text message saying that I could call **Person M**, who is team leader at the Zuiderstrandtheater project in Scheveningen. I called Person M on Wednesday the 22nd of February and we made an arrangement that I could visit the project on Monday the 27th of February. This was an amazing opportunity!

The Zuiderstrandtheater project is a collaboration between Company D, **Company E** and **Company F**. Company F is the architect, who based their design on the inventory assessment which Company D made of the existing building. This way, they can reuse 75% of the components in the new building which will be constructed in Oss. Company E is in charge of disassembling the main structure of the building, while Company D is responsible for smaller interventions. Person M also showed me how they register which materials are gathered from the building, where they are stored, and how they are categorized**. Via this way, I learned about the NL SFB list**, which is a crucial list for my research because it is the official way in the Netherlands to categorize building elements and components.

Via Person M I was also brought into contact with **Person N and Person O.** Person N is very much involved in the Zuiderstrandtheater project and could tell me more about it. I have not been able to get into contact with him yet. Person O is expert in the NLSFB list and I can still reach out to him.

Tuesday 21st of February

Me and **Person P** had a meeting planned today to get to know each other. We sparred a bit about my graduation topic and also about the projects Jeroen is involved in. Jeroen is also involved in the City Farm Rembrandpark as the main architect. **I should contact Jeroen for a potential project visit (based on what me and Person B discussed in meeting march 8th).**

Wednesday 22nd of February

I had a meeting with **Person Q** planned to get to know each other and talk about my graduation topic. This meeting was planned for an hour, so we could discuss a lot of topics. Person Q is very much involved in dealing with existing building stock, so the fact that we connected was great. We were connected via **Person F** from Company B, who we got connected to by **Person A** from Reborn Real Estate. Interesting how those lines get connected. The meeting we had was very fruitful. He was enthusiastic about the research I am doing and suggested me multiple people and companies to talk with, both within Arcadis and outside. **Person R and Person S** are colleagues within Arcadis I could contact. Furthermore, Ron also suggested the companies COMPANY H and COMPANY G, which are companies involved in circular demolition. Within **COMPANY G, Person T** could be contacted, which I did, and have a meeting planned for the 20th of March. **Person U** is the contact person within **COMPANY H**, who I also contacted. However, Herco is very busy and cannot plan in a meeting any time soon.

Person R was one of the colleagues within Arcadis who I could contact, which I did and planned a meeting in for Thursday the 2nd of March. Person S was too busy to plan in a meeting, but maybe I could get in contact with him later, via Person R. All-in all, the meeting with Ron was very helpful to get in contact with other valuable people and organizations.

On this day I also had a meeting planned with **Person V** in Rotterdam. Vanessa is very much involved in the process of handing out BREEAM certificates and the process that goes behind this. She explained me about the BREEAM website, and how circularity is graded within this certificate. **This was also brought up as a useful topic in the meeting I had with Person H on the 7th of March.** Furthermore, Vanessa pointed out the fact that other research regarding circularity within Arcadis had been done by other interns. This research was about circular building and making clear what **circularity ambitions within utility build** is. Lastly, Vanessa pointed out the **website** https://matchingmaterials.com/ , which is a market place for building materials. The information I gathered from this meeting with Vanessa was very helpful.

The weekly catch up meeting with Person C was also on this day. This was mostly to catch up with the progress I had made over the last days. Person C also provided me with the **Politie_Toolbox Duurzaam en Gezond Gebouw.**

Thursday 23rd of February

I had a meeting planned to get to know **Person W**, who is a commercial manager / sector lead commercial developers. During lunch, we talked about my graduation topic, which lead to Jeroen coupling it with some interesting project. **The Old Court building in Amersfoort**, Stationsplein 14 – 16. This is a redevelopment project in Amersfoort, aimed to become an iconic building which livens up the station area. I still need to ask Jeroen if this is a project which Arcadis wants to do or whether it is just simply an opportunity for me to visit a redevelopment project.

Monday 27th of February
Project visit **Zuiderstrandtheater in Schevening. Person M** guided me through this project. I was able to ask all my questions and it was a very helpful day. The companies **Company I and Company E** were also introduced, who are very much involved in circularity in the built environment. Furthermore, Person M also showed me how they keep track of what materials they get out of the building and how they categorize this. They use the **NL SFB list** for this. This is very useful for my research as well, and will form the basis for my tool. What was discovered on this day is that circularity is very much a mindset. When you decide to demolish a building circularly, there are a lot of possibilities to disassemble the building. 75% of the demolished building will be reused in a project in Oss, so when demolishing, there are definitely options to do it in a sustainable way.

Tuesday 28th of February
Meeting with **Person X** for the first time since my P2 presentation. We talked about the process of integrating within Arcadis and what I have gathered so far from my time there. He was very enthusiastic about the NL SFB list I found, and thought it was a valuable addition to the tool I was making. The questions this posed to me were the categorization of the list, and whether it should still be according to the Brand layers, or whether I should just make it according to the NL SFB list. Vincent suggested that the NL SFB list would suffice and that the **Brand layers should just be an extra layer of information** within the checklist. Furthermore, a question that came up with me is how to deal with large buildings, where not just 1 score can be given to all elements in the building. A **matrix** was suggested, which I also thought was a good way to deal with this. Lastly, something Vincent thought would really add to the quality of the checklist, is to somehow **add condition scores** to the tool. Therefore, to tag along with maintenance checks and the process of adding condition scores was recommended. **Person Y** was suggested to contact for this.

Wednesday 1st of March
Weekly catch up meeting with Robbin. **Person Z** is someone I can approach, who is part of the global sustainability impact team. They can for example show what sustainability impact of steel could be. Same goes for **Person AA**. **Person BB** is part of the coreteam when it comes to sustainability, and focusses on health & wellbeing**. Person CC** is part of Company B.

Thursday 2nd of March
On this day I had a meeting planned with **Person R**, who is a Junior Consultant within Arcadis. She is heavily involved in condition measurements and circularity. She also graduated from the TU Delft in a similar topic of what I did. What I gathered from our conversation is that there is definitely potential for my tool to be used in practice. Because of her involvement in maintenance checks, I requested if I could maybe join her one day to see how this process works. This is possible, so in April I will be able to join here to **Sealife**, but possibly earlier. They will see if there are easy projects where I can come along and see how the process works. She also provided me with **her own graduation research.**

Friday 3rd of March
Based on the suggestion from Vincent, I planned in a meeting with **Person Y**. Person Y is very much involved in condition scores and what they are based on. We talked about my graduation topic, where I explained him that Vincent thought condition scores could be a valuable addition to the tool I am developing. I want to connect this somehow to the R ladder. However Person Y thought that the simple

number that is a condition measurement is too broad, and I should rather check if the factors that the condition measurements are based on can be couple with the R ladder. He provided me with a document for this, which is ‘**Economische waarde PlatformCB23 maart 2022_’Y’**, showing all the criteria condition scores can be based on. I should definitely research this to see how it can be integrated in my research topic. Furthermore, Person Y also suggested that I should contact **Company J**, to potentially join a condition measurement. I did this, but have no reaction yet.

Tuesday 7th of March
On this day I had a meeting with **Person H**. We had a very nice getting to know each other meeting, where we also discussed my graduation topic. Person H is a sustainability advisor and program leader regarding circular building. She was very enthusiastic about the tool that I am developing and suggested a couple ways on how it can be improved. First of all, she suggested that the **condition measurements** is already a tool or method in itself, so it can simply be added as a column to my tool, and be filled in that way. Furthermore, **detachment** is something which can be added as well. Lastly, **impact regarding environment** can be added too. As these methods mostly exist already, they can be added and filled in easily, and then be coupled with the R ladder and the brand layers and the NL SFB categorization.
Person H also provided me with documents regarding the inventory assessment for the project **Ruijgoordweg**, where the Brand layers Structure, Skin and Services were used. She also provided me with the application from Company D for the Inquiry (uitvraag) for circular demolishing. This is also for the Ruijgoordweg.
Lastly, Person H had great suggestions for people I could contact. **Person DD** is team leader in the group Building, Design and Engineering. Person K is also part of this group. He is more knowledgeable about the police and defense projects
She also suggested **Person EE**, who works in Technical Due Diligence, which is a technical analysis of a building. He is also interested in measuring chances regarding circularity.

There was also a very interesting lunch lecture on this day, delivered by **Person FF**, who is a program manager regarding circularity at a company called **Company K**. They are also working on measuring circularity, and do so by coupling condition measurements to the R ladder. After the lunch lecture, I approached Peter to see if I could potentially join them for one of their condition measurements, to learn how their methods work. What resulted out of this is that I can join them for their condition measurement on the 21st of march.

Friday 10th of March
Meeting with **Person GG**. This meeting was mostly just a meeting to catch up with the progress that I had made.

Wednesday 15th of March
I had a weekly catch up meeting with Robbin. He suggested that I should get in contact with **Person HH** and Person QQ. They are involved with design principles within education projects. Furthermore, these projects are generally renovation projects, which nicely connects with my graduation topic. It was also suggested that I could go to the Triodosbank in Zeist, to test out my tool.

Friday 17th of March
Meeting with **Person EE**. Technical due diligence. Got a valuable document with scans and can also call Ronald every once in a while to see if there is a project I can join.

Monday 20th of march
Meeting with **Person T**, COMPANY G, circular demolishing. Very interesting conversation and also recorded it. What I got out of this is that I can visit a project on Friday the 24th of March, conducting a condition measurement.

Tuesday 21st of March
Today I had a project visit with the company **Company K**. I got to this project visit via the lunch lecture on the 7th of march. **Person FF** referred me to his colleagues **Persons II**, who work at **ingenieurs bureau Company L**. They conducted the analyses for the **Factorium building in Tilburg**. In two days, they had to make a material passport of the building. Furthermore, **Persons JJ** provided me with drawings of the Factorium building, so I could analyse the building I was going to visit in advance. This way I could know what to expect and prepare a bit.

The day itself was very interesting. I tagged along in the afternoon from 13:00 to 16:30, where I helped a bit with filling in the tool they use for making a material passport. I could ask all the questions I wanted and **Persons II** were enthusiastic to answer my questions and talk about their work. The following data I got from the day were useful to me:
They were making a material passport for a building for which it was unknown when it would be demolished. So it could be the case that the building is still there after 25 years, which by that time, the material passport made today is outdated and not very useful.
Furthermore, I noticed that the condition measurement they were doing was not based on the NEN 2767 norm. The way they did it within their tool was giving the elements a score in the form of words, such as 'good', 'damaged', 'user traces' etc.
Also, for the disassembly potential, they simply mentioned how it was attached. So 'bolted', 'framed', 'welded', etc. There was no direct disassembly potential index coupled to the elements. The same goes for the 10R framework. This framework wasn't adapted to in the tool 1 on 1. The options given in the app were translated to Dutch, and not the complete 10R framework was given as options.

I also learned that applying my own tool is absolutely possible, and could be useful for actual application. However, the tool has to be in the hands of the right people, who are knowledgeable about the topics that have to be filled in in the tool. The project I visited today had a specialist who recognised many elements and could instantly determine the disassembly potential, condition, and materials the elements were made out of. Because of this, much of the data could be filled in right away. I myself do not possess this knowledge, so for me it is difficult to fill it in. I have to get it in the hands of the right people.

Wednesday 22nd of March
I had a weekly catch up meeting with **Person B**. She suggested to me that I should visit projects that are already finished, or that include circular goals. I have to contact **Person P** again to see what has been implemented in projects so far. Apply this project to my tool and see what else could have been applied to the project. I also have to ask my mentors if it is ok for Person B to be present at my P4 presentation.

I should also try to contact **Persons KK** again. He is from the biobased materials publication. Circular economy is one of his specialties. He can tell me very interesting things about my personal research and my tool. Wouter is from integral circular design. Vice president of sustainable development committee.

Thursday 23rd of March
Today I had another meeting with my TU Delft mentor **Person X**. He was enthusiastic about the project visit I had in Tilburg. I asked him about whether my methodology for research was good, because I am not conducting many in depth interviews, but rather having many short conversations and project visits where I can ask all my questions. He told me that this was fine, but that I should update this in my research methodology.

Friday 24th of March
Today I joined **Person LL** from the company called **COMPANY G**. I got into contact with **Person LL** via **Person T**, who is a circularity specialist within COMPANY G. He was also involved with the **Prinsenhof A** project, where the complete concrete structure was reused 1 on 1 in another project. I got into contact with **Person T via Person Q**, so the line to get into contact with **Person LL** was quite long and interesting.

The actual project I visited today was an **old appartement building from the 1960s in Hoogvliet** in Rotterdam. For this project, the circular potential was checked for when it will be demolished. However, it was mentioned that because this was such an old building, it was not built to be disassembled. Therefore, the reuse potential is low. I could join Person LL who was making analyses for the material use within the building and whether they could be reused or recycled. The way they approach this at COMPANY G is rather simple. The building was already abandoned, so by demolishing small pieces of the structure, it could be checked what the materials were, and what this would mean for the circular intervention. Here, the disassembly potential was also checked.

I could also show my own graduation topic to Person LL and I could ask him if he could see an added value in practice for my tool. His answer was in the directing that everyone has their own preference when it comes to scanning the buildings. Some people indeed prefer to walk around with a tablet or a tool and to fill in the list on the spot. Others prefer to disassemble on the spot and make pictures and to study the floorplans. This way, the list could be filled in afterwards in the office. It differs from person to person.

We both agreed that our personal preference for my tool would be to do an analysis at the building itself, but fill in the tool afterwards, with the help of the made pictures and floorplans. The analysis of the building itself is something you do on location. This information is then used to fill in the tool at the office. This is also the way I approached it myself today. I made pictures of the appartement so that I could fill in the tool when I got home.

Person LL also provided me with some tips on how I could filter which cells were and were not filled in. This helped me to come up with a formula that only divides to total by the number of cells filled in, rather than the total number of cells there are. This whole day was a very useful experience.

Some things I ran into when I got home and wanted to fill in my tool. You have to know which walls are part of the structure and which walls aren't, in order to fill in the tool properly. Although this does not matter for the circular potential. It applies more to filling in the tool correctly.
The 'average R' score is influenced equally by every filled in cell. So the amount of CO2 emissions save by each, does not get taken into account here.
Figuring out the exact amount of m2 can take a lot of time if you just base it on the drawings. So it could be beneficial to measure the measurements on location itself.

Wednesday 29th of March
Weekly meeting with **Person B**. Was a short conversation. Person B still feels like I am making good progress. She recommended me to get into contact with a demolition company via **Person QQ.** Furthermore, she recommended me to plan in another meeting with **Person H** to check out the tool again and to see what came out of it.

Also, today I asked **Person LL** whether he was open to fill in my tool for the building we visited on the 24th of March. He agreed to fill it in! Eventually he would end up filling it in on Wednesday the 10th of May.

Friday 31st March
Today I had a meeting with **Person MM** from de company **DEMO**. This meeting went very well. Went very well. We talked about the measuring method used in the NEN 2767 norm. In general, these condition measurements are conducted as a recurring check which takes place once every 3 years. The check is always done based on Ernst, intensity and scale. An inventory of the building is made first, and it is analysed how the building is built up. In general, this is done based on drawings and maintenance rapports. This basic inventory check is generally fully conducted behind your desk. On the basis of this inventory check, an inspection protocol is developed, which is a checklist for points of attention. In general, this checklist contains questions which cannot be answered based on the drawings of the building.

Person MM Recommended me to check the NEN norm for myself, by asking for the part 1 and part 2 documents within Arcadis. I also showed Person MM my Tool and I could ask him where he would see the use of this tool. He saw potential in it, especially to apply it to larger portfolio's. Through many quick scans, you could see quickly which projects have a good circularity potential. Based on this, appropriate decisions can then be made.

Lastly, Person MM suggested to me that I should get into contact with **Person NN from Company M**. Maybe I could tag along in a condition measurement project they have running. He also suggested **Person OO** to me, who works at Arcadis. I have a meeting planned with him on the 5th of April.

Tuesday 4th of April
Reading document that was sent to me by **Persons II from Company L**. It is about the detachability, written by madaster.
They limit their detachability to the 4 layers of brand, so they do not include stuff and site. In my opinion, including it to stuff as well is better, because this includes circular principles. Company D was very much involved in reusing the stuff layer as well. De losmaakbaarheidsindex bestaat wel om te laten zien wat de losmaakbaarheid van het gehele gebouw is. Mijn tool doet dit voor circulariteit.

Wednesday 5th of April
Meeting with **Person OO**. Person OO is involved and knowledgeable about condition measurements. However, the meeting was moved to the 13th of April.

Thursday 6th of April
Meeting with **Person DD**. I got into contact with Willem via **Person H**, because he was more in contact with the project of the police and defence. This meeting was very nice. He informed me that he himself is not very involved with the circular potential of buildings, but he was surely interested in the tool that I was developing. Willem put me through with **Person PP**, who is involved further with the

Ruijgoordweg project. This is also in collaboration with **Company D**. Something of a project visit should be possible to arrange here.

I also had a meeting with **Person QQ** today. He was suggested to me by Person C and Person B. This is because he is involved in renovation projects, and could therefore bring me into contact with demolition companies. This was a nice conversation, however he could not really help me further. He does not have connections with demolition companies and is not really involved in projects with building, but rather more with the spaces around buildings.

The meeting with **Person HH** was cancelled and replaced to the 19th of April.

Friday 7th of April
Today I had a meeting with **Person CC**. Person CC works at **Company B** and can tell me more about their way of working and about how their rapports are created.
This meeting was rather confrontational but absolutely very helpful to bring my research to the next level. Person CC saw potential in my tool, but the way it is created now, it is not efficient. The tool has to be filled in by knowing everything yourself, and filling in everything yourself. This is all based on knowledge, but if you already have this knowledge, there is no reason to fill in a tool for it. If the tool has more automised features, everyone can fill it in, which makes the tool more valuable. The combination of a certain condition score and disassembly potential has to lead to a certain circular intervention. At the moment, the tool does not have this function yet. This causes the tool to take a lot of time to fill in, and the people who do fill it in, still have to come up with their own interventions for circularity. The same goes for the CO2 impact column. This one has to be filled in automatically, otherwise Sander guaranteed that no one is going to fill in this column. I would love to hear how Hilde and Vincent see this feedback.

Tuesday 11th of April
Today I had a meeting with **Person PP**, who was suggested to me by **Person DD**. Person PP is involved in the **Ruijgoordweg** project. The meeting I had with Person PP was extremely helpful. It was about the inquiry (aanbesteding) from the Ruijgoordweg. This goes as follows: the project has to be demolished in a circular way, which Arcadis has to inquire. They approached 5 parties for this. Some people at Arcadis were creating a tool, which has to be filled in by these 5 parties. This tool had many of the same elements as the tool that I am developing, which was nice to see. The tool by Arcadis does not provide an oversight of condition measurements, but it does show disassembly potential. Based on this, the approached companies had to show, via an R ladder matrix, how the project will be circularly demolished. They had a couple weeks to do this.
The amounts of materials are subtracted from a BIM model. Such a BIM model does not go much further in detail than just the architectural elements. Through this, CO2 emissions could be calculated.

Wednesday 12th of April
Weekly catch up meeting with **Person B**. She recommended me to talk to **Person RR** and **Person SS**. They are knowledgeable about BIM models and safety equipment respectively. Also see if you can tag along with the demolition companies who did not get the job for the Ruijgoordweg.

Thursday 13th of April
Meeting with **Person OO** about NEN norm and potential project visit. This meeting with Person OO was very nice. Person OO explained to me exactly how the NEN 2767 norm works, and also told me that it is definitely useful to tag along with such a condition measurement. We discussed a few things

about my tool, and Person OO was very eager to think along and how it could be improved. There are many factors that play into the condition measurements, and they have to be included in the 'R' score calculations too. I also got a new name, **Person TT**, who is also developing many tools in Excel and other programmes.

Tuesday 18th of April
Project visit Sealife with **Person R**.
It was very interesting to tag along with this condition measurement day. Together with Person R, building manager of Sealife and two inspectors from **Company N, Persons UU**, who conduct the condition measurement, I could walk along through the building. Through this way I got a clear image on how these condition measurements work and what is focussed on. I also noticed how the condition scores given via the NEN 2767 can sometimes give a wrong image on what the actual state of a building component is. For this reason, I added to the tool that you can explain why a certain condition score is given, and whether it is accurate or not.

Wednesday 19th of April
Today I planned a meeting with both my mentors from Arcadis, **Person C and Person B**. We planned this meeting so that I could show them my progress from my tool. They were both very positive about the progress I had made with the tool. They also told me that I should try to have it tested out in practice.

Thursday 20th of April
Meeting with **Person VV**. She approached me herself because she heard me talking with Person OO about my graduation topic. So I explained to her what my research and tool are all about and she was very enthusiastic about this. However, not much else was useful in our conversation.

I also had a meeting with **Person TT** today. He told me a lot about his Excel tools and realized my knowledge about Excel can still be vastly expanded. However, Eric was still very impressed with the tool I developed and even copies some of it in his own tools.

Lastly, I had a spontaneous conversation with **Person W**. He highlighted a couple points about how I can present my tool. A sort of timeline next to the different versions of the tools I developed can show in a nice way how my tool developed, and what the conversations I had made for difference per version. I should also explain why I added certain aspects in my tool, and why they are the best aspects instead of other aspects. NL SFB, material, amount, disassembly potential, condition, R ladder and CO2 impact are all aspects I should explain.

The last meeting I had today was **with Person WW**. Ida was involved with the development of the tool for the Ruijgoordweg. She told me that I should approach Person PP again if I want to use this project for my own case.

Friday 21st of April
Today I planned in a meeting with both my TU Delft mentors, **Person X and Person GG**. I showed them the progress of my tool and they were also very excited about it. They recommended me that I should have it tested out in practice. So I told them that it would be tested out by Person LL and Hilde gave me another contact. So I am going to test it out with them on the 26th of May. Because both my mentors were here, they were fine with the idea that this would be my P3 presentation. I would have to hand in my rapport on the 1st of May.

Tuesday 25th of April
Today I planned in another meeting with **Person H**. This was more just to catch up with the progress of my tool. She was very excited about it. Furthermore, she invited me to join a circularity meeting with other colleagues from Arcadis and we had a nice meeting about circularity aspects. Person K, Person H, Person DD, Person VV and me were there.

Monday 1st of May
Hand-in moment for P3 rapport.

Thursday 4th of May
I planned in a meeting with **Person GG and Person X** to discuss my P3 report. This was a useful meeting because they could explain some things to me. First of all, they noticed that my research does not really have a main research question, but rather a main research objective. Furthermore, they explained to me that I should refer to this appendix so that I can refer to actual empirical research in my report.

Friday 5th of May
Vincent and Hilde read my report and gave me solid feedback. The actual content is good, but they gave me some suggestions regarding structure. Furthermore, they gave me suggestions on how I could visualize the progress of my tool.

Tuesday 9th of May
Weekly conversation with **Person B**. Catch up moment, explaining that I am mostly typing on my report right now, and stress is increasing. Not much time left to plan in new meetings with different people.

Wednesday 10th of May
Meeting with **Person LL**. This meeting was extremely valuable, because Person LL is a professional in practice and agreed to fill in my tool. He gave me a lot of helpful feedback on how the tool can become more user friendly.

- First of all, all cells should only consist of a logical materials list to select
- Weight is an important factor
- Reinforced concrete is not a material in the list
- Small explanation with condition measurements
- You should be able to add extra lines, for when walls have more materials.
- The matrix for the R ladder was very well received
- See if you can add another column for upcycling and down cycling
- R6 and R7 are very much dependent on subjective factors, and most of the time the contractor will simply choose for recycling anyways.
- See if there can be another column for dangerous things such as asbestos
- English and dutch are mixed together now
- Filter on just the filled in columns
- The way it can be used is that the client can choose to which level the test will be done, so not all NL SFB categories will be analysed in every scan
- Add a way to add foto's to the document

Friday 12th of May
Meeting with **Person Z**. We talked about our professions and I showed her my tool. She was very excited about it and said I was doing a very good job. She would look into it if she could find some values for reinforced concrete regarding save CO2 emissions.

Thursday 8th of June
Meeting with **person XX** from the TU Delft. Very nice conversation and enthusiastic about the CPM. I handed over the CPM so that they could get inspiration from it and use it in their own tool development. It is nice to know that the CPM will be used further!

Friday 16th of June
Meeting with **person YY** from company F. This person was also extremely enthusiastic about the CPM and even requested if he could show it to his colleagues where they would test it out for their recent projects. He also wants to use it as inspiration for the development of his own tool/framework. Person YY was especially impressed by the simplicity in which the tool is set up, and how it is easy to understand and fill in.

8.2 Appendix B, Manual for the Circularity Potential Meter

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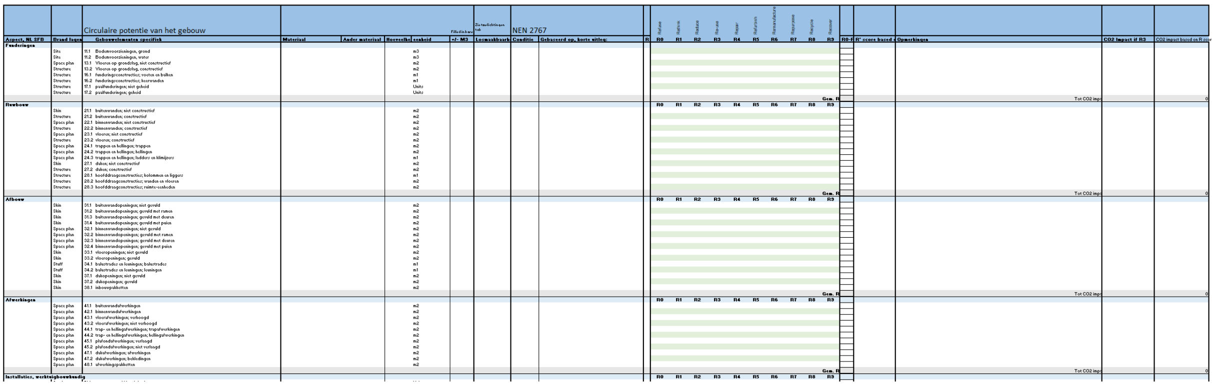
This manual explains how the Circularity Potential Meter works and how it should be filled in. The Circularity Potential Meter is a tool developed by Berend Langenberg. When the tool is filled in, the results will show what the circularity potential score is, and what the potential saved CO2 emissions are of building adaptation projects and building demolition projects.

Step 1: Open the Circularity Potential Meter

This is what the Circularity Potential Meter looks like when you first open it



Step 2: Fill in the materials for the building elements

The first three columns are 'Aspect, NL SFB', 'Brand lagen' and 'Gebouwelementen specifiek'. The 'Aspect, NL SFB' column shows the 9 categories of the NL SFB list and is meant to give a clear structure in the tool. The 'Brand lagen' column shows the 6 S layers of Brand, for each of the specific building elements that the NL SFB list contains. Through these Brand layers, analyses of the results from the tool can be made. It can for example be concluded that the most impact can be made in specific Brand Layers. 'Gebouwelementen specifiek' shows the specified building elements of the NL SFB list, including the proper numbering. In these first three columns, nothing has to be filled in by the user. This data is given.

After these three columns, the next two clumns show 'Materiaal' and 'Ander materiaal'. These are the first columns which have to be filled in by the user of the tool. As shown in the image. The 'Materiaal' column has a drop down menu, where the material for the specific building element can be selected.

This list of materials is the list of materials given by the 'Construction Material Pyramid' by CINARK. If the list does not contain correct material, it is possible to type in what the actual material is in the column 'Ander materiaal'. However, it should be noted that if the right material is not in the list, and thus the material is typed in in the next column, there will not be a calculation for the potential saved CO_2 emissions.

Step 3: Fill in the amounts and units of the materials for the building elements and check out your CO_2 impact

				Filled in based		
Materiaal	Ander materiaal	Hoeveelheid	eenheid	+/- M3		CO2 Impact
		2	m3	30		
			m3			
			m2			
			m2			
Concrete C30/37		300	m1	30		8.640
			m1			
			Units			
			Units			
					Tot CO2 impact	8.640

The next columns to fill in are 'Hoeveelheid', 'eenheid' and '+/- M3'. The 'Hoeveelheid' column shows the amount of the material that there is for the specific building element. These cells must be filled in in order for the later calculations to be made correctly. The 'Eenheid' column shows the unit in which the amount is calculated. For this column there is also a drop down menu, should it be wished that there is a different unit. The '+/- M3' column shows the amount of the material in cubic meters. This column, combined with the 'Materiaal' column will make the calculation for potential saved CO_2 emissions, as shown in the 'CO2 Impact' column.

Step 4: Fill in the disassembly potential and condition of the building elements and determine the 'R' score

Zie toelichtingen tab	NEN 2767			Refuse	Rethink	Reduce	Re-use	Repair	Refurbish	Remanufacture	Repurpose	Recycle	Recover	
Losmaakbaarheid	Conditie	Gebaseerd op, korte uitleg:	R	R0	R1	R2	R3	R4	R5	R6	R7	R8	R9	R0-R9
Matig	4		R6							100%				6
													Gem. R	6,0

After the '+/- M3' column has been filled in, 'Losmaakbaarheid' and 'Conditie' have to be filled in. The combination of these to columns will give a suggested 'R' score, which in the example in the image, is R6. The tool will automatically fill in that 100% of the specific building element will in this case be R6. However, this suggestion can easily be overwritten by simply typing in the correct percentages on the correct places, should this be necessary. Furthermore, there is an optional column which can be filled in which is the 'Gebaseerd op, korte uitleg' column. This is simply a column where a small explanation for the condition score or disassembly potential can be provided.

Step 5: Fill in a complete category of the NL SFB list, correct 'R' scores if necessary and check out the CO_2 impact and new 'R' scores.

	Refuse	Rethink	Reduce	Re-use	Repair	Refurbish	Remanufacture	Repurpose	Recycle	Recover				
R	R0	R1	R2	R3	R4	R5	R6	R7	R8	R9	R0-R9	R' score based on CO2	CO2 Impact if R3	CO2 impact based on R score
R6				80%	20%						3,2		16.950	11.865
R3				100%							3		1.063.120	1.063.120
R8									100%		8		141.210	70.605
R4					100%						4		38.100	34.290
R5						100%					5		18.960	15.168
R7								100%			7		5.700	3.420
R5						100%					5		5.320	4.256
R4					100%						4		5.580	5.022
R4					100%						4		6.510	5.859
R5						100%					5		84.700	67.760
R7								100%			7		47.400	28.440
R8									100%		8		450	225
R4					100%						4		13.550	12.195
R5						100%					5		46.860	37.488
										Gem. R	5,2	3,6	1.494.410	1.359.713

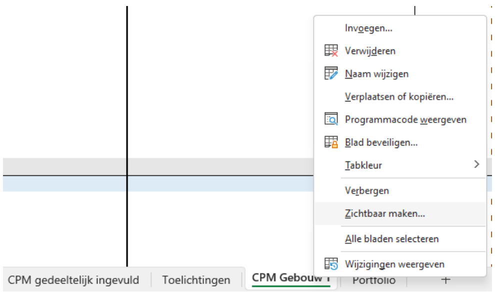
This last image gives an impression on what it looks like when a full category has been filled in, and what the results are. As can be seen in the first row, the ‘R6’ suggestion is overwritten manually by simply typing the correct percentages in the correct columns. Based on these percentages, an average ‘R’ score is calculated in the column ‘R0-R9’. Furthermore, it can be seen that there is a column ‘CO2 impact if R3’ and a column ‘CO2 impact based on R score’. The first column shows the maximum potentially saved CO2 emissions, should all elements be 100% reused. However, in reality this will rarely be the case, as can also be seen in the image. Therefore, the last column shows a correction on what the actual saved CO2 emissions are, based on the ‘R’ score.

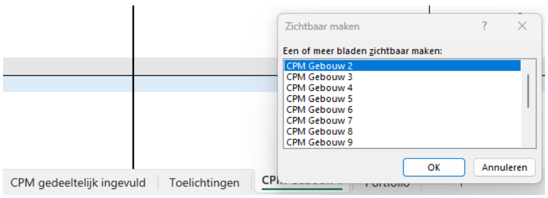
The last important results from the tool are shown at the bottom of the picture. Next to ‘Gem. R’, the average ‘R’ score is calculated based on the numbers shown above. However, in this calculation, each ‘R’ score is weighted equally, even though their CO2 impact is not equal. Therefore, the column ‘R’ score based on CO2’ shows a correction for a more realistic average ‘R’ score, based on the CO2 emissions.

Step 6: Check out the results in the portfolio tab, and fill in more buildings

	R fundering	R Ruwbouw	R Afbouw	R Afwerkingen	R Installaties, werktuigbouwkundig	R installaties elektrotechnisch	R Vaste voorzieningen	R Losse inventaris	R Terrein	Totaal
Gebouw 1	6,0	3,6	7,0	8,0	6,0	4,0	3,0	3,0	5,0	4,4
CO2 impact	6.048	1.364.798	797.340	143.325	59.290	3.973.950	122.090	5.650	183.448	6.655.939
Gebouw 2										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 3										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 4										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 5										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 6										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 7										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 8										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 9										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 10										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 11										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 12										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 13										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 14										
CO2 impact	0	0	0	0	0	0	0	0	0	0
Gebouw 15										
CO2 impact	0	0	0	0	0	0	0	0	0	0

The results of the tool will be shown in a portfolio tab, also provided by the tool. This way, multiple buildings can be analysed and compared to each other. Based on this data, choices on which projects to take on can be made.

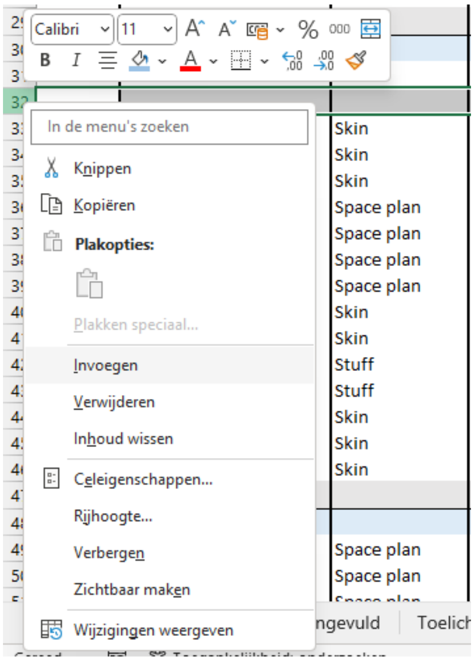




In the tabs underneath the document, you can show more tabs for new buildings by right clicking on one of the tabs and clicking ‘Zichtbaar maken’ (make visible). Then you can select the building you want to make visible, should you wish to fill in the tool for more buildings.

Step 7: Extra information

Furthermore, there is a tab called ‘CPM gedeeltelijk ingevuld’, which shows a partially filled in tool. This provides an impression on what it could look like, what the results are, and how the tool should be filled in. There is also a tab called ‘Toelichtingen’. This tab shows explanations on definitions regarding the disassembly potential, condition, NL SFB and the 10R framework.



It is also possible to insert an extra row, simply by right clicking on the rows on the left and pressing ‘invoegen’. This will insert an extra row where you can type in extra information. For example, if the exterior wall of a building is not the same throughout the whole building, an extra row is required for both types of exterior wall.