What's Next?

A study to the relationship between the technical aspects and reuse potential of reused building products

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Final version
June 19th 2023

Acknowledgements

This Master's Graduation Thesis is the outcome of a one-year research project in the Circular and Adaptable Property and Real Estate development of the Management in the Built Environment master track at the Delft University of Technology. This thesis aimed to understand the relationship between the technical aspects and the reuse potential of reused building products. It also includes a systematic overview of the different product typologies analysed and their reuse potential.

During the development of this thesis, I could count on the help and support of several people, whom I would hereby like to thank. First and foremost, I would like to express my sincere gratitude to my supervisors Hans Wamelink, Karel van den Bergh for their wisdom, guidance, support and encouragement throughout my research. Their expertise and insights have been invaluable in shaping my research and I am grateful for their time and effort.

Furthermore, my experience working with the team of Alba Concepts has greatly facilitated this research. I would like to especially thank Jan Jaap Blüm, for his insightful and supportive meetings from the beginning when shaping the research aim, at every critical moment and at every meeting where we could brainstorm and change thoughts on the research.

I want to extend my gratitude to all the interview participants who took the time to share their knowledge and experiences with me. Thank you for your time and goodwill in helping me out, your contributions have been extremely important for the execution of this research

I would like to thank all my friends who helped me overcome the challenging time faced during this process, especially Nin for her moral support from the beginning and Mari for all the weekends spent at the library and our coffee breaks while daydreaming about our future. Also thank Val, Nick, Chris, Sebastiaan and Nicole for sharing this incredible time with me. I would like to thank my family (papa, Andre and Ari) and Floyd for their incredible support during this process. Thank you for your love, help and patience.

And above all, a special thanks to my mom for proofreading all my texts patiently every time before a deadline and encouraging me to conquer all my dreams. Mami your support has been invaluable in helping me achieve my goals in life.

Astrid Brandt Wassink
June 18th 2023

Abstract

The climate crisis and resource scarcity have compelled industries to adopt new environmental and circular standards. The Netherlands has set a goal of achieving a fully circular economy by 2050, with a 50% reduction in the use of primary raw materials by 2030. In the circular built environment, circularity strategies like reuse are being implemented to reduce waste and carbon emissions. However, only about 1% of the building products that can be reused in The Netherlands are currently being reused for another lifecycle. This thesis aims to investigate the relationship between the technical aspects of reused building products and their reuse potential, which has received limited research attention thus far. To address this gap, a theoretical framework for assessing reuse potential is built through a literature review. A sampling study of over 30 building products is then conducted to evaluate their adaptability potential and disassembly level, generating a systematic overview of the technical aspects that influence reuse potential. The results demonstrate that refitability, adaptability, scalability and disassembly level are the most important aspects in determining the reuse potential for posterior lifecycles. By providing a deeper understanding of the technical aspects influencing the reuse potential of building products, this thesis aims to contribute to the development of circularity strategies in the built environment.

Key terms: *circularity, circular economy, reuse, reuse potential, circular built environment, disassembly, adaptability potential, circularity strategy, one-on-one reuse*

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Executive summary

Introduction

The built environment (BE) is responsible for more than a third of all carbon emissions in the world. Governments are eager to reduce waste generation and create a closed-loop system. The Netherlands aims to reach a fully circular economy by 2050 and reduce the use of primary raw materials by 50% by 2030. The country has formulated policy initiatives to integrate sustainability strategies at the beginning of construction projects to reduce this environmental impact. If the Dutch Built Environment aims to reach its goal by 2030, drastic measures must be taken. In The Netherlands, about 95% of the waste material from the residential and non-residential building sector is recycled in the civil engineering sector and only 3 to 4% of the material is used in the building sector. However, a more recent study states that only about 10% of the building projects where building products are available for reuse, only 1% of these are actually being reused for another lifecycle. These results imply that construction professionals need to have a greater focus on reusing building products during the design and construction phase.

In the circular built environment, different interpretations are made when referring to reuse. However, reusing building products in another construction project is actually one-on-one reuse since this strategy does not change the original function of the building product. One-on-one reuse of building products holds greater value compared to recycling because it extends the lifespan of the product and generates minimal waste.

A successful reuse of building products relies heavily on their technical condition prior to reuse. If the products are not in good condition, it can result in unnecessary waste. Therefore, the technical aspects of the building product play a crucial role in determining its suitability for reuse in another lifecycle.

In the built environment, only a small portion of the sector recognizes the potential for reusing building products. Circular buildings are increasingly being designed with the future in mind, incorporating the dismantling and reuse of used building products in new configurations. However, disassembly is not commonly practised, making the reuse of building products a challenging endeavour. Limited knowledge, required investments, and associated risks contribute to the barriers faced in promoting the reuse of building products.

Problem statement

The assumption that a longer lifecycle of building products leads to lower environmental impact and that integrating them into circular systems extends their lifespan lacks sufficient research evidence. Assessing the future scenario of used products is challenging, scholars argue that achieving one-on-one reuse of materials in new construction is a utopian concept due to time constraints and fitting issues. Similarly, the one-on-one reuse of building products not originally intended for reuse faces challenges associated with their attachment to the building's original function and user requirements. Additionally, the potential for reused building products in a third lifecycle depends on how they are reutilized in the second lifecycle.

There is a lack of comprehensive research on the technical aspects necessary to enable a second lifecycle for reused building products. Therefore, this study aims to fill this gap by investigating the relationship between the technical requirements that building products must meet to be potentially reused in a subsequent lifecycle. By addressing this research gap, a better understanding of the feasibility and potential benefits of reusing building products in multiple lifecycles can be achieved.

Research Questions

The main research question to be answered during this research thesis is formulated as follows:

"What is the relationship between the technical aspects and the reuse potential of reused building products?"

This main research question will be answered in parts by answering the following sub-questions:

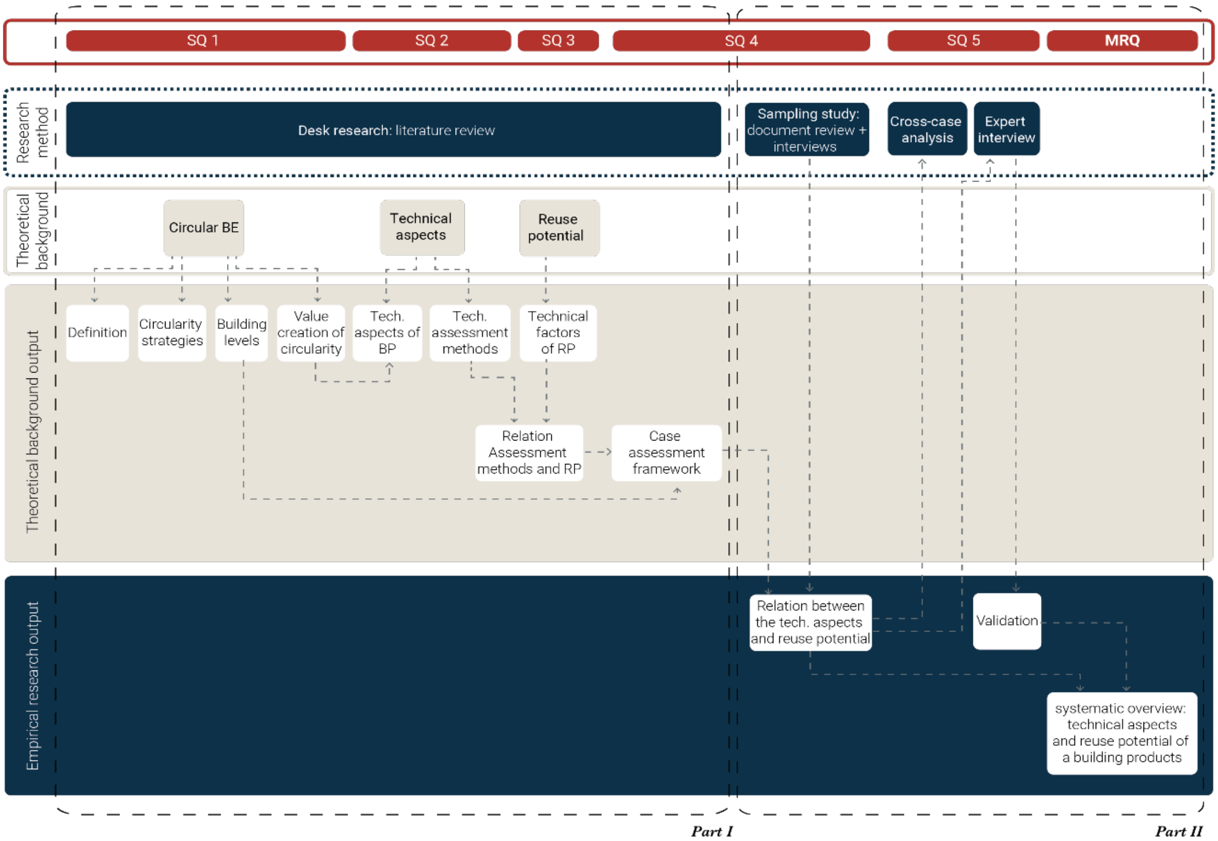
[SQ 1] What is the circular built environment?

[SQ 2] What are the technical aspects of a building product?

[SQ 3] What is the reuse potential of a building product?

[SQ 4] To what extent can the assessment methods of the technical aspects of a building product define its reuse potential?

[SQ 5] To what extent do the technical aspects of a reused building product and its reuse application during its second lifecycle determine its reuse potential for a third lifecycle?



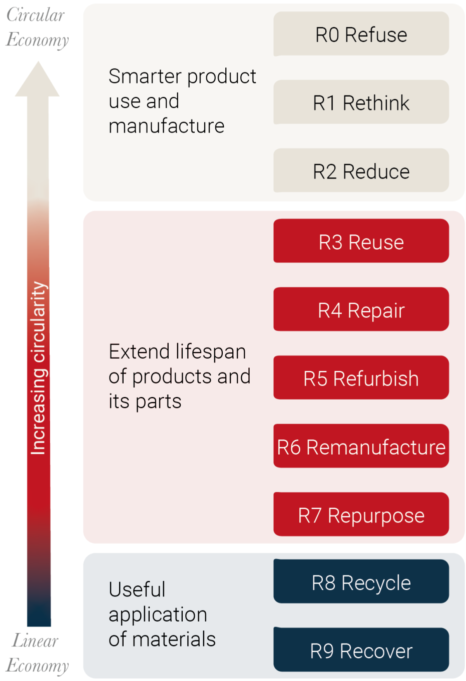
Executive Summary Figure I Research design and methods (Author)

Methodology

This research is exploratory by nature since it attempts to investigate research questions that have not previously been researched in-depth (Armstrong, 1970). This research consists of two parts: I and II, and each part is dependent on the other (see Figure I). Part I entails the main literature research and Part II entails the empirical research. By following the outcome of the framework built in Part I the first concept of this relationship between the technical aspects and reuse potential of reused building products can be assessed. This part is explored through a sampling study. Here 34 cases are collected based on the selection criteria and further assessed during interviews with the parties involved. The aim here is to generate a more in-depth understanding of what technical aspects influence the reuse potential of a building product.

Theoretical background

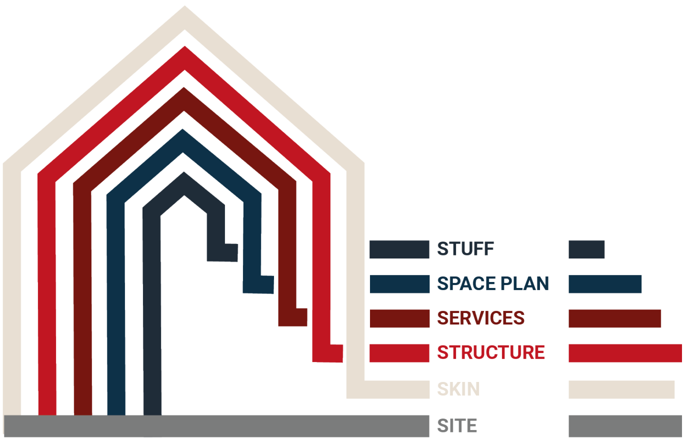
Circularity in the Built Environment



Executive Summary Figure II The 10R Framework. Adapted from Potting et al. (2017).

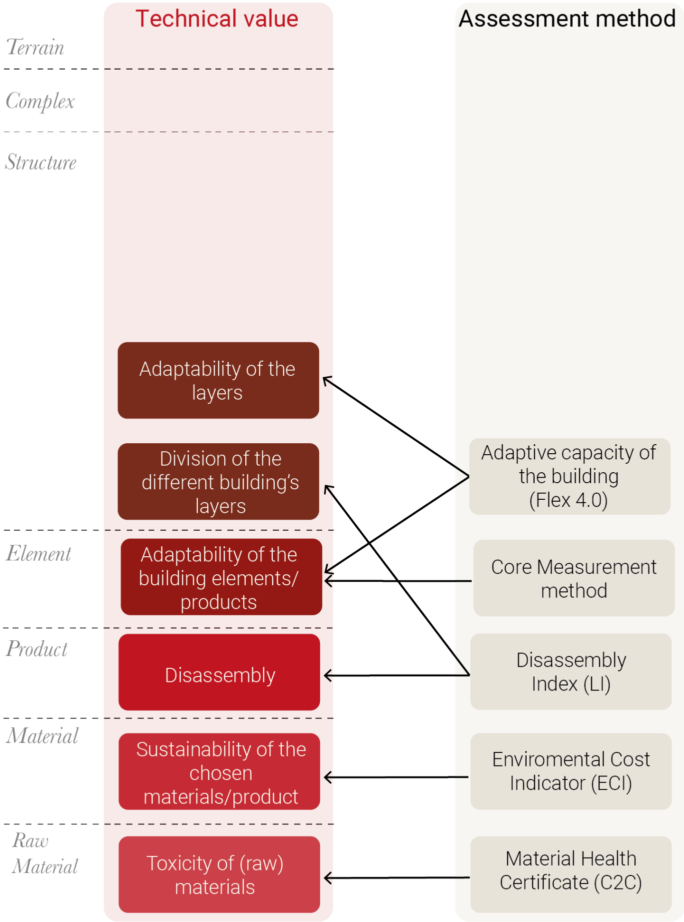
The circular built environment aims to restore or regenerate the industrial economy through intentional and design-focused practices. However, there is a lack of consensus on the understanding of circularity within the built environment. The circular economy employs various circularity strategies such as reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover to retain value in materials (see Figure II). While recycling plays a role in achieving circularity, optimal reuse of existing products is considered one of the most effective circular strategies. The circular built environment is defined as the context where the industrial economy is restorative or regenerative by intention and design. Circularity strategies are implemented at different scales within a building, ranging from material-level recycling to repurposing and reuse at the building product level. Buildings consist of various objects that can be classified into seven scale levels; terrain, complex, structure, element, product, material and raw material.

To accommodate the constant changes that buildings undergo due to user and environmental requirements, a layered approach, specifically the 6-s model, shearing layers defined by Brand (1990), is commonly used (see figure III). These layers possess varying degrees of circularity and sustainability, influencing people's perceptions and relationships with the building. In the circular built environment, these layers serve as a reference for designing buildings that can be effectively reused or recycled in subsequent lifecycles.



Executive Summary Figure III 6s model according to Brand (1994), each layer has different lifespan stuff (5), space plan (10), services (15), skin (20), structure (100) and site (500). Illustration adapted by Author.

In the built environment, the circular economy strives to create value in the present while also safeguarding the future (value retention), thereby protecting the environment and preserving the stock of materials (Platform CB'23, 2020b). This approach entails evaluating not only the monetary value but also the functional value of an object throughout its multiple lifecycles, taking into account its technical and social aspects. The application of a circular approach in the built environment recognizes four distinct types of values: economic value (business profitability and new opportunities); social value (well-being and protecting the natural environment);



Executive Summary Figure IV Relationship between the aspects of the technical values per building scale and possible assessment method. The assessment methods are independent from the building scale (Author)

technical value (technical requirements given by building regulations and user's needs); and the functional value (the performance that an object has by fulfilling its function)

Technical Aspects in the Circular Built Environment

The technical value can be quantified by measuring various technical aspects at different building scales. Figure IV illustrates the technical aspects and their corresponding assessment methods.

Reuse potential

The reuse potential of building products refers to their ability to be used again for the same purpose for which they were conceived, without further alteration. The literature distinguishes five factors for the reuse potential; adaptability, material quality, disassembly, standardisation and toxicity.

Case Assessment and Findings

The case assessment conducted in this study focuses on three building layers: structure, skin, and space plan. The results indicate that the reuse potential varies across these layers. Building products in the structure layer show a relatively positive possibility for reuse, considering their adaptability potential and scalability. The skin layer exhibits moderate reuse potential, while the space plan layer shows limited data but moderate reuse potential due to low adaptability potential and limited size modification.

Structure layer

From the structure layer, the possibility to reuse the assessed building products is relatively positive. The typology of this layer is given by the adaptability potential and their aspects to be scaled when the building products will be reused for a third or posterior lifecycle.

Skin layer

The assessed building products from the skin layer have moderate reuse potential. The convertible, scalable and refitable aspects of the assessed cases determine the different typologies for the assessed building products within this layer.

Space plan layer

Despite the limited data collection from this layer, the assessed building products show moderate reuse potential. This is mainly due to the low adaptability potential regarding new technical requirements and limited size modification.

Table I summarizes the typologies and their reuse potential per assessed building layer.

Executive Summary Table I Summary of the reuse potential per typology

<table>
<tr><th></th><th colspan="2">Typology</th><th>Reuse potential</th><th>Influencing factors</th></tr>
<tr><td rowspan="4">Structure layer</td><td colspan="2">Steel structure products</td><td>High</td><td>Adaptability potential and disassembly potential (+)</td></tr>
<tr><td colspan="2">Timber structure products</td><td>High</td><td>Adaptability potential and disassembly potential (+)</td></tr>
<tr><td colspan="2">Concrete floor slabs</td><td>Moderate</td><td>Disassembly potential and scalable aspect (-)</td></tr>
<tr><td colspan="2">Other concrete structure products</td><td>Low</td><td>Disassembly potential and scalable aspect (-)</td></tr>
<tr><td rowspan="6">Skin layer</td><td colspan="2">Non-timber window</td><td>Low</td><td>Adaptability potential (regarding building requirements) (-)</td></tr>
<tr><td>Ceramic cladding</td><td>Cement-based mortar</td><td>Low</td><td>Disassembly potential (-)</td></tr>
<tr><td rowspan="2">Non-ceramic cladding</td><td>Aluminium cladding</td><td rowspan="2">Moderate</td><td>Adaptability and scalable aspect (-)</td></tr>
<tr><td>Timber cladding</td><td>Adaptability and scalable aspect (-)</td></tr>
<tr><td>Insulation products</td><td>EPS insulation</td><td>High</td><td>Adaptability potential, refitable and scalable aspects and disassembly potential (+)</td></tr>
<tr><td colspan="2">Timber window</td><td>Moderate</td><td>Adaptability potential (regarding building requirements) and scalable aspect (-)</td></tr>
<tr><td rowspan="4">Space plan</td><td rowspan="2">Flooring</td><td>Slate tiles</td><td rowspan="2">Moderate</td><td rowspan="2">Disassembly potential and scalable aspect (-)</td></tr>
<tr><td>Stone tiles</td></tr>
<tr><td colspan="2">Ceiling products</td><td>Moderate</td><td>Scalable and convertible aspect (-)</td></tr>
<tr><td colspan="2">System wall</td><td>Low</td><td>Scalable aspect (-)</td></tr>
</table>

The case assessment results highlight four main technical aspects that significantly influence the reuse potential of a building product, not only in its second lifecycle but also in subsequent lifecycles disassembly, adaptability potential, scalable aspect and refitable aspect.

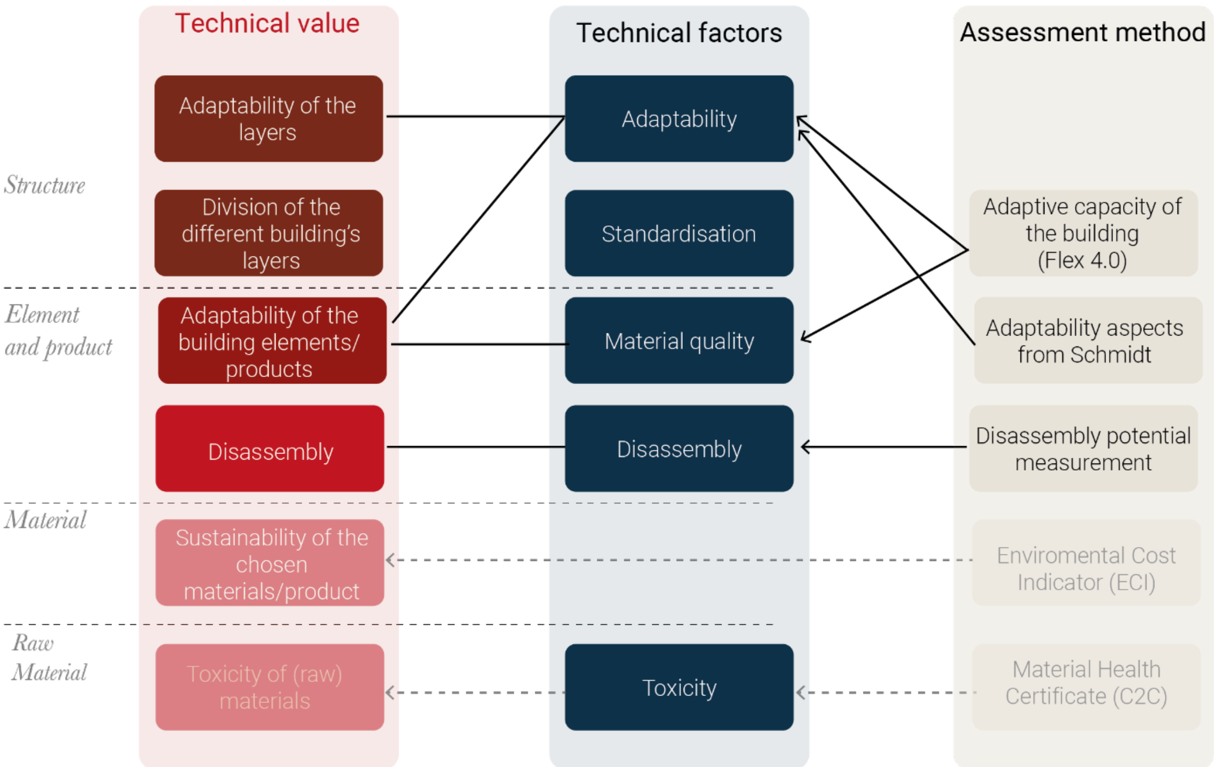
Conclusions

In conclusion, this research highlights the importance of considering technical aspects when assessing the reuse potential of building products. Designing for disassembly and incorporating technical assessment methods can increase the supply of reused building products and promote sustainable practices. However, financial incentives and a shift in mindset among construction professionals are necessary to prioritize posterior lifecycles and facilitate the reuse of building products.

Regarding the main research question - **What is the relationship between the technical aspects and the reuse potential of reused building products?** – the study suggests that the technical assessment methods explored in this research thesis offer valuable insights. Frameworks like FLEX 4.0, the disassembly potential measurement method, and Schmidt's framework provide a comprehensive understanding of a building product's adaptability, disassembly potential, and other technical aspects that contribute to its reuse potential. Factors such as versatility, refit, movability, adjustability, scalability, and convertibility are considered, shedding light on a product's ability to be reused in different contexts and applications.

Importantly, a building product's reuse potential is not solely determined by its inherent properties, but also by how it can be applied and adapted within specific building layers. The emergence of new techniques and innovations further expands the possibilities for reusing building products previously considered difficult or impossible to reuse.

In summary, the technical assessment methods discussed in this research offer valuable tools for understanding and maximizing the reuse potential of building products. By considering the interplay between technical factors, process-based factors, and financial factors, stakeholders can make more informed decisions and contribute to the goals of sustainability and resource conservation in the construction industry.



Executive Summary Figure V Relationship between the technical aspects (red), the technical factors of the reuse potential (blue) and the assessment methods (beige) (Author).

Chapter 1

Introduction

1 Introduction

1.1 Context

The climate crisis and resource scarcity have forced all industries to adapt new measurements for environmental and circular standards. One of these industries is the built environment (BE), which is responsible for more than a third of all carbon emissions in the world (UN Environment and International Energy Agency, 2017). Governments, such as the Netherlands, are eager to reduce waste generation and create a closed-loop system. Having a circular economy (CE) approach can help to reach this goal (Ministerie van Infrastructuur en Waterstaat, 2021). Although the built environment sector is considered to be less circular than other industries (e.g., electronic, food and textile) (Tokazhanov et al., 2022), the built environment sector has developed several circular strategies and assessment methods. These methods aim to minimalize and measure the environmental impact that buildings (will) have (BCI Gebouw, 2021; Brändström & Saidani, 2022; Buyle et al., 2019; Dams et al., 2021; Kubbinga et al., 2018; Saade et al., 2022). By 2050 The Netherlands aims to reach a fully circular economy, prior to this the country aims to reduce the use of primary raw materials by 50% by 2030 (Rijksoverheid, 2016). The country has formulated policy initiatives to integrate sustainability strategies at the beginning of construction projects so this environmental impact can be reduced (Ministerie van VROM, 2010; Rijkdients voor Ondernemend Nederland, 2017). If the Dutch Built Environment aims to reach its goal by 2030, drastic measures must be taken.

In The Netherlands, about 95% of the waste material from the residential and non-residential building sector is recycled in the civil engineering sector and only 3 to 4% of the material is used in the building sector (Schut et al., 2015). However, a more recent study (van den Minkelis, 2021) states that only about 10% of the building projects where building products are available for reuse, only 1% of these are actually being reused for another lifecycle (see Figure 1). These results imply that construction professionals need to have a greater focus on reusing building products during the design and construction phase.

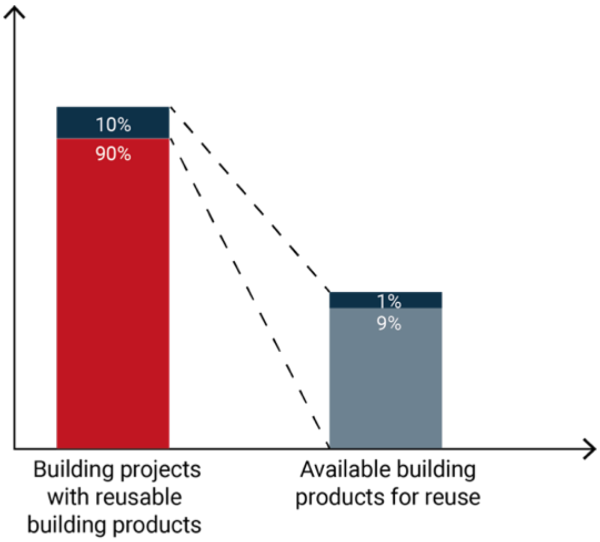


Figure 1 Ratio available for reuse building products and reused building products. Adapted from van den Minkelis (2021)

In the Dutch built environment, every time a construction permit is submitted, an environmental performance calculation of the building with a maximum value of 0,8 (in Dutch: MPG MilieuPrestatie Gebouwen) project must be submitted (Rijksdienst voor Ondernemend Nederland, 2017). This calculation expresses the 'environmental damage' that building projects have on climate change and resource depletion, including the transport, waste and especially the carbon emissions produced during the construction phase (Berghuis, n.d.). During the last period, it has become obvious that staying under the maximum value of this environmental performance is not difficult. However, the goal of the Netherlands is to reduce this value as we approach the circular goal for 2050 (Rijksdienst voor Ondernemend Nederland, 2017). This goal has helped increase awareness around the smart reuse of building materials and products since this helps reduce unnecessary carbon emissions.

1.1.1 Reuse at different building levels

An individual building consists of different separate materials that simultaneously form different products and elements. Each product has a unique production, replacement and lifespan (Marsh, 2017). Buildings are complex structures consisting of different products and elements. Buildings are planned, designed and built as one entity. However, there are seven different levels at which a building is classified terrain, complex, structure, element, product, material and raw material (NEN, 2022; Platform CB'23, 2019).

In the circular built environment, different interpretations are made when referring to reuse. For example, reusing a building structure should be referred to as sustainable building adaptation (e.g., adapting an old office building to a new use such as apartments) (Wilkinson et al., 2014). Reusing (raw) materials to produce a similar quality product should be referred to as recycling. However, reusing building products or building elements in another construction project is actually one-on-one reuse since this strategy does not change the original function of the building product or element (Platform CB'23, 2020b). The latter is usually considered the most circular approach since it does not produce more waste or make use of extra energy. Therefore, during this research, the one-on-one reuse of products and elements is referred to as reuse.

According to a study by FCRBE (Deweerdt & Mertens, 2020) only 1.5% of building products and 0.1% of building elements are reused in Europe on average. In the Netherlands, the reuse rate of building products is estimated at 4.5%. During this research, the reuse of these different building levels will be referred to as the reuse of building products.

The one-on-one reuse of building products has a higher value than the recycling of those since the lifespan of the product is extended and there is almost no waste produced (Faes, 2021). It also cuts carbon emissions. Reuse is a key strategy in the circular economy, which keeps resources in use (reduce, reuse and recycle), instead of disposing them like in a linear economy (take, make and dispose).

1.1.2 Circular value creation and reuse

A circular economy is a system that aims to eliminate waste and keep resources in use for as long as possible (Ellen MacArthur Foundation, n.d.). In the built environment, the concept of the circular economy goes beyond the monetary value that it can have for an organisation. The circular economy aims to design buildings and spaces that are adaptable, durable, reusable and recyclable (Arup, 2016). The economic changes and the increasing awareness of sustainability have influenced how organisations perceive a building. As well as how they perceive the building products within it. Buildings, nowadays, are deemed as 'material banks', where their building materials and products are being harvested to be reused in n subsequent lifecycles. This approach extends the functional lifespan of these building products and reduces their environmental impact.

However, despite the circular principles in the built environment, the reuse of building products remains uncommon. The lack of legislation facilitating the use of reused building products may be one of the limitations. Before delving into further research, it is crucial to explore the possibilities of how building products that were not initially designed for reuse can meet the technical requirements set by building codes and user expectations. Understanding these possibilities will provide valuable insights for advancing the reuse of building products in a circular built environment.

1.1.3 Values and lifecycle

The typical lifecycle of a building product consists of four phases (see Figure 2): design, construction, use and maintenance and end-of-life (European Committee for Standardization, 2021). When a building reaches its end-of-life phase it is usually because the economic, technical and functional values of its products have reached their lowest point (Dewulf et al., 2000). In other words, the used products have become obsolete (Wilkinson et al., 2014). To avoid this complete obsolesce, the products can be used in another lifecycle, so their values will remain equal or higher. This second (and posterior) lifecycle is referred to as the reuse phase. This concept aligns with the lifecycle of products within a circular building, as their lifecycle does not end with the end-of-life phase of the building. On the contrary, it continues through a reuse phase by deconstruction and disassembly of said products (Iyer-Raniga & Huovila, 2021), thereby extending the lifecycle and value of the building products.

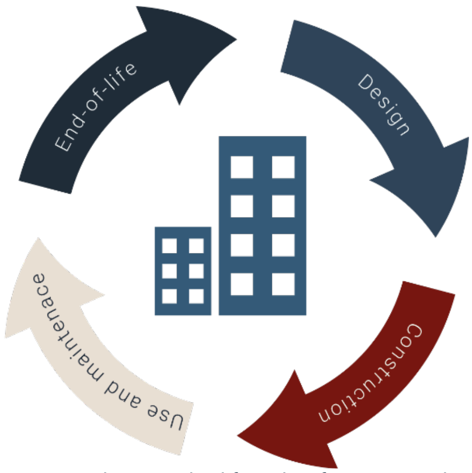


Figure 2 Phase in the lifecycle of a non-circular building (Author)

However, this can be harmful to them if these are not in good technical condition for the reuse phase. Which could lead to unnecessary waste of building products. Therefore, successful reuse largely depends on the technical aspects that the building product has before its reuse in another lifecycle.

Within the built environment, only a small segment of the sector is aware of the potential for reusing building products. Increasingly, circular buildings are being designed with the future scenario in mind, incorporating the dismantling and reutilization of used building products in new configurations (O'Grady et al., 2021). Although disassembly is commonly referred to as a main concept of the building circular approach, it is not a common practice, which makes the reuse of building products a challenge. This is mainly due to the scarce knowledge, needed investments and risks to take into account.

1.2 Problem statement

Even though it seems obvious that a longer lifecycle of building products means a lower environmental impact and that circularly integrating these means that the lifespan of this will be extended, there is little research that can confirm this assumption. The future scenario of used products is difficult to assess. Van den Berghe et al. (2021) state that the one-on-one reuse of material in new construction is a utopia due to the fact of time and fitting. Similarly, to this statement, the one-on-one reuse of building products that were not originally designed to be reused faces the challenge that this is attached to the building's original function and user's requirements. Furthermore, the reuse potential that these reused building products could have for another lifecycle (third lifecycle) is dependent on how these are being reapplied when reused in a second lifecycle.

There has been limited research conducted on the technical aspects that enable the realization of a third lifecycle for reused building products. Therefore, this research aims to bridge this gap by investigating the relationship between the technical requirements that building products must fulfil to be potentially reused in a third lifecycle.

1.3 Research aim

This research aims to analyse the relationship between the technical aspects and the reuse potential for a third lifecycle of building products. The scope of this research lies in the technical characteristics that a reused building product should meet when being one-on-one reused in new building projects and how this influences its posterior reuse potential.

The conceptual model for this research is shown in Figure 3. It reflects the topics this research engages with. The context of this research, the circular built environment, is given by the black dotted line. The red column entails the technical aspects and its assessment methods and the dark blue column the future reuse in a third lifecycle (reuse potential) of the building products. The first step is to define the technical aspects and the technical factors of the reuse potential. This is followed by assessing the relationship between the technical aspects of a reused building product and the technical factors of the reuse potential. This is done by classifying the existing assessment methods of the technical aspects and aligning them to the assessment of the reuse potential. To connect these ideas and produce a usable conclusion; a research question and sub-questions are formulated.

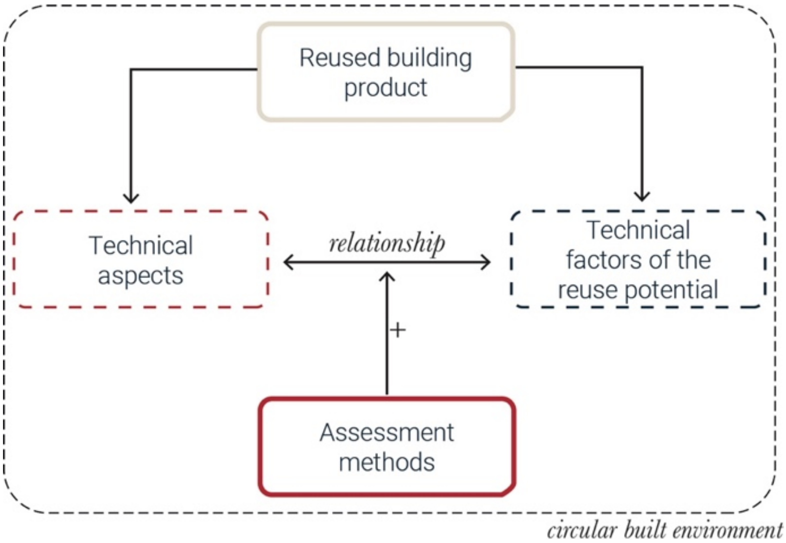


Figure 3 Conceptual model of the research (Author)

1.4 Research Question

To reach the proposed aim in the previous section, the main research question is formulated as follows:

"What is the relationship between the technical aspects and the reuse potential of reused building products?"

This main research question will be answered in parts by answering the following sub-questions:

[SQ 1] What is the circular built environment?

a. What are the circularity strategies used in the built environment?
b. How are the circularity strategies applied to the different building levels?
c. How does circularity create value in the built environment?

[SQ 2] What are the technical aspects of a building product?

a. How can the technical aspects of a building product be assessed?
b. What is the current state of the art on the assessment of the technical aspects?

[SQ 3] What is the reuse potential of a building product?

a. What are the technical factors that influence the reuse potential of a building product?

[SQ 4] To what extent can the assessment methods of the technical aspects of a building product define its reuse potential?

[SQ 5] To what extent do the technical aspects of a reused building product and its reuse application during its second lifecycle determine its reuse potential for a third lifecycle?

a. To what extent is a posterior lifecycle considered when reusing building products for a second lifecycle?

1.5 Research Output

This research aims to provide a comprehensive analysis of how the technical characteristics of a reused building product affect its viability for further reuse.

1.6 Societal and Scientific Relevance

The societal relevance of this research lies in the current role that circularity plays in the built environment. The construction sector is the largest consumer of raw materials and accounts for up to 40% of the carbon dioxide emissions globally (Pomponi & Moncaster, 2017), therefore efforts have to be made to decrease this use of raw materials and hence pollution. Nowadays, the built environment is seeking to apply circularity strategies, the reuse of existing building products one of them, however, this is still in its infancy. This research is of great value for those who are extrinsically aiming for and investing more in a circular approach but are insecure that the chosen products can be reused in the next cycle. Additionally, it aims to motivate construction professionals to think about the further lifecycles that the building products and materials can have after the designed building reaches its end-of-life phase. This research can help those construction professionals to take better decisions during the design phase of building projects; so, not only unnecessary waste production can be reduced but carbon emissions as well.

In terms of scientific relevance, the research on assessing circularity has focused so far on mainly circular design principles at a product and element level, as well as on minimizing carbon dioxide emissions from a material level (Van Vliet, 2018). According to the theory, most of the building products and materials available for urban mining can be recovered. However, the reuse of existing building products appears to be a complex process (da Rocha & Sattler, 2009). Designing a product to be disassembled and reused is a core competency of the circular approach (Rios & Grau, 2019). This requires flexibility from the design team when considering a design strategy in which the products can be reused for the next cycle (Gorgolewski, 2008). This is because their reuse is very site-specific and time-dependent (Gorgolewski, 2008; van den Berghe & Verhagen, 2021).

In 2018, Van Vliet concluded that disassembly is an important factor in the reusability of a building product (Van Vliet, 2018). Later, in 2021, Kentie proposed an assessment tool to measure the reusability potential of a building product (Kentie, 2021). However, this assessment tool was rather focused on the influencing factors than on the adaptability and quality level of building products. This research examines how the technical aspects of reused building products can influence the future function that these products can have.

1.7 Dissemination and Audience

This research is interesting for all involved parties in the built environment. Specifically, for those who are currently involved in the design phase of circular building projects and are willing to know what the added value of (reusing) existing building products is. In addition, the finding of this study will contribute to the integration of circularity strategies at a product or element level. Next to this, this research has also scientific relevance for those academics involved with the development of new quantifiable assessment methods for the value that a building product has after its first and second lifecycle.

1.8 Research Design and Methods

This research is exploratory by nature since it attempts to investigate research questions that have not previously been researched in-depth (Armstrong, 1970). The disadvantage of this type of research is that it is not possible to know in advance if an innovative outcome will result from the whole study (Swedberg, 2020). This research consists of two parts: I and II, and each part is dependent on each other. Part I entails the main literature research and Part II entails the empirical research. Figure 4 illustrates the research design to be followed during this research and their relation with the research questions (red bar on the top) and research methods (blue dotted line bar on the top).

Part I: Theoretical Background

Part I aims to provide insight into the different concepts of the research. This will form the theoretical framework to be used during this research. Firstly, the concepts of circular built environment and circular strategies will be described. This is followed by relevant concepts to understand the further development of this research, such as the in-depth description of the different building levels, the technical aspects and their possible assessment methods, as well as the reuse potential is explained. By doing this a theoretical framework for the assessment method of the reuse potential is built. As well, as the criteria to take into account for the sampling study are developed. During this part, sub-questions 1, 2, 3, and 4 will be addressed.

Part II: Systematic overview of the technical aspects and reuse potential

Part II aims to provide a systematic overview of the technical aspects and reuse potential of reused building products. By following the outcome of the framework built in Part I the first concept of this relation can be assessed. This part is explored through a sampling study. Different cases will be collected based on the criteria selected and further assessed during interviews with the parties involved. The aim here is twofold, first is to gain insight into the adaptive capacity of the different building products assessed and second, into the different technical aspects that a building product needs to meet in order to be reused. The outcomes of these case assessments will generate a more in-depth understanding of what technical aspects influence the reuse potential of a building product. This part is presented in chapters 4 and 5. During part II, sub-questions 4 and 5 will be answered.

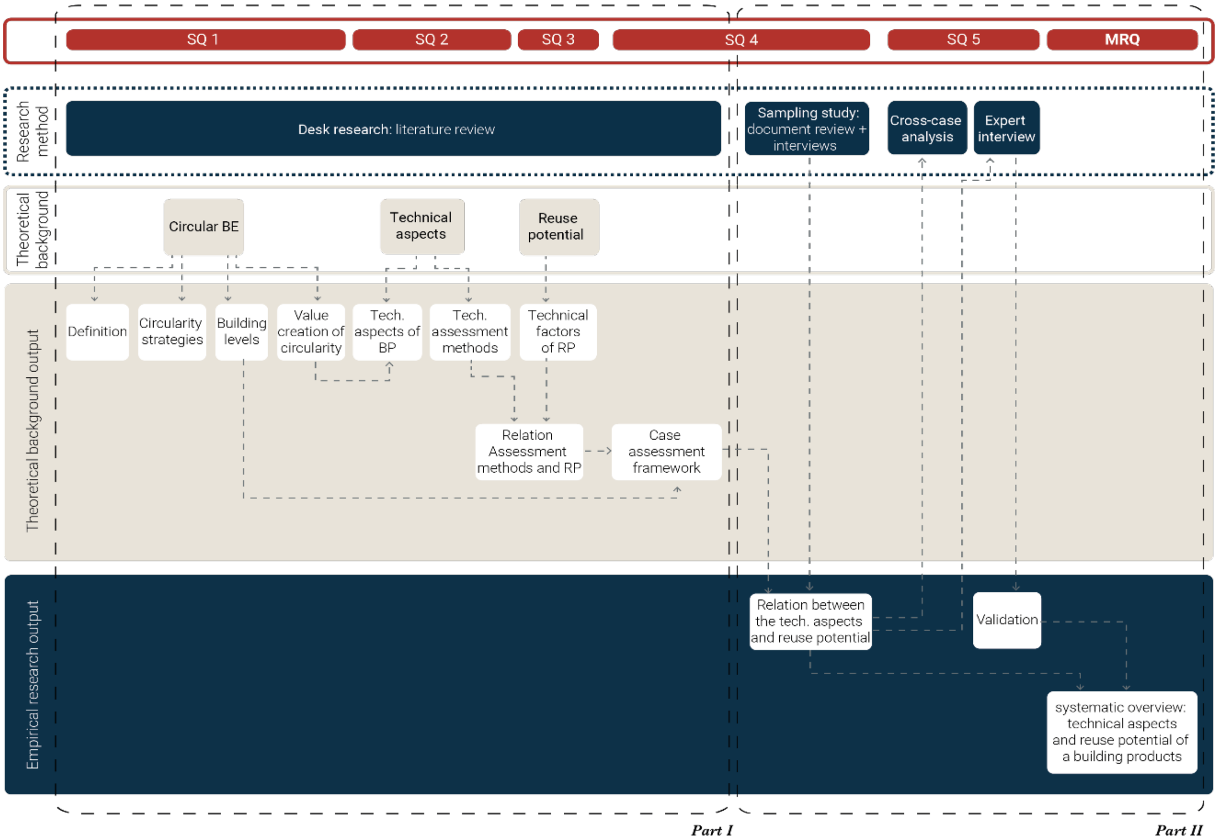


Figure 4 Research framework (RP: reuse potential, BP: building product, Tech: technical) (Author)

1.9 Thesis Outline

Table 1 provides an overview of the chapter and the content of the research.

Table 1 Outline of the research

Chapter	Content
1. **Introduction**	The introduction addresses several key topics. The problem statement, research aims and questions are presented and the relevance of the thesis is discussed.
2. **Theoretical Background**	The theoretical background contains information from other sources that will be used and applied in the empirical research.
3. **Research Approach**	The type of study, research method, data collection, analysis and management are described. Followed by the ethical considerations and practical implications.
4. **Case assessment framework**	The selection criteria and selected cases are presented. Furthermore the assessment criteria to follow are described.
5. **Case assessment results**	The findings of the case assessment are presented per building layer and the reuse potential of the typologies are discussed.
6. **Interpretation of the findings**	The main findings of the empirical research are positioned with the existing literature.
7. **Conclusion**	The answer to the research questions and the main research question are presented. In addition, the practical implications and limitations of the research and recommendations for further research are presented

Chapter 2

Theoretical Background

2 Theoretical Background

The context of this research is the circular built environment, which is mainly focused on the best reuse of waste material, but there is no common understanding of the concept. The circular economy can help to create value by applying different circularity strategies, one-on-one reuse creates the most value out of building products. This chapter aims to dive into the key concepts for this research such as the circular economy and its value creation, and the different building levels and layers to analyse during the research. During this chapter, the following research sub-questions will be addressed:

[SQ 1] What is the circular built environment?

[SQ 2] What are the technical aspects of a building product?

[SQ 3] What is the reuse potential of a building product?

[SQ 4] To what extent can the assessment methods of the technical aspects of a building product define its reuse potential?

2.1 Circular Built Environment

The adoption of the circular economy in the built environment (BE) is becoming inevitable as the consumerist society becomes more and more aware of our scarce limited resources. The Ellen MacArthur Foundation (2013) has introduced Circular Economy as "an industrial economy that is restorative or regenerative by intention and design". In the BE, the circular economy is:

During this research, by "circular built environment", it is meant the context within the built environment where the economic model of circular economy is applied. The circular economy model is about breaking up the linear economic model based on the "take-make-use" approach (Arup, 2016; Remøy et al., 2019; Tokazhanov et al., 2022). Circularity aims to design and build products and assets to have a long lifespan to decouple economic growth from resource consumption. The circular economy follows three main principles (Ellen MacArthur Foundation (EMF), 2013):

- Protecting and enhancing natural sources by managing finite stocks and balancing renewables resources flows;
- Maximizing resource yields by circulating products, components, and materials at the highest utility and value at all times in both the technical and biological cycles;
- And enhancing system effectiveness by identifying and designing out negative externalities.

Figure 5 shows the 'Butterfly model' by the Ellen MacArthur Foundation (2013). Here a distinction is made between the biological and the technical cycle.

Bocken et al. (2016) introduce the fundamental strategies for circular approaches: narrowing, slowing and closing loops. Van Stijn (2023) defines them as 'narrowing loops' to use fewer resources or achieve resource efficiency, and 'slowing loops' to delay the flow of resources by extending or increasing the usage period (for instance through repair, reuse, remanufacturing) and 'closing loops' to recycle materials that are at their end-of-life phase back to production. These strategies aim to maintain a higher intrinsic value of the materials, products and elements by holding them in repetitive loops so the natural resource is preserved and enhanced (Arup, 2016).

The BE sector is the largest consumer of raw materials and it is responsible for 25% to 40% of global CO_2 emissions. A circular approach in the BE sector could help to reduce its environmental footprint. Furthermore, the circular economy supports the BE by increasing the value of asset management, thereby indirectly supporting a longer lifecycle and durability. This means that these aspects should be considered during the initial design process of a building project so the end-of-life value of said building can be retained (Iyer-Raniga, 2019).

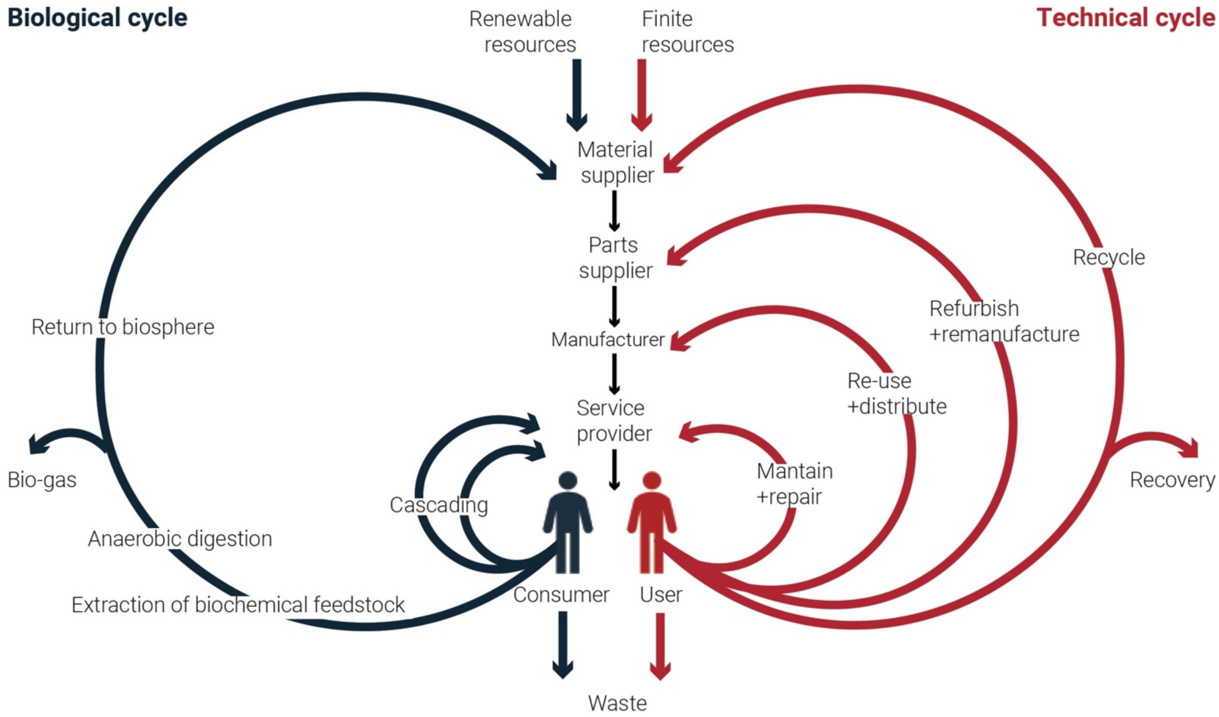


Figure 5 The butterfly model. Adapted and retrieved from Ellen MacArthur Foundation (2013)

The concept of circularity in the built environment is mainly focused on the best reuse of waste material, but there is no commonly accepted understanding of the concept. The circular economy applies different circularity strategies to help with the value retention process – such as reuse, repair, refurbish, remanufacture, repurpose, recycle and recover. Even though recycling can help to achieve a circular built environment (Van Stijn, 2023), one of the greatest circular strategies is to make optimum reuse of the existing products.

2.1.1 Circularity strategies

By circularity is also meant the principles, framework or strategy to approach a circular economy (Iyer-Raniga, 2019). Circularity strategies are characterized by their closed-loop approaches, resource efficiency and optimization of goods. Many frameworks, regarding the circular economy, have been developed and are used in the BE (Cheshire, 2019; Ellen MacArthur Foundation, 2019; Hamida et al., 2022; Kirchherr et al., 2017). Various frameworks, known as R-strategies, have been developed to achieve less resource and material consumption in the supply chain to make a more circular economy.

Potting et al. (2017) present a range of strategies ordered from their impact on the circular economy to the linear economy as shown in Figure 6.

The figure shows the hierarchy between the few natural resources and environmental pressure possibilities. Although R0 and R1 strategies do not involve the reuse of products and materials, they are generally considered circularity strategies (Potting et al., 2017). This framework entails ten strategies that can be applied to reduce waste, extend the life of the building and enable the (energy) recovery of material at the end-of-life phase.

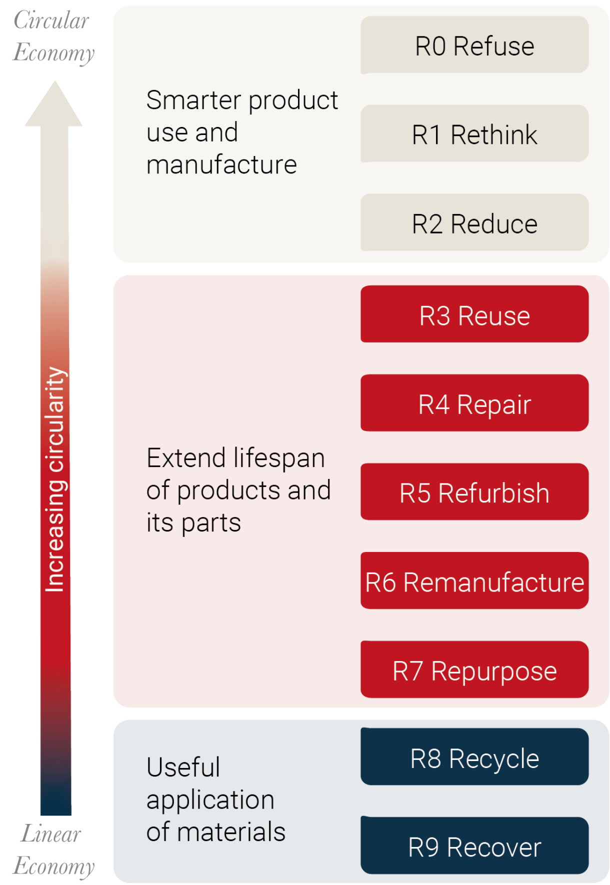


Figure 6 The 10R Framework. Adapted from Potting et al. (2017).

In the built environment, these strategies are defined as follows (Platform CB'23, 2020a);

- Refuse: prevent the unnecessary use of products or materials;
- Rethink: increase the product's use enabling the same object to deliver more numbers functions (e.g., multifunctional buildings, shared use of products);
- Reduce: reduce the use and quantity of new virgin materials while ensuring the same functional quality;
- Reuse: reuse building products with the same function;
- Repair: extend the use of a product or building layer by preventive and corrective maintenance;
- Remanufacture: use discarded products to create a new product or element with a similar function;
- Repurpose: reuse of a discarded product or a new product for another function;
- Recycle: recovering (virgin) materials from discarded products and reusing them to make products;
- Recover: recovering energy through direct and controlled combustion of raw materials that otherwise would become waste.

These circularity strategies aim to reduce the use of materials and resources to make a more circular economy (Potting et al., 2017). However, these R-strategies have been further developed (Potting et al., 2017; RLI, 2015; Vermeulen et al., 2014). The latest one, also known as the 10R framework, is presented by Potting et al. (2017). The hierarchy of the 10R framework represents the circularity level that each R-strategy has, from a high circular economy level to a low circular economy level, being the last one closer to what is known as the linear economy. The 10R framework increases the economic value of the existing product or element after this has reached its end-of-life phase (Mrad & Frölén Ribeiro, 2022). Additionally, it indirectly helps lower the environmental impact that a product or element can have if wasted before the end of its useful life (Mrad & Frölén Ribeiro, 2022). The 10R framework provides insight into how low or high a strategy is to the circular economy.

The circular economy applies different circularity strategies to help with the value retention process, as shown in Figure 6. The circularity strategy of reuse is commonly mistaken for recycling. Both circularity strategies involve using waste materials for construction purposes. However, recycling is often less efficient since it is a process where materials are processed into new materials that have lower quality and reduced functionality, this is usually referred to as 'downcycling' (Ellen MacArthur Foundation (EMF), 2013). Reuse, on the other hand, aims to use products for another lifecycle with little or no changes, which can save more materials and energy (Icibaci, 2019).

2.1.2 Building levels

The previously presented circularity strategies are implemented in different scale levels of a building (Platform CB'23, 2019), recycling occurs at a material level, and from repurposing to reuse at a more building product level. For the purpose of this research a clear definition of the different building levels is required these levels are further explained in the next section. Buildings can be breakdown to their lowest level. This being, for example, the cement used in a concrete floor slab of a school building or the stone wool insulation used for a division wall system. Different scholars (Brand, 1994; Durmisevic, 2006) approach this hierarchy differently, from a system approach to the building scales to a hierarchy of the building layers.

2.1.2.1 Building scales

Buildings are planned, designed and conceived as a whole. However, as earlier explained, buildings are a composition of different objects. There are seven scale levels in which these objects can be classified (see Figure 7). These are presented in a hierarchical order, where the highest-level compounds all the lower levels. The lowest scale is the raw material and the highest is the terrain where a building is placed (NEN, 2022; Platform CB'23, 2019).

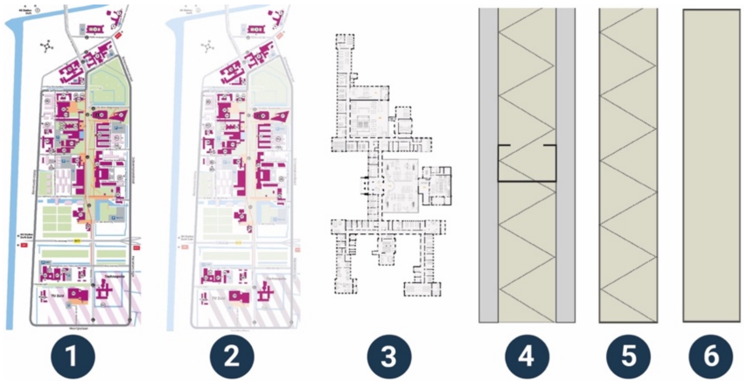


Figure 7 Example of the different levels to classify buildings. (1) Terrein: Campus TUDelft, including green area and infrastructure; (2) Complex: Faculties and facilitaire buildings; (3) Structure: Architecture Faculty; (4) Element: internal wall within structure; (5) Product: insulation board; (6) Material: Stone wool; seventh level not illustrated (Author)

1. Terrain: a building or a complex of buildings including the land and greenery.
2. Complex: a composition of different buildings that together form one function, e.g., an airport, university campus or a shopping mall.
3. Structure: a single building that forms an entity and performs a specific function, e.g., an airport terminal, a university faculty, or the parking garage of a shopping mall.
4. Element: a part of a building that is distinguished solely on the basis of a desired function (support structure, space separation), e.g., a building concrete skeleton or a wall system.
5. Product: products deliver to the construction site that will form part of an element after processing them, e.g., concrete, windows or handrail. In the case of prefabrication, products are already manufactured into elements before they are delivered to the construction site.
6. Material: a processed raw material that is used for the manufacture of building products, e.g.,
7. Raw material: materials are made from fossil raw materials through a mechanical process, returning to this original raw material is not easy, e.g., basalt used for stone wool insulation, cement used for concrete or bauxite used for aluminium.

In the Netherlands, the reuse rate of building products and elements is 4.5%, with products having a higher rate than elements (Deweerdt & Mertens, 2020). Henceforth, the term "building products" will subsume "building elements" unless otherwise specified.

2.1.2.2 Building layers

Buildings undergo constant changes due to user and environmental demands. Thus, each change implies an improvement in one of their levels. To facilitate this, buildings are often constructed with a functionally layered approach (Lstiburek, 2017), which allows replacing products with shorter lifespans without affecting those with longer ones. The layer concept was first introduced by architect Frank Duffy in 1970 (Schmidt & Austin, 2016), who argued that buildings should be measured by time rather than materials. Duffy proposed the 4S framework, dividing a building into four shearing layers: service, skin, structure and site. Later, in 1990 Brand added two more layers: stuff and space plan and noted that the more interconnected the layers are, the harder they are to adapt (Brand, 1994). This model is known as the 6S framework of Brand (see Figure 8), with 'Site' as the outermost layer and 'Stuff' as the innermost. Each layer consists of elements and products:

1. Site: defined by the geographical setting and location.
2. Structure: entails the primary support for the vertical and horizontal load (incl. foundation, beams, columns, loadbearing walls, skeleton)
3. Skin: protects the building from external factors (façade and the exterior)
4. Services: supplies and transport energy, water, communications (incl. mobility installations such as elevators)
5. Space plan: determines the interior layout of the building (incl. ceiling, floors and doors)
6. Stuff: (in)mobile objects for the user's use (e.g., chairs, curtains, mirrors)

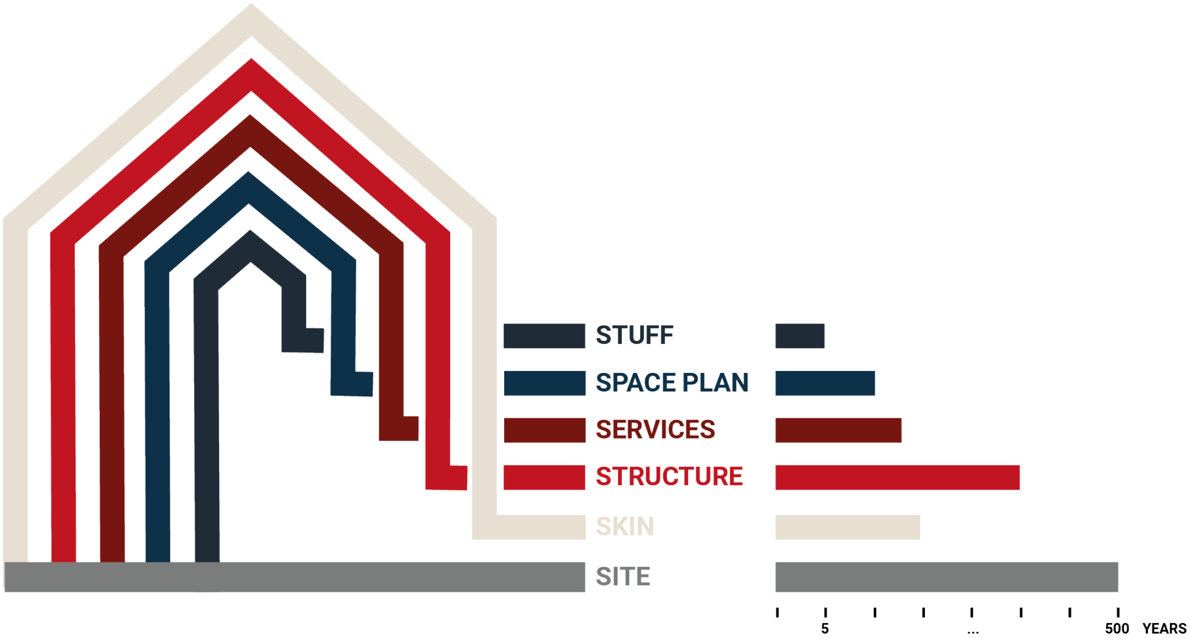


Figure 8 6s model according to Brand (1994), each layer has a different lifespan stuff (5), space plan (10), services (15), skin (20), structure (100) and site (500). Illustration adapted by author.

These layers have different degrees of circularity and sustainability, and they influence how people value and relate to the building. In the circular built environment, these layers are commonly used as a reference since a good circular design considers how they can be reused or recycled in a next lifecycle (Struiksma et al., 2020).

2.1.3 Value creation in the circular built environment

Value creation is a crucial aspect for understanding the circular economy. However, value is a subjective concept that depends on personal perceptions, but it generally reveals the relationship between performance, costs, benefits and risks (Goldbohm et al., 2018). The circular economy can create value in many aspects beyond the economic one (Tapaninaho & Heikkinen, 2022). In the built environment, the circular economy strives to create value in the present while also safeguarding the future (value retention), thereby protecting the environment and preserving the stock of materials (Platform CB'23, 2020b). This approach entails evaluating not only the monetary value but also the functional value of an object throughout its multiple lifecycles, taking into account its technical and social aspects According to van Oppen et al. (2021), the application of a circular approach in the built environment recognizes four distinct types of values (see Figure 9):

- Economic value: it relates to business profitability and new business opportunities (Tapaninaho & Heikkinen, 2022). It reflects the costs that an object has when it can be kept in the closed loop. In the circular economy, this means that an object has a higher economic value if it can be reused for another lifecycle.
- Social value: it refers to the social (well-being of people and future generations) and ecological (protecting the natural environment) benefits that the circular economy enhances.
- Technical value: it represents the technical requirements, mainly given by the legislation and regulations and it gives meaning to the user's need (Goldbohm et al., 2018). In the circular economy, it also refers to the potential that an object can fulfil in the future by making it detachable and adaptable, as well as considering the choice of material to be used (van Oppen et al., 2021).
- Functional value: it refers to the performance that an object has by fulfilling its function. The functional value reflects the needs of the users (Goldbohm et al., 2018). In the circular economy, this value is reflected by the performance that an object can have in different contexts and uses.

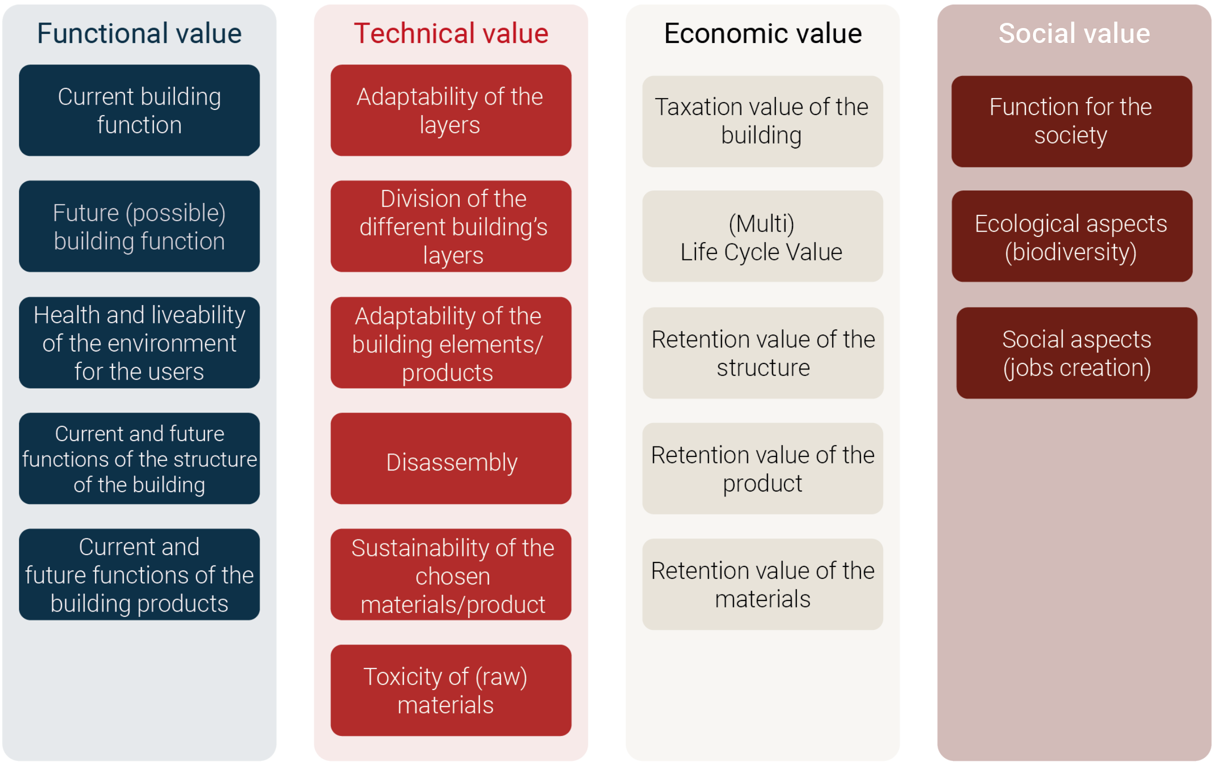


Figure 9 Functional, technical, economic and social value of circularity. Retrieved and adapted from van Oppen et al. (2021)

The functional value of a building product consists of two types of aspects: the current and potential functions of the product and the health and liveability of the environment for the users. A major challenge for reusing products is that building materials have different lifecycles and their durability often exceeds their function within the product (Durmisevic, 2006). To overcome this problem, some authors (Marsh, 2017) suggest that a functionally layered building can allow the replacement of products with shorter lifespans and different functions without affecting those with longer lifespans. The functional value of a product depends on its current and future performance. However, the functional value is also influenced by the technical value of the product, since a product that does not meet the technical requirements or expected quality will lose its functionality and become obsolete (A. den Heijer & van der Voordt, 2017; Durmisevic, 2006; Marsh, 2017). The concept of functional value is still vague and intangible. Therefore, this research will focus on the technical value.

2.2 Technical aspects in the circular built environment

The technical value of a building product in the circular built environment depends on its ability to meet the current and future requirements and its technical lifespan. The technical lifespan is the period in which the product satisfies the technical performance criteria of a chosen maintenance strategy (Dewulf et al., 2000). When the product reaches its end-of-life phase, its technical value becomes null. The technical value can be quantified by measuring various technical aspects at different building scales. Figure 10 illustrates the technical aspects and their corresponding assessment methods, based on a literature review of academic and market sources (Buyle et al., 2019; Cradle to Cradle Products Innovation Institute, 2022; Geraedts, 2016; Platform CB'23, 2020b; van Vliet et al., 2021). The following section will elaborate on each aspect and its suggested assessment method.

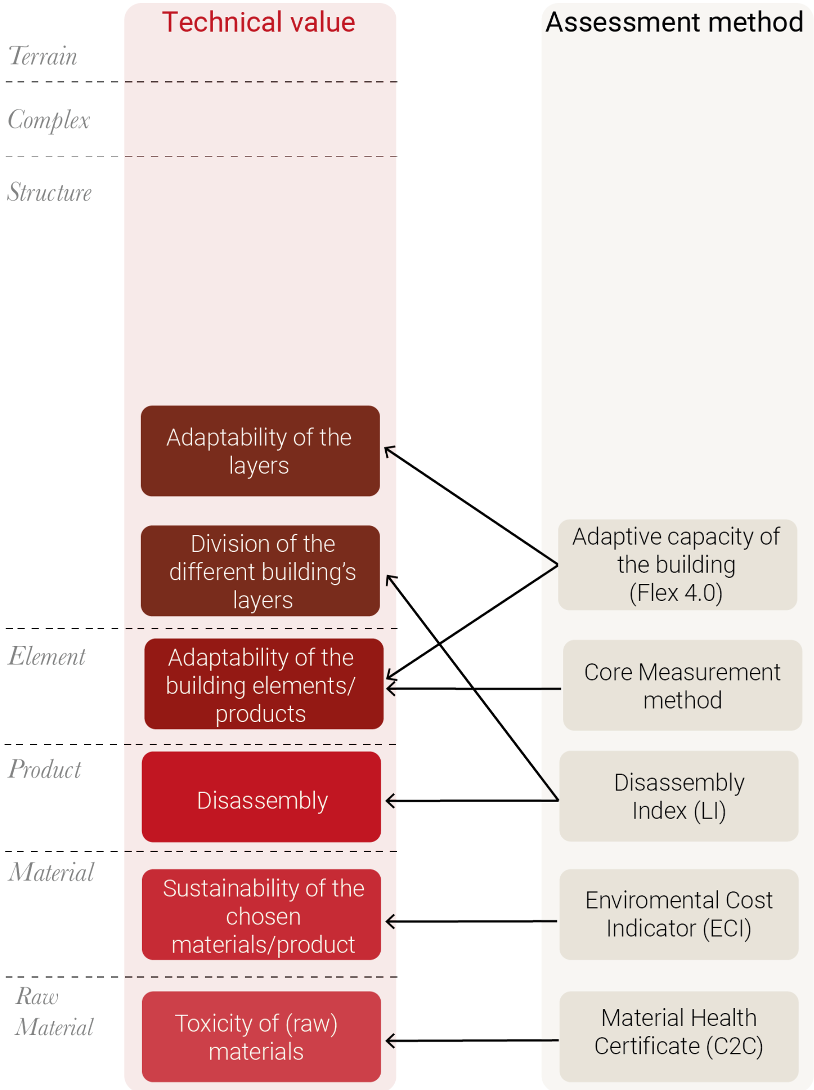


Figure 10 Relationship between the aspects of the technical values per building scale and possible assessment method. The assessment methods are independent from the building scale (Author)

2.2.1 Adaptability of the layers

Adaptation refers to the maximum retention of the original structure (Wilkinson et al., 2014), or in this case layer while extending its functional lifespan. Adaptability helps the concept of the circular economy because it involves less material use, transport of energy and pollution during construction since its main aim is to adapt the building rather than default demolition and build a new one (Wilkinson et al., 2014).

However, the adaptability of a building depends on the adaptability of each layer. The building's layers and their elements and products have their own technical, functional and economic lifespan. When a building can easily change its function, this increases its functional and economic value in the long term.

Adaptive capacity of the building instrument tool: FLEX 4.0

In 2016, Geraedts developed an instrument tool to assess the adaptive capacity of buildings, Flex 4.0, this assessment is done by a set of flexibility performance indicators that are relevant for each (sub) layer. It has two indicator categories, the generally applicable indicators (12) and the specific applicable indicators (32). The indicators are valued from 1 (bad) to 4 (better) according to their flexibility (adaptability) performance. The indicators are weighted and the score is expressed in a corresponding flexibility class, rating from class 1: not adaptable at all, class 2: hardly adaptable. Class 3: limited adaptable, class 4: very adaptable class 5: excellent adaptable. An extended description of each indicator per layer can be found in Appendix VI.

2.2.2 Divisions of the different building layers

The division of the different layers refers to the independence of each layer in relation to the other. When elements or products from different layers are dependent on each other this can have negative consequences when these need to be disassembled at the end of their life. The level of independency of a product or an element is assessed by the valuation of independency by Durmisevic (2006). Further explanation of the assessment is later given in the disassembly index assessment.

2.2.3 Adaptability of the building elements or products

The technical adaptability of a product or elements is given by its capacity to be reused and recycled at the end of its lifecycle. For the adaptability of a building element or product is important to estimate the expected degree of circularity and its potential to be reused in another lifecycle. A building element or product with a high level of adaptability can easily be changed and retain value for a longer time. The adaptive capacity of a building is given by the elements and products within the building, as described in section 2.1.2. the FLEX 4.0 can be used to assess this, however, to be more precise in the assessment of the element scale, the core measurement method proposed by Platform CB'23 is chosen as the instrument for reporting adaptive capacity. (Platform CB'23, 2020b).

Instrument for reporting adaptive capacity for structures from the core measurement method

Platform Circular Construction carried out an extensive desk study to establish an instrument to assess the adaptive capacity of the structure, this is part of the core measurement method. Platform Circular Construction defines four aspects that influence the adaptive capacity of each building's layer (Platform CB'23, 2020b). The first three are integrated into the FLEX 4.0 and the last one is a framework to define the measures that adaptability has.

- Uniformity: objects are uniform when they have the same shape or form in terms of measurements, properties and capacity.
- Flexibility: this indicates the degree to which elements can be adapted to new developments and needs.
- Building layer: the interlinkage with other construction layers, and the technical lifespan that an element or product has according to its functional lifespan
- Schmidt scale: adaptive capacity has six types of measures; these are developed by Schmidt and Austin (2014) and adapted by Pinder et al. (2017). Adjustable (change of task), versatile (change of space), refitable (change of performance), convertible (change of use), scalable (change of size) and movable (change of location).

2.2.4 Disassembly

As earlier stated, buildings are a compound of different building products that are interconnected. If all these products are inseparable, one cannot harvest them and therefore they cannot be reused. When designing a building that can be disassembled, one could easily replace elements in the case of changing needs and circumstances. The disassembly potential affects the reusability potential of a building element or product.

Disassembly index (LI)

The disassembly potential of a building product is the extent to which these can be separated without causing any damage to the products adjacent to it while retaining their functions (van Vliet et al., 2021). If components and elements of a building cannot be harvested by the end-of-life phase of a building they become obsolete. This potential can be calculated by measuring four aspects (van Vliet et al., 2021):

1. The connection type: dry connection, connections with added elements, direct integral connections, soft chemical connection or hard chemical connection.
2. The accessibility to the connection: freely accessible without additional actions, accessible with additional actions that do not cause damage, accessible with additional actions with fully repairable damage, accessible with additional actions with partially repairable damage or not accessible/irreparable damage to the product or adjacent products.
3. Independence: no independency, occasional independence or full integration.
4. The geometry of product edge: open, no obstacle to the (interim) removal of products or elements, overlapping, partial obstruction to the (interim) removal of products or elements or closed, complete obstruction to the (interim) removal of products or elements.

Despite the fact that disassembly is a relevant aspect of circularity, a high potential level of disassembly does not mean that a building product can be reused.

2.2.5 Sustainability of the chosen materials and products

The production process of material costs energy (CO_2), when choosing a material, it is relevant to know how sustainable this production is and what the future scenario of the material could be (i.e., the quantity of material for landfill, energy recovery, recycling or reuse). This is usually measured with a Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA)

A life cycle assessment (LCA) is a common indicator used to quantify and evaluate the circularity in the environmental performance of construction materials and facilities (Gomis et al., 2022). The outcomes of an LCA are determined by classifying all emissions and resources uses, including, if possible, their geographical location, and using factors derived from mathematical cause/effect models to determine the potential impacts on the environment of these emissions and resources used (M. Z. Hauschild et al., 2018). The life cycle phases of a building are generally divided into three; construction (extraction, manufacturing and transport), use (use, maintenance, repair, refurbishment and replacement) and end-of-life (demolition, disposal, next recycling potential) (M. Z. Hauschild et al., 2018).

The LCA has become the departure point for several circularity assessment methods in the built environment.

2.2.6 Toxicity of (raw) materials

The less the toxicity rate that a material has, the more likely it can be reused. The toxicity influences the health of the working and living environment and therefore, influences the future function of the building.

Material Health Certificate

A Material Health Certificate is based on the Material Health assessment methodology. This methodology rates the level of toxicity or chemical hazard that a product may have (Cradle to Cradle Products Innovation Institute, 2022). This assessment does not allow the use of banned chemicals and it identifies the appropriate metabolism of the products and their materials (Cradle to Cradle Products Innovation Institute, 2021).

2.3 Reuse potential

The reuse potential of building elements or products refers to their ability to be used again for the same purpose for which they were conceived, without further alteration (Deweerdt & Mertens, 2020; Iacovidou & Purnell, 2016). The reuse potential can be assessed by using different methods and indicators that measure the technical, environmental and economic aspects of reuse (Condotta & Zatta, 2021a; Rakhshan et al., 2020).

2.3.1 Technical aspects influencing the reuse potential

According to the literature, the relation between the technical value and the reuse potential of building elements or products depends on how the technical characteristics match the requirements and expectations of the new use. However, the reuse potential that a building product or element can have depends on different technical factors.

Van Vliet (2018) distinguishes three types of factors, based on the IPF model (Van Oppen & Eising, 2012), that influence the reuse potential of a building product or element. These types are technical-based, process-based and financial-based.

The literature distinguishes five factors for the reuse potential. Here, it is usually referred to the adaptivity (Durmisevic, 2006; Platform CB'23, 2020b; Webster & Costello, 2006), material quality (Meuffels & Hoppe, 2021; Van Dijk, 2018), disassembly (Akanbi et al., 2018; Coenen et al., 2021; Durmisevic, 2006; Durmisevic et al., 2017; Guy & Ciarimboli, 2005; Hobbs & Adams, 2017; van Vliet et al., 2021), standardisation(Akanbi et al., 2018; Coenen et al., 2021; Durmisevic et al., 2017; Hobbs & Adams, 2017; Platform CB'23, 2020b) and toxicity of the materials (Akanbi et al., 2018; Ellen MacArthur Foundation (EMF), 2013; Hobbs & Adams, 2017; Platform CB'23, 2020b; Van Kuppevelt & Stoutjesdijk, 2020).

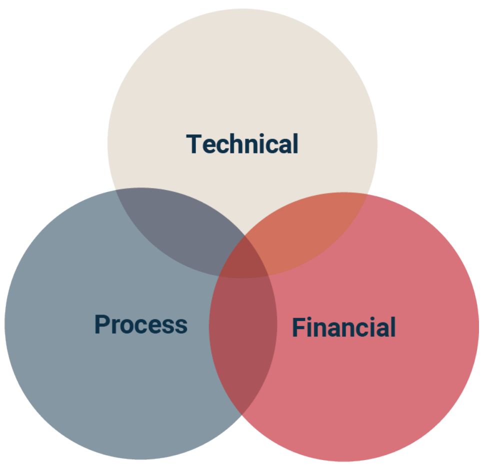


Figure 11 IPF-model. Adapted and retrieved from van Oppen & Eising (2012)

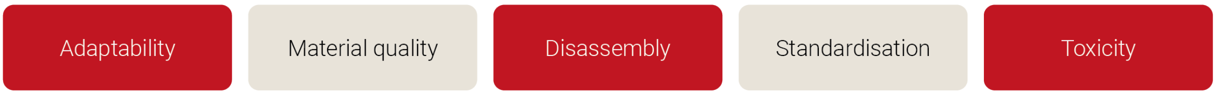


Figure 12 Technical factors that influence the reuse potential of building products and elements (red) similar to the technical aspects from the technical value

Adaptability

The adaptability of a building product measures its ability to augment its initial function and serve a different purpose. Typically, the direct reuse within the same function preserves more value (Webster & Costello, 2006).

Material quality

The material quality affects the reuse potential of building products. Low-quality materials can be recycled, but not reused. To prolong the functional lifespan of the building product, material quality is crucial (Van Dijk, 2018). Load-bearing structures must retain their function when reused. Hence, the quality assessment of the building product is important for reuse (Meuffels & Hoppe, 2021).

Disassembly

Disassembly is a key factor for reuse potential. Akanbi et al. (2018) argue that bolt and nut-joint, rather than nails and glue, enhance the reuse potential of products. When products are designed for deconstruction and disassembly (referred to as circularly applied in this research), their reuse potential increases (Coenen et al., 2021). Several schools assert that disassembly should be the basis of the design for reuse (Dams et al., 2021; Durmisevic et al., 2017; Van Vliet, 2018).

Standardisation

The dimensions of products can also limit their reuse potential (Durmisevic et al., 2017). Coenen et al. (2021) claim that unique objects with specific dimensions, materials or features are less likely to be reused. They also suggest that reducing complexity and promoting standardisation and simplicity can enhance the reuse potential of products and materials. Modular products with a disassembly strategy have a higher reuse potential (Akanbi et al., 2018; Platform CB'23, 2020a)

Toxicity

Toxic or hazardous materials are a major barrier to the circular economy (Condotta & Zatta, 2021b). They restrict the recycling and reuse of products at the end of their lifecycle (Akanbi et al., 2018; Ellen MacArthur Foundation (EMF), 2013). A way to mitigate their low reuse potential is to ensure a good disassembly within the materials and products so that a toxic or polluted material or product can be easily removed (R. Heijer & Kadijk, 2020).

The technical value and reuse potential of building products depend on how well their technical characteristics match the needs of their new use. This is similar to the technical aspects previously presented. For instance, a high level of adaptability and disassembly can increase the reuse potential of elements or products, as they can be easily modified or separated to suit different contexts and needs (Condotta & Zatta, 2021a; Rakhshan et al., 2020). On the other hand, a high level of toxicity or low material quality can decrease the reuse potential of building products, as they can pose health and safety risks or have poor durability and performance (Deweerdt & Mertens, 2020).

2.3.2 Reuse Potential of Building Products

Iacovidou & Purnell (2016) classified a number of building products and elements according to their ability to retain their functionality over the end of their first lifecycle.

Table 2 aims to depict the reuse potential rate for the building products from the skin, structure and space plan layer as presented in the literature.

Table 2 Reuse potential rate of building products and elements. Retrieved and adapted from Iacovidou & Purnell

No reuse potential (0%)	Low reuse potential (<50%)	Moderate reuse potential (~50%)	High reuse potential (>50%)
Ceramic cladding (cement-based mortar)	Mineral wool	Steel cladding	Ceramic cladding (with lime-based mortar)
Concrete structure element	Gypsum board (system wall)	Pre-cast concrete	Steel structure element
Steel connections	Steel rebar in pre-cast concrete	Slate tiles	Concrete block (with lime-based mortar)
Steel rebar	Timber trusses	Timber floorboards	Roof tiles
Non-ferrous metal elements (aluminium window frame, curtain walling, cladding, zinc sheets)	Concrete in-situ elements		Stone tiles
	Glass components		Stone walling

2.4 Main takeaways from the literature

This chapter explored the concept of a circular built environment and how it creates values. It discussed the economic, social, technical and functional values of circular construction and focused on the latter two. It also defined the reuse potential of building products and elements and identified the technical aspects that influence it. The main finding and implications of this chapter are:

- The technical aspects relevant to the building products and elements identified within the technical value are adaptability of the layers, division of the building layers, adaptability of the building product or element and disassembly potential. These aspects can be measured by existing assessment methods, such as the adaptive capacity of the building (FLEX 4.0), the disassembly potential measurement method (disassembly index) and the core measurement method. However, the latter is still under development, so this research used the adaptability framework proposed by Schmidt (Schmidt III et al., 2010; Schmidt et al., 2014) to assess the adaptability of the building products.
- Moreover, this chapter defined the reuse potential as the possibility that a building product or element can be reused, which means that its functional lifespan is extended. However, this does not imply that its functional value is higher when reused, as this depends on other factors such as user preferences, market demand and environmental impact. The functional value of building products and elements is still a vague and intangible concept that needs further clarification.
- Additionally, the technical value of reused building elements or products refers to their physical and functional characteristics that determine their suitability and performance for a specific use. These characteristics include aspects such as adaptability, disassembly, toxicity, standardisation and material quality. The reuse potential of building elements or products refers to their possibility to be used again for the same purpose as their primary functionality, without further alteration. The reuse potential can be assessed by using different methods and indicators that measure the technical aspects of reuse. However, these methods require validation.
- This chapter provided a theoretical foundation for understanding and assessing the reuse potential of building products and elements in the circular built environment. It also highlighted some of the challenges and gaps in existing methods and frameworks. This research will aim to further develop and validate these methods and frameworks.

Chapter 3

Research Approach

3 Research Approach

This chapter introduces the research methods used during this research. As mentioned in the first chapter, this report aims to fill the gap in knowledge regarding the technical value and reuse potential of building products. This aim is achieved by addressing the main research question:

"What is the relationship between the technical aspects and the reuse potential of reused building products?"

3.1 Data collection

This research comprises two methods of data collection, a literature review and a sampling study.

3.1.1 Literature review

The literature review aims to gain insight into the primary concepts for this research (circular economy, circularity strategies, circular value creation and reuse potential). The literature review provides the theoretical framework for the further development of the research (as presented in Chapter 2). For the literature review, the data is collected by using academic articles/journals, reports from institutions and companies, webpages, books and sources from well-known organisations within the Dutch context on the topic. The search engines used are Scopus, ResearchGate, Google Scholar, NEN Connect and TUDelft Online Library and Repository. For the collection of the most relevant references, all possible keywords for circularity strategies, circular economy, technical value, reuse potential and circularity assessment methods were used.

3.1.2 Sampling study

Sampling methods are intended to maximize the efficiency and validity of limited resources (Patton, 2015). Contrary to quantitative research which relies on established formulae for avoiding errors, qualitative research relies on precedents for determining the number of samples based on the type of analysis proposed, the level of detail required and the emphasis on homogeneity (Palinkas et al., 2015). For this research, a purposeful (also referred as purposive) sampling method is used, also known by quantitative methodologists as 'nonprobability sampling' (Patton, 2015). The challenge of using this method lies in the unknown range of variation for the sampling. Figure 13 Sampling study overview

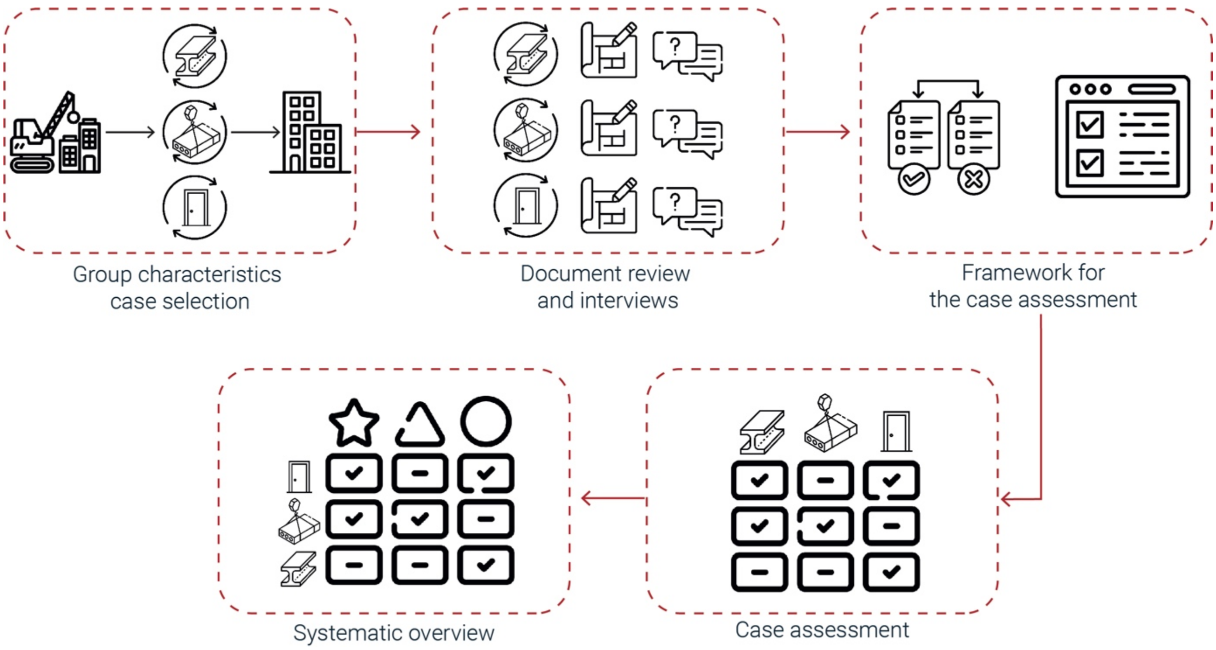


Figure 13 Sampling study overview (Author)

(Author) shows an overview of the steps to follow for the data collection and analysis for the sampling study.

3.1.2.1 Group characteristics sampling

A homogeneous or group characteristics sampling is the purposeful sampling strategy used during this research. This strategy has an emphasis on similarities. The objective here is to identify and select cases that meet some predetermined criterion of importance to study the characteristics they have in common (Patton, 2015). The purpose of this type of sampling is to describe some particular subgroup in depth (Patton, 2015, p. 510).

The sampling study will be focused on the review of available internal/external documents upon request that concern the building product or element to be assessed (from here on referred as cases). The documents to review can concern for instance: publications of the project, news articles, technical drawings of the project and supplier specifications.

3.1.2.2 Interviews

The review of the cases is further supported by interviews with involved stakeholders from the building projects from where the selected cases are. For some inquiries, the specific interview questions are the unit of interest for data collection and analysis. During the interviews, responses to specific questions become the unit of analysis. (Patton, 2015). During the interviews, interviewees will be asked to share their opinion about certain statements regarding the assessed building product. The topics and issues to be covered are specified in advance, in an interview protocol (see Appendix II). In some cases, the samples to assess are within the same project minimizing the number of interviews with the same stakeholder. Appendix II presents the classification of the cases according to the interviewee and project.

3.1.2.3 Data reduction

To be able to analyse the findings of the interviews, these will be recorded and minutes will be taken. These recordings and minutes will facilitate the analysis. After this, the recordings and minutes will be anonymized and deleted. For further ethical considerations and the data management plan see sections 3.3 and 3.5. The answers from the interviews will be summarised in quotes and findings that contain the message transmitted by the participant.

3.1.2.4 Selection criteria

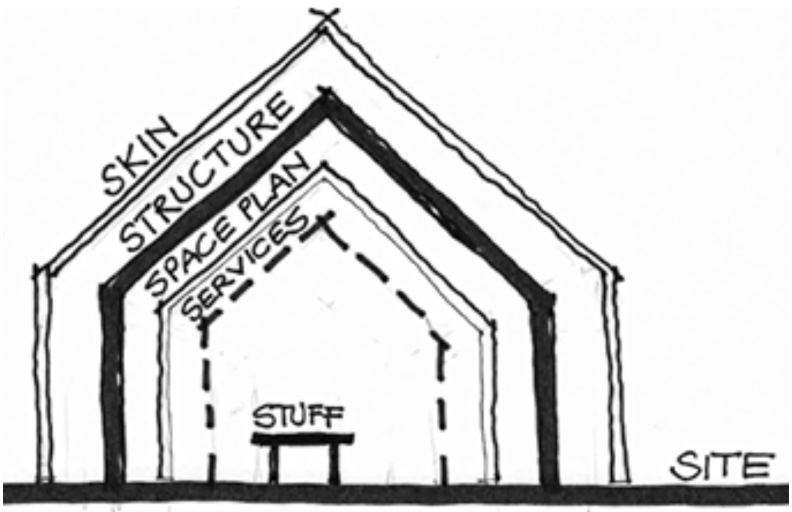


Figure 14 Shearing layer of Brand. Retrieved from building types online (n.d.)

For this research, a maximum of 60 cases will be selected. This has two reasons. First, the sampling study aims to analyse the technical aspects of different reused building products and their influence on the reuse potential. And by having multiple cases one can have different outcomes and compare them to each other. The second reason is due to the short time limit during which this research is executed. The benefit of a multicase study will be limited if fewer than 4 and will provide more uniqueness of interactivity if 15 to 30 cases are provided (Stake, 2006).

As earlier stated, a building is a composition of different building materials, products and elements. Each building product with a different function. Therefore, one cannot compare them to each other and expect similar outcomes. During this research, the building products are differentiated according to the shearing layers as defined by Brand (1994) (illustrated in Figure 14). The layers to analyse are the skin, structure and space plan. For each layer, a goal of 20 cases is set. The layers of the site, service and stuff are out of scope due to their level of complexity.

The cases will be selected based on certain criteria and dimensions. The selected cases must meet the following requirements:

- The case to assess must be a building product (as defined in section 2.1.2.1);
- The building product to assess must be during its second lifecycle or posterior to this;
- The building product to assess should be within the skin, space plan or structure layer as defined by Brand (1994);
- The building product to assess must be reused in a new building project in The Netherlands.

3.2 Data analysis

The data collected from the reviewed literature and documents for the sampling study will be analysed by using thematic analysis, which allows approaching a large data set easily by sorting it into broad themes.

3.2.1 Literature review

The literature study from Chapter 2 provides information on how the technical aspects of a building product can be assessed and the relation with the reuse potential. This is analysed by using thematic analysis (Braun & Clarke, 2006).

3.2.2 Sampling study

Once the raw data is collected from the selected cases, it is pulled together and organized into the case assessment, which collects all the data into a comprehensive, primary resource package. This is done by translating all the collected data into a form (Google form), which systematically organizes all the assembled data into an Excel document to facilitate the review and analysis of each assessed product. Figure 15 presents an overview of how the selected cases will be assessed and analysed. For each

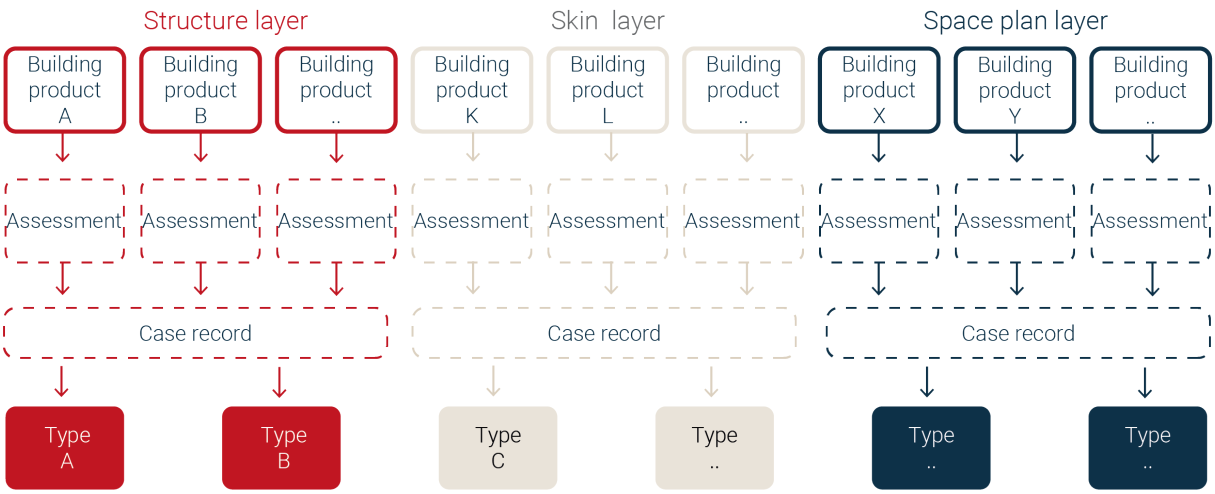


Figure 15 Case record design (Author)

assessed building product, the same assessment is followed. The process of constructing the case studies is as proposed by (Patton, 2015, p. 941):

1. Assemble the raw data case: these data consist of all the information collected from the building product to assess and the interviews with the involved stakeholder
2. Construct a case record: the raw data is condensed, organized, classified and edited into a manageable file; in this case, the assessment form
3. Write a final case study narrative: the results from the assessment are presented in a readable unit of analysis.

3.2.3 Triangulation of qualitative data

Qualitative research is considered to be more subjective than quantitative studies because the findings may be interpreted differently by researchers (Burnard et al., 2008). Therefore, to avoid the subjectivity of the findings and increase the credibility of the study, triangulation between different data collection techniques is used to compensate for this shortcoming. During the sampling study, similar building products from different building projects are assessed (e.g., steel beams from Project A and steel beams from Project B). Additionally, the interview findings are checked against project documents and other written evidence that can corroborate what the interviewee responded. This is finally validated by expert interviewees to corroborate the findings.

3.3 Data management

For this research, a data management plan (DMP) is developed using the DMPonline system, an online tool made available by Delft University of Technology. This DMP has been discussed with the data steward J. Strandberg. The main organisation involved in this research is the Delft University of Technology. Alba Concepts is the secondary organisation involved in the research. However, only data is collected from this organisation and thus not stored.

The FAIR data principles are applied in this research. This principle entails that data is Findable, Accessible, Interoperable and Reusable. After the research is finished the TU4.ResearchData will be responsible for publishing this thesis in the repository of the Delft University of Technology. Thus, the thesis is findable and accessible. This thesis is written in English, so it can be interoperable. Lastly, regarding the reusability of this thesis, all deliverables are added to the appendix or processed throughout the final thesis report. In addition, all references used can be found at the end of the report in the reference chapter.

3.3.1 Data storage

Regarding the data storage of the research during the project lifetime, all produced and non-sensitive data will be stored and backed up in a provided Project Storage (: U Drive).

3.4 Data access

This research is performed for and with the help of Alba Concepts. Many of the collected data come out of their project database or own expertise from their employees. Alba Concepts is a consultancy company in the built environment sector with wide expertise in circular economy and sustainability.

Areas of expertise for Alba Concepts include amongst others:

- Sustainability consultancy in all cycles of real estate;
- Management of sustainable real estate projects (process, project, procurement and financial management);
- Project development of sustainable concepts, products or processes within the built environment
- Circular strategy and organisation by formulating circular goals and KPIs for organisations;
- BCI gebouw: Building Circularity Index.

3.5 Ethical considerations

To ensure the ethical performance of this research, the approach of 'doing most good and least harm' is followed. The provided data during the interview will not contain any personal data about the participants or the project, only the type of project and the job title will be shared. In the case any personal statement is made, this will be omitted or rephrased, keeping the anonymity of the person. This research is fully voluntary and employees from the organisations are not obliged to answer a question if they are not willing to. However, if questions remain unanswered, there is a risk that some answers cannot be used in the data analysis. This measure ensures that the participants are not subjected to harm in any way whatsoever.

All participants are asked for their consent for data sharing and are informed about the purpose and benefits/risks behind the study before they decided to participate. This information is shared before the data collection in an informed consent form (IC) (see Appendix III). The participants are also informed about the methodology for the data collection and publication of this thesis. Lastly, every step of this research thesis will be honestly reported, to avoid deception or exaggeration. The work is free of plagiarism or research misconduct, and the final results are accurately reported.

Chapter 4

Case Assessment Framework

4 Case assessment framework

During this chapter, the selected cases and the assessment framework based on the findings from the literature review are presented.

4.1 Case selection

The selection of the cases consisted of a multi-phase process; initially, projects that met the selection criteria were selected from the database of Alba Concepts (see section 3.1.2.4 for the selection criteria) Here, 6 cases were collected in total. This was a convenience sample, as the data came from one organization (Andrade, 2021). To reduce sampling bias, an oversampling strategy was used. New desk research was conducted on recent projects in The Netherlands that reused building products. This added 15 projects, for a total of 34 cases. Each case is classified depending on its layer, Table 3 shows an overview of the cases per layer.

Table 3 Overview cases per layer

Layer	Product/Element	# of Cases
Skin	Aluminium cladding	2
	Brick cladding	1
	Tile cladding	1
	Timber cladding	3
	Aluminium window frame	2
	Timber window frame	1
	Timber roofing profile	1
	EPS insulation	4
	Glass panel	1
	Skin layer	16
Space Plan	Brick flooring	1
	Stone tiles	1
	System walls	1
	Timber ceiling panels	1
	Space plan layer	4

Layer	Product/Element	# of Cases
Structure	Concrete floor	1
	Foundation concrete blocks	1
	Hollow-core slab floor	1
	Precast concrete floor slab	3
	Timber roof construction	1
	Steel beam	2
	Steel column	3
	Timber beam	1
	Timber rafter	1
	Structure layer	14
	Total # of Cases	34

This case selection was followed by the in-depth analysis, consisting of a document review (project's news articles, available project documentation and disassembly potential assessment) and an interview with the organisation involved in each project (see Appendix II).

4.2 Case assessment protocol

The selected cases followed the same protocol: the first action was to contact the involved organization to participate in an interview. After the invitation was accepted, the data collection involved the following activities:

1. Individual (semi-structured) interviews with a professional from the organization. Most of the selected cases are obtained within the same project, facilitating the data collection. The interview protocol used during the survey interviews is based on the criteria that are used for the case assessment.
2. Reviews from project documents, i.e., project drawings, news articles, and internal evaluations.

Since each interview answers the same questions regarding the selected case, the data analysis of the case is carried out through an assessment. The assessment framework to use and its criteria are presented in the following section.

4.3 Assessment framework

The same criteria were used to assess each case. The assessment consisted of three types of information: general information about the assessed building product, specific information about the building layer where it was located, and specific information about the product itself. .

Table 4 summarizes the methods used for each criterion.

Table 4 Overview sample assessment criteria and methods

	Criteria	Method
General information	a. Product description	Document review
	b. Previous building function c. Current building function	Document review + Interview
	d. Building layer where the assessed building product is found	As defined in section 2.2.3
	e. Application	Document review + Interview
	f. Circularity strategy applied	As defined in section 2.1.2
Layer information	g. Adaptability level of the building layer	FLEX 4.0 Assessment with selected criteria + Document review
Information about the assessed building product	h. Adaptive capacity for structures according to the core measurement method: Schmidt scale	Literature review + Interview
	i. Condition assessment	Interview
	j. Technical requirements by building code	Document review + Interview
	k. Technical requirements by client	Interview
	l. Disassembly potential measurement method	Interview + Disassembly Assessment
	m. First lifespan of the previous lifecycle	Document review + Interview
	n. Remaining lifecycle lifespan	n= o – m
	o. Average technical lifespan for the product	National environmental data base (in dutch: Nationale milieudatabase)

4.3.1.1 General information about the assessed building product or element

a. Product Description

Description of the selected case, type of material and type of products

b. Previous building function

The function of the donor building from where the assessed building product was harvested. The goal of this indicator is to understand the past (technical) function of the assessed building product.

c. Current building function

The current function of the building where the assessed building product is used for a second or posterior lifecycle. This criterion aims to gain insight into the minimum technical requirements that the product should meet.

d. Building layer where the assessed building product is found

The building layer according to the shearing layers of Brand (1994). Whether it is from the skin, space plan or structure layer.

e. Application

A distinction is made between 'as is' (same function as originally) and other (specified). This criterion gives insight into the next criterion.

f. Circularity strategy applied

The circularity strategy is applied as described in section 2.1.1. A distinction is made between reuse, repair, refurbish, remanufactured and repurpose. This criterion helps to understand whether the assessed building product has been improved or its function has been changed when compared with its original function.

4.3.1.2 Information specifically about the building layer where the product is found

g. Adaptability level of the building layer

The aim of this criterion is to gather insight into the adaptability potential of the assessed element or product. This is mainly done by evaluating the indicators of the layer where the element or product is found. The indicators are divided into general applicable and specifically applicable indicators as presented in the FLEX 4.0 instrument to assess the adaptive capacity of buildings. Not all criteria from the FLEX 4.0 are applicable when assessing the building product or element, therefore a selection is made per selected sample. The selection of these criteria is based on the layer, uniformity and flexibility aspect of each assessed case. However, this assessment cannot be used for building products that have an aesthetic and weathering resistance technical function (e.g., products use as cladding or flooring). In this case, their reuse potential is based on their disassembly potential and adaptability aspects (See Appendix IV for the criteria applied per type of building product).

4.3.1.3 Information specifically about the assessed building product

h. Adaptive capacity for structures according to the core measurement method: Schmidt scale

This criterion aims to qualitatively assess the possibility of modifying the product to meet the building code regulations and (if needed) user requirements. This criterion aims to gain more insight into how the building product is normally reused and what the changes made to it are. For this, the instrument tool for the adaptive capacity for structures presented by the core measurement method is used (Platform CB'23, 2020b). During this criterion, the adaptability level of the building product is analysed by using the six types of measures for adaptive capacity (adjustable, versatile, refitable, convertible, scalable and movable) as defined by the Schmidt Scale (Schmidt III et al., 2010). Figure 16, presents the framework and to which layer is applied.

Able	Type of change	Decision-level	Time (cycle speed)	Brand's layer					
				Stuff	Space	Service	Skin	Structure	Site
Adjustable	Change of task	user	daily/monthly	●					
Versatile (flexible)	Change of space	user	daily/monthly	●	●				
Refitable	Change of perfomance	user/owner	7 years		●	●	●		
Convertible	Change of function	user/owner	15 years		●	●	●		
Scalable	Change of size	owner	15 years		●	●	●	●	
Movable	Change of location	owner	30 years					●	●

Figure 16 The framework with the six types of measures for adaptive capacity used for the assessment of the adaptability level of a product or element (only used when applicable). Retrieved and adapted from Schmidt III et al. (2010)

i. Condition assessment

The technical quality that a product or element has is based on the NEN 2767. This criterion gives insights into the state of the product before reusing it for the next lifecycle. If this condition assessment is not available, the condition will be assessed as 'good' unless stated otherwise by the interviewee.

j. Technical requirements by building code

The relevant technical requirements that the building product has to fulfil before reusing it in a newly built project. Here is important to mainly consider the technical requirements that influence the decision to reuse the product. The aim is to understand whether the technical quality of the product has been improved to fulfil the regulations.

k. Technical requirements by user

Based on the technical requirements as 'benchmark'. The aim is to understand whether the technical quality of the product has been improved to fulfil the user's requirement.

l. Disassembly potential measurement method

The aim of this criterion is to understand if reused building products are being integrated into the design to be easily changed in the future or for future reuse in another lifecycle. This information is retrieved from the Building Circularity Index (BCI Gebouw & Alba Concepts, 2022) or by assessing according to the disassembly potential measurement method (van Vliet et al., 2021). This entails the connection type, the accessibility to the connection, independence and geometry of the product edge.

m. First lifespan of previous lifecycle lifespan

The functional lifespan duration of the assessed building product in its previous lifecycle. This means how long the product was used before it was harvested for reuse.

n. Remaining lifecycle functional lifespan

The remaining technical lifespan that the building product has. This is based on the general assumption of the average lifespan of the element and product minus the already used lifespan from its previous lifecycle. The aim of this is to gain insight into how long the functional lifespan of the assessed building product is prognosticated if no further improvements are made.

o. Average technical lifespan for the element or product

The average technical lifespan that a building product has when well-maintained and correctly used. This information is based on the National Environmental Database (Nationale Milieudatabase, n.d.)

Chapter 5

Case Assessment

5 Case assessment results

This chapter assesses the selected building products per building layer using the framework from the previous chapter. Then, it conducts a cross-case analysis of the reuse potential of the assessed products. During this chapter, the following sub-questions will be addressed:

[SQ 4] To what extent can the assessment methods of the technical aspects of a building product define its reuse potential?

[SQ 5] To what extent do the technical aspects of a reused building product and its reuse application during its second lifecycle determine its reuse potential for a third lifecycle?

5.1 Case assessment analysis

Once the interviews were executed and the data was collected, the data is further condensed, organized and classified according to its level of adaptability and layer. This is done by assembling and analysing the collected data in the assessment form. The form used is shown in Appendix V.
The purpose of this analysis is to evaluate the potential for reusing building products based on their technical aspects, including adaptability potential, adaptability aspects, and disassembly potential. As each of these aspects is assessed using different criteria (designated as g, h, and I), the collected data is thematically analysed. Table 5 presents the coding of the various indicators used in this research. It is important to note that while the data for the case assessment is derived from interviews with the involved organizations, the interpretation of the results may be subjective, thus imposing limitations on the research study. The following sections will provide a summary of the analysis conducted on each building layer.

Table 5 Coding of the different indicators

	FLEX 4.0	Schmidt framework					Disassembly potential	
Indicators/ Score	**Adaptability potential**	**Versatile**	**Refitable**	**Convertible**	**Scalable**	**Movable**	**Disassembly index**	**Score**
	X=0	N/A or product not versatile	N/A or product cannot be refitted	N/A or product cannot be converted	N/A or product cannot be scaled	N/A or product cannot be transported or moved	X=0	**x No possible**
	2≤X≥26	not possible	product can be improved by adding external measures to meet building regulation or it can be aesthetically improved	product can change function within same layer	product can be modified in size by shorting it	product needs heavy machinery to be transported and/or it is a laborious process	0<X>0,59	**- Low**
	27≤X≥51	not possible	product can be improved by increasing the quantity to meet the building regulation	product can change function within 1 other layer	product can be modified in size by adding more product to meet the aesthetic requirements	product needs heavy machinery to be transported	0,60<X>0,79	**-/+ Moderate**
	52≤X≥76	not possible	product can be improved by adding a coating layer to meet building regulations	product can change function within 2 other layers or more	product can be modified in size by adding more product to meet the building regulations	product can be easily transported	X>0,80	**+ Better**

5.1.1 Structure layer

A total of 14 cases were analysed for the structural layer. Table 6 provides a summary of the assessment scores for the building products in this layer. The assessed building products within this layer share the common purpose of supporting and safely transmitting applied loads, while also meeting fire safety requirements. It should be noted that the specific technical requirements for fire safety may vary depending on the building type and its intended use.

Concrete building products generally exhibit greater resistance to fire compared to steel and timber. Conversely, steel building products offer higher load-bearing capacities than concrete and timber counterparts

Table 6 Score of the structure layer assessed building products (Author)

	Assessed product and case #		Application	Circularity strategy used	Adaptability potential	Assessment: Scalable	Movable	Condition	Disassembly	1st lifecycle	Avg. Technical lifespan
Structure layer	Steel beam	1	As is	Reuse	+	-	-/+	Good	-/+	9	75
	Precast concrete floor slab	2	As is	Reuse	-/+	-	-/+	Good	-	60	100
	Steel columns	3	As is	Reuse	+	-	-/+	Good	+	25	75
	Timber beam	4	As is	Reuse	-/+	-	+	Good	-/+	15	75
	Steel column	5	As is	Reuse	+	-	-/+	Good	-	59	75
	Precast concrete floor slab	6	As is	Reuse	-/+	-	-/+	Good	-	30	100
	Timber roof construction	7	From MDF panels	Repurpose	-/+	-	+	Excellent	-	2	25
	Hollow-core floor slab	8	As is	Reuse	+	-	-/+	Good	-	35	100
	Timber rafter	9	As is	Reuse	-/+	+	+	Good	+	15	100
	Precast concrete floor slab	10	As is	Reuse	-/+	-	-/+	Good	-	30	100
	Steel column	11	From old machinery	Repurpose	-/+	-	-/+	Good	-	30	100
	Foundation concrete blocks	12	As is	Reuse	-	X	-/+	Good	-	7	75
	Steel columns	13	As is	Reuse	+	-	-/+	Good	-	7	75
	Concrete floor	14	As is	Reuse	-/+	X	-/+	Good	-	7	75

Figure 17 Steel beams to be reused as columns (Alba Concepts, 2021)

Condition assessment and technical lifespan

All of the assessed cases had a condition assessment of 'Good' and occasionally 'Excellent', meaning incidental defects and some signs of deterioration, but no threat to the functionality of the building product.

Furthermore, most of the assessed building products in this layer, have an average technical lifespan of 75 years, and their first lifecycle was about 25 years on average.

Figure 18 Steel columns for the BioPartner5 project meet the designed height requirements. Image retrieved from Nationale Staalprijs (2023)

Adaptability potential of the assessed element or product within its building layer

Most of the assessed cases had a moderate adaptability potential, followed by a better adaptability and only one case had a low one. The building products that scored better adaptability had a surplus of height (> 3,40 m), load-bearing capacity and fire resistance capacity, allowing them to meet different requirements in case of a function change.

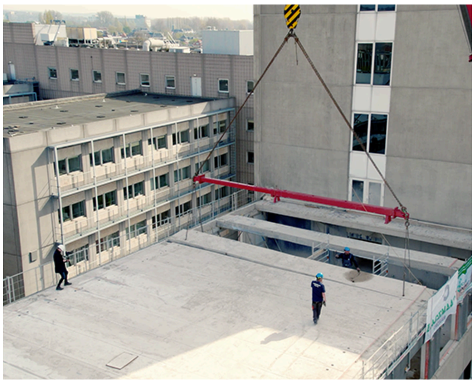


Figure 19 Hollow-core slab floor disassembly and transportation during the demolition process of the Prinsenhof Arnhem (Dycore, 2022)

Adaptive capacity for structures according to the core measurement method: Schmidt scale

Only the movable and scalable aspects of Schmidt's framework were considered for the structure layer. Most of the building products from this layer can be moved from their source to their destination, but they often require heavy machinery due to their size. Most of them cannot be extended in size, because they have to meet certain load-bearing and safety standards. However, timber rafter constructions can be lengthened by adding more elements without compromising their structural integrity.

Figure 20 Reuse application of a hollow-core slab floor for the ground floor (Dycore, 2023)

Disassembly potential measurement method

Only 4 out of 14 cases can be disassembled without damage, according to the disassembly potential scores. Steel construction elements are more circular and less likely to be damaged during disassembly. Concrete elements are hard to disassemble because they have chemical connections and multiple layers that cover the joints. In contrast, timber rafters and some steel elements have high disassembly potential, mainly due to their dry connections with added elements that are easy to reach.

5.1.2 Skin layer

A total of 16 cases were analysed for the skin layer. Table 7 provides a summary of the assessment scores for the building products in this layer. The building products within this layer serve as the exterior surface of the building and are exposed to external elements. These products are characterized by their technical requirements, including thermal resistance, resistance to weathering and corrosion, as well as ease of installation.

Table 7 Score of the structure layer assessed building products (Author)

						Assessment						
	Assessed product and case #		**Application**	**Circularity strategy used**	**Adaptability potential**	**Refit able**	**Convertible**	**Scalable**	**Condition**	**Disassembly**	**1st lifecycle**	**Avg. Technical lifespan**
Skin layer	Aluminium window frame	1	As is	Reuse	-	x	x	X	Good	-/+	9	50
	EPS insulation	2	From roof insulation to gf insulation	Reuse	-	-/+	x	+	Good	-	25	75
	Tile cladding	3	As is	Reuse	-	x	-	-	Excellent	-	unknown	100
	Timber window frame	4	As is	Repurpose	-	+	-	-	Good	-/+	30	30
	Timber roofing profile	5	From timber bollard	Repurpose	-	x	-	-	Good	+	unknown	100
	Aluminium cladding	6	As is	Reuse	x	-	-	-	Reasonable	+	15	75
	Curtain walling	7	As 2nd skin facade	Reuse	-	x	x	X	Good	-/+	27	75
	Aluminium window frames	8	As is	Reuse	-	x	x	X	Good	-/+	40	75
	EPS insulation	9	As is	Reuse	-	-/+	x	+	Good	+	unknown	75
	Timber cladding	10	As is	Reuse	-	-	x	-	Good	+	28	50
	Timber cladding	11	From timber bollard	Repurpose	-	-	-	-	Good	+	20	60
	Timber cladding	12	From existing wood planks	Repurpose	-	-	-	-	Good	+	15	75
	EPS insulation	13	As is	Reuse	-	-/+	x	+	Good	-/+	unknown	75
	Aluminium cladding	14	As is	Reuse	x	-	-	-	Good	+	20	75
	Brick cladding	15	As is	Reuse	-	X	-	-	Good	-	unknown	500
	Tile cladding	16	As is	Reuse	-	X	-	-	Good	-	unknown	60

Figure 21 Aluminium cladding to be reused (Alba Concepts, 2021)

Condition assessment and technical lifespan

Most of the cases we assessed had a 'Good' condition. Only a few had 'Excellent' or 'Reasonable' conditions. This means that some parts of the building product had minor defects or signs of wear. However, in this case, a new coat layer could be applied to meet the standards so the building product's function is not at risk. Most of the building products in this layer can last for 95 years on average. Their first lifecycle was about 20 years on average.

Figure 22 Timber cladding from a renovation project, stored to be later reused in a new built project (Paul de Ruiter Architects, 2021)

Adaptability potential of the assessed element or product within its building layer

All of the assessed cases have a low adaptability potential. This is mainly due to the fact that the building products from this layer have low adaptability and are not that flexible or uniform in use. The impact of the cladding product is low on their influence on the thermal insulation since it is mainly aesthetically used (Architect 4, personal communication, 3 April 2023).

Figure 23 Timber cladding from Tripolis buildings in Amsterdam. Retrieved from Architectenweb (2012)

Adaptive capacity for structures according to the core measurement method: Schmidt scale

For the skin layer only the refitable, convertible and scalable aspects from Schmidt's framework were taken into account. In general, all of the assessed building products with cladding functionality have an aesthetic function. So, they scored low on the convertible aspect. Their function will not change much.

For the scalable aspect, almost all of the assessed cases can be shortened in size. On the other hand, Insulation products are different. They cannot be modified in size easily. But we can add more products (more panels) to meet the insulation requirements.

Disassembly potential measurement method

The scores for the disassembly potential of the assessed building products show that most of the cases with timber or aluminium cladding can be disassembled easily without causing damage to the product itself or the construction behind it. Timber and aluminium window frames are also possible to disassemble, however, the question arises as to whether these still meet the current thermal requirements of the building regulations. Tile and brick cladding scored the lowest in disassembly due to the type of connection used when

Figure 24 Reuse application of timber cladding at HAVEP project (Paul de Ruiter, 2022)

applied (hard chemical type of connection). EPS insulation can be easily disassembled but depends on the type of application it was used for. One of the EPS insulations assessed (SKIN_CASE 13) scored a moderate disassembly potential since this is used as ground floor insulation which makes its accessibility difficult and damage cannot be avoided during the disassembly process, making the reuse of EPS in this case a challenge for posterior reuse.

5.1.3 Space plan layer

A total of 4 cases were analysed for the structure layer. Table 8 presents a summary of the assessment scores for this layer. The building products within this layer play a crucial role in shaping the interior layout of the building. Among the assessed building products, the technical requirements related to sound insulation and anti-slip properties (flooring) are particularly relevant. These products are designed to ensure a comfortable and safe environment by providing effective sound insulation and reducing the risk of slips or falls.

Table 8 Score of the space plan layer assessed building elements and product (Author)

Space Plan layer

					Assessment							
Assessed product and case #		Application	Circularity strategy used	Adaptability potential	Versatile	Refitable	Convertible	Scalable	Condition	Disassembly	1st lifecycle	Avg. Technical lifespan
Ceiling	1	As is	Reuse	-	x	x	-	-	Good	+	30	30
Stone tiles	2	From stairways cladding	Reuse	x	x	-	-	-	Good	-	59	75
System wall	3	As is	Reuse	-/+	x	-/+	x	-	Excellent	-/+	17	25
Brick flooring	4	As is	Reuse	-	x	-	-	-	Good	+	unknown	75

Figure 25 Stone tiles from stairways stored to be reused at the BioPartner5 project. Image retrieved from Popma ter Steege (2021)

Condition assessment and technical lifespan

All of the assessed cases had a condition assessment of 'Good' or 'Excellent', which means that the building products had incidental defects and, in some cases, some signs of deterioration, but the functionality of the building product was not threatened. Furthermore, most of the assessed building products within this layer, have an average technical lifespan of 75 or 25 years, and their first lifecycle was about 35 years on average.

Figure 26 Gypsum boards to reuse in system walls (New Horizons, n.d.)

Adaptability potential of the assessed element or product within its building layer

The assessed cases scored a low adaptability potential, but the system wall element scored a moderate adaptability potential thanks to its capacity to be applied in a modular way.

Figure 27 To reused gypsum boards (New Horizons, n.d.)

Figure 28 Reuse application of ceiling element. Image retrieved from Durzaamgebouw.nl (2015)

Adaptive capacity for structures according to the core measurement method: Schmidt scale

Only the aspects of versatility, refitability, convertibility and scalability from Schmidt's framework were considered for the space plan layer. Most of the cases evaluated had low scores in these aspects. The system walls were moderately scored because they could be improved with more insulation or plasterboards if the sound insulation requirements were not met. However, all the cases except for the system walls could be converted to another function with a different aesthetic. All the cases could also be scaled down in size if needed.

Disassembly potential measurement method

The disassembly potential scores of the cases indicate that they can be mostly disassembled without major damage. The stone tiles may suffer some damage during disassembly. The ceiling and brick flooring can be disassembled easily. The system wall may overlap with other elements for fire safety reasons, but it may still be possible to disassemble it without major damage.

5.2 Reuse potential

Through cross-case analysis, the main differences and similarities are identified between the cases in order to identify when similar building products can be potentially reused for another lifecycle. This cross-case analysis combines the previous section's assessment analysis and their reuse potential when reusing them for another lifecycle (thus a possible third lifecycle). In order to determine the level of reuse potential, a set of conditions have been set with the help of experts on the topic.

The reuse potential is classified as high, moderate or low:

- High reuse potential: building products can be disassembled, moved without damage, refitted, converted, and scaled if needed. The adaptability potential of the building product can be low, but it should be possible to refit, scale or convert it in order to meet the new requirements.
- Moderate reuse potential: building products can be disassembled and moved but have low adaptability potential for reuse, or they can be refitted despite some damage during disassembly. The building product can be scaled down in size.
- Low reuse potential: building products cannot be disassembled, moved, refitted or converted to meet new requirements

The following sections present the reuse potential of the building products assessed. The general findings are given first, then the findings by typology (if applicable).

5.2.1 Structure layer

From the structure layer, the possibility to reuse the assessed building products is relatively positive. Table 9 shows the given score of the reuse potential per assessed case.

Table 9 Score of reusability potential for the structure layer (Author)

	Assessed product	and case #	Adaptability potential	Scalable	Movable	Disassembly	Reuse Potential
Structure layer	Foundation concrete blocks	12	-	x	-/+	-	Low
	Concrete floor	14	-/+	x	-/+	-	Low
	Precast concrete floor slab	2	-/+	-	-/+	-	Moderate
	Precast concrete floor slab	6	-/+	-	-/+	-	Moderate
	Steel column	5	+	-	-/+	-	Moderate
	Precast concrete floor slab	10	-/+	-	-/+	-	Moderate
	Hollow-core floor slab	8	+	-	-/+	-	Moderate
	Timber roof construction	7	-/+	-	+	-	Moderate
	Steel column	5	+	-	-/+	-	Moderate
	Steel column	11	-/+	-	-/+	-	Moderate
	Steel columns	13	+	-	-/+	-	Moderate
	Steel columns	3	+	-	-/+	+	High
	Steel beam	1	+	-	-/+	-/+	High
	Timber beam	4	-/+	-	+	-/+	High
	Timber rafter	9	-/+	+	+	+	High

Low reuse potential

Building products such as the foundation concrete block or concrete floor score really low. This is mainly due to its inflexibility to modify its size and technical requirements to meet function changes. Furthermore, one of the assessed steel columns scored a really low potential, this is mainly due to its full integration with other building layers, which translates into a low disassembly potential.

Moderate reuse potential

Most of the assessed cases with a moderate reusability potential are mainly due to their non-circular application (no disassembled design) which makes it difficult to disassemble when the building element is being reused for another lifecycle. Some damages might occur when being disassembled and the uniformity level of these elements is already damaged from the previous disassembly process.

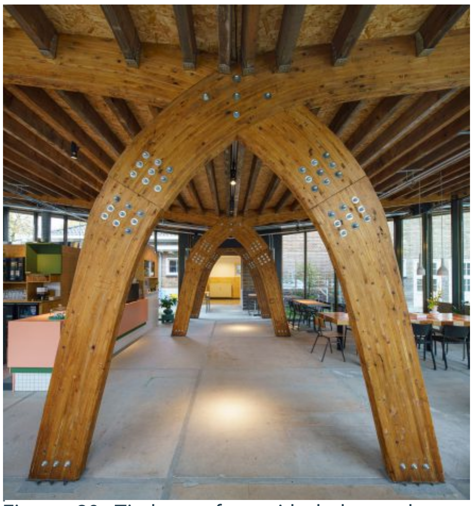


Figure 29 Timber rafter with bolts and nuts connection. Retrieved from SUPERUSE STUDIOS (2020)

Furthermore, the scalable aspects of these assessed cases are limited to only decreasing their dimensions.

High reuse potential

Steel and timber constructions have a high potential to be reused, this is mainly thanks to their uniformity (in form) and the possibility to disassemble when circularly applied. A great example of a building element with a high possibility to be reused is the timber rafter which is mainly thanks to its scalable aspect and its disassembly potential when using the right type of connections.

5.2.1.1 Typologies within the structure layer

Given the adaptability potential and their aspects to be scaled when the building products will be reused for a third or posterior lifecycle, the assessed cases within the structure layer can be categorized into four types of building products:

Steel structure products (steel columns and beams)

Steel elements can meet technical requirements such as load-bearing and fire safety and are adaptable products. The case assessment analysis showed that they have a high reuse potential for a next cycle if they can be disassembled without major damage.

Figure 30 Reused steel with integrated connection from different layers which makes disassembly a challenge. Image retrieved from Cuppens (2019).

Figure 31 Reused steel column with nuts and bolts which facilitate the disassembly. (Alba Concepts, 2021)

Figure 32 Reused steel construction with added steel connections and bolts which facilitates later the disassembly of this. Image retrieved from Staalprijs (2022)

Timber structure products (timber roof construction and timber beams)

Timber elements can scale in length and meet the load-bearing requirements, making them highly adaptable. This type of product also has a higher reuse potential when it can be disassembled properly.

Figure 33 To reused timber beams (Alba Concepts, 2023)

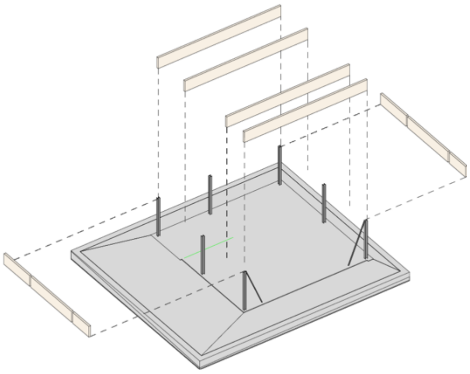


Figure 34 Integration of the reused timber beams in the design (Alba Concepts, 2023)

Figure 35 Timber roof structure with dry connections and different lengths. Image retrieved from PLNT (2021)

Concrete floor slabs (precast concrete floor slabs and hollow-core floor slabs)

Prefabricated floor slabs such as hollow-core floor slabs have moderate reuse potential for a third lifecycle because they may need small alterations to be disassembled intact as their connections are grouted. However, pre-cast concrete floor slabs have no joints or fittings that hinder disassembly but their accessibility is limited and may cause damage to the element.

Figure 36 Example of how pre-cast concrete floor slabs can be reused as structure foundation. Image retrieved from Kroftman (n.d.)

Figure 37 Damage on the hollow-core floor slab during the disassembly process (Dycore, 2022)

Other concrete structure products (concrete floor slabs and foundation concrete blocks)

The concrete floor slab was reused from a temporary project as part of a whole unit. It has a low reuse potential because it is hard to disassemble. Another element in this typology is the concrete block foundation. Both products have low reuse potential because they are hard to disassemble, may get damaged, and are not scalable or adaptable to new requirements.

Figure 38 Reused concrete foundation blocks and reused concrete floor slab for a project-specific. Image retrieved from Orga Architecten (2019)

Figure 39 Units to be reused (incl. concrete floor slabs) Image retrieved from Orga Architects (2019)

5.2.2 Skin layer

The assessed building products from the skin layer have a reasonable reuse potential. This is mainly because they can be disassembled easily but they are not adaptable according to Schmidt's framework as they only have an aesthetic function. Table 10 shows the reuse potential for each case.

Table 10 Score of reusability potential for the skin layer (Author)

	Assessed product and case #		Adaptability potential	Refit able	Convertible	Scalable	Disassembly	Reuse Potential
Skin layer	Aluminium window frame	1	-	x	x	x	-/+	Low
	Aluminium window frame	8	-	x	x	X	-/+	Low
	Curtain walling	7	-	x	x	X	-/+	Low
	Tile cladding	3	-	x	-	-	-	Low
	Tile cladding	16	-	x	-	-	-	Low
	Brick cladding	15	-	x	-	-	-	Low
	Timber window frame	4	-	+	-	-	-/+	Moderate
	Timber roofing profile	5	-	x	-	-	+	Moderate
	Aluminium cladding	6	x	-	-	-	+	Moderate
	EPS insulation	2	-	-/+	x	+	-	Moderate
	Aluminium cladding	14	x	-	-	-	+	Moderate
	Timber cladding	10	-	-	x	-	+	Moderate
	Timber cladding	11	-	-	-	-	+	Moderate
	Timber cladding	12	-	-	-	-	+	Moderate
	EPS insulation	2	-	-/+	x	+	-	Moderate
	EPS insulation	9	-	-/+	x	+	+	High
	EPS insulation	13	-	-/+	x	+	-/+	High

Low reuse potential

Building products which required a hard chemical connection (e.g., tile and brick cladding) as a type of connection are difficult and laborious to disassemble, and could cause irreparable damage to the product, which makes it a challenge to reuse. Aluminium window frames and curtain wailing scored with a low reuse potential due to their inflexibility to scale and low adaptability potential to meet new technical requirements.

Moderate reuse potential

Many of the assessed cases had moderate reuse potential, mainly because they had limited adaptability to change their function or meet new technical requirements. Non-ceramic cladding material (aluminium or timber cladding) is easy to disassemble as it had added elements (e.g., bolt and nut or screw connections) and is accessible without affecting other building layers. However, their reuse (for a third or later lifecycle) depends on their aesthetic aspect and the design team's expectations (Architect, 4, personal communication, 6 April 2023). Timber cladding could also be repurposed as suggested by one of the architects interviewed, who proposed using timber cladding as timber floor decking (Architect 4, personal communication, 3 April 2023).

Figure 40 EPS insulation application for new built project. Retrieved from PLNT (2022)

High reuse potential

The high reusability potential that EPS insulation can have, is mainly due to its scalable and refitable aspect. However, there was the case that EPS insulation was reused in such a way that it can be easily disassembled, which leads to the conclusion that this building product could have a real reuse potential if circularly applied.

5.2.2.1 Typologies within the skin layer

The convertible, scalable and refitable aspects of the assessed cases determine the different typologies for the assessed building products within the skin layer. Here a distinction between five types of building products is made:

Non-timber window (aluminium window frames and curtain walling)

Non-timber window elements, such as aluminium window frames and curtain walling, have low adaptability potential because they cannot meet the changing requirements of the building code. They cannot be refitted to have higher thermal insulation, converted to a new function, or scaled to a different dimension. However, they can be disassembled without damage, which gives them moderate reuse potential for another lifecycle.

Figure 41 Reused aluminium window frames (Alba Concepts, 2022)

Figure 42 Reused curtain walling at Greenhouse project (Lucas van der Wee, 2018)

Ceramic cladding (brick and tile cladding)

Brick and tile cladding have a low reuse potential, this is mainly due to their disassembly potential. The type of connection used does not facilitate the disassembly of the product without causing irreparable damage (cement-based mortar), this gives this type of product a low reuse potential

Figure 43 Ceramic cladding with cement-based mortar (left) are more difficult to disassembled without causing irreparable damages. However, when disassembling ceramic cladding with lime-based mortar (right) has a lower damage percentage. Image retrieved from McCoy Mart (2022)

Figure 44 Reused brick cladding and tiles (tiles not visible in the image) (Bouwfonds Property Development, 2020)

Figure 45 Used bricks to be reused. Some usage damage on the product can be appreciated. (Bouwfonds Property Development, 2019)

Non-ceramic cladding (timber and aluminium cladding)

Aluminium or timber cladding has a moderate reuse potential. This type of product can be easily disassembly without causing damage to it. However, a moderate reuse potential is given by the challenge that this type of product face due to its limited refitable and scalable aspect.

Figure 46 Reused timber cladding at De Warren project. Image retrieved from Natrufied (2023)

Figure 47 Reused timber roofing profile, scalable aspect of such product is limited to only decreasing its dimensions. (Lucas van der Wee, 2020)

Figure 48 Example of reused aluminium cladding at the waste collection station in The Hague. The disassembly of this type of cladding is easy and does not cause any irreparable damages. Image retrieved from Wessel van Geffen Architecten (2017)

EPS insulation

EPS insulation products have the facility to be refitted and scaled when thermal insulation requirements change which makes them a great adaptable insulation product. During the case assessment, EPS insulation products that were circularly applied scored a greater reuse potential than those that are not.

Figure 49 (EPS) insulation used as ground floor insulation is hardly possible to disassemble without causing major damages to the product (Alba Concepts, 2021)

Figure 50 (EPS) insulation to be reused (Alba Concepts, 2021)

Timber window

Contrary to aluminium window frames, the assessed timber window frame scored a moderate reuse potential. Timber products have a greater adaptability potential than aluminium window frames. This type of product has the advantage that with the right detailing and application technique, it can be easily disassembled and reused (Dieleman, 2021).

5.2.3 Space plan layer

Despite the limited data collection from this layer, the assessed building products show moderate reuse potential. This is mainly due to the low adaptability potential regarding new technical requirements and limited size modification. Table 11 shows the reuse potential of the assessed cases.

Table 11 Score of reusability potential for the space plan layer (Author)

	Assessed product and case #		Adaptability potential	Versatile	Refit able	Convertible	Scalable	Disassembly	Reuse Potential
Space plan layer	Stone tiles	2	x	x	-	-	-	-	Low
	Ceiling	1	-	x	x	-	-	+	Moderate
	System wall	3	-/+	x	-/+	x	-	-/+	Moderate
	Brick flooring	4	-	x	-	-	-	+	Moderate

Low reuse potential

The adaptability potential of a building product such as stone tiles is relatively similar to the ceramic cladding as presented in the previous layer. Its low reusability potential is mainly given to its laborious disassembly process and limited function as an aesthetic product.

Figure 51 Example of application of reused system walls. Plasterboards are transposed into a horizontal application. Image retrieved from Rijkswaterstaat (n.d.)

Moderate reuse potential

The moderate reuse potential of the ceiling, system wall and brick flooring are given by their disassembly potential, which is less laborious and damaging that the stone tile disassembly. In the case of the system wall, this building product can be modified in case this does not meet the expected technical requirements. However, its reusability potential is questioned when it is asked whether this element could be reused for another lifecycle (Expert interview 1, 4 April 2023).

5.2.3.1 Typologies within the space plan layer

Due to the limited collected cases for this layer, the reuse potential per building product will be presented.

Ceiling products

Ceiling products have a moderate reuse potential due to their low adaptability potential when new requirements are needed (acoustic insulation and safety measures). Furthermore, its scalable and convertible aspect limits its reuse potential. In contrast to system walls, ceiling products are easier to disassembly.

Brick flooring

Although this type of building product is similar to stone tiles, brick flooring has a moderate reuse potential because it can be applied circularly, unlike stone tiles.

Figure 52 Reused stone tiles and brick flooring at the BioPartner5 project. Image retrieved from Popma ter Steege Architecten (2022)

Stone tiles

The reuse potential of this type of product is similar to those of ceramic cladding. Although this type of product is part of the space plan layer its main technical characteristics are similar to the ceramic and non-ceramic cladding products, namely an impermeable function that protects the underlying construction. Contrary to cladding products from the skin layer, flooring products (for safety reasons) need to have a certain level of anti-slip, however, this problem can be solved by adding an anti-slip coat if needed (Architect 2, personal communication, March 2023). The fact that this type of product has a moderate reuse potential even with a high disassembly potential, is due to its limited convertible (change of function) and scalable aspects.

Figure 53 Reuse system walls at BioPartner5 project. Image retrieved from Popma ter Steege Architecten (2022)

System wall

Similar to ceiling products, system walls have a moderate adaptability potential since their limited capacity to adapt when necessary (acoustic insulation and safety measures). Furthermore, its scalable aspects limit its reuse potential since the gypsum board needed is already sized down when reused for a second lifecycle, which makes a third lifecycle almost impossible (Expert 1, personal communication, April 2023).

5.3 Main takeaways from the case assessment

This chapter delved into the determination of the reuse potential for the assessed building products. It is crucial to emphasize that the results vary for each building layer, depending on the specific technical requirements associated with that layer. The key findings from this chapter are summarized below, and the subsequent section will address the limitations of the case assessment.

The case assessment results highlight four main technical aspects that significantly influence the reuse potential of a building product, not only in its second lifecycle but also in subsequent lifecycles:

- Disassembly: building products that are not circularly applied during their second lifecycle pose challenges when it comes to disassembling them for future lifecycles. Many of the assessed building products, being not originally designed to be reused, suffered damage during their first disassembly, having as a consequence that these were not circularly applied during their second lifecycle (first reuse phase)
- Adaptability potential: this refers to how building products are designed to be modified or repurposed to meet new technical requirements for different uses over time. Building products with higher adaptability potential have greater reuse potential, as they can effectively adjust to changing technical requirements, including weather resistance, thermal properties, load-bearing capacity, fire safety, uniformity, and flexibility.
- Scalable aspect: building products that can be modified in terms of dimensions to meet new requirements are more likely to be reused. On the other hand, products that are difficult to alter in size, whether by shortening or extending them, face challenges in meeting diverse requirements, limiting their potential for reuse.
- Refitable aspect: building products that can be refitted to meet new technical requirements have a higher chance of being reused compared to those that cannot. Building products with technical requirements such as fire resistance and insulation resulted to have a higher refitable aspect.

By considering these technical aspects, the results from the case assessment provide valuable insights into the factors influencing the reuse potential of building products, facilitating sustainable practices and decision-making in subsequent lifecycles.

5.4 Limitations on the case assessment

During the execution of the case assessment, a number of limitations were encountered that affected the conclusions for the reuse potential. The main limitations were:

- Lack of proper condition assessment: when performing the assessments per layer, there was the case that there was no proper condition assessment of the building product. So, most of the time the decision to reuse them relies purely on the contractor's or the architect's expertise (Architect 1, personal communication, April 21 2023). Therefore, the assumption was made that these cases had at least a 'Good' condition score according to the condition assessment (NEN, 2019).
- Different circularity strategies applied: Another matter of contention was the fact that all the cases indicated as 'repurpose' came from other non-building products but the assessment was still performed due to its possible adaptability potential. However, the showed outcomes deviated from the expected ones. This was mainly due to the intrinsic motivation to choose existing products in an experimental way.
- Inconsistencies with Schmidt's framework of building layer: for the assessment of the cases different aspects were taken into account according to Schmidt's layers. However, during the interviews, interviewees were asked to give their opinion about how movable, versatile, adjustable, scalable, convertible and refitable the building product was, and in some cases, more of the aspects were possible than stated by Schmidt. In this case, it was possible to transport all of the assessed cases since they have been reused. Additionally, for the refitable aspect sometimes it is possible (mostly laborious and costly) to make some improvement in the building product so it can meet the new building regulations (Expert interviewee 2, personal communication, 17 April 2023).
- Unknown first lifecycle lifespan: some interviewees did not know how long the previous lifecycle of the building product was, so no conclusion could be drawn on this topic,
- Disassembly potential: precast concrete floors could be reused in posterior lifecycles (Architect 1, personal communication, 21 April 2023). However, its low disassembly potential is mainly given due to its overlapping with other building products. The disassembly potential assessment does not take into account the possibility of circular demolition which could lead to less obstruction and damage when reusing these elements.
- Lack of data collection: while data collection for the skin and structure layer was not significantly restricted in terms of the number of cases, the space plan layer faced limitations. This constraint prevented the establishment of a typology per building product, and as a result, the conclusions drawn for the assessed building products in this layer cannot be generalized.
- Subjectivity in interpreting reuse potential: it is important to acknowledge that the case assessment is subject to subjectivity due to the involvement of the research team. Although the responses were validated through expert interviews, it is possible that individuals may have differing opinions or experiences regarding the reuse of certain building products.

These limitations emphasize the need for careful consideration and further research to obtain more comprehensive and objective insights into the reuse potential of building products

Chapter 6

Interpretation of the findings

6 Interpretation of the findings

In the previous chapter, the case assessment and cross-case analysis were presented. In this chapter, the interpretation of the findings is discussed in light of the theoretical background. Four main sections are presented: circular built environment, technical aspects and reuse potential, technical characteristic and reuse potential and lastly, the posterior lifecycle of reused building products.

6.1 Circular Built Environment

In section 2.1.1 of the theoretical background, it was discussed that **reuse is a circularity strategy that involves utilizing products for their primary function again**. However, in the case of certain assessed building products, including timber cladding, steel columns, and timber roof construction, they were repurposed from existing products, yet they were still referred to as reused by the organizations and interviewees involved. The circular economy is essential in the built environment as it promotes a shift from a linear economy to one that reduces resource consumption, environmental damage, and waste. During this study, there was no clear distinction between repurposed and reused products, and the definition was primarily determined by the interviewee. The literature highlights the importance of adopting a circular economy approach in the built environment, where the optimal use of inner loops (Figure 5) such as reuse, remanufacture, and refurbishment can significantly reduce resource consumption, environmental damage, and waste (Van Stijn, 2023). However, the lack of a clear distinction between repurposed and reused products and the subjective definition of reuse can create confusion. As suggested by Icibaci (2019), allowing a degree of reconditioning in some definitions of reuse can be an effective approach to reducing material waste.

6.2 Technical Aspects and the Reuse Potential

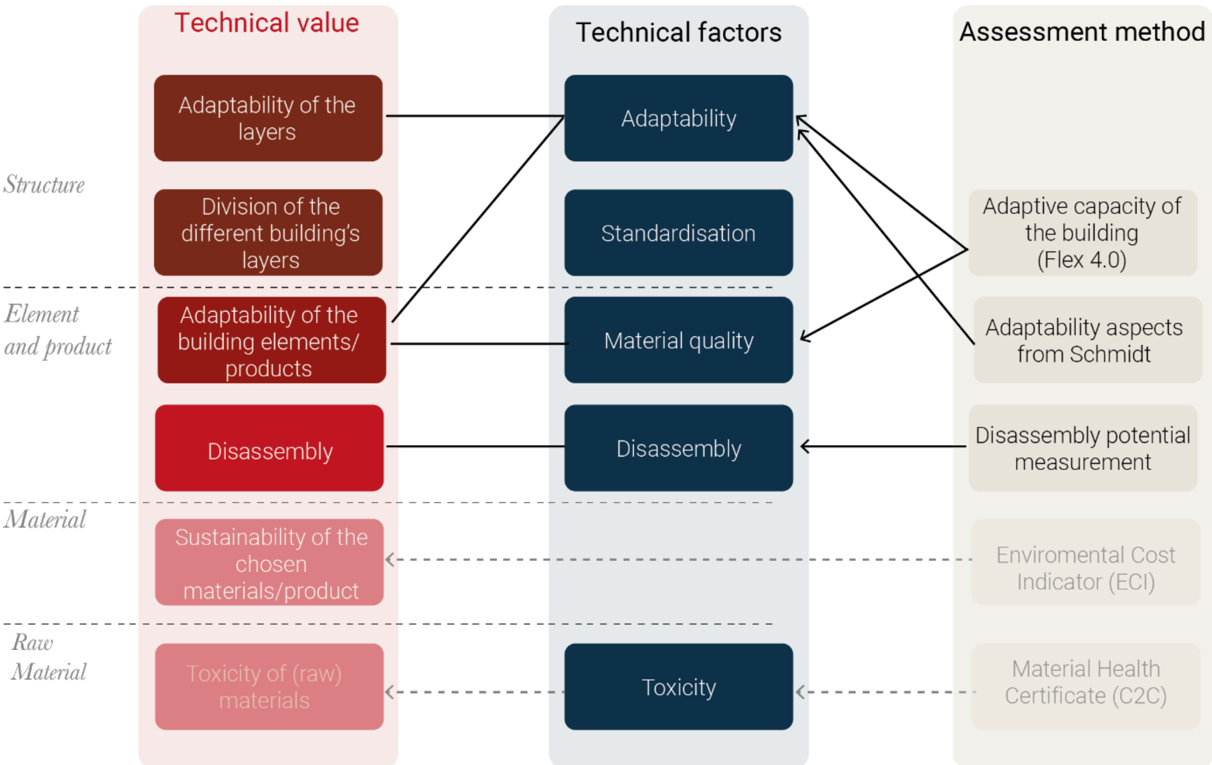


Figure 54 Relationship between the technical aspects (red), the technical factors of the reuse potential (blue) and the assessment methods (beige) (Author).

To fully understand the findings, it is crucial to have a clear understanding of the development of the assessment framework used to evaluate the reuse potential of building products. This framework was

created by integrating existing assessment methods from the literature, each of which evaluates different technical aspects related to the technical value of a building (as discussed in section 0).
Through expert interviews and discussions, the cases were evaluated, and the reuse potential was determined. Five technical factors influence the reuse potential of a building product, including adaptability, standardization, material quality, disassembly, and toxicity (as described in section 2.3.1). While these technical factors were not initially aligned during the development of the assessment framework, similarities between **adaptability, disassembly, and toxicity** became apparent after the case assessment (as illustrated in Figure 55).

It is worth noting that although the technical factor of **material quality** is not explicitly defined in the technical aspects, Meuffels and Hoppe (2021) suggest that **over-dimensioning can be a solution for improving material quality** to support a longer lifespan and better quality. During the case assessment, the FLEX 4.0 assessment framework was used to evaluate the **surplus of load-bearing capacity**, which leads to the assumption that material quality is related to the adaptability that a building product can have.

It is important to mention that this research evaluated building products at the product and element level, but not at the material level. Additionally, **the assessment framework did not explicitly consider the technical factor of toxicity**, but it was assumed that none of the assessed building products contained hazardous or toxic materials since this is a critical factor in the decision to reuse a building product (as noted by Deweerdt & Mertens (2020).

Standardization is another technical factor that enables building product reuse (Coenen et al., 2021). However, evaluating standardization can be challenging for building products that were not designed to be reused, and therefore, this factor was not assessed.

The relationship between the technical value and reuse potential of building products depends on how well they match the requirements and expectations of their new function. For instance, **high adaptability and disassembly increase the reuse potential** of building products, as they allow for easy modification or separation for different contexts and needs (Condotta & Zatta, 2021a; Rakhshan et al., 2020). **FLEX 4.0 and disassembly potential measurement** are two methods that can be used to assess these technical factors. On the other hand, **high toxicity or low material quality can decrease the reuse potential** of building products, as they can pose health and safety risks or have poor durability and performance (Deweerdt & Mertens, 2020). The assessment frameworks of FLEX 4.0 and the Material Health Assessment Methodology (Cradle to Cradle Products Innovation Institute, 2022) can be used to evaluate these technical factors.

6.3 Technical characteristics and reuse potential

The reuse potential of building products varies depending on their technical characteristics. Iacovidou & Purnell (2016) classified several building products according to their reuse potential. However, the selection of the building products and the findings of the case assessment diverge from the reuse potential presented in the literature. During the cross-case analysis in the previous chapter, the building products that have the same similarities and differences (technical characteristics and reuse potential) are categorized in a typology. Table 12 depict the selected cases and the reuse potential according to the literature (Iacovidou & Purnell, 2016) and the reuse potential according to the findings.

Table 12 Reuse potential findings from the case assessment and literature (Iacovidou & Purnell, 2016). Green coloured indicates match and red coloured mismatch. Positive influencing factor (+), negative influencing factors (-)

Layer	Typology		Reuse potential: Literature	Reuse potential: Case Assessment	Influencing factors
Structure layer	Steel structure products		High	High	Adaptability potential and disassembly potential (+)
Structure layer	Timber structure products		High	High	Adaptability potential and disassembly potential (+)
Structure layer	Concrete floor slabs		No possible	Moderate	Disassembly potential and scalable aspect (-)
Structure layer	Other concrete structure products		No possible	Low	Disassembly potential and scalable aspect (-)
Skin layer	Non-timber window		No possible	Low	Adaptability potential (regarding building requirements) (-)
Skin layer	Ceramic cladding	Cement-based mortar	No possible	Low	Disassembly potential (-)
Skin layer	Non-ceramic cladding	Aluminium cladding	No possible	Moderate	Adaptability and scalable aspect (-)
Skin layer	Non-ceramic cladding	Timber cladding	High	Moderate	Adaptability and scalable aspect (-)
Skin layer	Insulation products	EPS insulation	-	High	Adaptability potential, refitable and scalable aspects and disassembly potential (+)
Skin layer	Timber window		High	Moderate	Adaptability potential (regarding building requirements) and scalable aspect (-)
Space plan	Flooring	Slate tiles	Moderate	Moderate	Disassembly potential and scalable aspect (-)
Space plan	Flooring	Stone tiles	High	Moderate	Disassembly potential and scalable aspect (-)
Space plan	Ceiling products		-	Moderate	Scalable and convertible aspect (-)
Space plan	System wall		Low	Low	Scalable aspect (-)

According to the literature, some building products such as **aluminium cladding, concrete floor slabs and structures** face significant reuse barriers due to their size and disassembly challenges. Additionally, **non-timber windows** may also pose difficulties because of frequent updates to building insulation requirements. However, the case assessments revealed that these barriers did not prevent the reuse of such products in a second lifecycle, **challenging the assumption that they are impossible to reuse**.

The literature also suggests that some building products, such as **flooring, timber cladding, and windows, have high reuse potential** when used for a second lifecycle. However, the case assessment of this research has found that **their reuse potential declines as their functional lifespan is extended**, leading them to have moderate reuse potential for a third lifecycle. A similar case is the decrease of reuse potential for **system walls.** Although the literature suggests that this type of product has a **low reuse potential,** during the case assessments it was found that this type of product can be reused for a second lifecycle. However, its reuse potential is affected by its scalability aspect, making its reuse for a third lifecycle a challenge (Expert 1, personal communication, April 2023).

Meanwhile, **steel and timber structure products have a high reuse potential** thanks to their refit and adaptability potential. For example, timber structure products can be adapted to meet load-bearing requirements, while steel structure products can be over-dimensioned to increase their material quality.

On the other hand, **ceramic cladding products** assessed in the study had a **low reuse potential** due to their disassembly potential, when applied with a cement-based mortar.

Although the literature does not indicate a reuse potential for **EPS insulation**, Icibaci (2019) suggests that it is currently a reusable building product. According to the findings in this research, EPS insulation has a **high reuse potential,** mainly thanks to its refit and scalability aspects. Conversely, there is little literature discussing **ceiling products**, but during an interview, a participant noted that timber ceiling products are easily disassembled and could potentially be reused for a third lifecycle. However, due to their limited adaptability potential and lack of scalability and convertible features, **the reuse potential of such products is deemed to be moderate.**

When considering the reuse potential of building products, the specific building layer they belong to is an important factor to take into account. For example, in the structure layer, it is crucial to consider both the disassembly potential and adaptability potential of building products, especially in relation to load-bearing and safety requirements. In addition, scalability is also an important aspect to consider for concrete and steel building products.

For the building products in the skin layer, besides their disassembly potential, their adaptability potential is also important to consider, as there are currently limited techniques available in the market to meet the constant upgrades regarding insulation requirements. Furthermore, cladding building products in this layer have often an aesthetic function, which may impact their reusability, as they can only be scaled down in dimensions, limiting their reuse potential. Although this aspect was not evaluated in the case assessments, it is important to note its influence on their reuse potential.

Similarly, the disassembly potential and scalability of building products in the space plan layer are key aspects affecting their reuse potential. However, the limited number of collected cases in this building layer makes it difficult to draw general conclusions.

It is worth noting that some of the building products were indicated as impossible to reuse in the reviewed literature, which could be attributed to the fact that the study was conducted many years ago. As the built environment is in constant change, new techniques and innovations are emerging, and design and demolition contractor teams are exploring ways to disassemble whole building structures, such as the dismantling project from LCP Circulair (Cepezed, 2023), suggesting that new opportunities for reuse are being developed.

6.4 Posterior lifecycles

The findings of the study highlight the importance of designing for disassembly to achieve high reuse potential for building products in future lifecycles, as supported by previous research (Dams et al., 2021; Durmisevic et al., 2017; Van Vliet, 2018). However, the cases assessed in this research study involved building products that were not initially designed to be disassembled, which could challenge this claim. The interviewees' responses suggest that considering subsequent lifecycles during the reuse of building products is not always a priority due to the perceived difficulty of designing for disassembly and lack of client demand.

"Reused building products are not being applied in such a way that they can be easily disassembled for the next lifecycle simply because the client does not ask for it" – (Expert interviewee 1, Personal communication, April 2023)

This could be linked to the **stigma around the reuse of building products, and that clients are often unaware of the reuse possibilities** (Circular procurement expert, personal communication, May 2023). Additionally, several technical and social barriers, such as increased complexity, cost, and time, can hinder the adoption of a circular economy and consideration of a product's posterior lifecycle during the design and construction phases (Circularity expert, personal communication, May 2023).

"Any building product can be disassembled and reused for a next cycle" – (Expert interviewee 2, Personal communication, April 2023)

While the financial benefits of reusing building products have not been extensively researched, some construction professionals are recognizing their future value. To increase the supply of reused building products, current practices must change. Policies such as carbon pricing or promoting the marketability of second-hand building products could serve as incentives for construction professionals to become more aware of the potential for reuse. Ultimately, a shift in mindset and incentives for construction professionals could play a critical role in promoting greater consideration of a building product's posterior lifecycle and encouraging the supply of reused building products.

6.5 Generalization of the findings

During the course of this research, a series of 12 interviews were conducted with various organizations. It was found that these organizations were primarily motivated by intrinsic factors, driven by a genuine curiosity and interest in exploring innovative reuse possibilities for building products, rather than being solely motivated by practical or conventional reasons (i.e., legislation or business case improvement). This aligns with the understanding that the reuse of building products is still in its early stages of development.

While the research focused extensively on technical factors influencing the reuse potential of building products, it is crucial to recognize the interplay between these technical factors and other influencing factors. The aim of this section is to not only describe the significance of technical factors but also acknowledge the role of additional factors that affect the reuse potential of building products, highlighting their trans-contextual relevance.

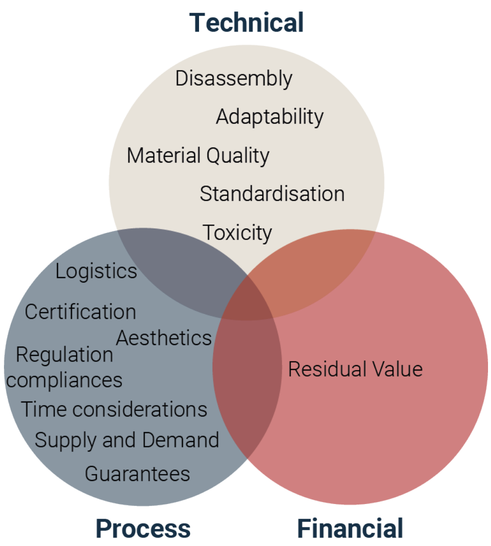


Figure 55 IPF-model and influencing financial-based, technical based and process-based factors. (Author)

Financial-based and **process-based factors** were identified as influential factors affecting reuse potential, as discussed in section 2.3.1 and observed consistently during the interviews. These factors included supply and demand, compliance with regulations, guarantees, availability of certifications, logistics, time considerations, residual value, and aesthetics (see Figure 55 for an overview of the influencing process-based, financial-based, and technical-based factors).

It is evident that the reuse potential of a building product does not solely depend on its technical factors, but also on the process and financial factors involved in the decision-making process. 56 illustrates the relationship between the different process-based, technical-based, and financial-based factors.

A high reuse potential does not guarantee immediate reuse in a building project, but it does indicate a higher likelihood compared to building products with lower potential. **Process-based factors**, such as **time considerations**, can influence the reuse potential if the building team lacks familiarity with reusing building products, leading to time-consuming problem-solving. Time considerations are also linked to **supply and**

demand, as an immature market for reusing building products can result in lengthier and costlier harvesting processes.

Guarantees and certifications emerged as recurring process-based factors. The lack of a protocol for certifying reused building products posed challenges, particularly for building products in the structure and space plan layer (i.e., load-bearing, fire safety or anti-slip requirements). Additional time and financial investment are required to demonstrate **compliance with building regulations**. This lack of protocol also resulted in a lack of guarantees that contractors could offer clients after reusing building products, making it challenging to fulfil warranty obligations and address hidden defects. Furthermore, the current building regulations and their allowances were not extensively studied in this research.

Another process-based factor, usually mentioned during the assessment of the building products from the skin layer, was **aesthetics.** The aesthetic aspect of reused building products can be approached in two ways: showcasing the character and history of the previous lifecycle or concealing the reused products for a more seamless design.

Turning to the **financial factor**, it can be assumed that its relationship with other factors mainly arises from clients and building project developers seeking to understand the economic benefits of reusing building products. Although this study focused primarily on intrinsically motivated projects, it was commonly noted that some clients refrain from reusing building products due to a lack of knowledge regarding the economic benefits involved. Figure 56 demonstrates how numerous factors influence the residual value of a reused building product, suggesting that a comprehensive understanding of economic value requires further research on these influencing factors.

6.5.1 Non-influencing factors

In addition to the technical-based, process-based, and financial-based factors, three new factors—**health, social, and ecological**—are introduced. **These factors do not directly influence the reuse potential of building products but are influenced at a macro level by the other influencing factors**. Within the context of the circular economy and its focus on the climate crisis and resource scarcity, **ecological factors** are influenced by the ability to reuse good-quality building products, supporting climate and resource conservation efforts while potentially promoting biodiversity through reduced carbon emissions.

The reuse of building products can also have positive **social** impacts, such as job creation and the development of the second-hand building product market. Lastly, **health factors** are influenced by the potential hazards associated with certain building materials, with implications for human well-being.

6.5.2 Relevance of Reuse Potential

Achieving a higher level of reused building products is complex by nature. While designing for disassembly is important, the challenge lies in retrofitting existing products that were not initially designed with disassembly in mind. In the past, there was little emphasis on improving the technical aspects of building products for reuse, leading to a lack of legislation and limited incentives for developing new business models in this area.

However, the growing awareness of the climate impact and the added value of the circular economy has shifted the focus towards optimizing the technical factors of building products. This increased awareness serves as a compelling reason to prioritize the reuse of valuable building products and eliminate any excuses for not doing so.

Despite these advancements, various barriers continue to hinder the widespread adoption of reuse practices in the construction industry. Technical and social obstacles, such as (a stigma of) increased complexity, cost, and time, pose significant challenges in transitioning to a circular economy. To overcome these barriers and increase the supply of reused building products, policy interventions and incentives are essential. Measures like implementing carbon pricing and promoting the marketability of second-hand building products can facilitate the transition.

The financial factor plays a crucial role in driving change, as stakeholders—including clients and developers—need to understand the economic benefits of reusing building products. By considering the technical, process-based, financial, health, social, and ecological factors associated with the reuse of building products, the construction industry can advance the principles of the circular economy. This comprehensive approach enables stakeholders to make more informed decisions and work towards the goals of sustainability, natural resource preservation, and maximizing resource yields in the built environment.

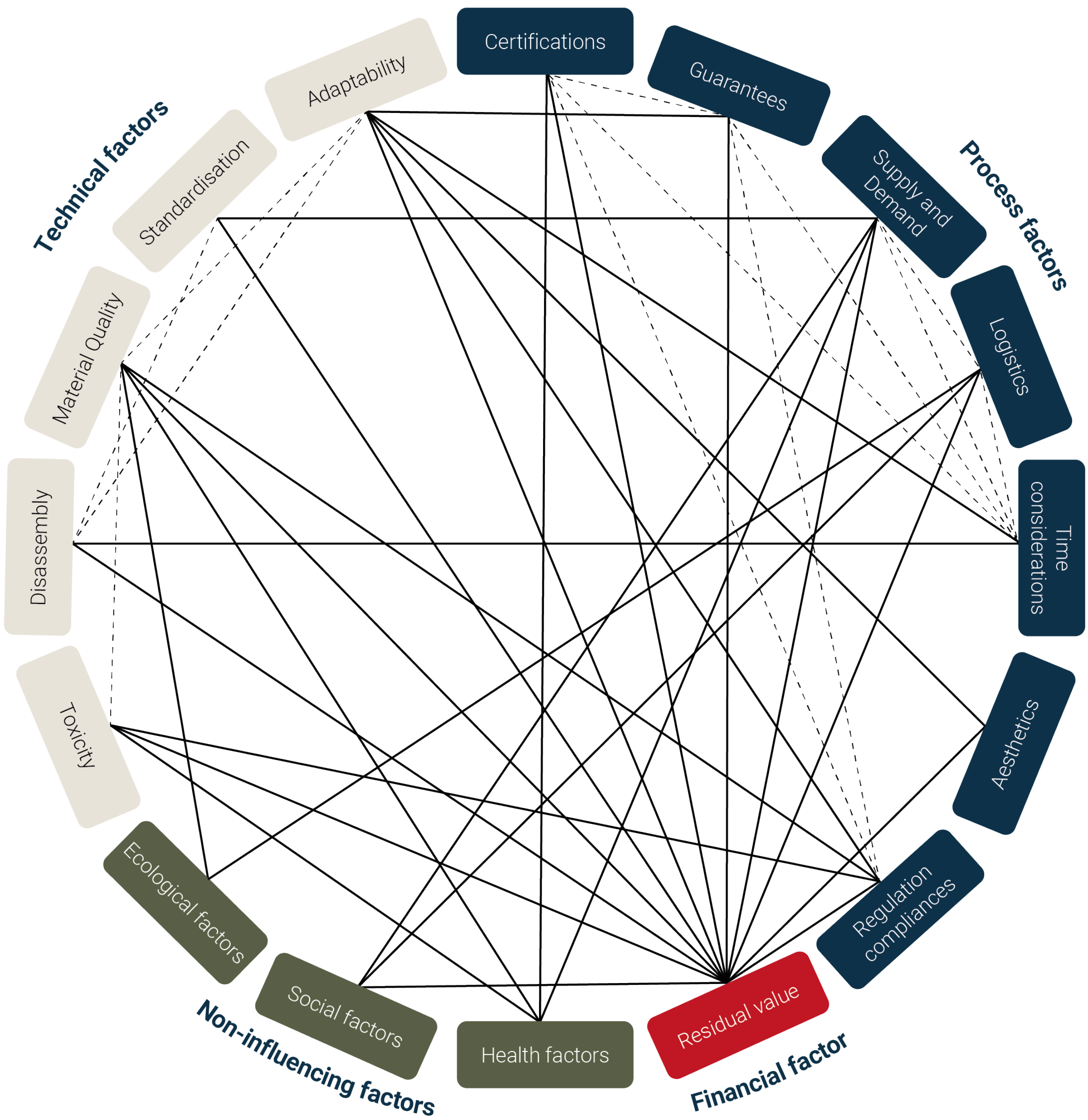


Figure 56 Relationship between the financial (red), process (blue), technical (beige), social, ecological and health-based (green) factors for the reuse potential of building products. The dotted lines depict to relationship within the factors and the non-dotted line the trans-contextual relationship between the factors (Author)

Chapter 7

Conclusion

7 Conclusion

This research study aimed to address the gap in the relationship between the technical aspects and the reuse potential of reused building products. This final chapter summarizes the key findings of this thesis research and answers the research questions. It also discusses the limitations of the study and provides recommendations for further research.

7.1 Answer to Research Questions

[SQ 1] What is the circular built environment?

This research thesis has emphasized the importance of understanding what the circular economy means for the built environment. The circular economy aims to create an economic system that is resource efficient and effective by applying various circularity strategies such as reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover. Reuse is considered the most efficient circularity strategy since it retains the primary function of the building product, although reconditioning of reused building products may be necessary.

To achieve a circular built environment, it is important to consider the different values that an object can have beyond its economic value, including social, technical, and functional value. The shearing layers of Brand (1994) are commonly used as a reference for circular design when wanting to create value. The circular built environment aims to create value for the present and future by considering the well-being of people and future generations (social value), the costs of keeping an object in a closed loop (economic value), its potential for future use (technical value), and its performance in fulfilling its function (functional value). However, there is currently no consensus on the definition of functional value.

During this study, it became apparent that there is no unanimity on the definition of the circular economy and how it is reflected in the built environment. The lack of a clear distinction between repurposed and reused products, and the subjective definition of reuse can create confusion. The literature highlights the importance of adopting a circular economy approach in the built environment, where the optimal use of inner loops such as reuse, remanufacture, and refurbishment can significantly reduce resource consumption, environmental damage, and waste. Therefore, it is essential to establish a clear and consistent definition of circularity strategies, including reuse and repurposing, to ensure that these strategies are implemented effectively and efficiently in the built environment.

[SQ2] What are the technical aspects of a building product?

The technical aspects of a building product are an important part of its technical value, which refers to its potential for future use and adaptability. These technical aspects include the adaptability of the layers, division of the building layers, adaptability of the building product, and disassembly potential.

To measure these technical aspects, several assessment methods exist, such as FLEX 4.0 for measuring the adaptive capacity of the building, the disassembly index for measuring disassembly potential and assessing the division of the building layers, and finally Schmidt's framework for assessing the adaptability of the building product. These methods help to evaluate the potential of a building product to be adapted and reused in the future, contributing to a more sustainable and circular built environment.

[SQ3] What is the reuse potential of a building product?

The reuse potential of a building product refers to its ability to be used again, thus extending its functional lifespan. There are five factors that affect the reuse potential of a building product: adaptability, material quality, disassembly, standardisation, and toxicity. During this research thesis, a relation between, these factors and the technical aspects of the technical value is made. For example, a building product with high adaptability and disassembly potential is more likely to be reused, while one with high toxicity or low material quality may not be suitable for reuse due to health and safety risks or poor durability and performance.

Based on this research thesis, it is evident that the reuse potential of building products is not solely determined by their inherent properties but also by their specific application within a building layer. Some building products, such as aluminium cladding and concrete floor slabs, face significant reuse barriers due to their size and disassembly challenges. However, the cases assessed have revealed that these barriers do not prevent their reuse in a second lifecycle. On the other hand, building products such as timber and steel structures have high reuse potential due to their adaptability and refit potential.

It is important to consider the specific building layer a product belongs to when evaluating its reuse potential, as factors such as adaptability, disassembly potential, refit and scalability are crucial in determining whether a product can be reused or not. Additionally, the constant upgrades in insulation requirements for building products in the skin layer can impact their reusability, especially as there are limited techniques available to meet these upgrades.

It is also worth noting that some building products were previously thought to be impossible to reuse, but as new techniques and innovations emerge, new opportunities for reuse are being developed. Therefore, it is important to regularly review the literature and stay up-to-date with new developments in the built environment to fully assess the reuse potential of building products.

[SQ4] To what extent can the assessment methods of the technical aspects of a building product define its reuse potential?

In conclusion, the assessment methods of the technical aspects of a building product can provide valuable information about its reuse potential. However, it is important to note that these methods can only define the potential, not guarantee it. The reuse potential of a building product also depends on factors such as disassembly potential, movability and how the building product can be refitted to meet the new requirements.

Assessment methods such as the disassembly potential measurement method and the adaptive capacity of the building (FLEX 4.0) can provide information on the ease of disassembly and adaptability of a building product, respectively. Schmidt's framework can also provide insight into the adaptability aspects (versatile, adjustable, movable, refitable, scalable and convertible) of a building product. Meanwhile, the toxicity of a building product can be evaluated using a material health assessment methodology. Although standardisation can facilitate reuse, it is not enough on its own to ensure it.

While the assessment methods studied do not take into account all the factors that can affect the reuse potential of building products, they can still provide valuable information about the technical aspects that contribute to their reuse potential.

[SQ5] To what extent do the technical aspects of a reused building product and its reuse application during its second lifecycle determine its reuse potential for a third lifecycle?

The reuse potential of a building product for a third lifecycle is influenced by both its technical aspects and its reuse application during its second lifecycle. While the technical factors, such as adaptability, movability, and refitability, are important considerations, they are not the sole determinants of a product's reuse potential. Additionally, the circularity of the product's reuse, particularly its ease of disassembly from its current application, plays a crucial role.

The building products examined in this thesis research were not originally designed with reuse or disassembly in mind. Consequently, when these products are disassembled and reused for a second lifecycle, they face various challenges that impact their potential for subsequent reuse. Some of the assessed building products even exhibited damages resulting from the initial disassembly process, which can further diminish their reuse potential for future lifecycles.

In conclusion, the technical aspects of a building product and its reuse application during the second lifecycle are important factors in determining its potential for a third lifecycle. However, they should be viewed within the context of a broader set of considerations. Factors such as the initial design, including design for disassembly, market demand for reused products, societal attitudes toward reuse, lack of awareness about the potential for reuse, and the cost and complexity associated with implementing circular practices in the construction industry, all play significant roles in determining a product's overall reuse potential.

To fully unlock the reuse potential of building products in third and subsequent lifecycles, it is crucial to address all these factors comprehensively. This entails promoting designs that facilitate disassembly, creating a market demand for reused products, fostering a culture that values reuse, raising awareness about the benefits of reuse, and overcoming the challenges related to cost and complexity in implementing circular practices within the construction industry. Only by considering and addressing this broad range of factors can we maximize the reuse potential of building products and move towards a sustainable and circular future.

[MRQ] What is the relationship between the technical aspects of reused building products and their reuse potential?

The research conducted in this thesis shed light on the relationship between the technical aspects of reused building products and their reuse potential. Several assessment methods, including FLEX 4.0, the disassembly potential measurement method, and Schmidt's framework, were employed to examine a building product's adaptability, disassembly potential, material quality, and other technical factors influencing its reuse potential.

These assessment methods provide valuable insights into the technical aspects of building products that contribute to their reuse potential. Factors such as versatility, refit capability, movability, adjustability, scalability, and convertibility are considered in evaluating a building product's adaptability and disassembly potential. By understanding these technical aspects, stakeholders can assess the feasibility of reusing specific building products in different applications and layers of a building.

It is important to note that a building product's reuse potential is not solely dependent on its inherent properties but also on its suitability for specific applications within a building layer. The adaptability, disassembly potential, and refit capability of a product are critical factors in determining its reuse potential. Importantly, new techniques and innovations are continually emerging, expanding the possibilities for reusing building products that were previously considered nonviable for reuse.

While the technical aspects play a crucial role in determining a building product's reuse potential, it is important to consider that other factors also come into play. Process-based factors, financial considerations, health implications, social impacts, and ecological factors are all interconnected with the reuse potential of building products.

Therefore, it is necessary to take a holistic approach that encompasses all these aspects when assessing the reuse potential of building products. This approach recognizes that a product's inherent properties must align with its specific application within a building layer, while also considering process-related factors such as time, logistics, and compliance with regulations. Additionally, financial factors, including understanding the economic benefits of reuse, play a significant role in driving change and promoting the adoption of reuse practices.

By actively addressing all these factors and considering the interconnectedness between them, the construction industry can foster the widespread adoption of reuse practices. This comprehensive approach contributes to a more sustainable and resource-efficient future, aligning with the goals of a circular economy and promoting the long-term well-being of both society and the environment.

7.2 Limitations and recommendations

This research has some limitations that affect the validity and generalizability of the findings. The main limitations are:

- The empirical research is based on information collected from organisations in the Netherlands, which may not reflect the situation in other countries with different social, political, historical and economic contexts. A wider cross-border case selection at a European level would be needed to account for these differences.
- The data collected during this research was limited by the scarce project examples that have reused building products. The conclusions made per building product are based on a small sample size and may not be representative of the building product typology. A larger sample size of at least 15 cases per product type would provide more reliable results (Sake, 2006).
- The case assessment revealed some inconsistencies with Schmidt's framework, which suggested that some building products could be refit or moved despite the framework stating the contrary. This indicates that the framework may not capture all the possible scenarios for reusing building products and that further research should explore the different ways of refitting or moving these products.
- The disassembly potential of some building products was assessed as low when they overlapped with other layers, which may not reflect their actual potential if circular demolition methods were applied. This assessment method does not consider circular demolition as a possible way of facilitating reuse and should be validated by an expert on this topic or revised to include this aspect.
- This thesis is based on qualitative research, primarily from the perspective of the design team, and does not consider the economic aspect of reusing building products. The economic aspect is essential and integral for the decision-making process to reuse building products and should be investigated in future research or practice.

These limitations suggest some directions for future research or practice that could enhance the understanding and implementation of circular design principles for building products. Some possible recommendations are:

- Conducting cross-border comparative studies on circular design practices for building products in different European countries and contexts.
- Collecting more data on existing projects that have reused building products and conducting statistical analyses to identify patterns and trends.
- Developing and testing alternative frameworks or methods for assessing the reuse potential of building products that account for different refitting or moving scenarios.
- Incorporating circular demolition methods into the assessment of disassembly potential and evaluating their impact on reuse outcomes.
- Integrating economic analysis into the evaluation of reuse potential and exploring the costs and benefits of reusing building products.
- Conducting research about the limitations encountered in failed reused building products to learn from mistakes and see how to improve this for future opportunities.
- Conducting in-depth research about the relationship between the financial, process and technical-based factors and the reuse potential of building products.

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Appendix

Appendix I: Interview protocol[1]

Interview protocol

Delft University of Technology
MSc Architecture, Urbanism and Building Sciences,
Department of Management in the Built Environment

Titel Onderzoek: What's next? A study of reused elements and products and their relation with the building structure

Naam van onderzoeker: Astrid Brandt W.

Datum interview:

Plaats:

Naam geïnterviewde:

Organisatie:

Mijn naam is Astrid Brandt Wassink, bedankt voor het meedoen aan mijn interview. Ik ben een master student in Management in the Built Environment aan de TU Delft. Ik voer mijn afstudeeronderzoek in samenwerking met Alba Concepts. Dit onderzoek maakt deel uit van mijn afstudeerscriptie over de relatie tussen de technische waarde en functionele waarde van een bouwproduct en zijn gebouwstructuur. Voordat ik begin zijn er een aantal aandachtspunten voor de uitvoering van het interview. Ten eerste, ik heb de getekende toestemmingsverklaring nodig voordat ik begin aan het interview, en ten tweede over uw toestemming om deze interview op te nemen, dit zal mij helpen met het verder verwerken van de informatie en analyseren hiervan. De informatie die u met mij deelt blijft ten alle tijd confidentieel en u mag met het interview stoppen op elk moment. Indien nodig, u mag altijd vragen om deel van uw antwoorden niet mee te nemen in het onderzoek.

Dit interview zal niet langer dan een uur duren. Ik heb er een aantal vragen die essentieel zijn voor mijn onderzoek, dus het kan het geval zijn dat ik u moet onderbreken om naar de volgende vraag te gaan.

De focus van mijn onderzoek ligt op de element en producten die zich bevinden binnen de skin, structure en space plan lagen als voorgesteld door Brand in zijn 6S-model.
Hergebruik is een belangrijk aspect binnen de circulaire economie. In mijn onderzoek maak ik onderscheid tussen hoogwaardig en laagwaardig hergebruikt a.d.h.v. het 10R ladder. Reuse tot en met Repurpose beschouw ik als hoogwaardig en Recycling en Recovery als laagwaardig hergebruik.

Vragen

De volgende vragen zijn opgesteld met betrekking tot het project [naam] en de toepassing van de volgende hergebruikte bouwelementen:

-

Context

1. Wat was uw rol binnen het project?
2. Voorafgaand het project, wat was uw ervaring met het hergebruiken van bouwelementen?
3. Wat is de aanleiding geweest om te kiezen voor het toepassen van gebruikte bouwelement binnen het project?
4. Wat zijn volgens u de belemmeringen om gebruikte bouwelementen toe te passen in nieuwbouwprojecten?

[1] English translation available upon request

Specifiek over de hergebruikte producten/elementen

5. Wat was de voormalige functie waar het hergebruikte bouwelement vandaan kwam?
6. Was de functie van het bouwelement veranderd? Zo ja, waarom?

De volgende vraag heeft te maken met hoe adaptabel het bouwelement is. Voor dit het volgende concept en aspecten zijn van toepassing:

Met adaptabiliteit wordt bedoeld het aanpassingsvermogen dat een bouwelement heeft om dit verder te kunnen blijven hergebruiken en nog steeds voldoen aan de eisen. Adaptabiliteit kan beoordeeld worden a.d.h.v. zes aspecten volgens Schmidt. Dit zijn:

- Verplaatsbaarheid van locatie (movable);
- Schaalbaar van afmetingen (scalable);
- Aanpasbaar (refitable): hoe de componenten gewisseld kunnen worden;
- Converteerbaar (convertible): hoe de functie kan worden aangepast;
- Multifunctioneel (versatile) door verplaatsbaarheid;
- Herinrichtbaar door losmaakbaarheid (adjustable).

7. Tot hoeverre denkt u dat deze aspecten van toepassing zijn voor het gebruikte element? en waarom?
8. Aan welke voorwaarden moet een element voldoen voor het moment wanneer het wordt besloten om dit in het ontwerp toe te passen?

Er wordt vanuit gegaan dat om een element te kunnen hergebruiken, dit minimaal aan de huidige bouwbesluit eisen moet voldoen.

9. Hoe wordt dit gewaarborgd?

-

10. Wat is het proces geweest om hiervoor te kunnen zorgen?

-

11. Waren er extra eisen gesteld op het bouwelement?

-

Uit deskresearch kwam er naar voren dat vaak bij projecten die gebruikte bouwelementen toepassen wordt er ook naar de volgende levenscyclus gekeken.

12. Tot hoeverre heeft u dit gedacht in het ontwerp meegenomen?

Indien, er rekening gehouden werd met losmaakbaarheid zijn de volgende vragen van toepassing (en andere optie voor deze vragen is het delen van een detailtekening van de gevraagde bouwelementen, de interviewer zal hiermee het losmaakbaarheid index a.d.h.v. losmaakbaarheid meetmethodiek zelf berekenen)

13. Wat is het type verbinding toegepast bij het bouwelement?

-

14. Tot hoever is de verbinding toegankelijk zonder het aantasten van naastliggende bouwproducten?

-

15. Tot hoever wordt er bouwelement doorgekruist door andere producten uit verschillende lagen?

-

16. Tot hoever wordt het bouwelement gesloten door andere bouwproducten?

-

17. Wil u naast de vragen nog iets kwijt?

-

Appendix II: Classification of the assessed building products

Case #	Case # per layer	Buildin product	Layer	Project	Building function	Responsible interview
case 2	SKIN_CASE 1	aluminium window frame	skin	A	Education	Intern / involved parties
case 3	SKIN_CASE 2	EPS insulation	skin	A	Education	Intern / involved parties
case 4	SKIN_CASE 3	tile cladding	skin	B	Multifunctional	Architect 1
case 5	SKIN_CASE 4	timber window frames	skin	B	Multifunctional	Architect 1
case 8	SKIN_CASE 5	timber roofing profile	skin	B	Multifunctional	Architect 1
case 11	SKIN_CASE 6	aluminium cladding	skin	C	Multifunctional	Intern / involved parties
case 12	SKIN_CASE 7	glass panels	skin	D	Multifunctional	Intern / involved parties
case 18	SKIN_CASE 8	aluminium window frame	skin	F	Multifunctional	Architect 2
case 20	SKIN_CASE 9	EPS insulation	skin	F	Multifunctional	Architect 2
case 21	SKIN_CASE 10	timber cladding	skin	G	Office	Architect 3
case 22	SKIN_CASE 11	timber cladding	skin	H	Housing	Architect 4
case 27	SKIN_CASE 12	timber cladding	skin	K	Housing	Architect 7
case 28	SKIN_CASE 13	EPS insulation	skin	K	Housing	Project developer 2
case 29	SKIN_CASE 14	aluminium cladding	skin	L	Multifunctional	Architect 7
case 30	SKIN_CASE 15	brick cladding	skin	M	Housing	Project developer 1
case 31	SKIN_CASE 16	tile cladding	skin	M	Housing	Project developer 1
case 6	SPACEPLAN_CASE 1	timber ceiling panels	space plan	B	Multifunctional	Architect 1
case 14	SPACEPLAN_CASE 2	stone tiles	space plan	E	Office	Architect 2
case 15	SPACEPLAN_CASE 3	system walls	space plan	E	Office	Architect 2
case 17	SPACEPLAN_CASE 4	brick flooring	space plan	F	Multifunctional	Architect 2
case 1	STRUCTURE_CASE 1	steel beam(s)	structure	A	Education	Intern / involved parties
case 7	STRUCTURE_CASE 2	precast concrete floor slab	structure	B	Multifunctional	Architect 1
case 9	STRUCTURE_CASE 3	steel columns	structure	C	Multifunctional	Intern / involved parties
case 10	STRUCTURE_CASE 4	timber beam(s)	structure	C	Multifunctional	Intern / involved parties
case 13	STRUCTURE_CASE 5	steel column(s)	structure	E	Office	Architect 2
case 16	STRUCTURE_CASE 6	precast concrete floor slab	structure	F	Multifunctional	Architect 2
case 19	STRUCTURE_CASE 7	timber roof construction	structure	F	Multifunctional	Architect 2
case 23	STRUCTURE_CASE 8	hollow-core slab floor	structure	I	Multifunctional	Constructor 1
case 24	STRUCTURE_CASE 9	timber rafter	structure	J	Multifunctional	Architect 5
case 25	STRUCTURE_CASE 10	precast concrete floor slab	structure	J	Multifunctional	Architect 5
case 26	STRUCTURE_CASE 11	steel columns	structure	K	Housing	Architect 7
case 32	STRUCTURE_CASE 12	fundation concrete blocks	structure	O	Housing	Architect 6
case 33	STRUCTURE_CASE 13	steel beam(s)	structure	O	Housing	Architect 6
case 34	STRUCTURE_CASE 14	concrete floor	structure	O	Housing	Architect 6
Expert interview 1						Supplier 1
Expert interview 2						Constructor 2

Appendix III: Informed Consent Letter[2]

Toestemmingsverklaring deelname aan wetenschappelijk onderzoek

Delft University of Technology
MSc Architecture, Urbanism and Building Sciences, Department of Management in the Built Environment

Titel Onderzoek: What's next? A study of reused elements and products and their relation with the building structure

Beste heer/mevrouw,

U wordt uitgenodigd om deel te nemen aan een onderzoek genaamd "What's next? A study of reused elements and products and their relation with the building structure". Dit onderzoek wordt uitgevoerd door Astrid Brandt Wassink van de TU Delft in samenwerking met Alba Concepts.

Het doel van dit onderzoek is om meer inzicht te krijgen over de invloed van hergebruikte bouwproducten op het adaptatief vermogen van het gebouw structuur en zal ongeveer 60 minuten in beslag nemen. Tijdens het interview u wordt gevraagd om uw rol te beschrijven en ervaring te delen over de benodigde werkzaamheden die een bepaald gebruikt bouwelement nodig heeft om aan de nieuwe technische voorwaarden te kunnen voldoen.

Zoals bij elke onlineactiviteit is het risico van een databreuk aanwezig. Wij doen ons best om uw antwoorden vertrouwelijk te houden. We minimaliseren de risico's door gegevens uit de interviews volledig anoniem te verwerken volgens de richtlijnen van de TU Delft. Persoonlijke informatie zou dan ook niet gedeeld worden met Alba Concepts en derden.

Uw deelname aan dit onderzoek is volledig vrijwillig, en u kunt zich elk moment terugtrekken zonder reden op te geven. U bent vrij om vragen niet te beantwoorden.

Dank voor uw aandacht,

Astrid Brandt Wassink
MSc student Management in the Built Environment, TU Delft
Afstudeerder – Alba Concepts

Door deel te nemen aan dit onderzoek ga ik akkoord met het volgende:

A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION

1. Ik heb de informatie over het onderzoek gedateerd 21/03/2023 gelezen en begrepen, of deze is aan mij voorgelezen. Ik heb de mogelijkheid gehad om vragen te stellen over het onderzoek en mijn vragen zijn naar tevredenheid beantwoord.
2. Ik doe vrijwillig mee aan dit onderzoek, en ik begrijp dat ik kan weigeren vragen te beantwoorden en mij op elk moment kan terugtrekken uit de studie, zonder een reden op te hoeven geven.
3. Ik begrijp dat mijn deelname aan het onderzoek de volgende punten betekent:
   - Audio en/of video opname van het interview
   - Aantekeningen van het interview
   - Transcriberen van het interview
4. Ik begrijp dat de studie in juli 2023 eindigt.

[2] English translation available upon request

B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)

5. Ik begrijp dat mijn deelname betekent dat er persoonlijke identificeerbare informatie (PII) en onderzoeksdata (PIRD) worden verzameld, met het risico dat ik hieruit geïdentificeerd kan worden. PII and PIRD-data:
   - PII: beroep, werkgever, emailadres, telefoonnummer en naam
   - PIRD: documentatie uit project
6. Ik begrijp dat de volgende stappen worden ondernomen om het risico van een databreuk te minimaliseren, en dat mijn identiteit op de volgende manieren wordt beschermd in het geval van een databreuk:
   - Pseudo anonymisation: uw naam wordt gecodeerd en de organisatie naam wordt niet openbaar. Niettemin, beroep en projectnaam, worden wel gedeeld
   - Audio en video opnames worden vernietigd nadat de interviews getranscribeerd zijn
   - Project documentatie wordt niet gedeeld met derden en wordt ook vernietigd na onderzoek
7. Ik begrijp dat de persoonlijke informatie die over mij verzameld wordt en mij kan identificeren, zoals naam, beroep, project documentatie niet gedeeld worden buiten het studieteam.
8. Ik begrijp dat de persoonlijke data die over mij verzameld wordt, vernietigd wordt aan het eind van dit onderzoek (zomer 2023).

C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION

9. Ik begrijp dat na het onderzoek de geanonimiseerde informatie gebruikt zal worden voor:
   - Master scriptie rapport dat gepubliceerd wordt in de open-access TU Delft repository
   - Onderzoek publicaties door Alba Concepts
10. Ik geef toestemming om mijn antwoorden, ideeën of andere bijdrages anoniem te quoten in resulterende producten.
11. Ik geef toestemming om project documentatie (zoals foto's, tekeningen) die gedeeld wordt met de onderzoeker te gebruiken als data input voor haar onderzoek.

☐ Nee, ik ga niet akkoord ☐ Ja, ik ga akkoord

________________________	________________________	______________
Naam deelnemer	Handtekening	Datum

Ik, **de onderzoeker**, verklaar dat ik de <u>informatie en het instemmingsformulier</u> correct aan de potentiële deelnemer heb voorgelezen en, naar het beste van mijn vermogen, heb verzekerd dat de deelnemer begrijpt waar hij/zij vrijwillig mee instemt.

Astrid Brandt Wassink	________________________	______________
Naam Onderzoeker	Handtekening	Datum

Bij vragen over het onderzoek kunt u contact opnemen met:

- Astrid Brandt Wassink
- TU Delft main supervisor: Prof.dr.ir. J.W.F. (Hans) Wamelink

- TU Delft second supervisor: Dr. K.B.J. (Karel) Van den Berghe
- Alba Concepts supervisor: Jan Jaap Blüm

Appendix IV: FLEX 4.0 Indicators per building product

FLEX 4.0: GENERALLY APPLICABLE INDICATORS			SKIN LAYER: aluminium cladding	aluminium window frame	brick cladding	EPS insulation	glass panels	insulation	tile cladding	timber cladding	timber roofing profile	timber window frames	SPACE PLAN: brick flooring	stone tiles	system walls	timber ceiling panels	STRUCTURE: concrete floor	fundation concrete blocks	hollow-core slab floor	precast concrete floor slab	roof construction	steel beam(s)	steel column(s)	timber beam(s)	timber rafter
LAYER	SUBLAYER	FLEXIBILITY PERFORMANCE																							
1. SITE		1. EXPANDABLE SITE/LOCATION																							
2. STRUCTURE	MEASUREMENT	2. SURPLUS OF BUILDING SPACE/ FLOOR																			X				
		3. SURPLUS OF FREE FLOOR HEIGHT																				X	X	X	X
	ACCESS	4. ACCESS TO BUILDING																							
	CONSTRUCTION	5. POSITIONING OBSTACLES/ COLUMNS																X				X	X	X	X
3. SKIN	FACADE	6. FACADE WINDOWS TO BE OPENED		X			X																		
		7. DAYLIGHT FACILITIES		X			X																		
4.FACILITIES (SERVICES)	MEASURE AND CONTROL	8. CUSTOMISABILITY/ CONTROLLABILITY																							
	DIMENSION	9. SURPLUS OF FACILITIES SHAFTS																			X				
		10. MODULARITY OF FACILITIES																							
5.SPACE (SPACE PLAN AND STUFF)	FUNCTIONAL	11. DISTINCTION BETWEEN SUPPORT-INFILL																							
	ACCESS	12. HORIZONTAL ACCESS TO BUILDING																							

FLEX 4.0: SPECIFICALLY APPLICABLE INDICATORS			SKIN LAYER: aluminium cladding	aluminium window frame	brick cladding	EPS insulation	glass panels	insulation	tile cladding	timber cladding	timber roofing profile	timber window frames	SPACE PLAN: brick flooring	stone tiles	system walls	timber ceiling panels	STRUCTURE: concrete floor	fundation concrete blocks	hollow-core slab floor	precast concrete floor slab	roof construction	steel beam(s)	steel column(s)	timber beam(s)	timber rafter
LAYER	SUBLAYER	FLEXIBILITY PERFORMANCE																							
1. SITE		1. SURPLUS OF SITE SPACE																							
		2. MULTIFUNCTIONAL SITE/LOCATION																							
2. STRUCTURE	MEASUREMENT	3. AVAILABLE FLOOR SPACE OF BUILDING															X		X	X	X				
		4. SIZE OF FLOOR BUILDING															X		X	X	X				
		5. MEASUREMENT SYSTEM															X		X	X	X				
		6. HORIZONTAL ZONE DIVISION/ LAYOUT															X		X	X	X				
		7. PRESENCE OF STAIRS/ELEVATORS																			X				
		8. EXTENSION/ REUSE OF																			X				
	CONSTRUCTION	9. SURPLUS OF LOAD BEARING CAPACITY															X	X	X	X	X	X	X	X	X
		10. SHAPE OF COLUMNS																				X	X	X	X
		11. POSITIONING OF FACILITIES ZONES																				X	X	X	X
		12. FIRE RESISTANCE MAIN BEARING															X		X	X		X	X	X	X
		13. EXTENDIBLE BUILDING/ UNITS HORIZONTAL																			X	X	X	X	X
		14. EXTENDIBLE BUILDING/ UNITS VERTICAL															X		X	X	X	X	X	X	X
		15. REJECTABLE PART OF BUILDING/UNIT																			X	X	X	X	
		16. INSULATION BETWEEN STORIES/UNITS				X		X							X	X	X		X	X	X				
3. SKIN	FACADE	17. DISMOUNTABLE FACADE		X	X		X		X	X	X	X													
		18. LOCATION/ SHAPE DAYLIGHT		X			X					X													
		19. INSULATION OF FACADE		X	X		X		X			X													
4.FACILITIES (SERVICES)	MEASURE AND CONTROL	20. MEASURE AND CONTROL TECHNIQUES																							
	DIMENSION	21. SURPLUS CAPACITY OF FACILITIES																							
	DISTRIBUTION	22. DISTRIBUTION FACILITIES																							
		23. LOCATION SOURCES FACILITIES																							
		24. DISCONNECTION OF FACILITY																							
		25. ACCESSABILITY OF FACILITY																							
		26. INDEPENDENCE OF USER UNITS																							
5.SPACE (SPACE PLAN AND STUFF)	FUNCTIONAL	27. MULTIFUNCTIONAL BUILDING/ UNITS													X	X									
	TECHNICAL	28. DISCONNECTABLE, REMOVABLE													X	X	X		X	X					
		29. DISCONNECTABLE/ REMOVABLE													X	X									
		30. DISCONNECTABLE CONNECTION DETAIL																							
		31. POSSIBILITY OF SUSPENDED CEILINGS																			X				
		32. POSSIBILITY OF RAISED FLOORS																			X				

Appendix V: Assessment form for the selected cases

Assessment form: sample study

Project

Kiezen

Function donor building

Kiezen

New function new building

Kiezen

Sample number

____

Assessed element or product

Kiezen

Assessed element or product

- [ ] Product
- [ ] Element

Layer

- [ ] Structure
- [ ] Skin
- [ ] Space plan

Application

- [ ] as is
- [ ] Anders:

Circularity strategy applied

- [ ] Reuse
- [ ] Repair

Other: (specified)

- [ ] Refurbish
- [ ] Remanufacture
- [ ] Repurpose

Generally applicable indicators

	1 BAD	2 NORMAL	3 BETTER	4 BEST	N/A
SITE	☐	☐	☐	☐	☐
2. SURPLUS OF BUILDING SPACE/ FLOOR	☐	☐	☐	☐	☐
3. SURPLUS OF FREE FLOOR HEIGHT	☐	☐	☐	☐	☐
4. ACCESS TO BUILDING	☐	☐	☐	☐	☐
5. POSITIONING OBSTACLES/ COLUMNS	☐	☐	☐	☐	☐
6. FACADE WINDOWS TO BE OPENED	☐	☐	☐	☐	☐
7. DAYLIGHT FACILITIES	☐	☐	☐	☐	☐
8. CUSTOMISABILITY/ CONTROLLABILITY	☐	☐	☐	☐	☐
9. SURPLUS OF FACILITIES SHAFTS	☐	☐	☐	☐	☐
10. MODULARITY OF FACILITIES	☐	☐	☐	☐	☐
11. DISTINCTION BETWEEN SUPPORT-INFILL	☐	☐	☐	☐	☐
12. HORIZONTAL ACCESS TO BUILDING	☐	☐	☐	☐	☐

Flexibility class, generally applicable indicators

- [ ] Not adaptable at all
- [ ] Hardly adaptable
- [ ] Limited adaptability
- [ ] Very adaptable
- [ ] Excellent adaptability

Specifically applicable indicators

	1 BAD	2 NORMAL	3 BETTER	4 BEST	N/A
1. SURPLUS OF SITE SPACE	☐	☐	☐	☐	☐
2. MULTIFUNCTIONAL SITE/LOCATION	☐	☐	☐	☐	☐
3. AVAILABLE FLOOR SPACE OF BUILDING	☐	☐	☐	☐	☐
4. SIZE OF FLOOR BUILDING	☐	☐	☐	☐	☐
5. MEASUREMENT SYSTEM	☐	☐	☐	☐	☐
6. HORIZONTAL ZONE DIVISION/ LAYOUT	☐	☐	☐	☐	☐
7. PRESENCE OF STAIRS/ELEVATORS	☐	☐	☐	☐	☐
8. EXTENSION/ REUSE OF	☐	☐	☐	☐	☐
9. SURPLUS OF LOAD BEARING CAPACITY	☐	☐	☐	☐	☐

10. SHAPE OF COLUMNS	☐	☐	☐	☐	☐
11. POSITIONING OF FACILITIES ZONES	☐	☐	☐	☐	☐
12. FIRE RESISTANCE MAIN BEARING	☐	☐	☐	☐	☐
13. EXTENDIBLE BUILDING/ UNITS HORIZONTAL	☐	☐	☐	☐	☐
14. EXTENDIBLE BUILDING/ UNITS VERTICAL	☐	☐	☐	☐	☐
15. REJECTABLE PART OF BUILDING/UNIT	☐	☐	☐	☐	☐
16. INSULATION BETWEEN STORIES/UNITS	☐	☐	☐	☐	☐
17. DISMOUNTABLE FACADE	☐	☐	☐	☐	☐
18. LOCATION/ SHAPE DAYLIGHT	☐	☐	☐	☐	☐
19. INSULATION OF FACADE	☐	☐	☐	☐	☐
20. MEASURE AND CONTROL TECHNIQUES	☐	☐	☐	☐	☐
21. SURPLUS CAPACITY OF FACILITIES	☐	☐	☐	☐	☐
22. DISTRIBUTION FACILITIES	☐	☐	☐	☐	☐
23. LOCATION SOURCES FACILITIES	☐	☐	☐	☐	☐

24. DISCONNECTION OF FACILITY	☐	☐	☐	☐	☐
25. ACCESSABILITY OF FACILITY	☐	☐	☐	☐	☐
26. INDEPENDENCE OF USER UNITS	☐	☐	☐	☐	☐
27. MULTIFUNCTIONAL BUILDING/ UNITS	☐	☐	☐	☐	☐
28. DISCONNECTABLE, REMOVABLE	☐	☐	☐	☐	☐
29. DISCONNECTABLE/ REMOVABLE	☐	☐	☐	☐	☐
30. DISCONNECTABLE CONNECTION DETAIL	☐	☐	☐	☐	☐
31. POSSIBILITY OF SUSPENDED CEILINGS	☐	☐	☐	☐	☐
32. POSSIBILITY OF RAISED FLOORS	☐	☐	☐	☐	☐

Flexibility class, specifically applicable indicators

- ☐ Not adaptable at all
- ☐ Hardly adaptable
- ☐ Limited adaptability
- ☐ Very adaptable
- ☐ Excellent adaptability

Adaptability potential of the assessed element or product within its layer

Answer

Adaptive capacity of the assessed element or product: Adjustable

Answer

Adaptive capacity of the assessed element or product: Versatile

Answer

Adaptive capacity of the assessed element or product: Refitable

Answer

Adaptive capacity of the assessed element or product: Convertible

Adaptive capacity of the assessed element or product: Scalable

Adaptive capacity of the assessed element or product: Movable

Condition assessment

Kiezen ▾

Technical requirements from the building code

Answer

Technical requirements from the user

Answer

Disassembly potential: Connection type

- ☐ Dry connection (1,0)
- ☐ Connection with added elements (0,8)
- ☐ Direct integral connection (0,6)
- ☐ Soft chemical connection (0,2)
- ☐ Hard chemical connection (0,1)

Disassembly potential: Accessibility to the connection

- ☐ Freely accessible without additional actions (1,0)
- ☐ Accessible with additional actions that do not cause damage (0,8)
- ☐ Accessible with additional actions with fully repairable damage (0,6)
- ☐ Accessible with additional actions with partially repairable damage (0,4)
- ☐ Not accessible - irreparable damage to the product or surrounding products (0,1)

Disassembly potential: Independence

- [ ] No independency - modular zoning of products or elements from different layers (1,
- [ ] Occasional independency of products or elements from different layers. (0,4)
- [ ] Full integration of products or elements from different layers. (0,1)

Disassembly potential: Geometry of product edge

- ○ Open, no obstacle to the (interim) removal of products or elements. (1,0)
- ○ Overlapping, partial obstruction to the (interim) removal of products or elements. (0,4)
- ○ Closed, complete obstruction to the (interim) removal of products or elements. (0,1

Disassembly potential 4/[(1/CT)+(1/CA)+(1/I)+(1/GE)]

Answer

First lifecycle lifespan

Answer

Average technical lifespan

Answer

Remaining technical lifespan

Answer

Information needed beforehand

Verzenden

Formulier wissen

Verzend nooit wachtwoorden via Google Formulieren.

Appendix VI: FLEX 4.0 Generally and specifically applicable indicators and weighting

Generally applicable indicators (Geraedts, 2016)

FLEX 4.0: GENERALLY APPLICABLE INDICATORS				
Layer	**Sub-layer**	**Flexibility Performance**	**Assessment Values**	**Remarks**
1. SITE		1. **Expandable site / location** Does the site have a surplus of space and is the building located at the centre?	1. No, the site has no surplus of space at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. The site has a surplus space of more than 50% (Best)	The more surplus space on site, the better the building is expandable.
2. STRUCTURE	Measurement	2. **Surplus of building space / floor** Does the building or the user units have a surplus of the needed usable floor space?	1. Not oversized (Bad) 2. 10-30% oversized (Normal) 3. 30-50% oversized (Better) 4. > 50% oversized (Best)	The more the building space/surface is oversized (for instance by the use of a zoning system with margin space), the more easily a building can be rearranged or transformed to other functions.
		3. **Surplus of free floor height** How much is the net free floor height?	1. < 2.60 m (Bad) 2. 2.60 - 3.00 m (Normal) 3. 3.00 - 3.40 m (Better) 4. > 3.40 m (Best)	The higher the free floor height, the better a building can be rearranged/transformed to other functions, the better a building can meet to changing user demands of facilities and quality.
	Access	4. **Access to building** To what extend a centralized building access has been implemented?	1. Decentralized/separated building entrance/core (Bad) 2. Decentralized/combined building entrance/core (Normal) 3. Building divided in different wings, each with centralized entrances/cores (Better) 4. 1 centralized building entrance and different wings with separate entrances/cores	The more a building entrance system can be used for a more independent use by different user groups the more easily a building can be rearranged.
	Construction	5. **Positioning obstacles / columns** Is the adaptation of the building obstructed by load bearing obstacles or columns?	1. Adaptation completely obstructed by difficult to replace load bearing obstacles 2. < 50% of the building adaptation is obstructed by load bearing obstacles (Normal) 3. < 10% of the building adaptation is obstructed by load bearing obstacles (Better) 4. No building space is obstructed by difficult to replace load bearing obstacles (Best)	The less obstructing parts of the load bearing construction, the more easily a building can be rearranged or transformed to other functions and is able to meet to changing user demands.
3. SKIN	Facade	6. **Facade windows to be opened** Can windows in the façade be opened per planning grid size?	1. No or < 10% of the windows can be opened (Bad) 2. 10 - 30% (Normal) 3. 30 - 80% (Better) 4. 80 - 100% (Best)	The more windows can be opened per planning grid size, the more easily a building can be rearranged/transformed to other functions, the better the building can meet changing demands.
		7. **Daylight facilities** What is the daylight factor for the spaces in the building?	1. Daylight factor < 1/20 (Bad) 2. Daylight factor 1/20-1/10 (Normal) 3. Daylight factor 1/10-1/5 (Better) 4. Daylight factor > 1/5 (Best)	The higher the daylight factor for spaces in the building, the more easily a building can be rearranged/transformed to other functions; the better the building can meet changing demands.
4. FACILITIES	Measure & Control	8. **Customisability/controllability** Is it possible to customize the facilities: temperature, ventilation, electricity, ICT?	1. Bad/not customizable; monofunctional or fixed centralized use (Bad) 2. Limited customizable; after drastic interventions (Normal) 3. Partly customizable; after simple interventions (Better) 4. Good and easy customizable without any interventions (best)	The more facilities are customisable/controllable to respond to changing functional requirements, the easier a building can be rearranged/transformed to other functions; less vacancy/adaptation costs.
	Dimensions	9. **Surplus of facilities shafts and** Do the facilities shafts and ducts have a surplus of space (heating, cooling, electricity, ICT)?	1. Shafts and ducts have no surplus at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. Surplus of space of more than 50% (Best)	The more surplus facilities shafts and ducts have, the easier a building can be rearranged or transformed to other functions, the better a building can meet to changing user demands.
		10. **Modularity of facilities** Are the facilities assembled by modular components according to the facade planning grid?	1. No facility is divided in modular components according to the façade planning grid 2. 1 of the 4 facilities is divided in modular components according to the grid (Normal 3. 2-3 of the 4 facilities are divided according to the façade planning grid (Better) 4. All of the 4 facilities are divided according to the façade planning grid (Best)	The more facilities are divided according to the facade planning grid (modularity), the more easily a building can be rearranged to other functions; the better the building can meet changing demands.
5. SPACE	Functional	11. **Distinction between support - infill** To which degree deals the building with the division between support and infill?	1. < 10% of the building is divided in a support and infill part (Bad) 2. 10 - 30% of the building is divided in a support and infill part (Normal) 3. 30 - 50% of the building is divided in a support and infill part (Better) 4. > 50% of the building is divided in a support and infill part (best)	The more construction components belong to the infill, the easier a building can be rearranged/transformed to other functions, the better a building can meet to changing demands.
	Access	12. **Horizontal access to building** In what way is the horizontal access of the units in the building accomplished?	1. Horizontal access is only by a single internal corridor (Bad) 2. Horizontal access is by a double internal corridor (Normal) 3. Horiz. access directly by a central core in the building with a surrounding corridor 4. Horizontal access is directly by a central core in the building, or an external gallery	The more the horizontal disclosure of the units is limited by a central core the more easily units in a building can be rearranged or transformed to other functions.

Specifically applicable indicators part 1 (Geraedts, 2016)

FLEX 4.0: SPECIFICALLY APPLICABLE INDICATORS, PART 1				
LAYER	**SUB-LAYER**	**Flexibility Performance**	**Assessment Values**	**Remarks**
1. SITE		1. **Surplus of site space** Does the site have a surplus of space and is the building located at the centre?	1. No, the site has no surplus of space at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. The site has a surplus space of more than 50% (Best)	The more surplus space on site, the better the building is expandable (horizontal).
		2. **Multifunctional site/location** Is the location capable to support more functions, like offices, living, care and shops?	1. Just one function; suited for offices or living or care or shops (Bad) 2. Two functions (Normal) 3. Three functions (Better) 4. > Three functions; suited for offices, living, care and shops as well (Best)	The more a location around a building supports more different functions of the building, the more easily a building can be rearranged or transformed to other functions.
2. STRUCTURE	Measurement	3. **Available floor space of building** Does the building or the user units have a surplus of the needed usable floor space?	1. No, the building or user units have no surplus of floor space at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. The building has a surplus of floor space of > 50% (Best)	The more surplus space a building/user units have, the more easily a building can be rearranged or transformed to other functions, the better a building can meet to changing user demands.
		4. **Size of floor buildings** What is the size of the usable floor surface?	1. The usable floor space < 400 m2 (Bad) 2. 400 - 600 m2 (Normal) 3. 600 - 1000 m2 (Better) 4. The usable floor space > 1000 m2 (Best)	The larger the size of the usable floor surface the more easily units in a building can be rearranged or transformed to other functions.
		5. **Measurement system** Have positioning/measurement modulare rules for construction components been used?	1. Rules for modular coordination are not implemented (Bad) 2. <50% implemented (Normal) 3. >50% implemented (better) 4. Rules for modular coordination are > 90% implemented (Best)	The more project independent, demountable and replaceable construction components have been implemented, the more easily a building can be rearranged or transformed to other functions.
		6. **Horizontal zone division/layout** Has use been made of a horizontal zoning system, including intermediate margins?	1. No zoning system of a zoning system without intermediate margins (Bad) 2.Yes, with 10-30% intermediate margins (Normal) 3. Yes, with 30-50% intermediate margins (Better) 4. Yes, with met > 50% intermediate margins	The more margins are used in the zoning system of the building, the more easily a building/units can be rearranged, extended or transformed to other functions.
		7. **Presence of stairs/elevators** Are sufficient stairs/elevators present in the building?	1. Only one decentred located stairs/elevator core is available in the building (Bad) 2. There is one central located stairs/elevator core available in the building (Normal) 3. The building is divided into different wings each with a central stairs/elevator core 4. The building has one central and several decentred stairs/elevator cores per wing	The more stairs/elevators are available in the building the more easily a building/units can be rearranged, rejected, extended or transformed to other functions.
		8. **Extension/reuse of** Is there a possibility to add new stairs/elevators to the building and reusing the existing ones?	1. No stairs/elevators can be added without drastic expensive measures (Bad) 2. A new stairs/elevators core can be accidently added and existing reused (Normal) 3. New stairs/elevators can be limited added and existing ones reused (Better) 4. New stairs/elevators can be easily without drastic expensive measures (Best)	The more stairs/elevators can be added to the building the more easily a building can be rearranged, rejected, extended or transformed to other functions.
	Construction	9. **Surplus of load bearing capacity** How large is the load bearing capacity of the floors in the building?	1. < 3 kN/m2 2. 3 - 3,5 kN/m2 3. 3,5 - 4 kN/m2 4. > 4 kN/m2 and several areas > 8 kN/m2	The larger the load bearing capacity of floors, the easier a building can be rearranged, transformed to other functions, or vertical extended, the better a building can meet to changing user demands.
		10. **Shape of columns** How are the columns in the building shaped?	1. The columns are shaped round and/or have vertical different sizes (Bad) 2. The columns are shaped octagonal (Normal) 3. The columns are shaped rectangular (Better) 4. The columns are shaped square (Best)	The less deviate from a square column, the better a building/units can be rearranged (standardized connection of inner walls).
		11. **Positioning of facilities zones** Are facilities zones and vertical shafts located at central building level and/or local unit level?	1.All facility zones and vertical shafts are only located at central level (Bad) 2. Facility zones/shafts are located at central level and occasionally at local level 3. Facility zones/shafts are located at central level and limited at local level (Better) 4. Facility zones/shafts are located at central level and at local level as well (Best)	The more facility zones/shafts are located at unit level, the easier a building can be rearranged, transformed to other functions.
		12. **Fire resistance main bearing** How many minutes is the fire resistance of the main load bearing construction?	1. The fire resistance of the load bearing construction is 30 minutes (Bad) 2. The fire resistance of the load bearing construction is 60 minutes (Normal) 3. The fire resistance of the load bearing construction is 90 minutes (Better) 4. The fire resistance of the load bearing construction is 120 minutes (Best)	The higher the fire resistance of the load bearing construction, the easier a building can be rearranged/transformed to other functions, the better a building can meet to changing demands.
		13. **Extendible building/units horiz.** Is it possible to expand the building horiz. for new extension to the building/user units?	1. Horizontal extension of building/units is not possible at all (Bad) 2. Horizontal extension of building/units is very limited possible (only at one side) 3. Horizontal extension of building/units is limited possible (at more sides) (Better) 4. Horizontal extension of building/units is easily possible at all sides (Best)	The more a building/unit can be expanded, the easier a building can be rearranged or transformed to other functions or expanded, the better a building can meet the changing user demands.
		14. **Extendible building/units vert.** Is it possible to expand the building vertically, for adding new floors or a new basement?	1. Vertical extension of building/units is not possible at all (Bad) 2. Vertical extension is limited possible; only for a few units in the building (Normal) 3. Vertical extension (added floor or basement) is possible after total rearrangement 4. Vertical extension (new floors/basement & individual user units) is possible (Best)	The more a building/unit can be vertically expanded, the easier a building can be rearranged or transformed to other functions or expanded, the better a building can meet changing user demands.
		15. **Rejectable part of building/unit** Is it possible to reject part of the building for selling/renting to third parties?	1. It is not possible to reject part of building/units (Bad) 2. It is possible to reject 10-30% of the building/units (Normal) 3. It is possible to reject 30-50% of the building units (Better) 4. It is possible to reject >50% of the building/units (Best)	The more (part of) a building/unit can be vertically rejected, the easier a building can be rearranged/transformed to other functions, the better a building can meet changing user demands.
		16. **Insulation between stories/units** How is the thermal and acoustic insulation between the different storeys in the building?	1. Insulation does not meet the current demands for office buildings anymore (Bad) 2. Meets the current demands for office buildings (Normal) 3. Also meets the current demands for housing and care (Better) 4. Meets 10% above the current demand for offices, housing and care (Best)	The better the thermal and acoustic insulation between the different storeys, the easier a building can be rearranged/transformed to other functions, the better a building can meet changing demands.

Specifically applicable indicators part 2 (Geraedts, 2016)

FLEX 4.0: SPECIFICALLY APPLICABLE INDICATORS, PART 2				
LAYER	**SUB-LAYER**	**Flexibility Performance**	**Assessment Values**	**Remarks**
3. SKIN	**Facade**	**17. Dismountable facade** To what extend can facade components be dismantled in case of transformation?	1. Facade components can not or hardly be dismantled without demolition (Bad) 2. A small part of the facade components can be dismantled (> 20 < 50%) (Normal) 3. A large part of the facade components can be dismantled (> 50 < 90%) (Better) 4. All facade components are easily dismountable (> 90%) (Best)	The more facade components are easily dismountable, the more easily a building can be rearranged or transformed to other functions.
		18. Location/shape daylight In what way are the facade/daylight openings positioned and shaped?	1. There are large closed surfaces in the facade (Bad) 2. There are small horizontal open surfaces in the facade (Normal) 3. Large open surfaces in the facade, but with different height sizes (Better) 4. Large continuous horiz. open surfaces; connections according to planning grid	The more regular open surfaces in the facade according to the planning grid, the better a building can meet changing demands in functions, quality and finishing of the building.
		19. Insulation of facade How is the thermal and acoustic insulation quality of the facade of the building?	1. Insulation does not meet the current demands for office buildings anymore (Bad) 2. Meets the current demands for office buildings (Normal) 3. Also meets the current demands for housing and care (Better) 4. Meets 10% above the current demand for offices, housing and care (Best)	The better the thermal and acoustic insulation of the facade, the easier a building can be rearranged or transformed to other functions, the better a building can meet the changing user demands.
4. FACILITIES	**Measure & Control**	**20. Measure & control techniques** Is it possible to control/measure facilities on building level as well on user unit level?	1. Control/measurement takes place only at central building level (Bad) 2. On central level and occasionally on unit level (Normal) 3. On central level and limited on unit level (Better) 4. As well central on building level as well completely on unit level (Best)	The more possibilities for measurement and control of the facilities on unit level, the more easily units in a building can be rearranged or transformed to other functions.
	Dimensions	**21. Surplus capacity of facilities** Does the capacity of (the sources of) the facilities have a surplus capacity?	1. The capacities of facilities have no surplus at all (Bad) 2. The capacities of facilities have a surplus of 10-30% (Normal) 3. The capacities of facilities have a surplus of 30-50% (Better) 4. The capacities of facilities have a surplus of > 50% (Best)	The more surplus capacity of the facilities, the easier a building can be rearranged or transformed to other functions, the better a building can meet to changing user demands.
	Distribution	**22. Distribution facilities** Does the building have a specific distribution facility for hot/cold water, heating, cooling, gas?	1. There is a specific distribution facility for all the different sources (Bad) 2. There is a specific distribution facility for some of the different sources (Normal) 3. There is a specific distribution facility for 2 of the different sources (Better) 4.There is no specific distribution facility one of the different sources (Best)	The less specific distribution equipment facilities have, the easier a building can be rearranged or transformed to other functions, the better a building can meet the changing user demands.
		23. Location sources facilities What is the location of the central facility sources?	1. The facilities sources are located at only one central location in the building (Bad) 2. The facilities sources are located at several locations in the building (Normal) 3. The sources are located at a central location and a decentred location as well. 4. The sources are located at outside the building at city level (district heating)	The more facility sources are localized at decentred level, the easier a building can be rearranged or transformed to other functions, the better a building can meet the changing user demands.
		24. Disconnection of facility Can the components of the facilities be easily disconnected?	1. Facility (parts) can not be disconnected or demounted; 'wet' connections (Bad) 2. Hardly be disconnected, demounted (Normal) 3. Partly be disconnected, demounted (Better) 4. Facility (parts) can be disconnected very easily (completely demountable) (Best)	The more facility parts can be disconnected or demounted, the easier a building can be rearranged/transformed to other functions, the better a building can meet to changing demands.
		25. Accessibility of facility To what extend are facility components good accessible?	1. Hardly or not accessible (components on support level; concreted in) (Bad) 2. Limited accessible (partly on support and infill level) (Normal) 3. Good accessible (a lot of components on infill level) (Better) 4. Very good accessible; most components at infill level; completely demountable	The higher the accessibility of facilities components, the more easily units in a building can be rearranged or transformed to other functions.
		26. Independence of user units In what way are the user units independent related to services as pantry, toilet facilities?	1. No services available at user unit level (Bad) 2. 1 - 2 services available (Normal) 3. 3 - 4 services available (Better) 4. > 4 services available (Best)	The more services are available at unit level, the more independent the units are opposite other units in the building, the more they meet to individual user demands.
5. SPACE	**Functional**	**27. Multifunctional building/Units** Is the building capable to support different functions, like offices, living, care and shops?	1. The building supports only one function (Bad) 2. The building supports 2 functions (Normal) 3. The building supports 3 functions (Better) 4. The building supports > 3 functions (Best)	The more a building supports more different functions of the building, the more easily a building can be rearranged or transformed to other functions.
	Technical	**28. Disconnectable, removable,** To what extend are the user units in a building removable, relocatable?	1. The user units in the building are not removable, relocatable (Bad) 2. The units are only relocatable with drastic expensive measures (Normal) 3. Units are easy relocatable; constructed with demountable components (Better) 4. Easy relocatable; constructed with 2D/3D modules, transportable by road (Best)	The more the units consist of demountable and reusable components, the better the units are relocatable to another location in or outside the building.
		29. Disconnectable, removable, To what extend are inner the walls in the building easily replaceable?	1. Inner walls are not replaceable without drastic/expensive interventions (bad) 2. Inner walls are not replaceable, but good destructible (Normal) 3. Inner walls replaceable by dismantling and rebuilding at another location (Better) 4. Inner walls are easily replaceable without radical/expensive interventions (Best)	The more inner walls can be easily replaced, the more easily a building can be rearranged or transformed to other functions, the better a building can meet to changing user demands.
		30. Disconnectable connection detail Which detailed construction is applied between the interior walls and support structure and facade?	1. The detailing connection consists of penetrating connections (Bad) 2. The detailing connection consists of wet connections (mortar, sealant, glue) 3. The detailing consists of specific project bound connection elements (Better) 4. The detailing consists of project unbound dismountable connections (Best)	The easier the connection of interior walls can be dismounted, the easier a building can be rearranged or transformed to other functions, the better a building can meet to changing demands.
		31. Possibility of suspended ceilings Is it possible to apply suspended ceilings (-0.20m) and to adapt these to the different user demands?	1. Suspended ceiling results in free floor height of < 2.60 m (Bad) 2. Suspended ceiling results in free floor height of 2.60-2.70m (Normal) 3. Suspended ceiling results in free floor height of 2.70-2.80m (Better) 4. Suspended ceiling results in free floor height of > 2.80m (Best)	The higher the free storey height, the better the building can meet to changing demands concerning functions, facilities, finishing and quality of the building.
		32. Possibility of raised floors Is it possible to apply raised floors and to adapt these to the different user demands?	1. Raised floor results in free floor height of < 2.6 m (bad) 2. Raised floor results in free floor height of 2.60-2.70m (Normal) 3.Raised floor results in free floor height of 2.70-2.80m (Better) 4. Raised floor results in free floor height of > 2.80m (Best)	The higher the free storey height, the better the building can meet to changing demands concerning functions, facilities, finishing and quality of the building.

FLEX 4.0 indicator weighting

SAMPLE	<# SAMPLE>	
LAYER	SKIN/STRUCTURE /SPACE PLAN	ELEMENT/ PRODUCT <DESCRIPTION>

FLEX 4.0: GENERALLY APPLICABLE INDICATORS					
LAYER	SUBLAYER	FLEXIBILITY PERFORMANCE	weighting	assessment	score
1. SITE		1. EXPANDABLE SITE/LOCATION	1		0
2. STRUCTURE	MEASUREMENT	2. SURPLUS OF BUILDING SPACE/ FLOOR	4		0
		3. SURPLUS OF FREE FLOOR HEIGHT	4		0
	ACCESS	4. ACCESS TO BUILDING	2		0
	CONSTRUCTION	5. POSITIONING OBSTACLES/ COLUMNS	3		0
					0
3. SKIN	FACADE	6. FACADE WINDOWS TO BE OPENED	1		0
		7. DAYLIGHT FACILITIES	2		0
4.FACILITIES (SERVICES)	MEASURE AND CONTROL	8. CUSTOMISABILITY/ CONTROLLABILITY	3		0
	DIMENSION	9. SURPLUS OF FACILITIES SHAFTS	4		0
		10. MODULARITY OF FACILITIES	2		0
					0
5.SPACE (SPACE PLAN AND STUFF)	FUNCTIONAL	11. DISTINCTION BETWEEN SUPPORT-INFILL	4		0
	ACCESS	12. HORIZONTAL ACCESS TO BUILDING	3		0
				Score	0

FLEX 4.0: SPECIFICALLY APPLICABLE INDICATORS					
LAYER	SUBLAYER	FLEXIBILITY PERFORMANCE	weighting	assessment	score
1. SITE		1. SURPLUS OF SITE SPACE	4		0
		2. MULTIFUNCTIONAL SITE/LOCATION	3		0
2. STRUCTURE	MEASUREMENT	3. AVAILABLE FLOOR SPACE OF BUILDING	4		0
		4. SIZE OF FLOOR BUILDING	3		0
		5. MEASUREMENT SYSTEM	3		0
		6. HORIZONTAL ZONE DIVISION/ LAYOUT	1		0
		7. PRESENCE OF STAIRS/ELEVATORS	2		0
		8. EXTENSION/ REUSE OF	1		0
	CONSTRUCTION	9. SURPLUS OF LOAD BEARING CAPACITY	2		0
		10. SHAPE OF COLUMNS	1		0
		11. POSITIONING OF FACILITIES ZONES	3		0
		12. FIRE RESISTANCE MAIN BEARING	3		0
		13. EXTENDIBLE BUILDING/ UNITS HORIZONTA	2		0
		14. EXTENDIBLE BUILDING/ UNITS VERTICAL	4		0
		15. REJECTABLE PART OF BUILDING/UNIT	2		0
		16. INSULATION BETWEEN STORIES/UNITS	2		0
3. SKIN	FACADE	17. DISMOUNTABLE FACADE	1		0
		18. LOCATION/ SHAPE DAYLIGHT	2		0
		19. INSULATION OF FACADE	1		0
4.FACILITIES (SERVICES)	MEASURE AND CONTROL	20. MEASURE AND CONTROL TECHNIQUES	4		0
	DIMENSION	21. SURPLUS CAPACITY OF FACILITIES	4		0
	DISTRIBUTION	22. DISTRIBUTION FACILITIES	4		0
		23. LOCATION SOURCES FACILITIES	3		0
		24. DISCONNECTION OF FACILITY	3		0
		25. ACCESSABILITY OF FACILITY	3		0
		26. INDEPENDENCE OF USER UNITS	1		0
5.SPACE (SPACE PLAN AND STUFF)	FUNCTIONAL	27. MULTIFUNCTIONAL BUILDING/ UNITS	2		0
	TECHNICAL	28. DISCONNECTABLE, REMOVABLE	1		0
		29. DISCONNECTABLE/ REMOVABLE	4		0
		30. DISCONNECTABLE CONNECTION DETAIL	4		0
		31. POSSIBILITY OF SUSPENDED CEILINGS	2		0
		32. POSSIBILITY OF RAISED FLOORS	2		0
				Score	0
				Total score	0

ADAPTIVE CAPACITY FOR STRUCTURES ACCORDING CORE MEASUREMENT AND			
ADJUSTABLE		CONVERTIBLE	
VERSATILE		SCALABLE	
REFITTABLE		MOVABLE	

N/A	NOT APPLICABLE
X	APPLICABLE
0	NOT APPLICABLE

Reflection

Reflection

The following part of the report aims to reflect on different aspects related to the development of this graduation project from the researcher's point of view. This reflection entails the several lessons learned during the execution of the research.

During this reflection chapter, I would like to address my previously presented personal study targets[3]:

1. Independence, study/work plan;
2. Being able to describe the functional value as an independent concept from the economic and technical value;
3. Learning to make a profound argumentation and reflection, by positioning myself in a broader context of the built environment;
4. Consider mishaps during my graduation process as challenges rather than as obstacles;
5. To gain in-depth knowledge about the subject to be studied (circular economy and its functional value) and to make practical and scientifically based statements and reasoning about it;
6. Working and conducting research in a professional environment with associated responsibilities

Research Topic

From the beginning of the graduation process, I found it relatively easy to identify a relevant and engaging topic. Throughout the final quarter of my Master's in Management in the Built Environment (MBE) program, I gained more insight into the circular economy and its growing significance. However, defining my research topic presented the main challenge of this thesis. In the initial stages, my objectives and perspectives led to frustration and feelings of being overwhelmed as I realized that my initial topic was infeasible due to ambiguous concepts in the literature.

Eventually, I chose to focus on the reuse of building products and elements due to my personal background. I come from a developing country where, in the past, all construction materials were fabricated and manufactured locally. The depletion of natural resources in this context led to material scarcity, which piqued my interest in exploring how building products could be repurposed to mitigate such risks.

This research topic aligns with the MBE program's coursework, which encourages students to think creatively beyond obstacles and identify enablers to overcome challenges. Throughout the Redesign project and the Urban and Infrastructure Redevelopment Game, I learned to be flexible and develop innovative solutions within given constraints. In executing this research, I deepened my knowledge of the topic and developed my skills in constructing persuasive arguments, which helped me meet my personal study targets (3 and 5)

While there was a clear research gap in the topic I studied, the experience taught me the importance of conducting early-phase interviews with experts in the field during the first stages of the graduation process (P1 and P2). Such interviews could help identify existing research and determine the specific research question.

Research Approach

This research was approached as exploratory research, where the final results were not yet known or tangible. To begin the data collection process, I delved into conducting interviews with construction professionals, who were keen to participate and share their knowledge about their unique projects. Although the interviews were enriching and interesting, there were times when it was challenging to

[3] Brandt Wassink, A. (2023) *What's next?* [Unpublished P2 Research Proposal]

collect the necessary data due to the unclarity of the research goal on my part (during this part I met my personal study targets 1 and 6).

Through conducting interviews, I began to understand the barriers to reusing building products and what construction professionals consider before making the decision to reuse them. Initially, I broadened the data selection to include all reused building products, but I soon realized that reused building products in new-built projects were the most relevant to my research. This helped me focus my research and better understand what technical aspects limit the reuse of building products.

After collecting data from the interviews, I created a Google Form survey to gather and organize all the information in one place. However, the data analysis process was time-consuming due to the different answers from the interviewees and their varied concept selections. To address this, I codified the answers and thematically analysed them as learned during Research Methods 2, which helped me draw conclusions on the type of building products analysed. However, in retrospect, I believe that doing market research beforehand to identify the type of building products to study could have led to more insightful questions, allowing me to interview different parties involved in the whole supply chain of the reused building product.

Research Process

Throughout the research process, I learned to embrace the unexpected and view each challenge as an opportunity to improve (personal study goal 4). Originally, my thesis focused on creating a conceptual assessment framework for building elements and products based on their functional value. However, I soon realized that this concept was too ambiguous and couldn't be defined (personal study goal 2 was not met). As a result, my focus shifted to exploring the relationship between the technical value of building elements and products and their potential for reuse.

While the research direction changed significantly, I learned to prioritize and analyse the data to find useful and interesting findings. This led to a more tangible and connected research question that was based on the collected data.

During this process, my supervisors provided valuable feedback and encouragement to be critical of my findings. Despite the challenges, I learned to trust the process and found the motivation to continue. Overall, this experience taught me the importance of flexibility, perseverance, and critical thinking in research.

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