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Digital Solutions for Advancing Reuse in the Industry: A Circular Economy Perspective

A critical review on related work and a practical study

Master's thesis in Design, Construction, and Project Management

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The Swedish Architectural, Engineering and Architectural (AEC) industry recognizes the importance of transitioning from Linear Economy (LE) to Circular Economy (CE) approach in order to reduce waste, promote sustainable resource utilization, and align with Sweden's vision of becoming a "net-zero emissions" country by 2045 (Adams et al., 2017; Boverket, 2023a).

This transition offers environmental, economic, and social benefits. However, implementing CE practices in the building sector requires collaboration among various stakeholders, including governmental agencies, stakeholders from the industry, and academia. Guidelines, policies, and incentives should be developed to encourage the adoption of CE practices. Furthermore, Comprehensive education and awareness-raising efforts are needed to ensure decision-makers, architects, engineers, and industry professionals are well-informed about the advantages of adopting circular economy practices and the necessary implementation steps. (Ghisellini, Ripa, and Ulgiati, 2018; Walker et al., 2021; Ababio and Lu, 2022; Bellini and Bang, 2022).

The thesis provides insights into the challenges and opportunities associated with incorporating CE practices in the Swedish AEC industry, emphasizing the role of information flow with a digital framework in order to enhance circularity. It underscores that the growing awareness to shift towards CE models in order to address the environmental impact within the industry. Fostering innovation, promoting eco-friendly technologies, addressing social and cultural barriers, updating regulations, overcoming financial obstacles, and developing innovative solutions are key aspects for a successful circular implementation.

The thesis also highlights the importance of collaboration, knowledge sharing, and information flow in establishing a common understanding of CE practices. Governments, regulatory bodies, and stakeholders in the industry should collaborate to develop supportive policies, regulations, and incentives. Digital tools, such as 3D scanning, inventory management systems, and databases, play a vital role in enhancing collaboration and value co-creation, but their adoption may face challenges. This is due to the fragmented and conservative characteristics of the industry. Furthermore, the thesis stresses the need for further development, standardization, and consensus on digital tools and software's for material reuse. Categorizing and grouping existing materials, conducting pre-demolition audits, and developing control plans are essential for streamlining information flow, facilitating inventory management, and identifying reusable building products. Life cycle assessment (LCA) and environmental product declarations (EPD) have limitations for reused materials, emphasizing the importance of a reliable basic material passport.

The thesis concludes that integrating CE practices, improving information flow, and embracing digitalization can lead to greater resource efficiency, waste reduction, and a more sustainable Swedish AEC industry. The findings and recommendations contribute to further research and actions for successful circular implementation in construction projects, advancing sustainable development and CE implementation.

Keywords: Environmental Degradation, Architectural, Engineering and Construction (AEC) Industry, Circular Economy (CE), Demolation Waste (DW), Digitalization, Database, Digital framework, Digital Tools, Building Information Modelling (BIM) and Data Sharing.

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We are sincerely grateful to all the respondents who graciously participated in this study. Their valuable time, thoughtful insights, and active involvement have been pivotal in gathering the necessary data and enriching the findings of this thesis. Their willingness to share their experiences and perspectives has been an invaluable contribution to the overall success of this research.

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We are deeply grateful to our beloved family and friends for their unwavering support, understanding, and encouragement during this challenging yet fulfilling academic journey. Their belief in my abilities, constant motivation, and invaluable presence have been pivotal in surmounting obstacles and maintaining focus on achieving my academic goals.

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Al Keek, Mohammad and Jiménez Parra, Jefferson - Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AEC	Architectural, Engineering and Construction
AI	Artificial Intelligence
BAMB	Buildings As Material Banks
BIM	Buildin Information Modelling
CCBuild	The Center for Circular Buildings
CD	Conventional Demolition
CE	Circular Economy
DW	Demolation Waste
EPD	Environmental Product Declaration
EPEA	Environmental Protection Encourangement Agency
GPR	Ground Penetrating Radar
IFC	Industry Foundation Class
LADAR	Laser Distance and Ranging
LCA	Life Cycle Analysis
LE	Linear Economy
LiDAR	Light Detection and Ranging
MD	Mixed Demolition
MP	Material Passport
PBL	The Swedish Plan and Building Act
RDF	Resource Description Framework
RFID	Radio Frequency Identification
SD	Selective Demolition
TLS	Terrestiral Laser Scanner

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1. Background

This chapter provides an introduction to the environmental impact caused by human activities, reviewing it on a global scale. It then narrows the focus to the Architectural, Engineering, and Construction (AEC) industry, specifically exploring the environmental impact of the construction sector worldwide. In addition, the chapter examines the current state of the Swedish AEC industry and its environmental footprint. It discusses how the implementation of Circular Economy principles seek to promote the environmental work in the industry. Finally, the chapter concludes by presenting the aim of the study and the research questions.

1.1 Environmental impact of the Architectural, Engineering and Construction Industry

Sustainability consists of three main pillars, Environmental, Social, and Economic. The majority of the countries in the world do not cover all dimensions of sustainability. The focus today is on the environmental pillar for its impact across all sectors (Lima et al., 2021). The current state of the world is undergoing rapid transformations, with the environment being a topic of increasing concern for individuals across all sectors. The academia has recognized this issue as a threat to human life, a viewpoint supported by Wijaya (2014) who notes that this is a result of human activities that will have a detrimental effect on the environment, economy, and society. Furthermore, studies indicate that climate change and global warming will disproportionately affect the world. According to Zaytsev et al. (2020) temperatures and the frequency of natural disasters have increased. Where, developing countries with the most vulnerable populations being those in third world nations will get negatively affected the most (Wijaya, 2014).

Additionally, Jemal et al. (2023) and United Nations (2022) states that the Architectural, Engineering and Construction Industry (AEC) plays a crucial role in the economic development of a nation, but it is also known to be one of the most resource-intensive industries, responsible for generating one-quarter of the world's waste, 39% of energy and gas emissions, and consuming 50% of all materials used in Europe. As a result the AEC industry plays a significant role in the global climate change crisis. According to Cossu and Williams (2015) building activities are expected to increase, which will result in a heightened consumption of limited natural resources and aggravate the challenge of providing sufficient land and materials. As consequence the AEC is a significant contributor to waste production, with an estimated of 3 billion tons of waste generated annually Akhtar and Sarmah (2018), whereas the European union stands for around one billion (Gallego-Schmid et al., 2020). The production of materials, products, and equipment also contributes negatively to the environment, with an estimated loss of between 1.6% and 8.4% for ceramic bricks alone (Garcia et al., 2014; Hentges et al., 2022).

According to Boverket (2023a), the Swedish AEC industry has a significant environmental impact, accounting for approximately 5-40% of Sweden's overall impact. While Sweden has made progress in reducing greenhouse gas emissions, nitrogen oxide emissions, and the use of hazardous chemicals over the past 15 years, there have been simultaneous increases in particle emissions, total energy usage, and the use of environmentally harmful substances. Despite the reduction in environmental impact, the industry has seen an increase in production, successfully decoupling production from climate impact along the value chain.

Furthermore, in 2020, the Swedish AEC industry was responsible for 9.8 million tons of CO_2 emissions, representing 21% of the country's total emissions, a 9% decrease from 2019. However, Sweden's domestic greenhouse gas emissions have increased by 1% since 2019 (Boverket, 2023b).

The AEC industry consume large quantities of materials, resulting in significant waste generation at the end of a building's lifespan. Sweden had set recycling goals, aiming for a minimum of 70% recycling and utilization of demolition waste by 2020. Currently, Sweden falls short of this goal, with building recycling rates ranging between 50-60%. The building sector is the second-largest waste generator in Sweden, contributing approximately 28% of the country's total waste and 33% of hazardous waste (Boverket, 2023a).

In 2020, waste generated by the Swedish AEC industry amounted to 14.2 million tons, accounting for 40% of Sweden's total waste. This represents a 16% increase since 2018 and a 55% increase since 2014. Aligning these parameters is crucial for Sweden to achieve its vision of becoming a "net zero emissions" country by 2045 (Boverket, 2023a).

These materials are often sent to landfills as a result of linear economic models that follows the "take, make and dispose of" approach (Jemal et al., 2023). However, the linear economy (LE) model remains the dominant model in the AEC industry (Bellini and Bang, 2022; Hentges et al., 2022). To reduce the environmental impact of human activities such as manufacturing, transporting goods, and generating electricity, are major contributors to carbon dioxide emissions. Consequently, countries and organization are promoting innovative solutions by adopting new technologies, sustainable material, clean and efficient processes, environmental protection, renewables and reusing (Zaytsev et al., 2020; Lima et al., 2021). Hence, it has become imperative to adopt a circular economy (CE) approach to effectively manage resources and make the AEC industry truly sustainable (Jemal et al., 2023).

CE aligns with industrial ecology and enhances construction sustainability by promoting resource sharing and industrial symbiosis. It aims to minimize resource extraction, environmental impact, and waste by extending material use, reducing consumption, and emphasizing material recovery and reuse. CE involves transforming materials into new products, designing for durability, minimizing waste, and utilizing renewable, non-toxic, and biodegradable materials (Deutz et al., 2017; Hossain et al., 2020).

In addition, according to Andersson et al. (2021) the process of material reuse is considered as a CE practice. Furthermore, the reuse of products and materials can increase their lifespan and reduce waste while being an effective strategy for using resources more sustainably and reducing the climate impact from resource extraction, production, and waste management.

There is great potential for the reuse of construction products, but lack of knowledge among actors in the construction industry questions the environmental benefits and many refrain from reuse. Hence, to promote reuse of materials and products in new construction, planning is required at an early stage, formal procedures, and systematic work processes to save and stockpile materials and products awaiting reuse. To further increase the reuse of construction materials and products, clients should make specific demands prior to the construction of a new property (Miliute-Plepiene et al., 2021).

The transition towards CE practices in the AEC industry faces numerous hinders and challenges. The barriers to Circular Economy adoption can be broadly categorized as social and cultural, political, and legislative, financial,and economic, and technological. To overcome these barriers there is need of collaboration among stakeholders and the adoption of diverse strategies (Ghisellini, Ripa, and Ulgiati, 2018; Walker et al., 2021; Ababio and Lu, 2022; Bellini and Bang, 2022).

1.2 Aim

Since the environmental and economic impacts of reused materials are not well understood, and their benefits are mainly assumed to stem from the reduction of new production and waste. While energy demand during a building's use phase decreases due to energy regulations, embodied energy consumption and environmental impacts increase from the initial production of materials and resources used in construction. While the reuse of materials has potential as a future strategy, it does not guarantee an environmental benefit. Increasing the sales and use of reused products is necessary to achieve a real reduction in environmental impacts.

Against this background, the study aims to design a digital framework that would help the Architectural, Engineering and Construction (AEC) Industry to advance in the sustainability work by increasing the use of reused materials. The digital framework is expected to streamline the information flow which could decrease the time spent inventing materials for existing buildings. Additionally, the framework would track the information flow of a material, providing the design team, suppliers, and other stakeholders with valuable information about the products. Consequently, this information could prove beneficial in various building phases, including design and renovation.

1.3 Research Questions

How can a digital framework create better conditions to successfully implement circular processes in an office project?

- What are the key challenges in implementing Circular Economy and scaling material reuse practices?
- How should existing materials be grouped, categorized, and stored to streamline information flow in order to facilitate reuse projects?
- How can digitalization help to design a digital framework?

2. Methodology

As we have a vest interest in sustainability, specifically within the Architectural, Engineering and Construction (ACE) industry, we initiated a process to identify the key sustainability challenges faced by the industry. These challenges include substantial energy consumption, significant CO_2 emissions during raw material extraction, and high levels of waste production, among others. Based on this, we concluded that construction companies require more practical research in order to advance sustainable practices within the AEC industry.

Subsequently, we approached Skanska, one of Sweden's largest construction companies and a driving force behind sustainable practices in the industry, to investigate whether they were interested in collaborating on sustainability research to reduce their environmental impact. After conducting interviews with Skanska, we identified an opportunity to investigate the potential to designing a digital framework that could promote the reuse of materials, which aligned with Skanska's ongoing sustainability work in Gothenburg.

The study will critically examine the interplay between digital technologies and circular practices, by investigating how various digital tools can be connected to enhance circular practices. Additionally, the study will also identify and analyze the barriers and challenges faced by people (stakeholders) in implementing circular economy practices and digitalization in the AEC industry.

2.1 Workflow

As a considerable part of the study aims to provide a clear understanding for the reader, the following figure (1) presents a detailed workflow of the stages employed in this research. The workflow outlines the various stages of the research process, highlighting their associations with each other.

The process commenced by collaboratively identifying relevant research questions with Skanska. Subsequently, a thorough understanding of the subject matter was acquired through relevant literature, forming the foundation for our methodology in conjunction with the research questions. Moreover, the interview questions were formulated based on the preceding information, providing crucial insights for the practical study, including the selection of materials and what digital tools/software's to employ.

Next, the results were analyzed and discussed in relation to the literature and pertinent previous information. These findings served as the basis for developing the digital framework, drawing conclusions, and addressing our research questions.

Therefore, the primary aim of this workflow is to offer a comprehensive and transparent overview of the research methodology employed in this study. This allows readers to grasp the specific steps undertaken to obtain the results presented in the subsequent sections.

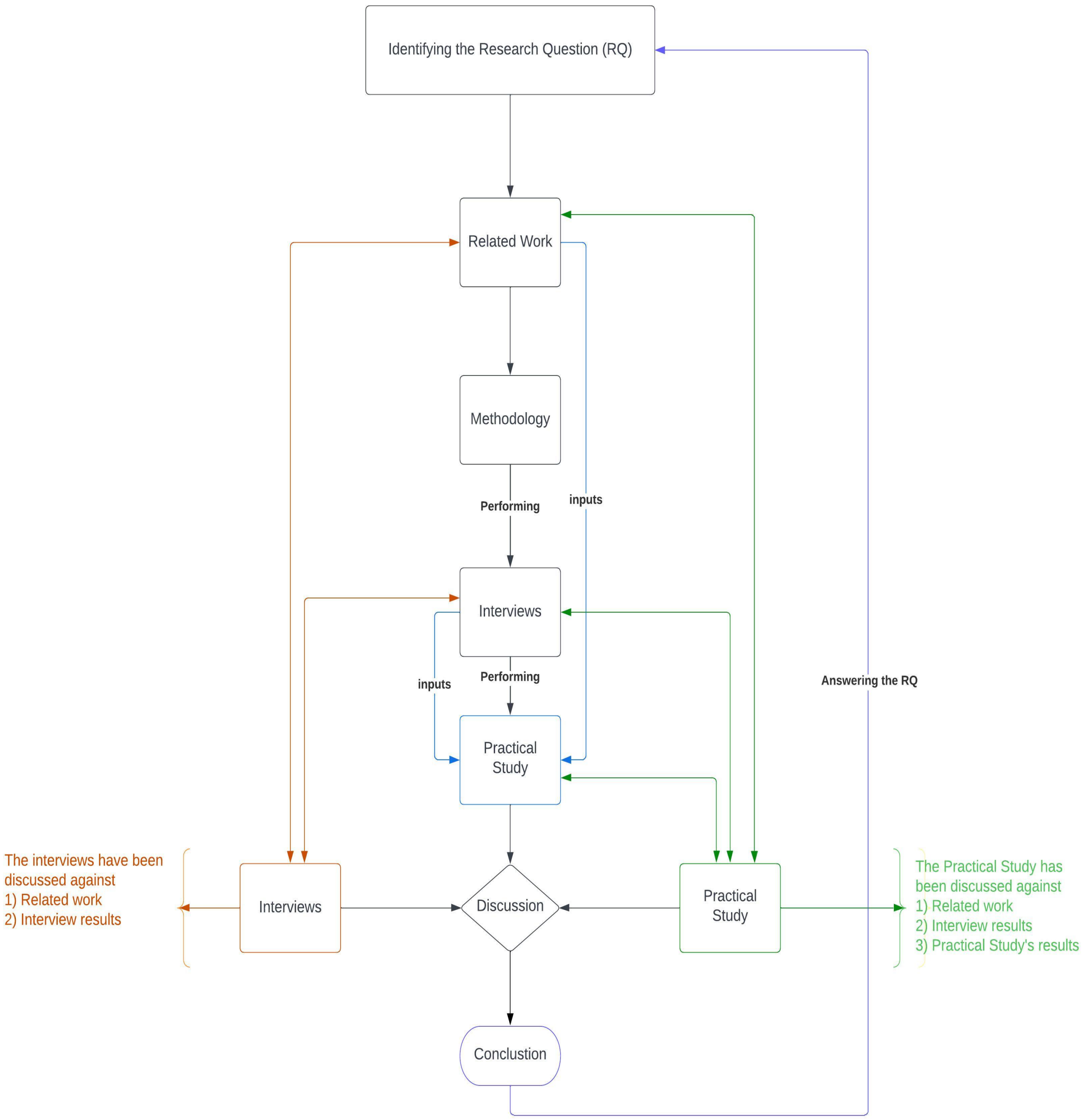

Figure 1: Workflow

2.2 Related work

In this study, well-known databases such as Google Scholars, Scopus, and Chalmers Library were used to find relevant articles using a combination of keywords, such as Environmental Degradation, Architectural, Engineering and Construction industry (ACE), Circular Economy (CE), Demolition Waste (DW), digitalization, Life Cycle Analysis (LCA), Building Information Modelling (BIM) and Data Sharing. The published research was divided into two intervals: 2015-2023 was chosen to gain more knowledge about recent industry developments related to the state of reuse of building components, and 2000-2015 was used to gain more background knowledge about the environmental impacts from the industry and the use of Linear Economy (LE).

Once the keywords were defined, online databases were used to guide inclusion and exclusion criteria (Bell, Bryman, and Harley, n.d.). The aim of this approach was to find relevant articles that could deepen understanding of environmental impacts from the industry and how the industry is dealing with these issues, by e.g., increasing the implementation of CE practices over the LE practices. The next step involved examining the titles and abstracts for relevance to the study purpose, selecting the most relevant articles, and arranging them.

Additionally, the study adopted a qualitative abductive research approach, which seeks to identify conditions that would make the phenomenon less puzzling, turning surprising facts into a matter of course (Bell, Bryman, and Harley, n.d.). This approach will help to build a practical study to design a digital framework. The selected articles were read deeper and analyzed, including qualitative interview studies, quantitative studies, systemic literature reviews, case studies, and experiments, to build both background knowledge and a related work. Furthermore, the literature in this study is a narrative review, which aims to develop an understanding of the subject, rather than simply gathering knowledge (Bryman, n.d.). This means that the review was based on finding what is interesting to explore further and to build a foundation for developing semi-structured interview questions.

2.3 Interviews

Semi-structured interviews are a method of collecting qualitative data and exploring complex issues. These interviews are selected for their ability to provide rich and detailed data on a wide range of topics. The choice of using semi-structured interviews is based on several factors (Bell, Bryman, and Harley, n.d.).

To begin with it allows for flexibility in questioning and on the course of the conversation. This means that questions can be tailored to the specific respondent based on their working positions, and new topics can be explored as they arise. Subsequently, semi-structured interviews can provide more detailed and nuanced responses from respondents. Hence, this depth allows for valuable insights into their perspectives and behaviors. Despite the flexibility, semi-structured interviews still follow a general guide or set of core questions, which promotes data collection in a standardized way. This standardization enables comparison and analysis of data across different respondents. Lastly, semi-structured interviews can create a more engaged and collaborative relationship between the interviewer and participant, leading to more honest and detailed responses (Bell, Bryman, and Harley, n.d.).

In addition, primary objective of conducting semi-structured interviews is to obtain a broader understanding of how the Swedish construction companies deal with Circular Economy (CE), specifically reused materials. The information gathered from these interviews will contribute to formulating a deeper and more comprehensive practical study. Thus, to achieve this goal, the interview questions were divided into three key areas based on the research questions which contribute to provide critical insights of the topic and further answer the research question :

- How companies in the Architectural, Engineering and Construction (AEC) Industry view and approach Circular Economy (CE).
- The inventory process of the expected reused materials, including the methods and digital tools involved.
- The challenges associated with implementing Circular Economy (CE) practices in the industry.

These key areas were developed based on the related work and were predominantly open-ended. Additional questions were raised during the interviews. The interview questions are show in Appendix 1.

Furthermore, the process of selecting suitable respondents commenced with an interview with our supervisor at Skanska, who suggested respondents with experience in sustainability, Circular Economy (CE) and projects with focus on reuse. The respondents hold diverse positions in the Swedish Architectural, Engineering and Construction (AEC) Industry, ranging from product and technology development managers to design managers and sustainability specialists with several holding degrees from Chalmers University of Technology. Moreover, the respondents work in various construction companies, and the purpose of it is to gain an overall understanding of how they deal with CE which would be helpful to deeply understand the topic and further design a digital framework . However, various criteria were employed when selecting the respondents, such as relevant knowledge or experience that aligns with the research questions, accessibility, and diversity. The study was set to nine interviews due to its time limit. Hence, the inclusion of perspectives and experiences can provide a more nuanced and comprehensive understanding of the topic under investigation and further help to design the practical study.

Moreover, the level of involvement in CE projects varies among the respondents. Some have been engaged in the field for several years, while others have recently started focusing on circularity (projects with focus on reuse). Additionally, the communication with the chosen respondents were via email and phone calls providing them with an overview of our study and organization. We also offered them the flexibility to schedule interviews, which was beneficial for coordinating our work during the interview period.

To avoided stress for both the respondents and us, the interviews were limited to 1.5 hours, and respondents were given clear instructions regarding the topics to be discussed and informed of the recording of the interview. Respondents also had the opportunity to receive the expected questions in advance. The interviews were conducted in Swedish and just one interview in English, either online or in-person based on the respondent's preference. Finally, and importantly, to safeguard the confidentiality of respondents and promote free speech and open communication, the study ultimately decided to utilize anonymous names.

In the final stage, the obtained results were analyzed using Nvivo 12, a software capable of efficiently processing large amount of data, thereby saving valuable time. It is worth noting that in order to analyze the data, we developed categories based on the related work, thereby enhancing the reliability and accuracy of the results.

2.4 Practical study

The aim of the practical study is to design a digital framework that can promote the inventory process by providing relevant stakeholders, such as the design team, with comprehensive data on a single reused product. Where the relevant data and the grouping (categorizing) of the reused materials will be stored in a database. This will promote the reuse of materials by tracking the supplied data and regulating the information flow of the reused product. Furthermore, it will simplify the design phase with reused products, while promoting sustainability and Circular Economy (CE) in the Architectural, Engineering and Construction (AEC) Industry.

According to Bell, Bryman, and Harley (n.d.), a practical study employing a qualitative research strategy typically employs an inductive approach in exploring the connection between theory and research. Hence, the practical study described here utilized an inductive approach to ensure the dependability of the case. This was achieved by designing the practical case and the digital framework on the related work, interviews, and additional documents from the consulting firm that conducted the inventory of Tennet 3.

This helped us in identifying crucial aspects, such as material selection and drawing inspiration from various digital tools utilized in the inventory process. Additionally, the initial phase (first round) involved inventory of the chosen components (materials) and scanning by using a 3D-scanner, 360 cameras, and smartphones. However, the data collected from smartphones and 360 cameras proved insufficient when processing the data. Consequently, a subsequent round (second round) of scanning was carried out, resulting in getting better data to process and analyze. Thereafter, a database was developed to organize the information gathered during the inventory of materials, incorporating the most relevant data from the practical study. The sequential stages undertaken to design a digital framework and will be shown in figure

2. However, more information about the practical study and how it was preformed including what digital tools and software's that were used is outlined in chapter 4.2 This is done to be more easier to the reader to follow up.

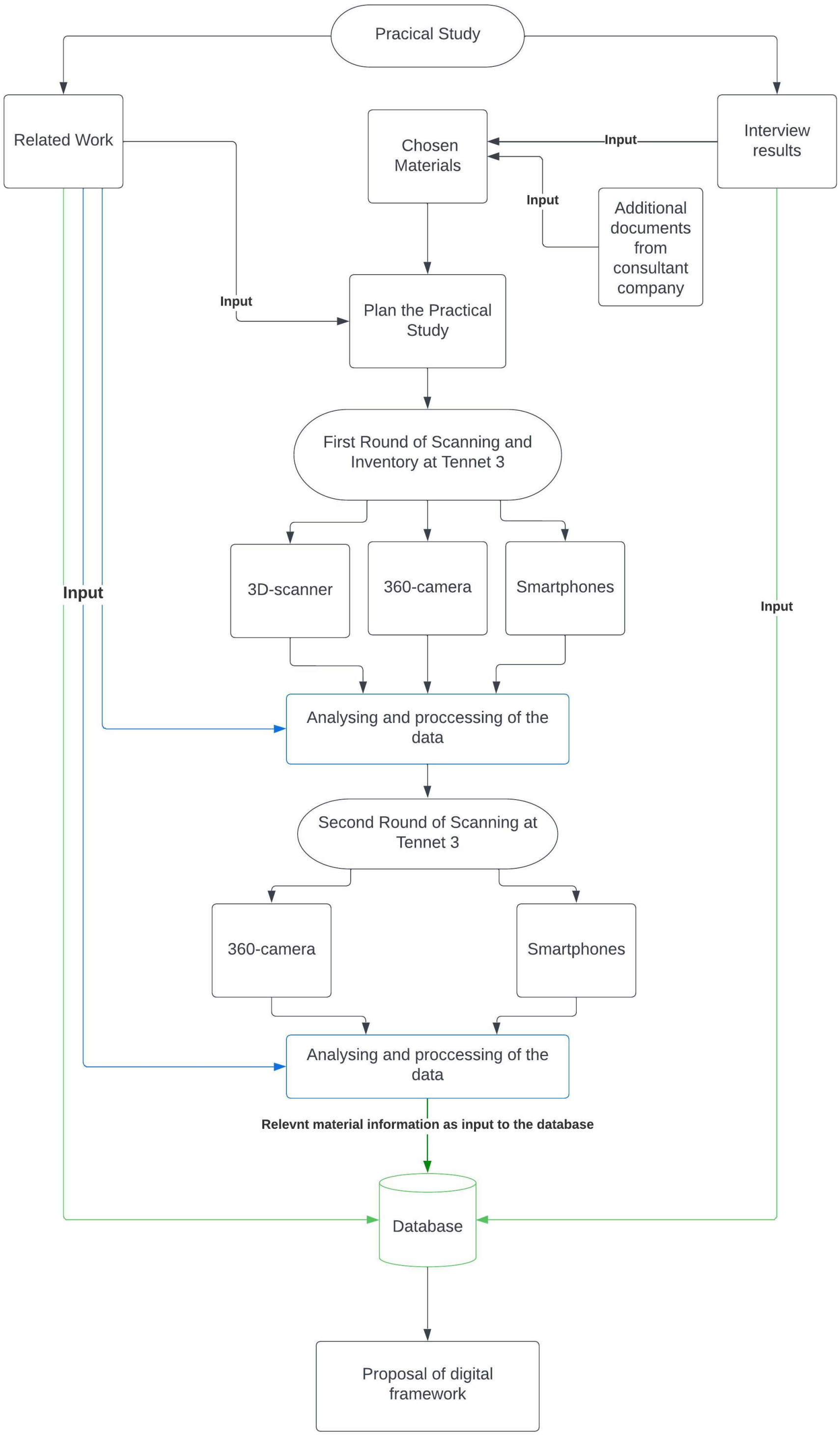

Figure 2: Workflow for practical study

2.4.1 Tennet 3

Before the start of the master's thesis, we performed a site-visit to Tennet 3, located in Kämpegatan, Gothenburg. Skanska, the project owner, plans to deconstruct the old office building "Holmens Herr" and rebuild it into another office building. Tennet 3 aims to enhance the attractiveness of the urban environment, offering a garden floor and developing office space with ample natural light that connects the existing and new buildings in the block (see figures 3, 4 and 5).

Skanska has the ambition to maximize the reuse or recycling of all materials that have the potential to be reused or recycled. Furthermore, the materials will be used either to rebuild the new office building or in other projects, in line with Skanska's ambitions to reduce its environmental impact by 50% by 2030 and achieve climate neutrality throughout its entire value chain no later than 2045 (Skanska, 2022).

As previously mentioned, the practical study commenced prior to the start of our master's thesis, during our discussions with Skanska regarding the research question at the beginning of January 2023. The initial step involved a site-visit to ''Holmens Herr" office building, with the objective of exploring the building and identifying potential materials for investigation. We then conducted the related work to identify various digital tools and held interviews with stakeholders who work with those tools. Combining the literature with the interviews was necessary for two reasons. Firstly, there is limited information on these tools in other projects or academic literature, such as BuildID, CCbuild and Palats, although they have been used in some reused projects according to some practice reports. Secondly, as the digital framework would assist in promoting Circular Economy (CE), specifically the reuse of materials, it was important to gain a comprehensive understanding of how different stakeholders and disciplines utilize these digital tools and identify any barriers and needs. This information would be valuable in designing the digital framework, which will comprise a combination of different digital tools.

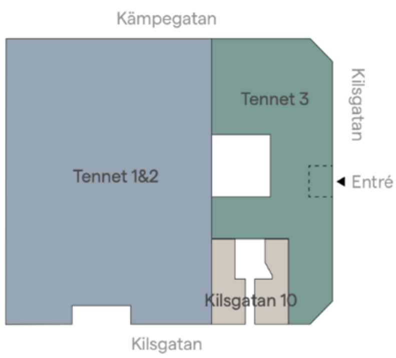

Figure 3: Location of Tennet 3 in Gothenburg

Figure 4: Overview from south

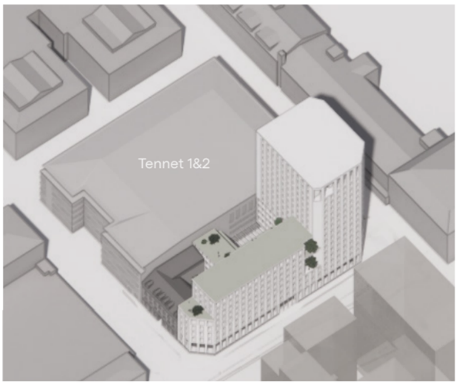

Figure 5: Illustration of Tennet 3

2.4.2 Choice of materials

The pracical study will also involve testing of three building components: entrance windows, façade window, and door. The reason for choosing these components is two-folded. To begin with, according to a report from Andersson et al. (2018) and Miliute-Plepiene, Almasi, and Hwargård (2020) , these products have a high potential for reuse, along with other items such as glass partitions, bricks, roof tiles, stoves and fridges, wardrobes, mirrors, and bathtubs, these components are significant contributors to waste in the building industry, hence there is a need to investigate and improve their reuse potential. Additionally, the study has a time limitation that makes it challenging to select a complicated elements such as wall that incorporates numerous components and obtain data and results for a single wall, which may require a significant amount of time. Likewise, the interview study investigates the building components with high reuse potential based on their environmental impact, ease of investigation, and that there is a market demand. The related work and interview study together with the limitations of the study will decide which building components that are most suitable for us to investigate.

2.5 Data Analysis

According to Yin (2007), analyzing the data from the practical study can be a challenging process because the strategies and techniques for doing so are not always well-defined or concrete. Experience with various tools and manipulative techniques can be helpful, but it is important to strive to formulate a general analytical strategy for each practical study. Yin (2007) describes three different strategies as following:

1. The first strategy is to rely on theoretical hypotheses. This strategy involves following the theoretical hypotheses that underlie the practical study. moreover, this may include research questions, a related work, or new hypotheses or propositions. By using the theoretical hypotheses, an analysis can be created that aligns with the original purpose of the practical study.ow companies in the construction industry view and approach Circular Economy (CE).
2. The second strategy is to have ideas about rival explanations. This strategy

involves defining and testing rival or competing explanations. This may involve investigating hypotheses that were not necessarily part of the original theoretical hypotheses. By using this strategy, different ways of interpreting and explaining the results of the practical study can be found.

3. The third strategy is to design a case description. This strategy involves developing a descriptive framework for the practical study. This is a less fruitful strategy than using theoretical hypotheses and rival explanations, but it can be used as an alternative when other approaches do not work. By using this strategy, an overview of the case and its context can be created.

In this study we will use the first strategy ‘‘ theoretical hypotheses” where our hypotheses consist of both the Circular Economy (CE) and digital tools. In other words, the digitalization has seen a significant increase over the last decade within the industry, likewise, CE has also earned much attention which could be promoted through digitalization (Kovacic, Honic, and Sreckovic, 2020; Jemal et al., 2023). Therefore, the designing of a digital framework could begin with the hypotheses as a starting point to promote Circular Economy practices, which suggests that the use of digitalization could promote Circular Economy practices and the implementation of an efficient digital framework would lead to an increase in the reuse of materials. The digital framework would be partly based on the related work where we identify the most relevant technologies and tools such as 3D-scanners, CAD-programs and inventory tools among others and further evaluate those by testing them in the practical study. Moreover, the data from the 3D-scanning will be cross-checked to a 3D-Revit family to assess the accuracy and quality of the 3D-scanning. Additionally, the practical study will provide essential information for the database from the digital tools that are evaluated. Finally, the interview result have been analyzed using Nvivo 12 as it is outlined in section 2.3 which will contribute with essential information for the database and the digital framework since it will be used by different stakeholders, such as decision makers, suppliers, design team, etc.

2.6 Limitations

This study is subject to certain limitations that must be acknowledged. To begin with, sustainability comprises three dimensions, namely the Environmental, Social, and Economic aspects, but this study will focus solely on the Environmental dimension due to time constraints. Additionally, the study will be limited to tracking three products from the inventory phase to the design phase, providing a limited scope of analysis. The study will explore investigate the inventory process through three different scanning methods, 3D-scanning, 360-camera and smartphones. Moreover, the study will only investigate three existing digital tools, BuildID, CCbuild and Palats to use as underlay to design the digital framework. Furthermore, the chosen methods and digital tools may not be representative of the wider range of options available. Furthermore, the selected methods need to be compatible with each other to able to perform the study. Additionally, the study requires the use of the following software’s, Autodesk Revit, Autodesk ReCap, Autodesk ReCap Photo, Reality Capture, Agisoft Metashape, Scaniverse, Matterport, Supabase, and Autodesk BIM data tool to process the data, storage the data, and for visualization of 3D-models. Thus, due to the time restrain software developers were not contacted and therefore the software's used were limited to free versions and to those accessible through Skanska's organization.

Moreover, the lack of familiarity with the used methods, software's, and digital tools poses implications for the study. It could result in reduced efficiency, accuracy, and effectiveness of data collection, analysis, and interpretation. Hence, we may encounter difficulties in implementing specific techniques, utilizing relevant software's, or leveraging digital tools to their full potential. As a consequence, the study's outcomes and conclusions may be limited in their scope and validity, potentially hindering the overall quality and reliability of the study findings.

The practical study will be performed on an existing building, Tennet 3, owned by Skanska, thus limiting the generalization of the findings. Lastly, the study will not consider the work environment, economic, or logistical aspects of the circular economy, which may impact the overall sustainability of a project.

2.7 Ethic

The Academy of Management (AOM) code of ethics places the responsibility on researchers to carefully assess the potential harm to research respondents and to minimize harm to the extent possible. Ethical considerations should extend beyond harm to respondents and include non-respondents, with the researcher making careful decisions about what is ethical in conducting their research (Bell, Bryman, and Harley, n.d.) .

From the mentioned view of point, the study focused on minimizing stress for both researchers and respondents, the interview duration was limited to 1.5 hours and respondents were given clear instructions on the topics to be discussed and that the interview will be recorded. Respondents were also given the opportunity to receive a copy of expected questions in advance if they wished. Furthermore, the interviews were conducted either online or in person at the respondent's discretion.

Additionally, to protect the privacy of respondents and encourage open communication, the study opted to use anonymous names. Moreover, we signed confidentiality agreements with Skanska's legal department and were restricted in the information they could access and disclose about the company.

The aim of the study is to promote the sustainability work in the Architectural, Engineering and Construction (ACE) industry and designing a digital framework that minimizes the industry's harmful impact on the planet.

In summary the study's ethical considerations include careful assessment of potential harm, minimizing stress for respondents, protecting privacy and confidential information, and extending ethical considerations beyond respondents to non-respondents.

2.8 Reflection over methodology

The chosen method for conducting semi-structured interviews in this study provided flexibility. However, the practical implementation was constrained due to the requirement of using free or easily accessible tools. Furthermore, the data analysis methods employed were not the most practical for the study as they were complex and time-consuming. Nonetheless, they proved efficient for collecting data in a consistent and straightforward manner.

Despite the efficacy of the chosen method, the quality of the data collected could have been improved if we had more practical knowledge of the digital tools and software's used. Additionally, a better understanding of data analysis tools could have resulted in higher-quality data analysis. Therefore, we suggest that future studies should consider incorporating these improvements to enhance the quality of data collected and analyzed.

Multiple interviews with the same respondents would be more beneficial to gain a broader understanding of the research topic. However, the restriction of a 1.5-hour duration per interview proved to be inadequate and increased stress towards the end of each session. Consequently, a free speech approach with the assurance of anonymity was chosen, and it proved to be an effective method for conducting the research.

To improve the efficiency of the research method, a comprehensive survey of stakeholders involved in or anticipated to be involved in the utilization of reused materials would be beneficial. Including individuals who work with digital tools and software would provide further valuable insights. This approach would help identify additional key areas that require consideration in the design of a user-friendly digital framework.

3. Related Work

This chapter will review related work on Circular Economy (CE), beginning with linear economy and its consequences. The chapter continues with CE and its technical requirements and legislation. Thereafter, it reviews existing reuse practices such as deconstruction and control plans. Follow up by digitalization and how it seeks to promote sustainability and CE-practices. Lastly review existing hinders and challenges.

3.1 Linear Economy

One of the main issues regarding environmental degradation in the architectural, engineering and construction (AEC) industry is the huge amount of waste generation. This is because construction and demolition (C&D) is a pervasive issue throughout the life cycle of buildings, from the planning and design phases, where there is often a lack of consideration for waste management and waste reduction (Esa, Halog, and Rigamonti, 2017). However, the most significant phase in terms of C&D waste generation is at the end of a building's life (Kibert, 2016). This is because most building materials are disposed of at the end of their life, as they do not have potential for reuse (Akanbi et al., 2018). This problem is primarily driven by the AEC reliance on a linear economic model, based on the idea of "take, make, dispose". In this model, raw materials are extracted from the environment, processed into construction materials, and assembled on construction sites in ways that cannot be deconstructed, becoming obsolete at the end of the building's life, ultimately being disposed of in landfills or incinerated, along with all the waste generated throughout the entire process (Mangialardo and Micelli, 2018). Hence, this has placed significant pressure on the AEC to shift away from linear economy models towards more Circular Economy models.

As mentioned before, linear economy (LE) primarily focuses on the procurement of raw materials, manufacturing, and converting them into finished products, with little attention paid to regaining value from the end-cycle of products. The major challenges of LE include the wastage of potential value, waste management issues, an over-reliance on landfills, increasing environmental hazards, a lack of competitive advantage, and incompatibility with sustainable development programs (Luttenberger, 2020). To address these challenges, there has been a growing need to transition to Circular Economy (CE) practices (Hartley, Santen, and Kirchherr, 2020).

3.2 Circular Economy

Circular Economy (CE) was first utilized in 1990 within the economic discipline with the objective of supporting the idea that "everything is input to everything else". However, until 2007, the Architectural, Engineering and Construction (AEC) industry paid limited attention to the concept, in the early stages of its introduction (Osobajo et al., 2022). Since 2016 the AEC industry has gain increasing attention in the transition towards CE, specifically with regards to material reuse (Adams et al., 2017). Studies have shown that the AEC industry has great potential for implementing CE strategies and achieving both environmental and economic benefits (Koutamanis, Reijn, and Bueren, 2018; Nußholz et al., 2020; Osobajo et al., 2022). Additionally, these strategies have the potential to create new jobs (Econometrics, Trinomics, and ICF, 2018) and provide superior value to customers (Schenkel et al., 2015; Nußholz et al., 2020).

Additionally, CE is seen to align with industrial ecology and improve construction sustainability Deutz et al. (2017) by sharing resources, particularly residues and by-products, between different industries through industrial symbiosis, thus keeping the value of materials in circulation. Moreover, CE is defined as a production and consumption model that aims to minimize overall natural resource extraction and environmental impact. This is done by extending the use of materials, reducing material and energy consumption, and waste. Which can be achieved through the transformation of materials into new products, designing for longevity, minimizing waste, and recovering and reusing materials. Likewise, it prioritizes the use of renewable, non-toxic, and biodegradable materials with the lowest possible life-cycle impacts. As a sustainability concept, CE must be integrated into a social structure that promotes well-being for all within the biophysical limits of the planet (Hossain et al., 2020).

As mentioned before, ACE industry is facing increasing pressure to become more resource-efficient and sustainable, due to rising demand for construction materials, scarcity of material supply, and growing environmental concerns. The concept of CE has emerged in recent years as a potential solution at various levels, including governments, industries, and academia (Kirchherr, Reike, and Hekkert, 2017; Reike, Vermeulen, and Witjes, 2018). As a result, Circular Economy strategies in the AEC industry can improve competitive advantage (Schenkel et al., 2015; Witjes and Lozano, 2016), promote innovation, and enhance user value e.g., sustainable design and ease of use of reuse materials (Klotz, Horman, and Bodenschatz, 2007; Schenkel et al., 2015). Furthermore, reducing environmental impacts, such as from raw material consumption and waste, can have a positive impact on corporate image and marketing (Klotz, Horman, and Bodenschatz, 2007; Schenkel et al., 2015; Witjes and Lozano, 2016).

Additionally, according Hossain et al. (2020), the broader implications of adopting CE practices in the AEC industry include: (i) improving the use of sustainable materials by sourcing sustainable materials and collaborating among various parties;

(ii) promoting materials efficiency by recycling and reusing construction materials; and (iii) avoiding unnecessary waste generation and reducing waste disposal in landfills. The recent CE agenda and its potential adoption in the AEC industry has led to a rethinking of construction supply chains, with the goal of reducing and reusing waste materials. Moreover, the recovery of construction materials for further recycling and/or direct reuse is key in the transition towards successful CE implementation. Such activities would ensure a significant reduction in the demand for new raw materials and minimize materials being disposed of in landfills.

The industry currently only manages to reap a small percentage of such materials' inherent economic value and durability under its prevailing system. Therefore, effective implementation of CE principles can eliminate these problems through material re-circulation, for example, by designing for disassembly with mechanical joints, which can potentially prolong the service life of construction components for reuse in another construction project or even in another system (Eberhardt, Birgisdottir, and Birkved, 2019; Schiller et al., 2019).

Additionally, research has shown that green building development, such as CE implementation, can reduce total life cycle costs of buildings (Mokhlesian and Holmén, 2012). However, there is a common perception that environmental sustainability increases initial investment costs, which is a significant factor in decision-making within the AEC industry (Azcarate-Aguerre et al., 2018). Customers may also benefit financially through the ability to charge premium for buildings with lower environmental impacts (Witjes and Lozano, 2016).

In conclusion the high resource consumption, waste generation, and environmental impact, in the ACE industry is considered a priority for closer attention. Hence, the adoption of CE models in the AEC industry can help it become more sustainable and ultimately achieve better sustainability performance. Additionally, the AEC industry is also considered to have significant potential for moving towards a CE approach, by adopting eco-friendly products and technologies (Smol et al., 2015). By increasing the use of waste materials at different stages of a building's life cycle, it is possible to reduce materials costs, overall construction costs, and embodied energy, as well as reduce environmental impacts due to excessive consumption of construction materials (Akanbi et al., 2019).

3.3 Reuse of Building Materials

According to a study by Göteborg Stad (2019), reuse is a process where products or materials that are not waste can be used again for the purpose they were originally intended for. This means that the product or material does not need to be sent for recycling or landfill (Göteborg Stad, 2019). When it comes to the potential use of used materials, Andersson et al. (2021), declare, reuse of products and materials can increase their lifespan and reduce waste while being an effective strategy for using resources more sustainably and reducing the climate impact from resource extraction, production, and waste management.

There is great potential for the reuse of construction products, but lack of knowledge among actors in the construction industry questions the environmental benefits and many refrain from reuse. Hence, to promote reuse of materials and products in new construction, planning is required at an early stage, formal procedures, and systematic work processes to save and stockpile materials and products awaiting reuse. To further increase the reuse of construction materials and products, clients should make specific demands prior to the construction of a new property (Miliute-Plepiene et al., 2021).

It is worth to mention that the environmental benefits of material reuse depend on the specific case and processes affected by reuse (Geyer et al., 2016; Zink and Allen, 2017). The environmental benefits of using secondary materials can vary depending on factors such as the recovery processes required to ensure that the secondary product meets the same functional requirements as the primary product (Vadenbo, Hellweg, and Astrup, 2017). For instance, Nußholz, Rasmussen, and Milios (2019) found that brick reuse has a carbon saving potential of 99% compared to primary-based alternatives, and plastic reuse in the construction of façades made from a wood-plastic composite has a carbon saving potential of 50-70%. Andersson et al. (2021) noted that, reuse increases the lifespan of products/materials and reduces waste while being an effective way to better utilize resources and reduce climate impacts associated with resource extraction, production, and waste management. There is great potential for the reuse of building products as it is still relatively uncommon, but many believe it is difficult to evaluate the quality of reusable products and information on hazardous substances.

According to Andersson et al. (2021), reuse can vary depending on the purpose. One way is to disassemble and reassemble the product in another location or renovate it so that it can be reassembled in its original condition. Reuse can occur within the same project or in another. If the product is not touched, it is not considered reuse but rather material or waste minimization. Nationalencyklopedin (NE) defines reuse as reusing consumed goods or packaging for the original or similar purpose (Nationalencyklopedin, n.d.), while the Environmental Code defines reuse as using a product or component that is not waste again to fill the same function as it was originally intended for (Sveriges Riksdag, n.d.[a]).

This study will utilize Andersson et al. (2021) definition to some extent, in order to enhance the potential for reusing the product either within the same company or externally through marketplaces, for both the original intended function and another function, as long as the product meets the necessary requirements. The aim is to increase opportunities for product reuse, which can contribute to the advancement of the Circular Economy (Andersson et al., 2021).

3.3.1 Material inventory

According to Ehlert et al. (2019) pre-demolition audits play a vital role for the controlled deconstruction of a building and the resource management. Moreover, Naturvårdsverket (n.d.) supports that by considering the material inventory as an important measure before demolishing a building is to conduct a material inventory. The purpose of this is to prevent waste and handle construction and demolition materials in a safe manner. Through a material inventory, it is also possible to identify the building products that can be reused and to determine the types of waste that can arise during demolition, including the hazardous substances that may be present in materials and components (Miliute-Plepiene, Almasi, and Hwargård, 2020; Naturvårdsverket, n.d.). Ehlert et al. (2019) continues, despite legal requirements in some European countries, the level of implementation of pre-demolition audits remains low due to limited awareness of the existing legislation, time constraints and the required expertise.

However, during a material inventory, building products that can be reused and the types of waste that can arise during demolition, including hazardous materials in materials and components, are identified. The result of the inventory is important for developing a control plan according to the Planning and Building Act (PBL) (2010:900). To meet the requirements of the control plan, it is necessary to identify which building products can be reused and how they should be handled, which waste can arise and how it should be managed, especially how to enable high-quality material recycling and safe handling of hazardous materials (Naturvårdsverket, n.d.).

A memo from White Arkitekter et al. (2021) describes fifth stages that could optimize the inventory process that end with a control plan and give recommendations that based on practical experiences from reuse inventories. The stages are review below.

1. Overall inventory and data collection: An overall inventory, data about the object should be collected, including drawings, material lists, operational records, environmental inventories, as well as information on its previous use and renovations. Additionally, a site visit can be undertaken to get a better understanding of the condition of the materials. The primary aim of this stage is to identify the available materials in the object and evaluate their potential for reuse in the subsequent step.

2. Assessment of reuse potential: After gathering data on the materials present in the building, an inventory is performed to determine which areas or building components require further attention. It's worth to mention that even small objects can have numerous materials and products, and some of them may not be suitable for reuse. By analyzing the potential for materials and products to be reused early on, the detailed inventory can focus on materials that are easy to dismantle, provide substantial environmental benefits, and offer good economic returns.

3. Detailed inventory of items with high potential: A physical inventory is carried out to examine the condition, dimensions, and functional requirements of the selected products to assess their potential for reuse. It's worth to mention that some product groups may be entirely reusable, but they are not suitable due to unexpected wear and tear, difficult mounting, or discrepancies between documentation and actual products. Additionally, the inventory process also involves collecting information about the manufacturer, condition, and quantity, and documenting them in the inventory tool. The product's location in the building is also preferably noted to make it easy to locate later in the inventory tool. Something to mention is that products containing hazardous substances should be excluded. It is worth collected data is supported with plentiful photos.

4. Supplementing with quality specifications: The detailed inventory provides a comprehensive understanding of the potential for reuse, but additional information may be necessary. This could involve reaching out to suppliers for information on the possibility of reconditioning or rebuilding products or obtaining information on functional requirements. Regard this, for some building materials, it is important to obtain details such as sound and fire ratings. Additionally, product testing, such as strength testing for bricks and quality information for windows, may be necessary. Hence, addressing guaranty issues should also be a priority at this stage.

5. Development of reuse plan: Developing a reuse plan with activities for how reuse should practically take place. Importantly, time for disassembly needs to be allocated, and identifying the logistical solutions, packaging, transport, and storage should be developed. Equally important is that the designers and contractors must be aware about the materials that will be reused and include them the process. Additionally, the reuse plan also shows what follow-up is to be carried out, such as the amount of reused material and its calculation of possible environmental savings.

3.3.2 Disassembly methods

Construction and demolition (C&D) waste is a heterogeneous mix of materials that varies in composition based on multiple factors, including the source of the waste (e.g., residential, commercial, or industrial buildings, roads, bridges), the size of the construction (low-rise or high-rise), the type of activity performed (construction, renovation, repair, or demolition/deconstruction), and the geographic location of the development (Silva, Brito, and Dhir, 2017; Ghisellini, Ripa, and Ulgiati, 2018). Moreover, in European countries, the primary components of C&D waste are bricks and concrete, making up approximately 80% to 83% of the waste stream, while the remainder consists of packaging and structure support materials, including plastics, wood, metal, paper, and cardboard, as well as overburden, which refers to material coming from excavation sites such as clay, rocks, and asphalt. In contrast, in the United States, wood is the most commonly used material in building construction, comprising between one-quarter and two-thirds of C&D waste (Diyamandoglu and Fortuna, 2015).

Nevertheless, demolition activities produce a considerably higher amount of waste, which can be more than ten times greater than that of construction projects (Duan, Wang, and Huang, 2015). The percentage of waste recovered from this substantial quantity of waste can vary depending on the type of demolition method employed. Therefore, based on the work of Ghisellini, Ripa, and Ulgiati (2018) the various methods of demolition will be presented as following:

Conventional demolition (CD) is a method of building demolition that involves the use of mechanical equipment and doesn't prioritize the separation of components. Although CD is a fast and cost-effective way of clearing building sites, it generates a significant amount of mixed waste materials that are usually disposed of in landfills.
Selective demolition (SD) is commonly referred to as "construction in reverse" as it involves systematically dismantling building components to selectively separate and sort valuable materials such as bricks, windows, and tiles. The technical categorization of SD or deconstruction is generally divided into two types: demolition of structural elements and deconstruction of non-structural elements, which is also known as soft stripping.
Mixed demolition of the two techniques combining selective demolition with conventional demolition, such as extracting non-structural elements for recycling through deconstruction, then demolishing the remaining materials conventionally, is not an environmentally advantageous approach due to the extensive distance's diesel trucks travel to recycling plants.

Ghisellini, Ripa, and Ulgiati (2018) state that, the compression of the environmental impacts of SD and CD have shown that SD is a better option due to its ability to divert a high percentage of materials from landfills and recover them for reuse. However, the environmental benefits of SD depend on transportation distances. Ghisellini, Ripa, and Ulgiati (2018) continue, the scenarios involving 100% selective demolition, recycling of recyclable waste on-site, recycling of inorganic materials in a mobile recycling unit, transfer of recyclable organic materials to the recycling center, and non-recyclable material to landfill are the most preferred environmentally friendly. Additionally, SD can reduce potential health hazards and site disturbances caused by conventional demolition. Furthermore, Ghisellini, Ripa, and Ulgiati (2018) present a study in the Netherlands with a landfill ban on C&D waste, where recyclable materials has made conventional demolition rare in the country, with a fraction of about 95% of reused/recycled C&D waste.

On August 1st, 2020, an amendment to the Swedish Planning and Building Act (PBL) came into effect with the aim of promoting better management of construction and demolition waste through selective demolition and safe handling of hazardous substances. The goal is to facilitate reuse and high-quality material recycling (Brander, Boubitsas, and Gabrielsson, 2021; Sveriges Riksdag, n.d.[b]). Hence, Brander, Boubitsas, and Gabrielsson (2021) continue and assert, to increase the reuse building components, standardization of quality and quality assurance systems need to be developed, and efforts should be made to change the Building Products Regulation and technical product standards so that CE marking becomes possible for reused building components, not just new products. Environmental economic incentives that favor reuse are also required, which can be achieved by measuring and reporting environmental benefits/economics.

Furthermore, to reduce waste and restrict the increase of C&D waste, it is crucial to implement the EU waste hierarchy. This entails prioritizing the avoidance of demolition and instead focusing on upgrading existing buildings through reconditioning. However, when demolition becomes necessary, the emphasis should be on reuse first, followed by recycling (Brander, Boubitsas, and Gabrielsson, 2021). In addition, according to Sveriges Riksdag (n.d.[b]), buildings within designated areas require a demolition permit. The builder is responsible for creating a control plan, which includes a material inventory and outlines the proper handling of hazardous substances/materials. Additionally, the plan specifies the appropriate measures for managing non-hazardous materials.

3.3.3 Technical requirements

According to The Swedish Planning and Building Act (PBL) stipulates specific technical requirements that must be met when modifying, renovating or reconstructing a building. When renovating/ reconstruction the requirements apply to the entire building or the significantly renewed part, while for changes, they only apply to the specific part being modified. Regard this modifying or reconstruction is a type of alteration that occurs in a building. In order for a change to a building to be considered remodeling, either the entire building or a significant and clearly defined part of the building must undergo a noticeable renewal (Boverket, 2011; Boverket, 2017; Boverket, 2018).

As a result, the design and materials used in the building must meet specific standards that may affect the reuse of building materials. Compared to new construction, caution is required when modifying a building to preserve its technical, historical, cultural, environmental, and artistic values. Historical, cultural, environmental, or artistic buildings must not be altered (Boverket, 2011; Boverket, 2017; Boverket, 2018).

The technical requirements for changes include:

- Accessibility, room height, and operational space
- Fire protection
- Hygiene and health
- Noise protection
- Safety
- Energy conservation

When making changes to buildings, it is important to adhere to various requirements. Firstly, the same accessibility, housing design, room height, and operational space requirements apply as for new constructions. However, there is flexibility in meeting these requirements as long as equivalent accessibility and usability are achieved. Additionally, fire protection requirements must be met, with alternative solutions permitted as long as they provide an equivalent level of safety through analytical dimensioning (Boverket, 2011; Boverket, 2017; Boverket, 2018).

Exceptions may be considered based on the scope of changes and building conditions, but they should not pose unacceptable risks to human health. Similarly, noise protection standards should be maintained or improved during changes, particularly in rooms intended for rest and sleep (Boverket, 2011; Boverket, 2017; Boverket, 2018).

Building safety requirements, equivalent to those for new constructions, must be met, with alternative methods acceptable as long as they ensure a similar level of safety without introducing excessive risks. Energy conservation is another crucial aspect to consider, focusing on limiting energy usage through measures like reducing heat loss, optimizing heating and cooling systems, and efficient electricity use. These requirements should be implemented without compromising other technical standards or cultural-historical values. It is essential to maintain energy efficiency to a degree that satisfies new construction standards throughout the changes (Boverket, 2011; Boverket, 2017; Boverket, 2018).

3.3.4 Legislation

There are two main laws that govern the management of construction and demolition waste: the Planning and Building Act (PBL) (2010:900) and the Environmental Code (1998-808) - enacted by the Swedish Parliament. Waste management is regulated through the requirements stipulated by the Planning and Building Act (2010:900) when applying for demolition or construction measures and when notifying of demolition or building permits. The legislation aims to increase the use of reuse building materials. The Swedish Environmental Protection Agency recommends that a control plan, in accordance with the Planning and Building Act, be prepared for the management of waste from the construction sector during the demolition process (Sveriges Riksdag, n.d.[a]; Sveriges Riksdag, n.d.[b]). Therefore, a material inventory should be conducted before demolition measures to plan and prevent waste management in the most efficient and safe way possible. The material inventory should help identify products from the process that can be reused and the types of waste that may occur. A well-executed material inventory provides a suitable basis for developing the control plan according to the Planning and Building Act (Sveriges Riksdag, n.d.[a]; Sveriges Riksdag, n.d.[b]). The basic requirements for the control plan can be summarized in two points:

- Identification of building products that can be reused and how they will be handled.
- How to manage the waste generated during the process, particularly how to facilitate high-quality material recycling and safely handle hazardous substances (Naturvårdsverket, n.d.).

The requirements set by the Planning and Building Act and the Environmental Code for the demolition and construction processes aim to achieve:

- Increased reuse.
- Increased material recycling.
- Safe collection of hazardous waste.
- Reduction in the amount of waste deposited (Naturvårdsverket, n.d.).

By the introduction of the new control plan for demolition a new requirement for sorting out has also been introduced in Miljöbalken. This approach is supposed to promote recycling and reused by keeping clean waste streams to reach reuse of highest quality of recycling and better preparation for reuse.

However, in the actuality there are no requirement for reuse in Sweden. Furthermore, the responsibility nowadays falls on the contractor as he sets the boundaries for the project and the procuring organization should also develop a sustainability policy that include goal and execution plan which allows to include the environment, climate and social when procuring (Upphandlingsmyndigheten et al., 2020). There are initiatives where EU seeks to promote Circular Economy practices such as Agenda 2030 and more practical initiatives such as Buildings As Material Banks (BAMB) (Rosado et al., 2017; Munaro and Tavares, 2021; Haider et al., 2022).

3.4 Assessment Tools

The following chapter reviews existing assessment tools that ensure the quality of materials. The literature is reviewed to understand pros and cons with these tools in order to promote reuse in the Architectural, Engineering, and Construction industry.

The promotion of sustainable building materials and reduction of overall life-cycle costs for construction projects has been a focus in recent years. Environmental product declarations (EPDs) and life-cycle assessments (LCAs) have been implemented in building and infrastructure projects in an effort to achieve this goal. However, it is suggested that these methodologies have not been effectively linked to the ongoing digitalization of the building environment. Additionally, there is a lack of review of the current tools being used to calculate and manage the carbon footprint of construction projects, and there is little connection between these tools and other digital technologies such as Building Information Modelling (BIM) and Internet of Things (IoT). In order to address these issues, a review of current carbon estimation and management tools is needed, to better understand their capabilities and limitations. Furthermore, a critical evaluation of different tools is necessary to understand their functionalities in more detail (Yan et al., 2022).

3.4.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is an important tool in assessing the environmental impact of a product or building throughout its entire life cycle. This includes evaluating the impact of extracting natural resources, the manufacturing process, the use phase, and the disposal or end-of-life phase. With an LCA, professionals such as architects, developers, and contractors can identify which stage of a building's life cycle has the greatest environmental impact and make informed decisions on how to reduce this impact (Boverket, 2019a). In other words, the exploratory LCA aims to compare the environmental impact of 12 experimental treatments and conclude on the technical and environmental performance of circular particle-boards versus traditional (linear) particleboard production systems. The life cycle of a building can be divided into three modules (A, B and C): modules A1 to A3 (product stage) and A4 to A5 (construction stage), modules B1 to B7 (use stage), and modules C1 to C4 (end of life stage), as outlined in (Boverket, 2019a; Uemura Silva et al., 2021).

According to Boverket (2019a), one of the key benefits of LCA is the ability to gain an in-depth understanding of the various resource flows and environmental impact of a building. This knowledge can be used to design and construct buildings with a reduced environmental impact. This is important for professionals in the construction industry, whether they are developers, property owners, managers, contractors, designers, or architects. Moreover, in Sweden, several commercial systems are used to certify buildings based on their environmental impact. These certification systems, such as Miljöbyggnad, Breeam, and Leed, all require some form of LCA calculation in addition to other indicators. This helps to ensure that buildings are constructed in a sustainable manner, reducing their environmental impact, and promoting a greener future.

3.4.2 Environmental Product Declaration

Environmental product declaration (EPD) for a building product is a comprehensive document that provides detailed information about the environmental impact of the product throughout its entire lifecycle. This information is used to conduct a life-cycle assessment (LCA) for buildings, which is a tool that helps to evaluate the environmental performance of a product or a building project (Boverket, 2019b).

The EPD of a building product presents the results of a life-cycle assessment in a condensed format, providing a summary of the environmental impacts of the product throughout its lifecycle. The information in an EPD is largely based on a life-cycle analysis of the product, which includes data on the product's raw materials, production, transportation, use, and disposal. In some cases, an EPD may only cover certain parts of a product's lifecycle (Boverket, 2019b).

Furthermore, an EPD consists of three main parts: a product data sheet, a method selection, and the results of the assessment of environmental impact. The product data sheet provides detailed information about the product, including its composition, characteristics, and performance. While the method selection section describes the methodology used to conduct the life-cycle assessment and the data sources used. The results of the assessment of environmental impact provide an overview of the environmental impacts of the product throughout its lifecycle, including data on energy consumption, greenhouse gas emissions, water consumption, and waste generation (Boverket, 2019b).

Additionally, the EPD applies between three to five years and must comply with the standards for sustainability in building works, environmental declarations, and product-specific regulations (SS-EN 15804:2012+A2:2019). These standards ensure that the information in the EPD is accurate, reliable, and comparable with other products. Environmental product declarations are reviewed and approved by independent verification to ensure that the information is credible (Boverket, 2019b).

However, when a manufacturer is preparing an EPD, they must follow a set of product-specific regulations (criteria) before conducting a life-cycle analysis of the product. These criteria include detailed guidelines for delimitation, method selection, data sources, and more for a specific product group, such as doors, building panels, or insulation materials. These product-specific regulations are usually referred to as PCR, which stands for product category rules. These requirements are usually developed in consultation with industry organizations to ensure that the EPDs are accurate and consistent across different products within the same category (Boverket, 2019b).

Overall, an EPD is an important tool for architects, builders, and other professionals involved in the construction industry to make informed decisions about the environmental impact of building products. By providing detailed information about the environmental performance of a product throughout its lifecycle, an EPD enables professionals to select products that are more sustainable and that have a lower environmental impact (Boverket, 2019b).

Regarding legislation, in Sweden, the parliament has decided to introduce a requirement for developers to submit a climate declaration for new buildings starting January 1, 2022. The construction and real estate sector play a significant role in today's environmental and climate impact. Boverket, has been tasked with developing an open database of relevant climate data, a climate declaration register, and information and guidance materials. They have also developed a plan for the continued development of the climate declaration of buildings to include the entire life cycle and limit values for climate impact (Boverket, 2019b). While in the European Union, the work to describe the environmental impacts of construction products has been carried out under the mandate of the European Commission. This has resulted in the SS-EN 15804 standard, which is used to make EPDs for construction products. However, there is currently no legal connection between an EPD under SS-EN 15804 and the harmonized construction product standards. This means that it is not yet possible to impose requirements for the use of product specific EPDs for harmonized construction products. To address this, the state will provide a database of generic data for construction products, to be used in climate declarations if generic data is used. However, these data can be substituted with product-specific data (EPD) if they exist for the selected construction products (Boverket, 2019b).

3.5 Digitalization

Circular Economy (CE) enhanced by digitalization has gotten a lot of attention recently. Digital tools can help to develop Circular Economy strategies by combining existing and upcoming strategies in the industry. Therefore, digital tools will play a driving role in the realization of an innovative digitalization-led CE in the industry

(Çetin, Gruis, and Straub, 2022; Liu et al., 2022; Jemal et al., 2023). Additionally, Jemal et al. (2023) presents a study by the Association of German Chambers of Commerce and Industry where 93% of the companies agreed that digitalization would influence all their process. However, the industry needs to focus on developing a business model where it provides values to all actors involved.

The European commission has outlined an action plan for EU's green transition where tracking resource flows, dematerialization, and realizing circular service business models, material passport tags, watermark for sustainable products and encourage establishing digital logbooks for the buildings are essential for a paradigm shift. Furthermore, the industry is seeking to incorporate digitalization together with other strategies such as Industry 4.0 to enable a more practical implementation of Circular Economy processes (Çetin, Gruis, and Straub, 2022; Liu et al., 2022; Jemal et al., 2023).

Urban mining is one of many circular strategies, it seeks to reduce waste and reduce raw material consumption, which can be enhanced through digitalization. Çetin, Gruis, and Straub (2022) performed a study on social housing where a detailed inventory of materials of an existing building could be crated with the help of a 3D laser scanning technology and the software automatically generates a material passport of the reusable elements.

Furthermore, according to Kovacic, Honic, and Sreckovic (2020) and Jemal et al. (2023) collaboration and value co-creation could be enhanced through digitalization, which in turn enhances Circular Economy (CE) in the industry. Those benefits would be among others better communication, higher management efficiency, better and more suitable sustainable processes, increased safety, simulations and digital modelling of different scenarios, a more accurate forecasting, and enhanced document management (Jemal et al., 2023).

This could be achieved through existing digital tools in the industry such as document-based collaboration and documentation between disciplines and supply chains, web- or cloud-based management in design and construction projects (Singh, Gu, and Wang, 2011), electronic procurement along the Architectural, Engineering and Construction (AEC) Industry value chain (Grilo and Jardim-Goncalves, 2010), exchange of domain specific model data on open or closed BIM-servers, web-based virtual reality cloud platforms for integrated AEC projects (Editors et al., 2014), or user-centered knowledge-management platforms (Kovacic, Honic, and Sreckovic, 2020). In addition, Brander, Boubitsas, and Gabrielsson (2021) supports this by stating that CE benefits can be achieved through the digitalization of data, a common database and marketplace. Furthermore, there are various existing digital tools and processes that comply and seek to promote CE practices, which will be review in this chapter.

3.6 Building Information Modelling

Building Information Modeling (BIM) is now at the forefront of transferring project information through three-dimensional models. With the help of BIM technologies, a model can be generated with accurate geometry and complete information about the construction procedures, technologies used, and procurement process. This centralizes the flow of information exchange among stakeholders, providing the necessary data for virtual simulations such as building behavior, quantities, environmental impacts, costs, and deadlines, thereby reducing the risk of information loss compared to traditional methods. This leads to better predictability and reduced risks in building projects (Lima et al., 2021).

Moreover, to manage the large amount of data produced, new tools are required. The BIM model provides all the technical information of any component or material in the building (Pavan et al., 2019; Kovacic, Honic, and Sreckovic, 2020). The digital representation of the building can be created using software such as Revit, Allplan, Archicad, Microstation, Tekla, and Edificius. The information is then shared through cloud-based solutions (Pavan et al., 2019). The model also provides all the information needed for cost estimation, material inventories, and planning.

Building Information Modelling (BIM) allows different actors to share information about a project from the conceptual phase to demolition. It consists of a shared 3D-digital representation of any physical object and enables data management through the entire life cycle of the building, thereby facilitating the generation of a Material Passport (MP). Studies have shown that BIM can serve as an instrument for the automated generation of MPs, as an optimization tool, material inventory, and as a building stock throughout the life cycle of the building (Kovacic, Honic, and Sreckovic, 2020).

Nowadays, the combination of 3D laser scanners and BIM is becoming more common. The 3D scanner creates an as-built BIM model, which is later enriched with material information, allowing the model to efficiently generate MPs of the material (Kovacic, Honic, and Sreckovic, 2020; Çetin, Gruis, and Straub, 2022).

Building Information Modelling (BIM) has become an important building process in recent years, with the goal of enhancing all operations and building phases in a project. BIM has become the core of digital transformation and is crucial for the transition to a more circular economy-centered industry. BIM supports urban mining by integrating information from various sources and accurately identifying building components at the end-of-their life. It also offers new possibilities for circularity, such as Material Passport (MP) development, circularity assessment, and end-of-life model generation. The decision support tool developed by (Akanbi et al., 2019) provides designers with insights into reducing waste and resource consumption during a building's end-of-life phase. Berg, Voordijk, and Adriaanse (2021) demonstrate the use of BIM in a deconstruction project, where valuable elements were labeled in BIM for reuse in another construction project. Recently, BIM-based circularity indicators, such as the BIM framework proposed by (Zhai, 2020) have been introduced to automate the circularity assessment of buildings from the early design stage.

3.6.1 3D-Scanning

Building Information Modelling (BIM) is typically associated with the production of new building projects. One effective way of obtaining information about the construction process is through 3D-scanning. Laser scanning and photogrammetry scanning are two methods that can complement each other. In recent years, 3D-scanning has become more accessible and user-friendly, thanks to advancements in technology such as the iPad Pro 12 and iPhone 13, as well as more advanced scanners like Metterport and Leica (Prušková, Dědič, and Kaiser, 2019; Potangaroa, 2022).

During the 3D-scanning process, the object is transformed into a digital geometric shape of point/cloud/mesh type. Various techniques can be used to scan the object, including optical, laser scanning, thermal and seismic acoustic, radar, and more. The scanning techniques involve the response of the object under study to a light source, such as triangulation and time-of-flight techniques, structured light, and photogrammetry, which generates a 3D-model using software to reconstruct it. However, all these techniques have in common the generation of holes where the reflected light cannot be collected by the scanner for various reasons (Badillo, Parfenov, and Shchegoleva, 2021; Afteni et al., 2022).

Furthermore, some techniques are more common in the Architectural Engineering and Construction (AEC) industry to 3D-scan existing objects, such as Digital Photogrammetry, Terrestrial Laser Scanner (TLS) also known as Light Detection and Ranging (LiDAR) or Laser Distance and Ranging (LADAR) and Ground Penetrating Radar (GPR) (Hossain and Yeoh, 2018). Digital photogrammetry turns still images into 3D point clouds, while laser scanners measure the distance to its target through multiple points of amplified light. Ground-penetrating radar locates the object through high-frequency radio signals (Hossain and Yeoh, 2018; Badillo, Parfenov, and Shchegoleva, 2021).

A 3D-object can be created through 3D-point clouds captured through LiDAR or photogrammetry (Scan-to-BIM). Scan-to-BIM approach uses spatial data collected through Laser Scanning (LiDAR), which uses light to measure distances and transform point clouds into 3D data, and photogrammetry, which converts digital images into 3D point clouds. Scan-to-BIM enables better data flows since the same type of data (3D point cloud) is used, and it yields accurate results (Longman et al., 2023).

3.6.2 Data Transfer

The sharing of data in the industry is hindered by various factors such as different data formats, structures, and standards, as well as varying business workflows. To facilitate data sharing, different technologies have been introduced. (LI, Nederveen, and Wolfert, 2017) identified three main options for data transfer: Building Information Modelling and Industry Foundation Classes (BIM and IFC), Semantic Web Technology and Linked Data. Additionally, Artificial Intelligence (AI) could be used as complement to these technologies in order to enhance circularity.

Building Information Modelling (BIM) and Industry Foundation Class (IFC) enable information sharing through open standards, workflows, tools, and data structure specifications that cover the life cycle of a building. IFC, in particular, supports various infrastructure domains and allows for data exchange and collaboration in BIM-based programs. It functions as an information organization and transformation system that encodes rich semantic and hierarchical information. The IFC's semantic information also enables the differentiation of 3D components, although it is too generic to capture the full semantic information required for different applications, which can lead to data loss and errors (LI, Nederveen, and Wolfert, 2017; Sherafat, Taghaddos, and Shafaghat, 2022; Longman et al., 2023).

The Semantic Web and Linked Data extend the web through standards that allow for common data formats and protocols. It is based on the Resource Description Framework (RDF), which integrates different applications and enables more flexible information sharing and exchange. The use of ifcOWL, an IFC base ontology, allows for the conversion of structured or semi-structured data from unknown domains into a readable format. This approach enables full support for buildings from design to destruction and collaborative information handling by multiple actors´(Vanlande, Cruz, and Nicolle, 2010; LI, Nederveen, and Wolfert, 2017; Niknam and Karshenas, 2017).

The Smart Information Retrieval approach allows for data sharing agreements, relying on intelligent software rather than data standards. An information crawler gathers information from various information systems, regardless of format or content, which can result in inconsistent or unstructured data (LI, Nederveen, and Wolfert, 2017).

Finally, Artificial Intelligence (AI), a software with intelligent behavior, has been introduced in various industries, including the medical industry, which is information intensive. AI can help filter and find relevant information instantly by answering questions (LI, Nederveen, and Wolfert, 2017). Combining AI with existing data sharing technologies could enhance circularity in the industry.

3.7 Material Passport

Circular practices have gained increasing popularity as a means of promoting sustainable development in various sectors, including the building industry. Material passport (MP) is one such practice that has gained prominence for its potential to facilitate the documentation, tracking, and reuse of building materials and products. MP provides a digital register of the material or product through its entire life cycle, thereby enabling recovery and reuse, and promoting Circular Economy (Munaro and

Tavares, 2021; Bellini and Bang, 2022). By providing users with useful information about materials and products, MPs enable the evaluation and communication of the performance of buildings, indicating the level of circularity achieved.

The European project buildings as material banks (BAMB) is being introduced in the industry through Material Passport's (MP) to promote circularity. This involves storing the information of the material in a database, which can be retrieved and reused as long as the material allows for it. While there are other technologies similar to MPs, such as Environmental Product Declarations (EPD), the Environmental Protection Encouragement Agency (EPEA), and Building Information Modelling (BIMobject), none of them cover the full requirements of MPs, which specifically focus on the end-of-life of materials (Munaro and Tavares, 2021).

Material Passport's (MP) can serve as optimization tools to reduce fiscal barriers, increase reuse and recycling, and indicate the potential for circularity. In addition, MPs provide a standardized methodology for collecting and handling relevant information that is compatible with multiple software, closing the information gap in the industry. This enables a clear image of building performance and promotes fast, reliable, standardized, and streamlined flow and processes in the industry, thereby increasing the value of the building (Munaro and Tavares, 2021).

Other digital tool that could be a complement to the above mentioned are Artificial Intelligence (AI), which can help in the maintenance operations. AI helps to inspect the building by searching for anomalies in the components surface and detect hazardous contents which is done by using an image recognition system through the digital twin (Çetin, Gruis, and Straub, 2022). Another useful digital tool for Circular Economy is machine learning. Çetin, Gruis, and Straub (2022) describe in their study that a digital twin could be model through machine learning from 2D architectural drawings. However, it requires relevant information on specification and requirements for the building.

3.8 Inventory tools in Sweden

The Center for Circular Buildings (CCbuild) is a platform that seeks to promote Circular Economy practices in Sweden. CCbuild offers a range of features, including an inventory tool, product bank, and marketplace. These functions enable users to document and share information about materials with potential for reuse, as well as to buy and sell materials for this purpose. The inventory tool allows users to input data about materials, including technical information, dimensions, and volumes. Users can also add environmental performance data based on information from sources such as Environmental Product Declarations (EPD's), product sheets, construction product declarations (eBVD), and webshops. In addition, the product bank feature of CCbuild provides users with a range of pre-existing materials that can be used for different projects. This allows users to access materials that have already been documented and evaluated for their potential for reuse. Finally, the

CCbuild marketplace enables users to buy and sell materials for reuse purposes. This feature provides an additional avenue for users to access and share information about materials with potential for reuse and can help to create a more efficient Circular Economy in Sweden (Rydberg et al., 2022; Centrum för cirkulärt byggande, 2023).

Cirkulära (buildID) is a tool that aims to promote circularity practices in Sweden. The tool offers a unique solution that allows materials to be tracked using radio frequency identification (RFID), enabling users to easily locate and identify products or materials. This feature is complemented by the storage of the tagged material in a materials bank. Users can access information about the materials via a webpage that is linked to the material bank. The information provided is a basis for environmental declaration (BuildID, 2023). The RFID-technology facilitates the logistically work and management of the supply chain by identifying and keeping track of individual materials through radio waves (Mabad et al., 2021).

Palats is a digital tool designed to promote circularity in Sweden, similar to CCBuild, by providing an inventory management system. It allows users to input various details such as dimensions, weight, technical requirements, condition, volume, and prices of items. One of the key features of Palats is the ability to generate a QR-code, which serves as a means to track the flow of information. Additionally, it aims to enhance administrative efficiency by enabling users to create relocation tasks and receive notifications upon their completion through the platform. This is achieved by creating a relocation task within the app, which is digitally processed within the agreed-upon timeframe (Palats, n.d.).

Furthermore, Palats aims to provide users with information regarding the climate impact of the inventoried products. It also offers the capability to generate reports that highlight specific climate savings. The overarching goal of Palats is to streamline the process of reusing items and drive circularity in Sweden (Palats, n.d.).

In conclusion, these platforms facilitate product inventory, tracking the carbon dioxide footprint, providing insight to what products that can be reused, marketplace, cost calculation, location and providing a general project overview. As mentioned earlier there are platform that help with cost and carbon dioxide calculation that can be used to calculate the economic and climate savings of reusing a product or material (Rydberg et al., 2022; Centrum för cirkulärt byggande, 2023; BuildID, 2023; Palats, n.d.; Mabad et al., 2021).

3.9 Hinders and Challenges

The transition to a Circular Economy (CE) approach in the Architectural, Engineering, and Construction (AEC) industry is encountering several well-known obstacles and challenges. These barriers have been identified in several studies, including those conducted by (Ghisellini, Ripa, and Ulgiati, 2018; Ababio and Lu, 2022; Bellini and Bang, 2022). These studies highlight various challenges to the implementation of Circular Economy principles in the building industry, including social and cultural barriers, political and legislative barriers, financial and economic barriers, and technological barriers.

To overcome these challenges, the implementation of CE practices requires strategies that bring together various stakeholders, such as communities, industries, governments, and suppliers, to collaborate extensively on technical, social, and economic aspects, as highlighted by (Walker et al., 2021; Ababio and Lu, 2022). However, a research study by Andersson et al. (2021) examined the main barriers to CE implementation in the Swedish AEC industry. This study identified the current habits and attitudes, lack of time and resources, limited knowledge and experience, limited market, and uncertainty and lack of warranties for reusable products as the main issues. These challenges may be attributed to the lack of knowledge and experience, as well as the immature market for reuse.

This chapter examines the main hinders and challenges to CE adoption in the industry as identified in previous studies. The hinders and challenges to CE implementation will be classified into social and cultural, political, and legislative, financial, and economic, and technological and will be review in the following sections.

3.9.1 Social and cultural

The transition to Circular Economy (CE) in the Architecture, Engineering, and Construction (AEC) industry is hampered by various challenges and barriers. Several studies have identified societal and cultural barriers as behavioral and managerial issues, rooted in the linear economy, silo thinking, and attitudes and opinions on ownership and status (Hart et al., 2019). The fragmented nature of the industry also makes it resistant to change, hindering the transition from a linear to a Circular Economy (Lines et al., 2015; Kirchherr et al., 2018; Hart et al., 2019; Munaro, Tavares, and Bragança, 2020).

Conventional regimes bring difficulties to the industry, as their mindset of "this is how we have always done" hinders the implementation of new working methods and innovative ideas (Acharya, Boyd, and Finch, 2018). This results in a lack of interest, awareness, knowledge, and engagement throughout the value chain, hindering the introduction and adoption of circular practices (Kirchherr et al., 2018; Munaro, Tavares, and Bragança, 2020). Hart et al. (2019) and Ababio and Lu (2022) further describes the mentality in business functions as rigid and simplistic, which is not suitable for the complexity of the building industry that requires collaboration, communication, and commitment throughout the entire value chain.

Furthermore, Jemal et al. (2023) argue that the lack of stakeholder awareness of the impact of sustainable design also hinders the implementation of CE. (Çetin, Gruis, and Straub, 2022) also highlight cultural barriers when adopting new technologies, as many resists new technologies because they have always worked with the same programs and processes for many years. Therefore, to overcome these challenges, the process of implementing CE requires strategies that bring together technical, social, economic, and other aspects, which requires extensive collaboration among various stakeholders such as communities, industry, government, and suppliers (Walker et al., 2021; Ababio and Lu, 2022).

Moreover, Brander, Boubitsas, and Gabrielsson (2021) highlights issues for reuse in Sweden such as lack of information, knowledge, and awareness throughout the reuse chain, from manufactures and contractors to retailers and service providers in areas such as reconditioning and inventory management.

3.9.2 Political and legislative

In the adoption of Circular Economy (CE) practices, legislative makers play a crucial role in facilitating the implementation of new working methods and driving change through incentives and regulations. However, weak, and inappropriate policies and regulations have hindered the implementation of CE, limiting the reuse of materials on a larger scale (Rios, Grau, and Bilec, 2021; Sandberg, Ann, and Kvellheim, 2021). To enable a paradigm shift towards CE in the Architecture, Engineering, and Construction (AEC) industry, support from city and regional levels is necessary to provide sustainable laws and regulations that allow for better collaboration (Charef and Lu, 2021; Ababio and Lu, 2022).

To incentivize the adoption of more CE practices, the industry requires fiscal or regulatory solutions that motivate stakeholders to adopt CE more quickly (Ababio and Lu, 2022). The lack of green financing and regulations at both the country and company level also poses a hindrance (Jemal et al., 2023). (Çetin, Gruis, and Straub, 2022) highlight regulatory issues associated with CE, such as meeting quality requirements for potential reusable materials and a lack of sufficient information regarding their properties on the marketplace. They also stress the importance of national standardization for data exchange to ease the generation of material passports, given the current uncertainty regarding data requirements. The government must also raise awareness of CE by building rules, codes, and regulations that comply with CE regulations.

3.9.3 Financial and economic

The implementation of Circular Economy (CE) practices in the Architecture, Engineering, and Construction (AEC) industry requires significant investment in digital infrastructure, research, and certification, but the industry typically prioritizes short-term gains and fast payback instead of long-term cooperation and broader social and environmental goals (Carra and Magdani, 2017; Guerra and Leite, 2021; Ababio and Lu, 2022). This attitude hinders the adoption of CE, which also faces barriers such as the availability and low cost of raw materials compared to reused materials, resulting in reduced end-of-life value and market penetration (Adams et al., 2017; Kirchherr et al., 2018). The lack of sufficient financial resources is another major hindrance to the adoption of CE, and better budget distribution strategies, incentives for sustainable projects, creation of Circular Economy investment platforms, and involvement of international organizations are necessary (Çetin, Gruis, and Straub, 2022).

3.9.4 Technological

The transition to a circular business model requires new tools and innovative solutions to facilitate this shift (Eijk, 2015; Ababio and Lu, 2022). The the Architecture, Engineering, and Construction (AEC) industry is complex, involving numerous operations and actors, and requires solutions for maintenance, dismantling, reuse, recycling, recovery and disposal of materials and components, as well as minimizing production waste, enhancing logistics, and more (Hart et al., 2019; Ababio and Lu, 2022). To achieve this, the industry needs tools that allow for better communication, coordination, and planning, providing greater transparency throughout the entire value chain (Ababio and Lu, 2022). However, the industry must move away from its fragmented state and embrace new solutions and ways of working. The implementation of new technologies within conventional processes is inadequate and fails to realize the expected economic, technical, and processual benefits offered by new technologies (Kovacic, Honic, and Sreckovic, 2020).

Furthermore, Kovacic, Honic, and Sreckovic (2020) contend that platforms for collective value creation and knowledge management, from cradle to grave for Circular Economy (CE), are still missing. Jemal et al. (2023) notes that the industry lacks proper infrastructure for recycling, a lack of a reuse and resale market for durable certified materials, and that digital tools are left behind in the initial design framework, hindering the full adoption of CE. Çetin, Gruis, and Straub (2022) also highlight the uncertainty regarding data requirements for CE as a hindrance, adding that there is a lack of instruments to organize and translate the large amounts of data stored in systems or digital twins for CE strategies.

4. Results

This research thesis consists of two different types of studies, one literature study and one practical study, which will be presented in this chapter. The interview study shows the current status of maturity (knowledge and experience, etc.) of circular economy (CE) in the industry, which have strong correlations to the literature study. Meanwhile, the practical study shows efficient tools that could enhance circularity and at the same time that the digitalization path is still lacking in the industry and specially in terms of circularity. Importantly, some of the interview's input have been used to perform the practical study.

4.1 Interviews

Since the interviews were semi-structured, the open-ended questions elicited a wide range of responses. Therefore, this paragraph will focus on the most important and relevant findings from the study.

4.1.1 Circular Economy and Reuse Materials

The respondents offered various viewpoints regarding the concept of Circular Economy (CE). A majority of them lacked a precise understanding of the term. Only two respondents who works as designer and the other works as sustainability specialists, who defined CE as an economic model that strives to reduce waste and encourage the sustainable utilization of resources by keeping materials and products in circulation for extended periods. This approach encompasses designing products and manufacturing processes that prioritize resource efficiency, reuse, repair, and recycling. Meanwhile, other respondents confused the concept of CE with merely increasing the use of recycled or reused materials, without providing a clear definition. In summary, they characterized the Circular Economy as an economic model that emphasizes the need to augment the use of reused materials. However, 8 of 9 of our respondents mentioned that the construction industry generates a huge amount waste and has a big responsibility to the contribution of the climate change responsible for and this should be reduced by shafting from linear economy (LE) to more Circular Economy (CE).

All respondents noted that the industry has undergone significant changes in terms of sustainability over the past few years, due to increased awareness of climate change, initiatives from various actors, and new government goals. They acknowledged that the number of stakeholders, such as contractors, government agencies, and consultants, who are taking the initiatives to drive the CE forward in the industry have increased. However, they also emphasized the importance of collaboration among these different stakeholders to ensure success in achieving sustainability and advancing the implementation CE.

Additionally, the respondents offered various definitions of reuse, often highlighting different aspects of the concept. Some defined reuse as the utilization of a product without any changes in design or function, while others emphasized the importance of also finding a new purpose, function, or design for the material or product. One respondent mentioned.

''The idea of reuse as a spectrum, ranging from restoring to upcycling".

Moreover, all respondents underscored the environmental benefits of reuse, such as reduced CO_2 emissions during the manufacturing stage which is not present when materials are reused and decreased extraction of new resources from the earth.

Moreover, regarding inventory process, 7 of 9 respondents described the inventory process as a procedure that typically involves examining construction documents, conducting site visits, and recording essential information if they exist. Half of the respondents emphasized the importance of digital data entry but were uncertain about the best digital tools for this purpose. Three respondents mentioned the use of on-site photography, 3D-scanning, and collaboration with architects or other professionals as crucial for evaluating the condition and potential reuse of materials but acknowledged that this process is time-consuming. Most of our respondents brought up the time aspect in the inventory process, suggesting that current methods are lengthy and should be streamlined through innovation.

However, regarding which building objects and elements should be considered in the practical study, the respondents offered a diverse range of choices, which will be presented in table 1.

In addition, a variety of other materials were mentioned, encompassing structural elements, ceiling tiles, and fixtures. In fact, it is important to note that some materials were mentioned in the context of their potential for reuse which reduce their impact on the environment, while others were mentioned for their significant carbon emissions during extraction and manufacturing or their large volumes.

Regarding disassembly, 3 out of 9 respondents acknowledged the importance of circular design and adaptability, with some expressing concern about working in a tougher environment outside their comfort zone. Some respondents mentioned the importance's to have a specific plan for reusing materials, such as glass parts, while 4 of 9 emphasized the importance of avoiding full demolition and finding solutions to retain building components because this could be more environmentally friendly and less costly but 2 of them highlighted the need of the right competence for this propose in the industry.

Table 1: Materials with high reuse potential

Materials	Respondets	Main reason(s) for reuse suggestion
Suspended ceilings	4	High reuse potential, most climate-damaging product.
Facade material	3	Significant climate impact
Glass and doors	3	Ease of reconditioning, Need for tests for noise and brand when information is missing.
Gypsum board	3	High volume, but there are concerns about material's ability to meet current demands especially in older buildings.
Steel	3	Considerable environmental impact, Crucial from a climate perspective.
Brick	5	Environmental impact but easy to reuse, Existence of a supplier for disassembly and reconditioning.

4.1.2 Assessment Tools

According to the interview results, 6 out of 9 respondents discussed Environmental Product Declarations (EPDs) and material passports (MP) to varying degrees. One respondent stated that an EPD must be for real and require producer responsibility which might be time-consuming and difficult to apply to already used materials. Another respondent emphasized the importance of basic material passports for the future. These passports could include crucial information about reused materials, addressing requirements such as fire safety, sound, accessibility, dimensions and CO2 savings. An additional respondent talked about using the CCbuild tools for continuous climate calculations and the obligation of suppliers to provide EPDs. Furthermore, another respondent mentioned the challenges in creating EPDs for reused materials and the necessity for rough estimates or expert assistance in calculating the climate impact of reconditioning and transportation.

Regarding Life Cycle Assessment (LCA), two respondents noted that if it is relevant, it's crucial to exclude stages A1-A5 from the LCA analysis. However, they stated that this approach may not be advantageous for already used materials and more beneficial to new materials.

4.1.3 Digitalization and Information Flow

The interview results shows that there was no consensus among most respondents regarding the ideal digital tools and software's for promoting material reuse within and beyond projects. Some tools mentioned by 4 out of 9 respondents included using smartphones/tablets to photograph objects and uploading them to platforms like CCbuild, enabling sharing or selling within the organization to external parties. However, 4 respondents found CCbuild not beneficial due to its difficult usage and inability to facilitate sales.

In addition, one respondent mentioned the beneficial of using a combination of GoPro cameras, Cirkulära (BuildID) and BIM programs. GoPro cameras were used to create 3D models of components, while Cirkulära (BuildID) facilitated material grouping and tracking with QR-codes and RFID technology, benefiting logistics in reconstruction and inventory management. Revit was used to refine the GoPro-generated models. Additionally, 4 respondents mentioned Excel for providing a list of reusable materials with specifications. However, 3 of 4 respondents found Excel not beneficial due to difficulties in finding relevant information, which may not always be available, and the lack of specific requirements such as fire safety, sound, and accessibility.

Equally important, all 9 respondents emphasized the importance of digitalization and combining various tools and software in developing the Circular Economy (CE). They stressed the need for digitalization and a common understanding across different perspectives to achieve value in the value chain. Furthermore, six of the respondents pointed out the importance of a structured database with predetermined categories, sometimes linked to search and filtering functions, for organizing materials. Categories may consist of reuse within or outside the project, placement, color, dimensions, reuse and waste, reuse potential, or the use of BIM models for grouping and categorizing materials. They also stressed the need to track reused materials and ensure compliance with relevant requirements such as fire and sound regulations, accessibility standards, and environmental rules. Furthermore, one respondents mentioned the importance of having standard words to reduce uncertainty. This concept was discussed in connection with a combination of different digital tools.

4.1.4 Hinders and Challenges

Figure 6 shows the most highlighted hinders and challenges from the interview study which will further be reviewed in this section.

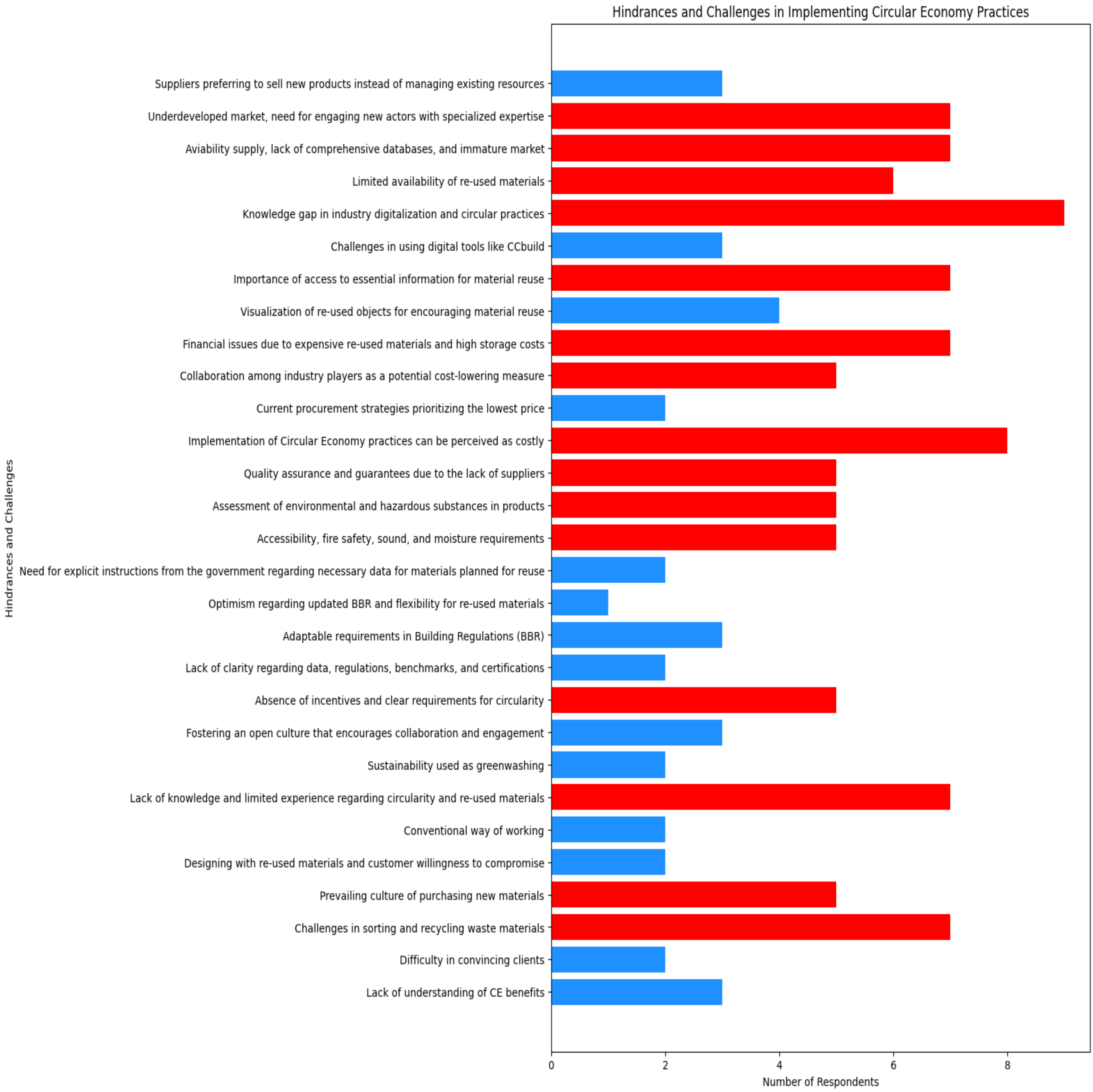

Figure 6: Hinders & Challenges

Social and Cultural

A third of the respondents pointed out that individuals often lack an understanding of the benefits of Circular Economy (CE) and may not recognize its value. Two respondents also emphasized the difficulty in convincing clients to adopt CE practices. Furthermore, some interviewees highlighted that effectively sorting and recycling waste materials can pose challenges which also a cultural aspect. As one respondent explained.

'' Many do not sort. Even if we sort, most of it is burned, for example, wood, which is about 30% of waste, is burned because there are no effective recycling solutions for it. If we reduced our waste, we would do much more for sustainability than reusing 5 windows."

In fact, over half of the respondents believe that the prevailing culture of purchasing new materials significantly impacts the use of reused materials, as designers find it easier and more time-efficient to work with new materials. Moreover, it has been noted that designing with reused materials can be challenging, requiring customers to be willing to compromise. In addition, some respondents highlighted the conventional way of working as significant challenge, mostly known for, as one of the respondents stated:

''This is how we always have done."

Regarding lack of knowledge, 7 out of 9 respondents believe that the construction industry must recognize the significant knowledge gap and limited experience regarding circularity and the use of reused materials. Additionally, 2 of the respondents highlighted that some companies have begun using the term "sustainability" as a form of green-washing. They also pointed out that high sustainability ambitions alone are insufficient, as projects planned 5-10 years ago did not consider this factor in circularity at the time.

''Today, we are working on ideas from 5-6 years ago. It's always lagging behind. What we understand today is very difficult to implement and make possible because we didn't understand it 6 years ago."

However, a third of the respondents stress the importance of fostering an open culture that encourages collaboration and engagement from various industry players in order to learn from each other and further promote circularity.

Political and Legislative

Most respondents, more than 50%, assert that the absence of incentives and clear requirements for circularity can hinder the prioritization of Circular Economy practices (CE). They also highlight that challenges may arise from a lack of clarity regarding data, regulations, and well-defined benchmarks or certifications from the government.

Furthermore, approximately one-third of the respondents believe that the requirements in BBR should be more adaptable in order to promote the reuse of materials in the construction industry. As one respondent stated:

''Some materials, built in the 1960s and have environmental benefits when

compared to buying new ones, but due to current requirements, they can't be used. For example, doors that may differ from today's accessibility requirements by just 2-3 mm are deemed unusable due to stringent regulations that treat reused materials as new so the requirement should me more flexible if we want to increase the reuse of building materials."

Nevertheless, the respondent also expressed optimism that the updated BBR may grant the industry greater flexibility, possibly promoting the utilization of reused materials. Moreover, some respondents called for more explicit instructions from the government concerning the necessary data for materials planned for reuse.

Based on the interview results, the technical issues vary depending on the type of material being reused. The most frequently mentioned technical concerns by half of the respondents are accessibility, fire safety, sound and moisture requirements. Also, assessment of environmental and hazardous substances in products and quality assurance, guarantees, because of the lack of suppliers how could guarantee a reused product for some years. According to one of our respondents this problem could be solved by building a large scale of reused materials.

''We don't have a supplier to rely on who can guarantee that a reused product for 10 years. Normally, when we buy new materials, we collaborate with suppliers who guarantee the product and also take responsibility in the project. Sourcing and obtaining the right quantities are a challenge. We build on such a large scale that guarantees become crucial. Imagine needing 100 nice reused outer doors for a project but only having three available. We would then have to collect the rest, which is a daunting tasks."

Economic

According to the interview results, 8 out of 9 respondents believe that implementing CE practices requires significant effort and time, and further can be perceived as costly, making it imperative for the client to drive the initiative. Additionally, some respondents expressed that the current procurement strategies can pose a challenge, as companies tend to prioritize the lowest price and are hesitant to take substantial risks. On the other hand, half of the respondents believed that collaboration among various industry players could mitigate uncertainties and eventually lower costs. As pointed out by one of the respondents:

''It is only when it will be cheaper to work with reused materials for everyone in the chain, then this big shift will occur (Manage with laws or a shortage of a material)"

Equally important, the majority of our respondents believe that one of the significant challenging aspects in the reuse of materials is financial issues due to the expensive compared to buying new materials and high cost of storage. For instance, three respondents highlighted that the cost of bricks is three times higher than that of new bricks, illustrating the potential economic challenges associated with adopting CE practices. According to one of our respondents:

''Using a reused bricks could be 3 times costly than using new one"

Technology

Based on the interview findings, 4 out of 9 respondents assert that visualizing reused objects with essential specifications, such as dimensions, reuse potential, sound and fire requirements, etc., could encourage greater material reuse. Whereas the rest of the respondents emphasized the importance of having access to the essential information, while the visualization of the object is not necessary. According to one respondent, this approach can create a partial information flow through various digital connections for material mapping. Furthermore, one-third of the respondents mentioned that the use of some digital tools, like CCbuild, can be challenging, which in turn acts as an obstacle for material reuse.

The interview result showed that are is gap in knowledge in the industry of digitization. Also, that the industry is still immature in both circular practices and digital infrastructure. Moreover, the respondents emphasized the importance of having databases that facilitate the process of implementing reused material into new projects such as marketplaces and better inventory tools.

A key challenge in utilizing reused materials, as reported by 6 respondents, is their limited availability. They observed that the architectural, engineering and construction industry contends with a scarce supply of these materials, a lack of comprehensive databases providing accurate information on sourcing, and an immature market. Moreover, on respondents stated:

‘’We need to know almost as much as we do with new construction. We need to know about the availability of reused materials, and it would benefit having a database for this purpose. So, it would have been good to have some kind of database or something like that that one could use when starting to plan a new project. The difference is that with new products, it is just a matter of drawing them and they are available in the market.”

Equally important, 8 of respondents consider the market to be quite underdeveloped. Half of them believe that engaging new actors with specialized expertise is crucial to address quality assurance responsibilities and bring clarity to the market. Additionally, 3 respondents have mentioned that some suppliers prefer selling new products instead of managing existing resources.

Other Findings

Overall, the respondents expressed optimism regarding the future of Circular Economy (CE) and the use of reused materials. Over half of them believe that stricter requirements imposed on the construction industry by various stakeholders will drive this development. Additionally, five respondents anticipate that the CE and reused materials will gain greater significance and become more integrated within the construction sector. One respondent specifically emphasized the need for change, stating:

"It is essential to move in this direction and cannot continue with our current practices of extraction, usage, and disposal."

4.2 Practical Study

The practical study was carried out on an existing building owned by Skanska, Tennet 3. The purpose of the practical study was to evaluate different tools that seek to promote Circular Economy and analyze exiting circular working methods. This will set a baseline to suggest an effective digital framework for circular practices. The practical study was carried out on the following products, see table 2.

Table 2: Chosen products

Object	**Dimension (mm)**	**Material**	**Reuse potential**
Door	845x2053	Wood	High
Entrance window	1137x2990	Steel & Glass	High
Façade window	2298x2926	Aluminum, Steel & Glass	High

4.2.1 3D-scanning

3D Laser Scanner

During the practical study an 3D-scanning was performed and together with an inventory of the chosen objects. One of methods chosen for the 3D-scanning was a scanning with a laser scanner (Faro Focus Laser Scanner). This method requires a basic level of knowledge to performed and process the data. It is also important to remark that the scanning was performed on the lowest quality level to make it more time efficient. The process of scanning was smooth and quick, it required minimal effort to performed and point-cloud model was generated automatically. Also, the software (Autodesk ReCap) could automatically match points between the scanned models and merge those. This method generated a huge amount of data with high quality and high accuracy, even in narrow spaces. Additionally, the scanning was performed in both light and dark environment with no difference in results. Results from this method are presented below.

Figure 7: Entrance window (3D-scanner)

Figure 8: Entrance window with dimensions (3D-scanner)

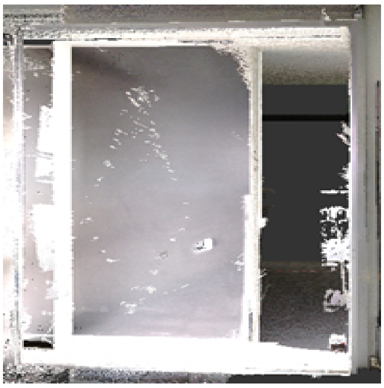

Figure 9: Facade window (3D-scanner)

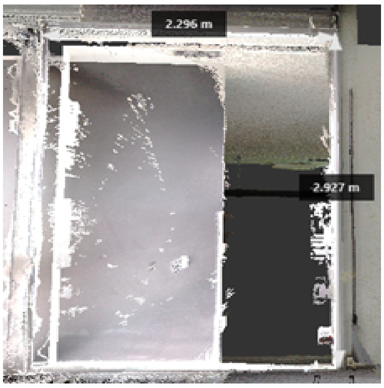

Figure 10: Facade window with dimensions (3D-scanner)

Figure 11: Door (3D-scanner)

Figure 12: Door with dimensions (3D-scanner)

360-video

Hereafter, a 3D-scanning was made with the Gopro Max and Insta360 cameras. This method was performed with videos in a 360-format, which is entirely different to the laser scanner. The process of videotaping was smooth and did not require much effort. However, this method is based on photogrammetry which requires the videos to be converted into still JPG images in order to process the data into 3D point-cloud model. The software's used to process the data were Autodesk ReCap Photo, Agisoft Metashape, and Reality Capture. This method is much more complex than the laser scanner and introduces new software's, this requires a high level of knowledge. Additionally, the lightning is essential with this method. The first problem encountered with this method was that Autodesk ReCap Photo does not support 360-images, which ''forced" us to process the data in Agisoft Metashape and Reality Capture but the images failed to align successfully for various reasons, see figure 13 , 14 & 15. Additionally, the processing of the data is not automated and the difference in the quality was noticeable.

Figure 13: Door (Agisoft Metashape)

Figure 14: Door (Agisoft Metashape)

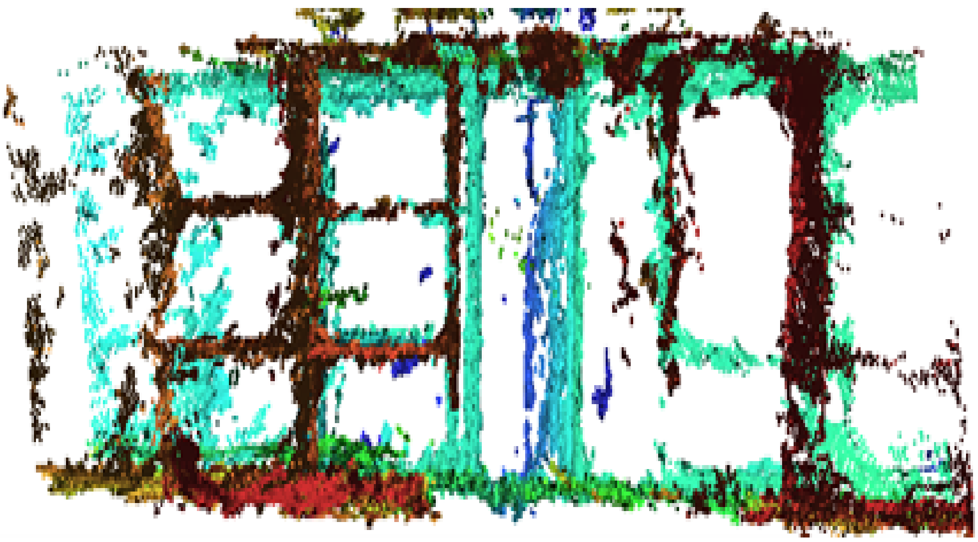

Figure 15: Point-cloud model - door (Agisoft Metashape)

This error was common for all the scanned objects in both Agisoft Metashape and Reality Capture. This method could not be used to create a 3D-model based on the point cloud data. The objects were therefore captured using regular images with the GoPro Max since the 360-video did not generate good results and processed in Autodesk ReCap Photo. This alternative created a 3D-model using photogrammetry as well, results are shown in figure 16, 17 & 18. However, it did not generate better results than the 360-videos. Overall, both these methods required much effort and higher level of knowledge.

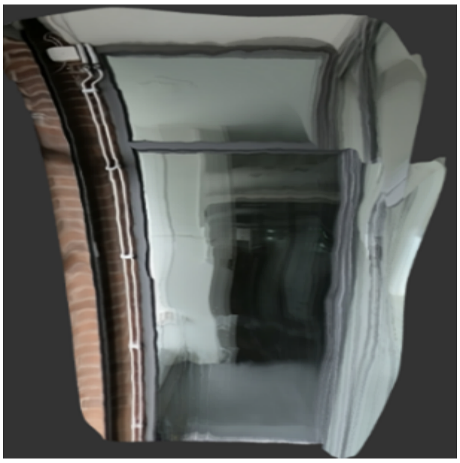

Figure 16: Entrance window (Autodesk ReCap Photo)

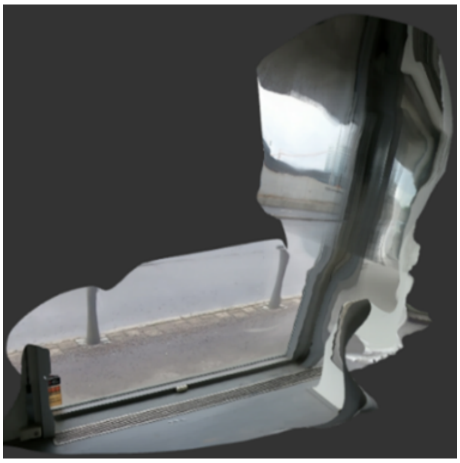

Figure 17: Facade window (Autodesk ReCap Photo)

Figure 18: Door (Autodesk ReCap Photo)

Smartphone

Lastly the objects were scanned using iPhone 11 Pro and iPhone 13 using software's that allowed to generate a 3D-model instantly using photogrammetry. The objects were scanned using Scaniverse which was very handy and flexible as it depends only on your mobile phone. The issues encountered were mainly based on the contrast of the lightning. However, a 3D-model was instantly generated on-site which saved a lot of time when reviewing the object. The generation of the 3D-model was automated with good quality and provided valuable data, assuming that the model was accurate. See figure 19, 20, 21 & 22, for results from Scaniverse.

Figure 19: Facade Window (Scaniverse)

Figure 20: Facade window with dimensions (Scaniverse)

Figure 21: Door (Scaniverse)

Figure 22: Door with dimensions (Scaniverse))

Additionally, the web-based platform Matterport was also used as an alternative to scan the chosen objects. Matterport allows the user to instantly create an accurate digital twin of the scanned object/area using their own 360-camra or one compatible to their platform or a mobile phone. This method required much effort and was complicated, especially in terms of merging and relocating different scans and repetitive connection issues. Matterport provides a virtual tour of a facility or building as a services but does not provide the option to expert the model to other file-formats. The results are shown in figure 23 & 24.

Figure 23: Door (Matterport)

Figure 24: Door with dimensions (Matterport)

3D-Revit Family Type

Furthermore, a 3D Revit Family for each object was design using the information gathered from the inventory such as dimensions and material type. The Revit Families were used to check-off the accuracy to the 3D-models generated from the different scanning methods, and to provide the design team with a accurate 3D-model of the object. Additionally, the object was enriched with remaining information in Autodesk Revit and an IFC-file was created to facilitate sharing between disciplines. This also allows more or missing information to be added to the model through platforms like StreamBIM. Revit families are presented below in figure 25, 26, 27, 28, 29 & 30.

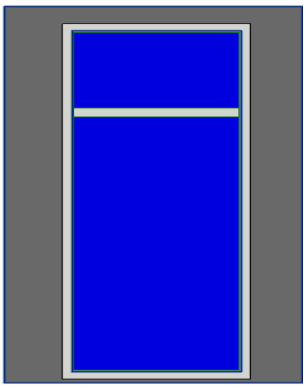

Figure 25: Entrance window (Revit Family

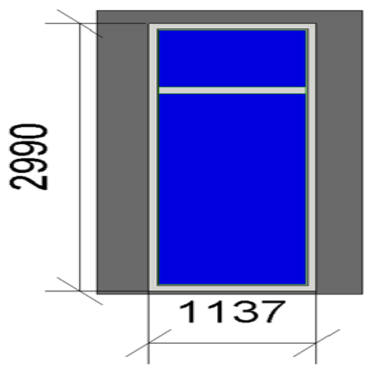

Figure 26: Entrance window with dimensions (Revit Family)

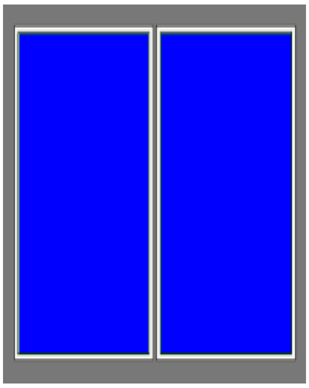

Figure 27: Facade window (Revit Family)

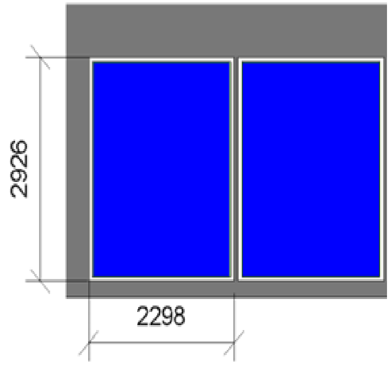

Figure 28: Facade window with dimensions (Revit Family)

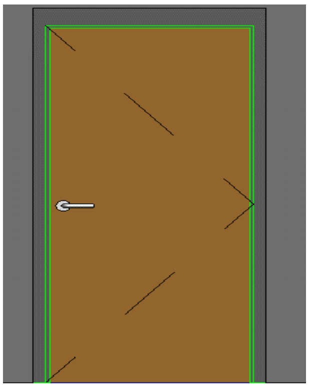

Figure 29: Door (Revit Family)

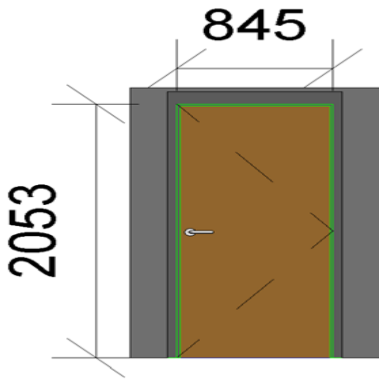

Figure 30: Door with dimensions (Revit Family)

4.2.2 Information Flow

Inventory Tools

There are several existing inventory tools available on the market which seek to increase circularity. Therefore, an inventory was performed using CCbuild, Palats and Crikulära (BuildID) where the point was to evaluate and understand how Circular Economy is implemented today and gain knowledge both about the inventory process and tracking of the information flow. The inventory using the mentioned tools was performed parallel to the 3D-scanning. This process allowed to map out relevant and useful information needed for the different actors in different stages of circular economy. Additionally, important parameters for an efficient inventory were outlined based on the categorizing and filtering method of the different tools. These parameters were used to design a database to storage the inventoried material/products. Also, it generated an idea to provide a 3D-model with an QR-code which allows for a unique identification of the real-world object.

Database

The first step was to design a basic structure of the database on excel (figure 31) based on the parameters from the results from the practical study, literature study and the related work, shown in table 3. Continuously, the database was developed and hosted as a Structured Query Language (SQL) database in Supabase. Furthermore, using JavaScript a simple interface was developed through Replit and linked to Autodesk BIM data tool. This allowed for essential information from the inventory to be store and in the same turn the materials intended for reuse could be preview or crosschecked to the BIM-model. Lastly, a project filtering option was added due to its potential to facilitate the availability of the product and facilitating the information flow between projects. Moreover, the database instantly generates a QR-code based on the unique ID which facilitates both tracking the information and streamlines the information flow of the product. It is also possible for the user to upload essential documents such as images, IFC-file, material documentation, etc., of the product. The database is shown in figure 32. It is important to remark that technical requirements include important aspects highlighted in the report such as accessibility, fire protection, hygiene and health, noise protection, safety and energy conservation.

Table 3: Chosen parameters for the database

Inventory tools	**Interview results**	**Related work**
Project name	Project name	
Object name	Object name	
UniqueID	UniqueID	
Amount	Amount	
	Reuse potential	
Condition	Condition	
	Availability	Availability
Material	Material	
Dimensions	Dimensions	
Color	Color	
	Location	
Year of manufacture	Year of manufacture	
Technical requirement	Technical requirements	Technical requirements
	Technical lifespan	
	Recomendations	
Climate saving	Climate saving	
	Quality assurance	Quality assurance
	Waste	Waste
	Documentation	
	Inventory by	

Project name	Object name	Unique ID	Amount	Re-use potential	Condition	Availability	Material	Dimensions (mm)	Color	Location	Year of Manufacture	Technical Requirements	Technical lifespan	Recommendation	Climate saving	Quality assurance	Waste	Documentation	Inventory Performed By
Tennet 3	Facade window	"Unique ID"	1	High	Good	Available	Aluminum, Steel & Glass	(2298x2926)	Grey	Facade	2009	Safety (B1 & 2B2), Security (P2A-P5A)	30	Need Reconditioning	-	Assessed after disassembly	Assessed after disassembly		Jefferson & Mohammad
Tennet 3	Entrance Window	"Unique ID"	1	High	Good	Available	Steel & Glass	(3137x2990)	Grey	Entrance	2009	Safety (B1 & 2B2), Security (P2A-P5A)	30	Need Reconditioning	-	Assessed after disassembly	Assessed after disassembly		Jefferson & Mohammad
Tennet 3	Door	"Unique ID"	1	Hhigh	Good	Available	Wood	(845x2053)	Brown	Office first floor	2001	Sound class 30dB	40	Need Reconditioning	-	Assessed after disassembly	Assessed after disassembly		Jefferson & Mohammad

Figure 31: Database structure on excel

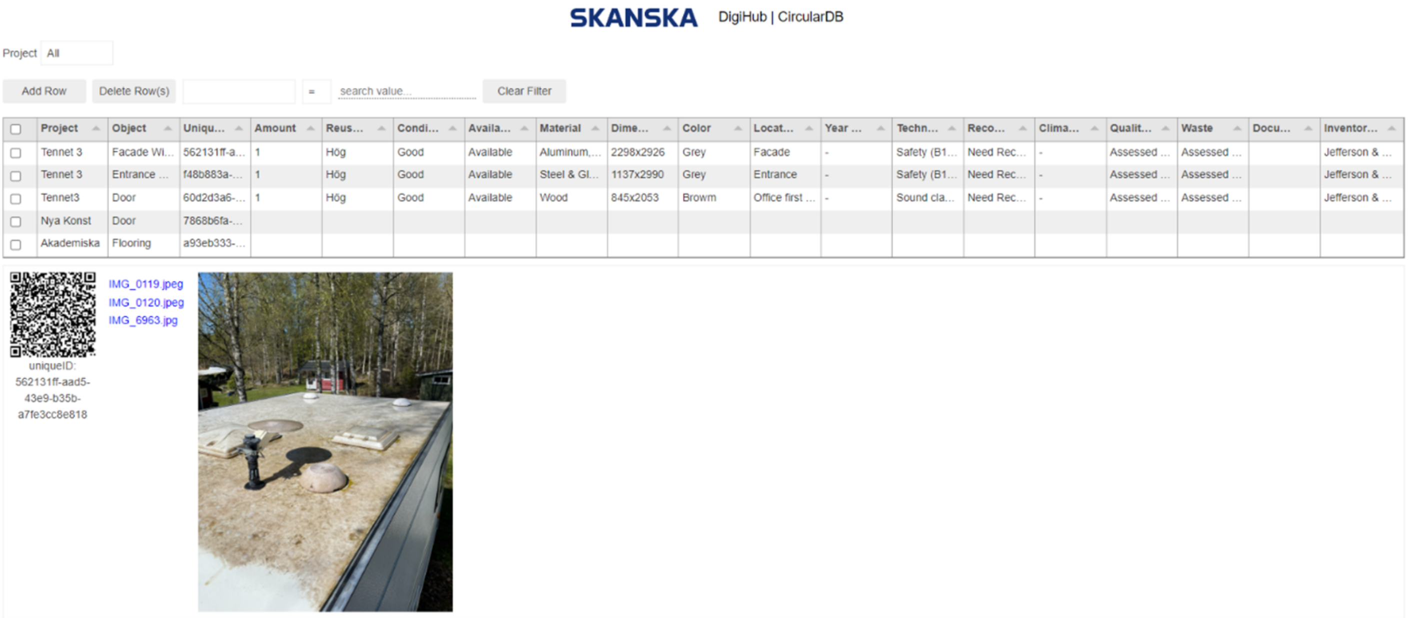

Figure 32: Database

5. Discussion

Based on the related work and the interview results, it is evident that there is a growing awareness of the need for a shift towards a Circular Economy (CE) in the Swedish Architectural, Engineering, and Construction (AEC) industry. Despite the lack of a clear understanding of the concept among some respondents, there is a general consensus that the industry generates a significant amount of waste and contributes to climate change, which should be addressed through the adoption of CE models. In this chapter the Related work, interview results and the practical study will be discussed in border perspective.

5.1 Interviews

This section examines CE implantation and reuse in the Swedish AEC industry for sustainable development. Despite some progress, challenges persist. The chapter discusses overcoming barriers through legislation, policy, digital tools, and stakeholder collaboration to achieve Sweden's net-zero emissions goal by 2045.

5.1.1 Circular Economy and Reuse

Boverket (2023a) highlights that the Swedish AEC industry has made progress in reducing its environmental impact by decreasing greenhouse gas emissions and hazardous chemical use. However, it has not met recycling goals, and there has been an increase in particle emissions, energy usage, and environmentally hazardous chemicals. This situation calls for a more holistic approach to sustainability in the construction sector, emphasizing the importance of transitioning from a linear economy to a circular one. Furthermore, CE can address the challenges posed by the linear economy model by minimizing waste and promoting the sustainable use of resources through efficient design, material reuse, and recycling. This also acknowledged in the interview result. Additionally, the literature suggests that implementing CE strategies in the building sector can lead to environmental, economic, and social benefits, such as reducing life cycle costs, creating new jobs, and improving the well-being of communities (Schenkel et al., 2015; Econometrics, Trinomics, and ICF, 2018; Koutamanis, Reijn, and Bueren, 2018; Nußholz et al., 2020).

Interview results shows that there is a confusion between the CE concept and merely increasing the use of recycled materials demonstrates a lack of understanding about the broader benefits of CE. This indicates a need for more comprehensive education and awareness-raising efforts in the industry. Decision-makers, architects, engineers, and other stakeholders should be well-informed about the potential benefits of adopting CE practices, as well as the necessary steps to implement them effectively. Likewise, Ghisellini, Ripa, and Ulgiati (2018), Ababio and Lu (2022), and Bellini and Bang (2022) mentioned that there are some significant barriers such as lack of knowledge, collaboration among different actors, lack of information, lack of sustainable process and additionally lack of interest throughout the value chain.

The implementation of CE practices in the Swedish AEC industry will require collaboration among various parties, including government agencies, industry stakeholders, and academia. Developing guidelines, policies, and incentives to encourage the adoption of CE strategies can help drive the transition. Furthermore, fostering innovation and promoting eco-friendly technologies can facilitate the shift towards a circular economy, ultimately contributing to the achievement of Sweden's vision of becoming a "net-zero emissions" country by 2045.

Additionally, Andersson et al. (2021) and the interview results provide valuable insights into the current state of reuse in the Swedish ACE industry. Both sources highlight the importance of reuse for environmental benefits, including reduced CO_2 emissions and resource extraction. Henec, Brander, Boubitsas, and Gabrielsson (2021) emphasizes the need to follow the EU waste hierarchy by prioritizing reuse over recycling, while the interview results suggest that practitioners consider reuse as a spectrum, ranging from restoring to up-cycling.

Regarding on which demolition's method is suitable to the Swedish ACE industry. The interview results could not show the differences among various methods of demolition. But a key finding from the related work is the difference between conventional demolition (CD) and selective demolition (SD). SD is considered more environmentally friendly, as it diverts a higher percentage of materials from landfills and recovers them for reuse. However, the environmental benefits of SD are contingent on factors such as transportation distances and operational costs (Ghisellini, Ripa, and Ulgiati, 2018). Whereas, the interview results reflect this understanding, as some respondent's express concerns about working outside their comfort zone and the need of having a specific plan for reusing materials before the project start.

5.1.2 Assessment Tools

According to Boverket (2019a), Life Cycle Assessment (LCA) is an important tool in assessing the environmental impact of a product or building throughout its entire life cycle. This includes evaluating the impact of extracting natural resources, the manufacturing process, the use phase, and the disposal or end-of-life phase. On the other hand, the interview result shows that having an LCA for reused material is not relevant. In the case of doing an LCA for the reused material it should exclude A1-A5, which means excluding product stage and construction stage. This is understood because the product exists already and there is no need for extracting new natural resources and there is no need for manufacturing. Additionally, according to the Boverket (2019a) the key benefits of LCA is the ability to gain an in-depth understanding of the various resource flows and environmental impact of a building. This knowledge can be used to design and construct buildings with a reduced environmental impact. This not supported by the interview result due to the more time consuming under the inventory process and because some materials are old do not have in-depth information.

Equally, the Environmental Product Declaration (EPD) for a building product is a comprehensive document that provides detailed information about the environmental impact of the product throughout its entire lifecycle which requires in-depth information about the product (Boverket, 2019b). This is supported by the interview results suggesting that generating an EPD for reused materials requires significant effort. However, Munaro and Tavares (2021) and Bellini and Bang (2022) inface the power of having a material passport which contains essential information for circularity throughout the product life cycle. Whereas the interview result shows that a basic material passport that includes critical information about the reused material, addressing requirement such as accessibility, fire safety, moisture, and sound would be more beneficial. The respondents also highlighted the need for assessing the environmental and hazardous substances in products, ensuring quality assurance and guarantees, and calculating the climate saving. It is crucial to have a reliable database and expert support to estimate the climate impact of reconditioning and transportation, thereby achieving significant savings.

5.1.3 Digitalization and Information Flow

Kovacic, Honic, and Sreckovic (2020) and Jemal et al. (2023) states that digitalization is expected to enhance collaboration and value co-creation. Additionally, it is highlighted that there is a need in developing business models where it provides values to all actors involved in order to promotes CE. This is supported by the interview results as it shows that there is a need of combining various digital tools and software's, and collaboration among different actors in the industry in order to achieve value in the value chain, which could enhance CE practices and further facilitate reuse.

In contrast, the interview results shows that there is no consensus among different actors in the industry regarding the ideal digital tools, software's, digital working practices in order to promote material reuse. This could be according to the related work subsection 3.6.2 due various factors such as different data formats, structures, and standards, as well as varying business workflows. In sum, the current high amount of available digital tools and working practices, including BIM, data transfer formats, and emerging tools suggests that the mere availability of technological tools does not necessarily guarantee their effective utilization, which in turn undermines the anticipated benefits. Ehlert et al. (2019) and the interview results highlight the importance of pre-demolition audits and material inventories in managing resources and preventing waste during the demolition of a building. The inventory process serves to identify reusable building products, types of waste that may arise during demolition, and the presence of hazardous substances. It also aids in the development of a control plan according to the Planning and Building Act (PBL) (2010:900), outlining how materials should be handled and waste managed, with a focus on high-quality material recycling and safe handling of hazardous materials (Naturvårdsverket, n.d.).

White Arkitekter et al. (2021) provides a five-stage approach that results in a control plan with recommendation for reuse in order to improve the inventory process. This seeks to optimize the inventory management and achieve greater sustainability and at the same time facilitating the track of the information flow. The interview results infaces the importance of the information flow as the majority of respondents emphasized the importance of reviewing construction documents, conducting site visits, and filling in necessary information. However, some respondents remark on the significance of using digital tools for this purpose, but there is no clear standard of how the inventory process should be performed digitally. They also acknowledged the value of using on-site photography, 3D-scanning, and collaborating with architects or other professionals in assessing the condition and potential reuse of materials. However, the time-consuming nature of the inventory process was a concern for most respondents. Additionally, the interview results emphasize that digitalization could be the solution to solve these issues and promote reuse in the industry. Digitalization could also help to track the reused materials by using technologies like RFID which could be beneficial to the inventory management and reconstruction. Furthermore, using some technologies such as 3D-scan and Revit to get a digital twin of the product could help reduce the inventory time. This could enhance the information flow when building a database where most critical requirements about the materials are included.

5.1.4 Hinders and Challenges

Additionally, the Related work identifies several barriers to increased reuse in Sweden, including a lack of information, knowledge, and awareness throughout the reuse chain. The interviews results also touch upon these challenges, as some respondents find it difficult to evaluate the quality of reusable products and information on hazardous substances.

5.1.4.1 Social and Cultural

Kirchherr et al. (2018) and Munaro, Tavares, and Bragança (2020) identified the lack of awareness, lack of knowledge and limited experience in CE practices and reused materials as significant challenges. This is supported by the interviews as they specifically touch upon the mentioned challenges, additionally some respondents find it difficult to evaluate the quality of reusable products and information on hazardous substances. The social and cultural barriers identified in the interview results relate to the culture of buying new materials and the difficulties in designing with reused and recycled materials. Admittedly, Lines et al. (2015), Kirchherr et al. (2018), Hart et al. (2019), and Munaro, Tavares, and Bragança (2020) support this by highlighting that the fragmented and conventional regimes impose a challenge for new working method and innovative ideas. One significant aspect that was raised in the interview result is the need to create a new open culture of involvement and engagement from different actors in order to learn from each other and further drive for circularity. This could change the simplistic mentality in the industry which in turn could reduce the uncertainty and complexity highlighted. Another important cultural barriers that arouse in the results is that people is resisting to new technologies and still comfortable with the same ways as they always done, This is also supported by (Çetin, Gruis, and Straub, 2022). In order to address the identified barriers and successfully implement a CE practices, it is necessary to adopt strategies that incorporate technical, social, economic, and other relevant aspects. As highlighted by Walker et al. (2021) and Ababio and Lu (2022) achieving this requires extensive collaboration among diverse stakeholders, including communities, industry players, government bodies, and suppliers. Which also supported by the interview results.

5.1.4.2 Political and Legislative

The legislation and policy, such as the amendment to the Swedish Planning and Building Act (PBL) and the need for standardization and quality assurance systems could according to Brander, Boubitsas, and Gabrielsson (2021) have a significant impact in the development of CE and promote the reuse of materials. This is also supported by the interview results. In addition, the interview results also acknowledge the importance beyond reuse and should consider circular design and adaptability and the need for the right competence in the industry.

Both Rios, Grau, and Bilec (2021) and Sandberg, Ann, and Kvellheim (2021) and the interview results highlight the importance of driving changes through incentives and regulations. Çetin, Gruis, and Straub (2022) also shows the importance of adapting buildings rules, codes, and regulations to comply with CE practices. Accordingly, the interview results support this statement and mentions some requirements that could specifically increase the reused materials. Those requirements could be accessibility, sound, fire safety and moisture. Additionally, the interview results highlighted that the new version of BBR would provide more room and flexibility for the industry to promote CE practices in general and the reuse of materials. However, it was not clear how the process would look like. It also suggested at the same time that the government should clearly define the data needed for materials that can be reused. This aligns with Çetin, Gruis, and Straub (2022) asserting the importance of having national standardization for data exchange to ease the generation of material passports, given the current uncertainty regarding data requirements. This will in turn facilitate the implementation of CE and promote reuse due to the increased transparency and accessibility of information about reusable materials. Additionally, the interview result mentioned the lack of suppliers that provides quality assurance and guarantees for reused materials is a critical aspect. Therefore, according to the interview result it is important to building a large scale of reused materials or material banks which could promote CE practices.

5.1.4.3 Financial and Economic

Carra and Magdani (2017), Guerra and Leite (2021), and Ababio and Lu (2022) sate that industry lacks environmental financing and prioritize short-term gains and fast payback. In addition, Adams et al. (2017) and Kirchherr et al. (2018) claim that the end-life-value of reused materials is reduced by the availability and low cost of raw material, which are seen as significant parameters to hinder the adoption of the implementation of CE and reuse materials. There is a strong correlation to the interview result as the majority of the respondents concur that the implementation of CE is costly, and reused materials are seen as expensive and risky. Additionally, the interview result has shown that the current procurement strategies is challenge because companies tend to prioritize the lowest prices and are hesitant to take substantial risk. Equally important, Miliute-Plepiene et al. (2021) claims that the client has responsibility in taking initiatives towards the implementation of CE practices. Hence, the majority of respondents argue that convincing clients to take initiative towards implementing CE practices can be challenging. This is because CE is often perceived as costly, which further hinders its implementation.

5.1.4.4 Technological

Eijk (2015) and Ababio and Lu (2022) argue that technology and innovative solutions are necessary in the transition to CE. This is emphasized by the respondents, although some respondents state that new tools can be challenging which can become an obstacle. According to, Ababio and Lu (2022) there is a need of innovative solutions and new tools that facilitate communication, coordination, and planning, allowing for transparency throughout the value chain. Jemal et al. (2023) claims that CE is being hindered by the lack of proper digital infrastructure and recycling infrastructure, and lack of reliable marketplace for reuse and resale of certified durable materials. In the same way the interview results highlight that market of reused material is underdeveloped, due to among other things inefficient marketplaces. Additionally, the availability of material or products was stressed by most of the respondents as a significant factor to hinder reuse, which is highly dependent on the marketplace and material databases available. Munaro and Tavares (2021), mentioned the European initiatives Buildings As Material Banks (BAMB), that could address these issues and provide a more standardize way of working and facilitating data storage and data sharing. Furthermore, the interview result highlights the need for new actors with special competence to get involved in order to solve quality assurance responsibility and make the market transparent.

5.2 Practical study

This section examines the practical study and its process, hinders that arise and positive outcomes. It reviews the practical study in relation to the related work and interview study.

5.2.1 Digitalization and Information Flow

Kovacic, Honic, and Sreckovic (2020) and Jemal et al. (2023) highlight digitalization as essential in the transition to circular practices. Circular Economy is increasing in popularity in the same pace as the climate crisis is becoming the most relevant topic in all sectors (Wijaya, 2014; Adams et al., 2017; Jemal et al., 2023) to promote CE there is a necessity of digital tools that includes the whole value chain. The academia highlights digitalization as essential for circularity which is also acknowledge in the interview results. However, digitalization requires people to re-educate themselves, as new knowledge is being introduced together with new working methods and tools. This can become an obstacle as the industry is known for being fragmented and conservative (Lines et al., 2015; Kirchherr et al., 2018; Hart et al., 2019; Munaro, Tavares, and Bragança, 2020). Accordingly, the interview results support this statement. One of the respondents stated the following:

''This is how we always have done."

This can also be supported from the practical study as new digital tools were introduced along the way, which required new knowledge to be acquired and to develop new ways of working.

Furthermore, the interview result showed the importance of efficient inventory, availability, and quality assurance, one of the respondents highlighted the importance of a BIM-model. Equally important, Munaro and Tavares (2021) and Bellini and Bang (2022) suggest that a Material Passport (MP) would facilitate keeping track of important information for reuse promoting circular economy. Therefore, it is essential to link product information in a database to the real object through unique material ID and if possible, provide a 3D-model/IFC/Sharing-formats of the object which could work as a basic MP.

The practical study consisted of 3D-scanning, material inventory, and the development of a database. The scanning was performed through three different methods as it was mentioned in chapter 4.2, whereas the most efficient scanning methods were the laser scanner followed by the mobile phone. However, a laser scanner fits more in bigger project as it can easily create a point-cloud of huge areas, whereas a mobile phone could be used for single objects. Additionally, the laser scanner requires a certain level of knowledge but works perfectly as underlay for a digital twin as it is accurate. However, the data needs to be transferred manually to a computer and processed to generate a model through a compatible software such as, FARO's own software or Autodesk ReCap. On the other hand, the mobile phone can instantly generate a point-cloud model which can be studied on-site to determine if the model is valuable, which can save a lot of time. Scanning with the mobile phone has huge potential to promote circularity in the industry, but it still requires development to fit in the industry. Badillo, Parfenov, and Shchegoleva (2021) and Afteni et al. (2022) highlight issues concerning photogrammetry such as the generation of holes due to that the reflected light cannot be collected, which was a reoccurring issue using the mobile phone for the 3D-scanning. This needs to be solved for the mobile phone in order to be optimal for the building industry. Furthermore, 360-cameras are not an option as it requires too much effort and knowledge to get valuable results. As mentioned earlier, it is essential to re-educate and to find new innovative solutions and working methods (Eijk, 2015; Ababio and Lu, 2022). The software's used in the practical study did not generate good results due to the quality of the images and 360-images. However, it is important to remark that there are existing software's that support 360-videos and are adapted to the building industry, that were not tested in this practical study due to that they were unavailable for its subscription. Moreover, the industry requires the 3D-model to be exported in different file-formats as the industry depends on different software's LI, Nederveen, and Wolfert (2017), which made platforms like Matterport irrelevant for the digital framework.

According to Andersson et al. (2021) and interview results the industry is still immature regarding circular practices which is why the market of reused materials is still lacking. Therefore, a database was developed to facilitate reuse and to provide a basic Material Passport (MP) as mentioned earlier. Moreover, is important to include only essential information of the product as the interview results suggest. As a result, this could work as a MP for the reused material, which was emphasized by the majority of the respondents. It is also found from the interview results that the industry relies on the availability of materials and quality assurance. Therefore, platforms like CCbuild and palats lose their potential to promote circularity and are manly used as inventory tools as no guarantees can be provided. Therefore, a parameter for quality assurance was included in the database. However, according to Walker et al. (2021) and Ababio and Lu (2022) and interview results remarks there is a need of collaboration among actors in the industry to create efficient ways of working, where new actors and suppliers should engage in order to ensure the availability and quality of products in the market. Additionally, the interviews results highlight that the building industry need to cope from best practices of other industries. One example is the way Cirkulära is working with radio frequency technology (RFID)-technology to track and facilitate the logistic. This could be linked to the unique ID of a product in the database which could facilitate the logistics but was not included in the practical study.

Throughout the development process of the database system, the goal was to create a more efficient and user-friendly digital framewotk. In order to streamline the workflow within the organization, the database was linked to the Autodesk BIM data tool and an extern interface. Furthermore, this could provide an object viewer for the reused product in the future, which could facilitate decision making and the design team. Additionally, most important parameters found in the study were included in the database due to their significance in helping the design team and driving the reuse of materials, see table 2.

One of the primary goals of the database was to enable categorization and grouping of materials, as this was a critical requirement identified through the interview results. This feature would allow the involved actors to have more insight into the materials and their quantities. Additionally, it was discovered through the interview results that stakeholders did not want to have the inventory materials listed in multiple Excel documents, making a database a more beneficial option.

According to Brander, Boubitsas, and Gabrielsson (2021) and Çetin, Gruis, and Straub (2022), to increase the use of reused building components, standardization of quality and quality assurance systems need to be developed. Equally important, quality assurance was identified in the interview results as a critical parameter that should be included in the database. To ensure the quality of the product after deconstruction, expert suppliers need approve the quality of the products in the database. It is important to remark that the digital framework nor the database would provide a standardize system to ensure quality of the reused material, but it will solely drive forward the work toward a standardize system. Furthermore, logistics work was identified as a significant hindrance to tracking deconstructed materials. To address this issue, a unique ID for each product was added to the database, allowing for better tracking and information flow. According to Mabad et al. (2021), the RFID-technology could facilitate both the logistically work and the management of the supply chain. Additionally, such technology was not tested in the practical study, but it was found in the interview results that RFID-technology would certainly facilitate the logistic work and documentation. Regarding information flow (documentation), RFID-technology could also be linked together with the unique ID of the product enhancing reuse with a more efficient information flow and better logistic work. Consequently, this feature would help the design team and relevant stakeholders to know where the reconstructed materials are and the amount of products with the same specifications in different projects, helping to solve the availability issue. During the development process, it was discovered that a 3D model was not necessary, as the design team always used standard products. Instead, a 3D scanning process was considered to be more efficient for obtaining the correct dimensions and creating a digital twin of the product. Additionally, an extra filtering option was added to the database to allow for filtering by project which could facilitate searching for specific product in a specific project.

Finally, it was discussed that integration with Excel could be a future development, and pricing was excluded from the database since it would only be available for in-house projects at Skanska. Overall, the database system was developed with the aim of creating a user-friendly and efficient platform for managing inventory and materials.

6. Suggestion on digital framework

The suggestion of the digital framework was designed according to the results from the interview study, practical study, and some input from the related work, which gave three key processes, which are illustrated in figure 33:

1. **Inventory Management:** This process begins with, a well established and comprehensive control plan (see section 3.3.1 & 3.3.2). Furthermore, pre-demolition audits are a critical aspect to achieve a high degree of reuse in the projects (see section 3.3.1 & 3.3.2). These plans outline the necessary steps to be taken, identify the key stakeholders who should be involved right from the beginning and what software's should be use. Then, starting with identifying products suitable for reuse across various project. The inventory can be enriched with descriptions, images, and 3D-scans. The collected data will be processed and uploaded to the database. If 3D-scanning is used, it can serve as a base layer for creating a 3D model of the product using Autodesk Revit. Additionally, an Excel sheet detailing potential products for reuse can be generated by the organization. This spreadsheet will contain critical parameters and relevant information necessary for the database, using standardized terminology. An IFC-format from CAD programs can also be imported into the database, enabling stakeholders to preview product models.

2. **Database:** The database serves as a digital repository for the products. Quality experts are recommended to be involved from the begging (inventory phase) and have access to the database to validate the quality of products that have undergone scrutiny during inventory management. There's also the potential to link the product via IFC-format to a BIM-model of the new building, fostering collaboration among project stakeholders and facilitating decision-making. The database can also perform a generic climate savings calculation for individual products. Therefore, coupled with other parameters discussed earlier in table 2, the database can generate a basic material passport for each product. An additional key feature of the database is its ability to generate a QR-code that can be attached to the material. The QR-code can be connected to an RFID-chip to streamline logistics during reconstruction or if the materials are stored. This feature assists in tracking the product's information flow.

3. **Reuse:** The digital framework aims to add value by optimizing reuse. The database can be employed to trace of the reused material's life cycle, ensuring the material remains in the economic loop.

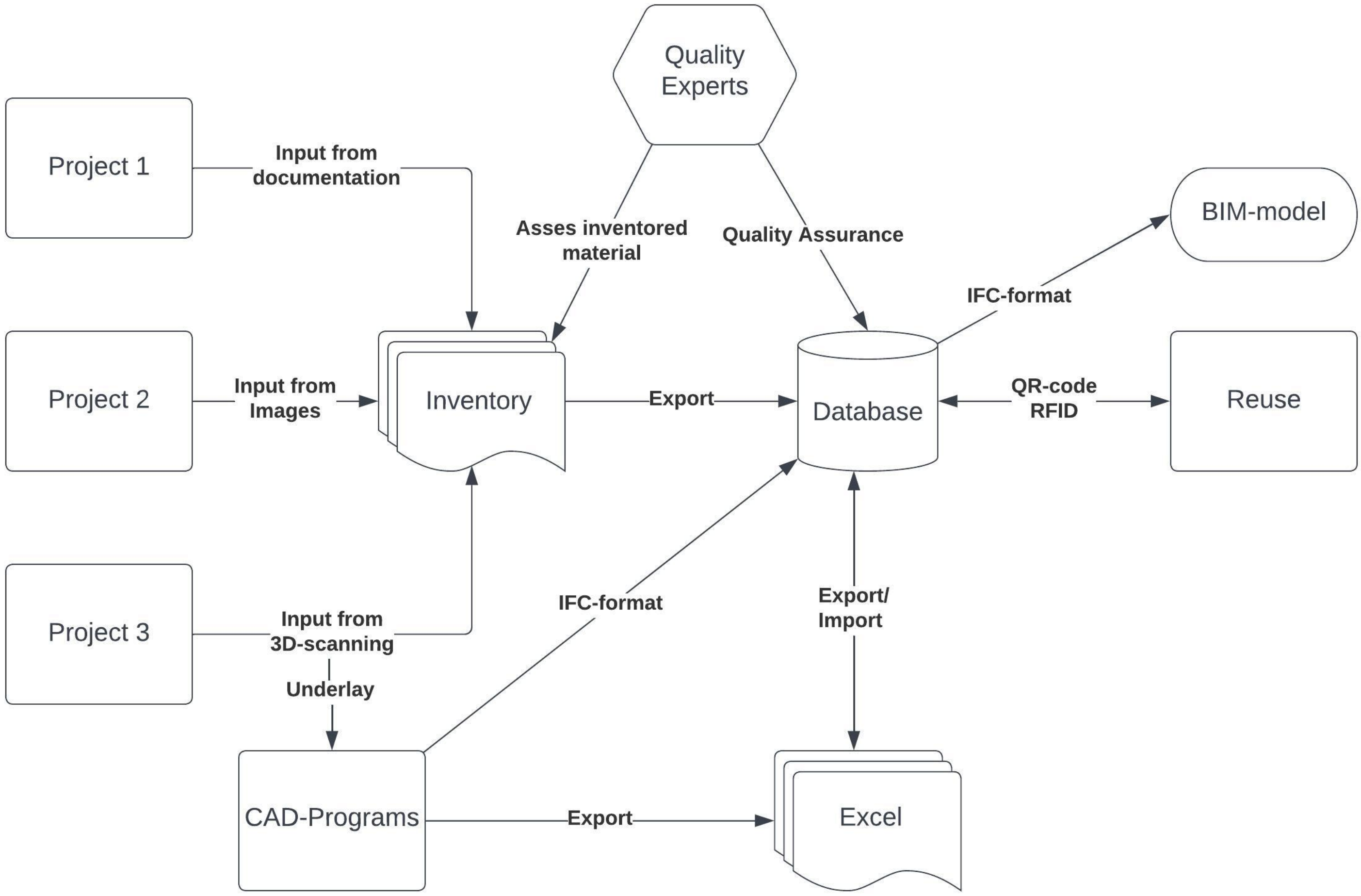

Figure 33: Suggested Digital Framework

7. Conclusion

The Swedish Architectural, Engineering, and Construction (AEC) industry needs to transition from linear economy (LE) to circular economy to reduce waste, promote sustainable use of resources in order to achieve Sweden's vision of becoming a "net-zero emissions" country by 2045. But also gaining environmental, economic, and social benefits. Therefore, the implementation of CE practices in the AEC industry can bring significant improvements, but it requires collaboration among various stakeholders, including government agencies, industry players, and academia. Developing guidelines, policies, and incentives that encourage the adoption of circular economy strategies can facilitate the transition. However, it also exposed a lack of clear understanding among some stakeholders regarding the broader benefits and practices of CE. This highlights the need for comprehensive education and awareness-raising efforts to ensure that decision-makers, architects, engineers, and other industry professionals are well-informed about the potential advantages of adopting CE practices and the necessary steps to implement them effectively. Additionally, collaboration among diverse stakeholders is crucial for creating a conducive environment for circular practices, which includes government agencies, industry players, academia, and communities.

This thesis has provided valuable insights into the challenges and opportunities associated with incorporating CE practices in the Swedish AEC industry, emphasizing the role of information and digital framework in driving their adoption. It revealed a growing awareness within the industry of the need to shift towards CE to address the environmental impact of construction activities. Additionally, fostering innovation and promoting the use of eco-friendly technologies are crucial in driving the industry towards a CE.

Overall, the research findings highlight the complexity of implementing circular processes in the AEC industry and the multifaceted nature of the challenges involved. Social and cultural barriers, such as resistance to change and a fragmented industry structure, pose significant obstacles to the widespread adoption of circular practices. Political and legislative barriers, such as the need for updated regulations and standardization, need to be addressed to provide a supportive framework for circular implementation. Financial and economic barriers, including the perception of increased costs and short-term priorities, require strategies that highlight the long-term benefits and potential cost savings of circular approaches. Technological barriers, such as the need for innovative solutions and seamless integration of digital tools, necessitate ongoing research and development efforts.

Effectively addressing these barriers is essential for the widespread adoption of circular economy and promote the reused of materials in office projects. Overcoming social and cultural barriers, such as resistance to change and the fragmented nature of the industry, requires concerted efforts to foster a new culture of involvement and engagement among stakeholders. Political and legislative barriers necessitate the development of supportive policies, regulations, and incentives that promote circular approaches and facilitate the transition. Financial and economic barriers can be overcome by highlighting the long-term benefits and potential cost savings associated with circular practices. Technological barriers require ongoing research and development to enhance digital tools, improve information flow, and enable seamless integration across the value chain.

Additionally, stakeholders in the AEC industry must collaborate and engage in knowledge sharing to establish a common understanding of circular economy principles and practices. Governments and regulatory bodies should actively create supportive policies and regulations that incentivize circular approaches, including the establishment of national standardization for data exchange and material passports. Industry players should invest in research and development to enhance digital tools, improve information flow, and facilitate material tracking and quality assurance.

A significant challenge in implementing circular processes is the lack of information, knowledge, and awareness throughout the reuse chain. Efficient information flow and digitalization are vital for enhancing collaboration and value co-creation in the industry. Utilizing digital tools like 3D scanning, inventory management systems, and databases is necessary to promote circular economy practices. However, the adoption of digitalization may encounter obstacles, as it requires individuals to re-educate themselves, which can be challenging in an industry known for its fragmentation and conservatism. Furthermore, the lack of consensus on the ideal digital tools and software to promote material reuse poses a significant challenge that needs to be addressed.

The practical study explored the digitalization and information flow aspects of implementing circular processes. It demonstrated the potential of digital tools to enhance collaboration, value co-creation, and transparency throughout the value chain. The use of 3D scanning, material inventory, and database development were identified as key elements in streamlining inventory management and promoting material reuse. However, it is important to note that the practical study also revealed challenges and areas for improvement. These include the need for further development and standardization of digital tools, such as 3D scanning with mobile phones, to overcome limitations in quality and efficiency.

Moreover, the inclusion of 3D-scanning was expected to enhance the effectiveness of the reuse process. However, the study revealed that 3D-scanning the building components did not make the inventory more efficient. The design team usually use the same standard 3D model of the specific component during the design phase. Additionally, the design team provides a document with the information of the component to the purchasing team, who ultimately decided which product to procure for the project. Consequently, the need for a detailed model of the reused product rendered the 3D-scanning irrelevant. Nevertheless, it can be argued that 3D-scanning could still serve a purpose in terms of accuracy and the quality of the reused product. It could be employed as a foundation for dimensions or as a tool to preview the product as a digital twin as it can be seen in the digital framework proposal 5.3.

Furthermore, the industry needs to adopt effective practices and technologies from other industries to promote circularity and to ensure the availability and quality of products in the market. Additionally, the establishment of a reliable database with a basic material passport that contains critical information for circularity is more beneficial as it is essential for facilitating material reuse.

To streamline information flow and facilitate the inventory of materials and building objects, existing materials should be grouped and categorized to ensure critical information, such as fire resistance, insulation requirements, sound requirements, etc., is readily available. The inventory process, including pre-demolition audits and material inventories, is crucial to identify reusable building products, types of waste, and the presence of hazardous substances, and to develop a control plan outlining how materials should be handled and waste managed. Life cycle assessment (LCA) and environmental product declarations (EPD) in assessing the environmental impact of products and buildings are highlighted as not being relevant to reused materials due to the time consuming and they require significant effort. While a basic material passport that includes critical information about the reused material would be more beneficial.

Moreover, the thesis argues that incorporating a digital framework encompassing all the previously mentioned stages can significantly improve CE practices. In simpler terms, it suggests starting with pre-demolition audits and material inventories, while implementing a control plan that outlines the necessary steps and identifies the stakeholders involved. Additionally, it emphasizes the importance of establishing a database where materials can be organized and categorized. Additionally, the database provides highlighted parameters that assist in grouping and categorizing reusable materials, see figure 31 and figure 32. Furthermore, the generation of a QR-code system plays a crucial role in effectively tracking the information flow related to the disassembled materials see section 4.2 and figure 32.

In conclusion, this thesis contributes to the understanding of implementing circular processes in the AEC industry. By integrating CE principles, improving information flow, and embracing digitalization, the industry can achieve greater resource efficiency, reduce waste generation, and contribute to a more sustainable future. The findings and recommendations of this thesis provide a foundation for further research and actions to promote the successful implementation of circular processes in office projects, ultimately contributing to sustainable development and a more circular economy in the Swedish AEC industry.

7.1 Future research

To enhance reuse in the industry, there are several key areas that require attention and exploration. One area is the potential use of 3D scanning technology, specifically on smartphone devices, to optimize the reuse process. Conducting further studies to understand how 3D scanning can effectively identify and catalog reusable materials would have significant implications for improving inventory management systems. This could result in enhanced efficiency and accuracy in tracking and managing available resources.

Another crucial aspect that requires investigation is the assurance of material quality in the reuse industry. Research should be conducted to develop methods and protocols for assessing the quality and performance of reused materials. This would help build trust and confidence in the Circular Economy (CE) by ensuring that reused materials meet the required standards and specifications.

Furthermore, it is essential to examine how legislation and regulatory frameworks can be adapted to accommodate and promote circular practices. Investigating the legal barriers and opportunities in implementing CE practices can lead to the development of policies and regulations that incentivize and facilitate the transition towards CE.

In addition, exploring the potential of Artificial Intelligence (AI) technology to enhance material reuse processes is another important area of study. This area of study holds significant importance as it has the potential to minimize the time required for reuse operations, thereby enhancing operational efficiency and potentially contributing to increased profitability for organizations.

Lastly, exploring the feasibility and potential benefits of establishing a national common material bank or a centralized material database can be a valuable avenue for future research. Such a database could provide comprehensive information about available materials, their properties, and potential applications, thereby fostering collaboration and increasing the efficiency of material reuse across various industries.

By addressing these research areas, we can advance our understanding of how to enhance reuse in the industry, ensure material quality, adapt legislation to circular practices, explore the potential of AI technology, and investigate the feasibility of a national common material bank. These insights will contribute to the development of sustainable and circular practices, ultimately leading to a more resource-efficient and environmentally friendly future.

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A. Appendix

A.1 Interview questions

Circular Economy

1) Please tell us briefly about your background and your work experience.
2) When did you first encounter circular economy?
3) What does the process of circular economy look like in your organization?
4) Which phase of the circular economy process are you working in?
5) What challenges have you encountered in implementing Circular Economy?

Reuse and the process of inventory

6) What does reuse of construction materials mean to you?
7) How many reuse projects have you been involved in? (process/contact)
8) What are your top three materials, building components, or objects in terms of reuse potential?
9) Why do you choose those three?
10) What does the inventory process look like for reuse?
11) How do you find information about the inventoried materials in general?
12) What digital tools do you use for inventorying?
13) How do you categorize the inventoried materials?
14) How do you trace the inventoried materials (material flows)?
15) Do you create an Environmental Product Declaration (EPD) for the inventoried materials?
    a. If yes, how do you do it and why?
    b. If no, why?
16) How do you approach demolition for reuse? (Demolition plan or contractors?)

Challenges and the future of circular economy

17) What obstacles have you encountered in your reuse projects?
18) How do you align with the current building regulations regarding reuse? Are there any areas that may conflict with reuse?
19) What is your vision for the future of Circular Economy and reuse?
20) Is there anything else you would like to add?

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