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Assessing the sustainability of prefabricated Hollow-Core Slabs

A feasibility study on the reuse potential of Hollow-Core slabs

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Abstract

This thesis delves into the sustainability of Hollow-Core Slabs (HCSs), examining their environmental impacts not only during their initial lifecycle but also through their potential for reuse. By advocating for repurposing HCSs as a preferable alternative to demolition, this research emphasizes the environmental benefits of reuse. It highlights the critical role of HCSs in reducing the construction industry's ecological footprint and promoting a circular economy.

The methodological framework extended beyond theoretical assessment to include practical evaluations of existing structural connections and the development of guidelines aimed at facilitating the reuse of HCSs. It employs a mixed-method approach that incorporates both qualitative and quantitative analysis. The methodology focused particularly on a comprehensive review of literature, case studies, and a practical case study of SIS-Velferdsbygg. A pre-disassembly evaluation, disassembly guideline and testing guideline was crafted and tailored to optimize the reuse process.

The framework included a comprehensive Cradle-to-Grave analysis of the HCSs used in the SIS-Velferdsbygg project in Stavanger. The analysis utilized the Environmental Product Declaration (EPD) provided by Veidekke Prefab. This analysis was used to assess the main environmental phases impacted by the production and implementation of HCSs.

The findings reveal that while existing connection methods generally support the reuse of HCSs, the HCS-Wall connections require innovative approaches to ensure structural integrity and safety. The environmental impact assessment showed significant environmental advantages both in the initial lifecycle and upon reuse. While the disassembly process for HCS reuse does involve higher emissions compared to demolition, the overall environmental assessment demonstrates a net positive outcome from reuse. The data showed significant reduction in material wastage, CO2 emission/ Global Warming Potential and Water depletion Potential. The established guidelines are structured to enhance the sustainability and streamline the reuse of HCSs in existing projects, emphasizing efficiency and environmental benefits.

This study establishes that the use of prefabricated HCSs significantly enhances the sustainability of construction practices by reducing environmental impacts during both the initial use and upon reuse. The findings advocate for the implementation of HCS reuse over demolition, illustrating its benefits in promoting a circular economy and diminishing the construction industry's ecological footprint. By developing targeted guidelines for the reuse of HCSs in existing structures, this research fills a crucial gap in current construction standards. It provides a practical framework for extending the lifecycle of construction components and advancing sustainable development.

Sammendrag

Denne avhandlingen tar for seg den totale bærekraften til hulldekker (Hollow-Core Slabs, HCS), og undersøker miljøpåvirkningen ikke bare i løpet av deres opprinnelige livssyklus, men også gjennom deres potensial for gjenbruk. Ved å ta til orde for gjenbruk av hulldekker som et bedre alternativ enn riving, understreker denne forskningen de miljømessige fordelene ved gjenbruk. Den fremhever den kritiske rollen hulldekker spiller når det gjelder å redusere bygge bransjens økologiske fotavtrykk og fremme en sirkulær økonomi.

Det metodologiske rammeverket strekker seg lenger enn teoretiske vurderinger, og omfatter også praktiske evalueringer av eksisterende strukturelle forbindelser og utvikling av retningslinjer for å legge til rette for gjenbruk av hulldekker. Det ble benyttet en blandet metode som omfatter både kvalitative og kvantitative analyser. Metoden fokuserte spesielt på en omfattende litteraturgjennomgang, casestudier og en praktisk casestudie av SIS-Velferdsbygg. En evaluering før demontering, retningslinjer for demontering og testing ble utarbeidet og skreddersydd for å optimalisere ombruksprosessen.

Rammeverket inkluderte en omfattende vugge-til-grav-analyse av hulldekkene som ble brukt i SIS-Velferdsbygg-prosjektet i Stavanger. Analysen tok utgangspunkt i miljødeklarasjonen (EPD) fra Veidekke Prefab. Denne analysen ble brukt til å vurdere de viktigste miljø fasene som påvirkes av produksjon og implementering av hulldekker.

Funnene viser at selv om eksisterende tilkoblingsmetoder generelt støtter gjenbruk av hulldekker, krever hulldekke-vegg forbindelsene innovative løsninger for å sikre strukturell integritet og sikkerhet. Vurderingen av miljøpåvirkningen viste betydelige miljøfordeler både i den innledende livssyklusen og ved gjenbruk. Selv om demonteringsprosessen for gjenbruk av hulldekker medfører høyere utslipp sammenlignet med riving, viser den samlede miljøvurderingen at gjenbruk gir et positivt nettoresultat. Dataene viste en betydelig reduksjon i materialsvinn, CO2-utslipp/ globalt oppvarmingspotensial og vannuttømmingspotensial. De etablerte retningslinjene er strukturert for å forbedre bærekraften og effektivisere gjenbruk av hulldekker i eksisterende prosjekter, med vekt på effektivitet og miljøfordeler.

Denne studien viser at bruk av prefabrikkerte hulldekker forbedrer bærekraften i bygg- og anleggspraksisen betydelig ved å redusere miljøpåvirkningen både ved første gangs bruk og ved gjenbruk. Funnene taler for å iverksette gjenbruk av hulldekker fremfor riving, og illustrerer fordelene ved å fremme en sirkulær økonomi og redusere bygge bransjens økologiske fotavtrykk. Ved å utvikle målrettede retningslinjer for gjenbruk av hulldekker i eksisterende konstruksjoner, fyller denne forskningen et viktig hull i dagens bygge standarder. Den gir et praktisk rammeverk for å forlenge livssyklusen til byggeelementer og fremme bærekraftig utvikling.

Acknowledgement

First and foremost, I extend my deepest gratitude to my GOD. Without His divine presence, none of this would have been possible. All praise to Him, for every moment of inspiration and perseverance throughout this journey.

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I would also like to express my sincere appreciation to Veidekke Prefab for their support and for granting me access to their systems, which significantly enriched my research.

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I am thankful to the professors at the University of Stavanger, whose rigorous instruction and insightful perspectives have greatly enriched my academic and professional skills. Their dedication to teaching and research has left a lasting impact on my educational journey.

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1 Introduction

This chapter presents the background, objectives, scope and limitations, term explanations and structure of this thesis. The main objective of the thesis will be explained followed by multiple research questions to work on answering the main objective.

1.1 Background of the study

Globally, the production and utilization of concrete rank only behind water in terms of volume, with an annual usage that exceeds 30 billion tonnes and is on an upward trajectory [1]. This substantial use of concrete is a significant factor in the construction industry's carbon emissions, contributing approximately 37% to the worldwide total [2]. Despite the sector's commitment to decisive measures towards a more sustainable and low-carbon output, the adoption rate of innovative, emission-reducing technologies remains sluggish. Reports from United Nations environmental update indicates that without acceleration in technology, the cement sector is projected to fall short of global climate objectives, potentially reaching only half of the CO2 emission reductions mandated by the Paris Agreement's benchmarks by 2018.

The construction industry is in dire need of more sustainable building practices as it faces increased environmental challenges such as pollution and resource depletion. Current research publications have mostly focused on more environmentally friendly concrete mixtures, aggregates, and the use of other building materials such as timber. Whereas research on circular options for existing buildings has not been focused on to the same extent. Building principles such as design for disassembly and design for deconstruction have been introduced but clear guidelines for the procedure are lacking. This thesis will investigate the synergy between sustainable building principles and prefabricated concrete construction to evaluate their collective impact on waste reduction and environmental pollution in the construction sector. Specifically, it will focus on hollow-core slabs (HCS), whose design efficiencies propose an extended lifecycle offering a promising avenue for minimizing the environmental footprint.

Guided by the ambitious vision of the Norwegian government, the Oslo municipal, the Paris agreement, and the UN sustainable development goals to achieve an emission-free construction process, this research will scrutinize prefabricated construction's initial environmental benefits as opposed to traditional cast-in-situ methods. A pre-case study in Hong Kong, where prefabrication has been employed to mitigate construction waste, provides an initial comparative backdrop, highlighting the global relevance and application of these principles.

Following that, the thesis will then consider the potential reuse of prefabricated elements, more specifically Hollow-core slabs on the assumption that there is unused potential that can be used by forestalling the end-of-service demolition. The thesis will therefore intertwine circular economy principles such as Cradle-to-Cradle with reuse of elements to showcase the environmental benefits achievable by extending the lifecycle of HCS instead of demolition at its end-of-service-life.

The current guidelines for reusing elements in the concrete industry are vague. There are not many specific guidelines on how the existing built environment should be handled for reuse, as compared to the guidelines for new projects. This thesis will, therefore, use the newly built construction SIS-Velferdsbygg on UIS by Veidekke-Prefab to showcase the reuse possibilities of HCS as a case study. Guidelines will be presented for how the reuse work should be conducted according to the current standard on the topic.

1.2 Objectives

Building upon the need for an improved sustainable method of concrete usage in the construction industry, this thesis sets forth the following objectives:

Primary objective: Explore the potential for prefabrication to become a sustainable building practice to reduce waste and mitigate the environmental impact of the construction industry.

Specific objectives:

- Assess the environmental advantages of using prefabricated HCS compared to cast-in-situ concrete methods.
- Assess the practicality of repurposing and extending the lifecycle of HCS to support the principles of circular economies.
- Identify the current barriers to the widespread adoption of HCS reuse practices and propose solutions to overcome these challenges.
- Develop a comprehensive guideline outlining the possibility for reuse, disassembly, and testing of reusable HCS.
- Evaluate the economic and social aspects of adopting HCS reuse practices in the construction industry.

1.3 Scope and limitations

The scope of this thesis is strategically defined to focus on the intersection of sustainable architecture and the use of prefabricated HCS. Within this framework, the study will:

- Conduct an in-depth analysis of the environmental impact of HCS, comparing it to traditional construction methods.
- Evaluate the environmental impact and practical procedures associated with the reuse and lifecycle extension of HCS within the context of circular economy principles such as reuse.
- Formulate guidelines tailored for the construction industry on the adoption and implementation of HCS reuse strategies.

Conversely, the research will not encompass:

- A detailed chemical analysis of concrete materials.
- An extensive survey of all prefabricated construction components outside of HCS,
- Economic calculations such as cost of disassembly and reuse.

The limitations of this research are recognized as follows:

- The thesis will primarily concentrate on the Norwegian construction sector, but it will use Hong Kong as a pre-case study to use as a comparative advantage for urbanised areas.
- The proposed guidelines for HCS reuse will be developed based on available literature, case studies, and reported experiences. It is worth noting that this may not capture all possible on-site contingencies.
- The economic analysis will be indicative rather than exhaustive, due to the variability in financial reporting practices across different organizations.

1.4 Term explanations

Abbreviation	Meaning
SVB	SIS Velferdsbygg
HCS(s)	Hollow-Core Slab(s)
CtG	Cradle-to-Grave
CtC	Cradle-to-Cradle
EPD	Environmental p dec
GWP	Global Warming Potential
DfD	Design for Disassembly
NS	Norwegian Standard
DOK	Regulations on documentation of construction products
TEK17	Building technical regulations

1.5 Structure of thesis

This thesis is structured into eleven chapters. A brief overview is given below of each chapter. The chapters will build upon one another to work on the thesis's central argument: promoting sustainable building practises through reusing prefabricated concrete elements.

- Chapter 1- Introduction: This chapter outlines the background, objectives, scope, and limitations. It also provides a brief overview of the subsequent chapters, helping to frame the research questions and methodology.

- Chapter 2- Methodology review: Details the mixed method approach. This chapter explains how various research methods such as literature- and document reviews, case studies, and empirical data collection are utilized to address the research questions.

- Chapter 3- Theory: Discusses the theoretical framework and concepts underlying sustainable construction practises. It focuses on prefabrication, waste reduction, circular buildings practises, and the theoretical models supporting these concepts.

- Chapter 4- Reusability: This chapter discusses the potential for reusing prefabricated HCSs. This chapter reviews previous case studies and discusses the implications for sustainability and cost-effectiveness.

- Chapter 5- Project Case: This chapter present a case using SIS-Velferdsbygg. This building will be examined for its reuse possibilities. This includes a project overview of both SVB and a reuse case consisting of the HCSs used in the donor structure, applied loads, and analysis of reusability.

- Chapter 6- Produced guidelines: This chapter presents guidelines developed from the research findings. It covers guidelines for disassembly, reuse, and testing of construction materials, with a focus on practical applications in the industry.

- Chapter 7- Connection possibilities in reuse: This chapter analyses different types of connections possibilities between the reused HCS and beam or wall. It highlights both benefits and drawbacks of each connection method.

- Chapter 8- Environmental impact: The environmental impact of using HCSs in SVB and reusing the chosen HCSs in the reuse case will be assessed. This includes analysis of resource conservation, greenhouse gas emissions, and overall sustainability benefits.

- Chapter 9- Discussion: This chapter critically evaluates the research findings against the research questions and literature review. This chapter discusses the usability of the guidelines produces, connection strategies, and the broader environmental, economic, and social impacts.

- Chapter 10- Conclusion: Summarizes the key findings of the thesis, the implications for the construction industry, and the contribution to the field of sustainable construction.

- Chapter 11- Future research: Outlines potential areas for further research, highlighting unresolved issues and new questions that have emerged from the current research.

2 Methodology review

This chapter outlines the methodological framework adopted to investigate the research questions mentioned in section 1.2 systematically. The thesis will use a mixed approach of both qualitative and quantitative research models. The mixed approach was chosen to harness the strengths and offset the limitations associated with each model. This method will not only facilitate a comprehensive exploration of the research questions but will also increase the strength of the findings through a diversified methodological approach. The research will derive its information and data from a range of sources, including academic literature, empirical studies, case studies, standards and regulations.

The qualitative aspect of the thesis will be used to formulate the guidelines for reuse by exploring the experiences and the underlying motivations and perceptions within the field. It involves a comprehensive review of documents and literature to gain insights into the environmental impacts of prefabricated elements and the reuse of HCS as a viable option for sustainable construction.

The quantitative aspect, on the other hand, seeks to analyse the potential of improving the sustainability of the produced HCS through data collection and data analysis. The combination of these methods will be of great advantage in validating the results of this thesis by substantiating the research outcomes effectively [3].

Opting for a mixed-method approach such as the one depicted in Figure 1 will enrich the research with a multifaceted. perspective. The work on the thesis began with a combination of exploratory and descriptive research. The initial phase called the exploratory phase, was important to gain a deeper understanding of the sustainability issues of concrete construction in the beginning phases of this thesis. It gives a clearer picture of the environmental impact of concrete and the current lifecycle standards for produced elements. Following this, the research entered the descriptive phase. This phase took doing cross-sectional research on multiple sections on the reuse topic such as the use of case studies and documentation review.

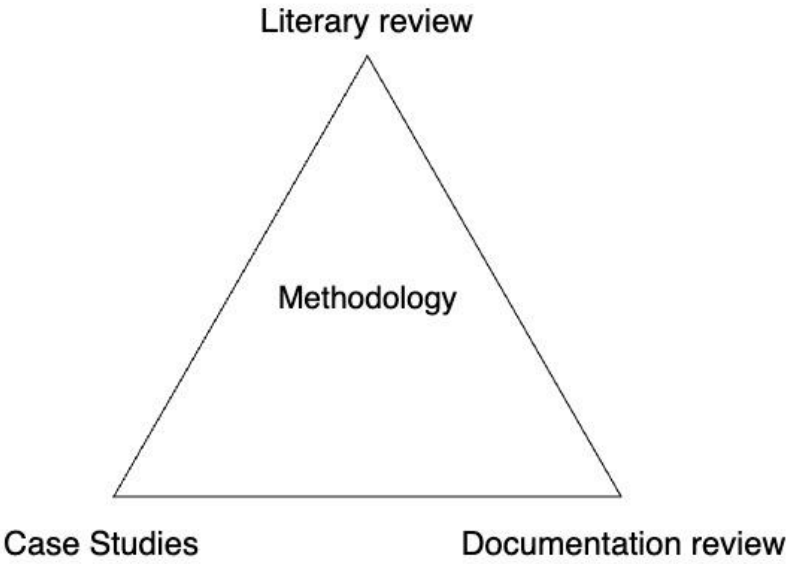


Figure 1- Methods for research triangle

2.1 Literature review

The literature review establishes the foundation for the research questions by examining a broad range of relevant sources. This review provides insights into current knowledge on sustainability and circular building principles. It accomplishes three key objectives: Firstly, it provides a comprehensive understanding of sustainable concrete construction by integrating diverse academic perspectives. Secondly, it identifies and addresses gaps in existing literature, guiding future research directions. Lastly, it critically evaluates previous studies and methodologies to assess their effectiveness and limitations. This review is essential for guiding the research methodology and ensuring the thesis contributes significantly to the field and future studies.

2.1.1 Snowballing

Snowballing in research is a method often used in the literary review process. It starts with a core set of primary resources, from these primary resources additional relevant works are identified by examining the references and citations in them. The method is called snowballing as the process collects more and more sources related to the topic of interest, like a snowball rolling down a hill accumulating more snow [4] [5].

Snowballing was used to enhance the scope of the literature base, starting with key articles on prefabrication and concrete structures, particularly focused on sustainability and component reuse. This method involved reviewing references and citations within these articles to identify and select additional sources that either supported the existing findings, presented new viewpoints, or contributed further details on methods to address the topic.

2.1.2 TONE- choosing sources

Sources for the thesis were critically chosen using the Norwegian TONE principle. TONE is an acronym representing credibility. Objectivity, accuracy, and suitability. The Norwegian meaning for each letter and the translations have been given in Table 1. Using this principle has been of great advantage in navigating the vast array of information available, particularly online to ensure that the sources are reliable and relevant for the research.

Determining the **credibility** of a source involves examining the authors of the literature and their identity, if necessary, the organization publishing/backing the information. **Objectivity** involves determining if a source is impartial, or neutral without pushing a specific viewpoint. Sources must be read critically to assess the author´s intent, whether it is to inform neutrally or to persuade a specific agenda on the reader. **Accuracy** focuses on the precision and detail of the source, including whether the authors provide their sources to allow for verification, avoiding plagiarism. Lastly, **suitability** concerns whether the source fits the research needs and whether the content is appropriate for the research purpose [6]. These criteria formed the cornerstone of the evaluative process, ensuring that each source was scrutinized to withstand the critical examination based on the TONE principle.

Table 1- Meaning for the letters in TONE

Letter	Meaning Norwegian	Meaning English
T	Troverdighet	Credibility
O	Objektiv	Objective
N	Nøyaktig	Accurate
E	Egnes	Suitable

2.1.3 Search engines

A strategic approach was taken to the literary review by employing three distinct search engines: Oria, Google Scholar and ScienceDirect. Each platform brought its unique strengths to the research process, collectively ensuring a broad and deep exploration of relevant literature.

Google Scholar was used as it has an extensive database that spans various fields. This makes it an invaluable tool for accessing a wide array of scholarly articles, books, and papers. It also has a feature to set date limits (based on year) and track citations which were particularly beneficial in the searching process.

ScienceDirect specializes in offering a vast collection of scientific and technical research, predominantly from Elsevier´s extensive publication catalogue. This search engine has access to high-quality, peer-reviewed content, especially valuable for detailed studies in specific scientific areas. The limitation is its restriction to Elsevier publications, which will potentially exclude relevant studies from other sources. This is where the snowballing method proved to be valuable.

Oria specialises in accessing resources within the Norwegian libraries. It provides a gateway to a diverse range of materials, including local thesis and academic works which may not be widely available. This makes this search engine an indispensable tool for incorporating regional research and publications. Its limitation lies in the potential focus on only Norwegian and Scandinavian content, which may not encompass international literature.

The utilization of these three platforms in conjunction provides a comprehensive framework for the literary review. The broad reach of Google Scholar complements the in-depth information and quality of ScienceDirect, while Oria ensures the inclusion of regional studies and data such as standards and regulations. This multifaceted approach ensured a thorough and diverse collection of academic sources crucial for the research topic at hand.

2.1.4 Search words

A Venn diagram was created before diving in to find articles for the research. This diagram was employed as a strategic method to systematically organize and highlight the relationships between the central themes of the research. By visually mapping out where these topics converge and diverge, the diagram effectively facilitated the identification of the most relevant search terms for each area. Figure 2 shows the Venn diagram with the most relevant topics for this thesis.

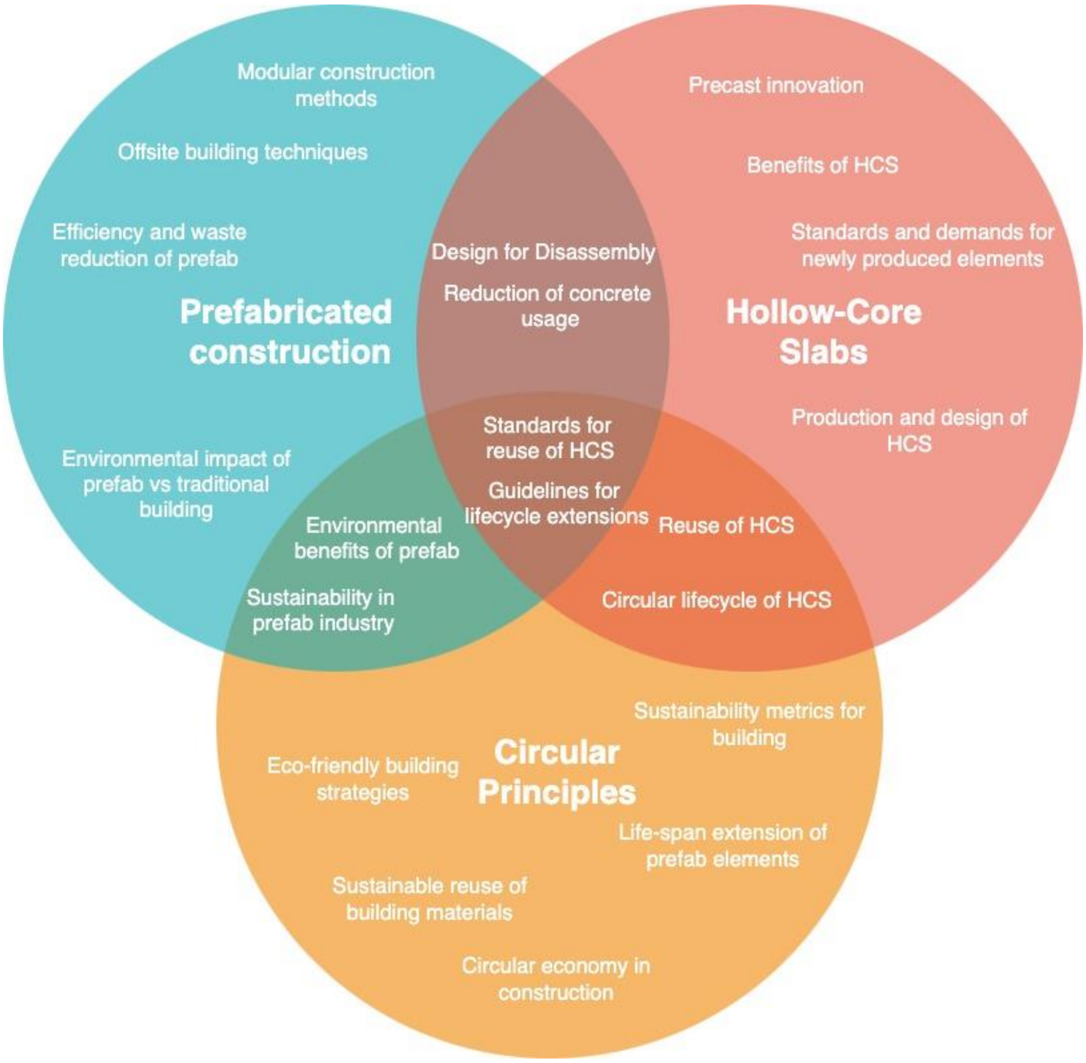


Figure 2- VENN diagram for searched words

2.2 Documentation review

A documentation review was conducted to underpin the research with a solid foundation of existing knowledge, standards, and practises relevant to concrete sustainability and reuse. This review involved a detailed examination of the selected documents, each chosen for their direct relevance to the thesis topic, to accumulate information needed for the development of guidelines for sustainable construction practices.

The documentation review for this thesis will be an analytical process that examines standards, regulations, and guidelines relevant to the research subject. This method was particularly relevant for this thesis to ensure that the proposed guidelines for the reuse of HCS align with existing standards and regulations. The main documents chosen and examined for this thesis are:

- **Norwegian Standards (NS) 3682:** This standard was chosen for its detailed guidelines on reusing hollow core slabs. It was of great benefit to encompass the testing requirements. It provided critical insights into the expected quality and safety metrics for reusable HCS.
- **ISO standards 20887:** This standard was incorporated to provide an international perspective on sustainable building practices. It had valuable information regarding DfD, reuse, and economic business models for reuse which were quite relevant for this thesis. This standard helped ensure that the research adhered to globally recognized sustainability criteria, making the findings relevant both within and beyond the Norwegian context.
- **TEK17:** This is a technical regulations document provided by the Norwegian directorate for building quality. It outlines the minimum requirements that a building must meet to be legally constructed in Norway. TEK17 gives clear guidelines for the functional requirements of elements which will be relevant for this thesis.
- **DOK- Regulations on Documentation of Construction Products:** This document was instrumental in understanding the requirements for documenting the quality, safety and sustainability of construction materials in Norway. It provided a basis for proposing how HCS should be documented for reuse.
- **EPD (Environmental Product Declaration):** The EPD provided by Veidekke was instrumental in the calculations regarding GWP, material, and water savings for the reuse scenario. It provided detailed data for the lifecycle of the HCS from CtG, multiple factors in the added LCA were important for the calculations in this thesis.

2.3 Used applications

Several applications were instrumental in conducting analyses, designing solutions, and performing calculations relevant to the research objectives. The applications are:

- **Solibri** was utilized for analysing the structural aspects of SVB. It provided insights into the building´s construction, facilitating a deeper understanding of potential areas for reuse.

- **AutoCAD** played a vital part in the detailed examination and redesign of the SVB building´s floor plan. It enabled precise crane placement planning for the disassembly process and was crucial in drafting a new floor plan and connection proposals for the building´s reuse scenario.

- **Excel** was employed for its robust computational capabilities, particularly in quantifying the GWP, as well as assessing the material and water salvage possibilities. Its versatility in complex calculations contributed to the thesis by providing accurate and reliable quantitative insights.

- **Draw.io** was used for creating diagrams, flow charts and visual representations that clarified complex concepts and processes within the thesis.

3 Sustainability of prefabrication first use- Theory

3.1 Sustainability

In today's society, the rapid advancements in technology and industry emphasise the importance of sustainability. As we strive for progress and expansion, we must prioritize our duty to the environment and adopt sustainable practices. This emphasis on sustainability is especially critical for the construction sector, which often has a significant impact on the environment and consumes vast resources. The target of achieving sustainability encompasses a multitude of aspects, but they are mainly aimed into three main categories.

Sustainable development encompasses three important sections: economic, social conditions and environment. When examining the United Nations' sustainable development goals, it becomes evident that several goals are relevant to the construction industry (Figure 3). 40% of the global energy consumption and 30% of global greenhouse gas emissions are from construction and buildings [7]. According to an article written by “Mur og Betong” in 2016, Norway produces approximately 4,4 million m^3 of ready-mixed concrete and prefabricated concrete elements [8]. When producing concrete in such large volumes, society must put more focus on sustainability in our building practices.

Figure 3- Sustainable development goals, source: UN [26]

3.1.1 Waste reduction

As the population continues to grow and the economy expands, there will be a greater need for buildings to accommodate people, families, and businesses. As a result, more construction projects will be undertaken, leading to an increase in material wastage. The latest data from SSB (refer Figure 4) , shows that the construction sector contributes to the most waste in tonnes compared to other sectors [9].

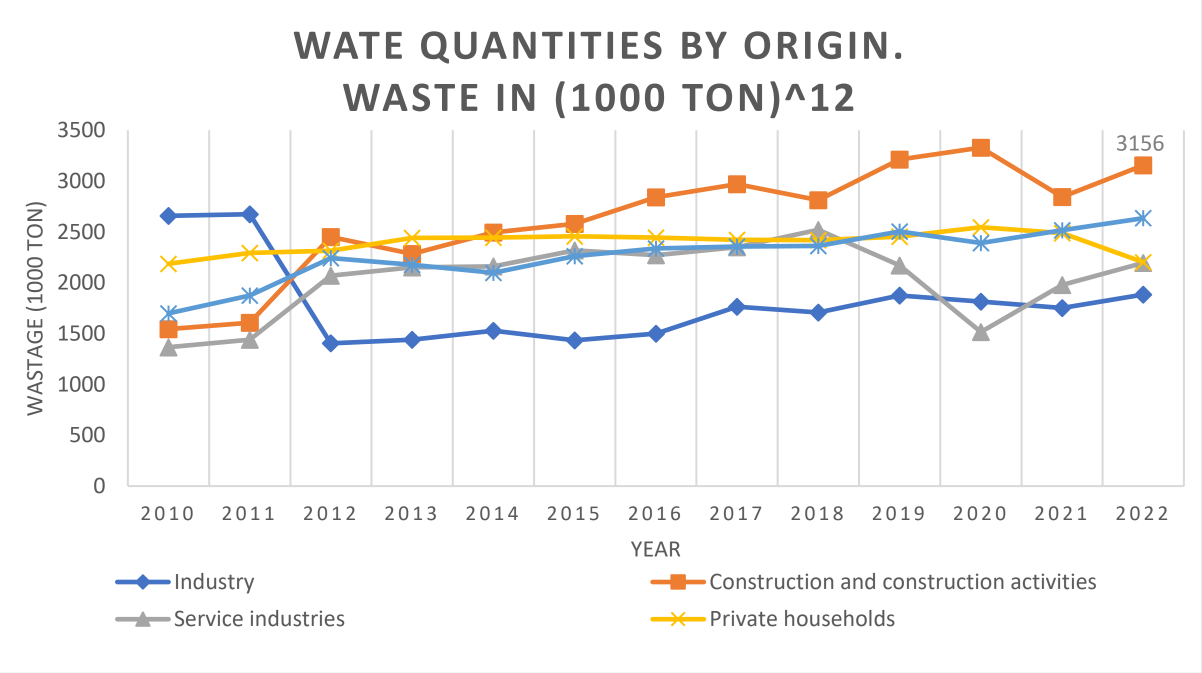


Figure 4- Total wastage across sectors, Source: [9]

As of now, SSB has data on material waste in Norway up until the end of 2022. The given data can be seen in Figure 5 and Figure 6. Figure 6 shows that most of the concrete waste results from demolition. The data shows that concrete and bricks are the primary materials wasted, corresponding to 829,892 tonnes [10].

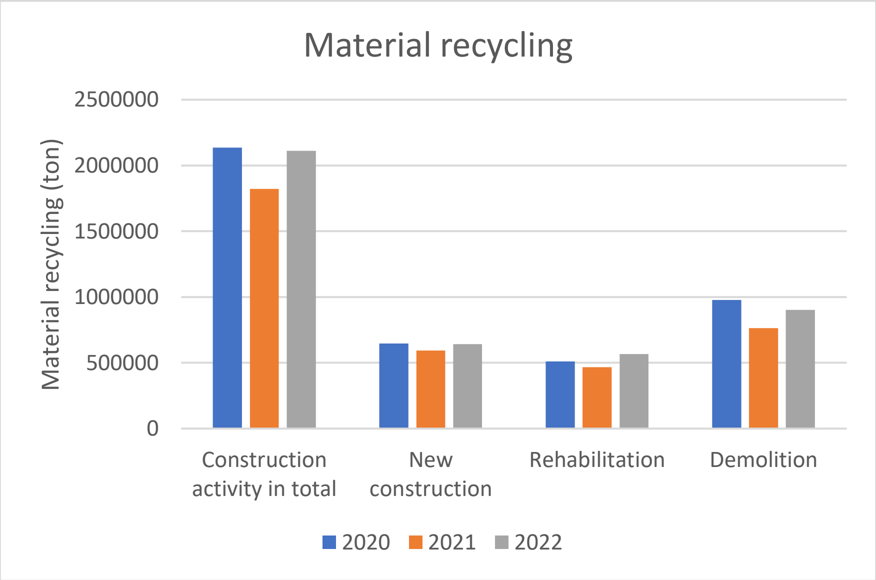


Figure 5- Total material wastage, source: [10]

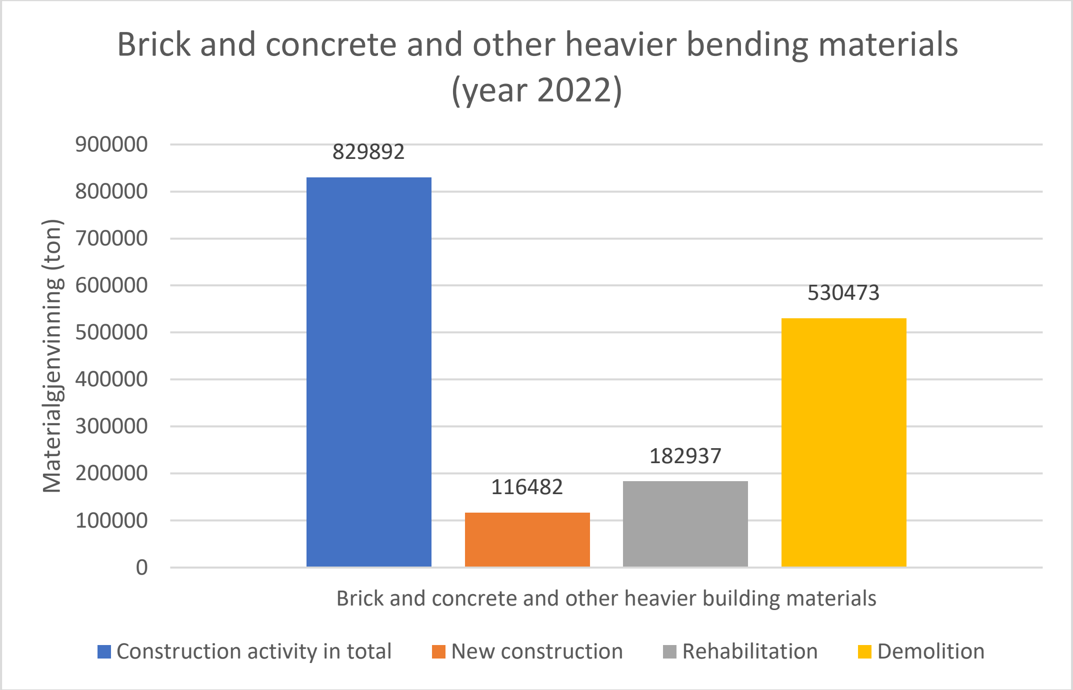


Figure 6- Total wastage from concrete, Source: [10]

Due to high levels of wastage in the construction sector, various organizations have joined hands to establish targets aimed at reducing waste generation. The Climate and Environment Department of Norway has worked out a strategy to reduce the wastage levels of materials. As Figure 7 shows, the wastage hierarchy is divided into 5 categories, where waste prevention has a majority stake. The primary target is to prevent wastage from occurring and then to control the wastage that has been made in a prioritized order.

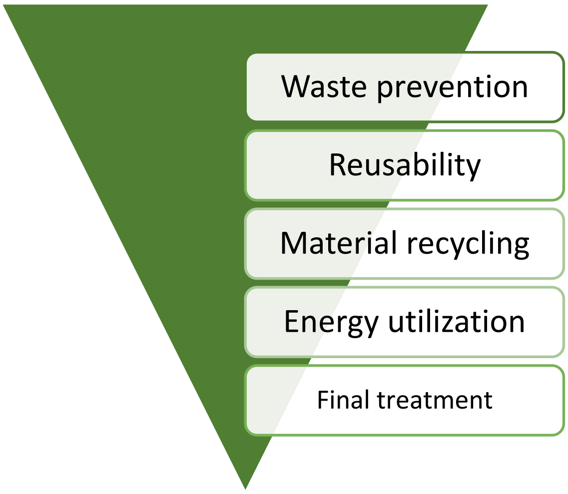


Figure 7- Wastage hierarchy, Source: NHP

In addition to the waste hierarchy, the National Action Plan for Construction Waste (NHP) has set clear goals for contractors to minimize waste and contribute to a more sustainable and circular economy, as shown in Figure 8.

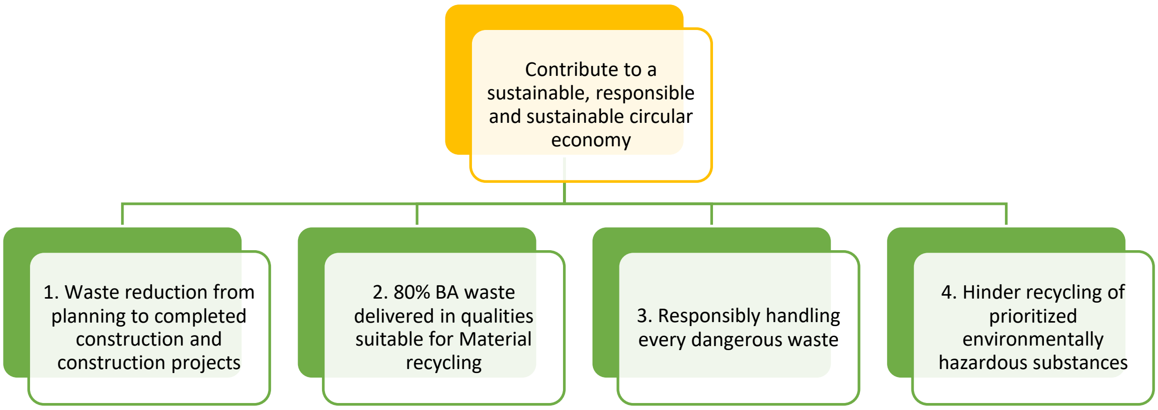


Figure 8-Goals for wastage reduction, Source: NHP

A study by Socio-economic analysis and NIBIO analysed the costs and benefits of reducing material waste in construction [11]. The main points that were studied are reducing generated waste, increasing the reuse of construction waste, and increasing material recycling. According to the research, the most financially viable and socio-economically optimal option for businesses among these three points is to reduce the generation of waste. As a crucial task that businesses can easily prioritise, it should be included in their workflow.

3.2 Overview of prefabricated construction

The construction industry continues to evolve as new research and technology emerge. When compared to traditional approaches, prefabricated concrete comes forth as an important contributor to this progression. This section will focus on the nature and characteristics of prefabricated concrete. Prefabricated concrete refers to a process where concrete components, including walls, columns, beams and HCSs, are produced under controlled conditions within a factory or at a production site ideally close to the construction area. The main steps of the manufacturing process consist of:

- **Design and engineering:** This phase is called the pre-planning phase. This is where the initial structural engineering work is done. The structure is designed by both architects and engineers. Each of the prefabricated elements will be detailed here, this includes considering the relevant dimensions, reinforcement, required strength and applied loads.
- **Form preparation:** The forms will be prepared according to the dimensions specified in the design phase. These forms are often made of wood.
- **Casting:** A concrete mix is made and poured into the forms. The reinforcement needed for the element is added, and the placement of the reinforcement follows the detailed drawings made during the pre-plan phase. After pouring the concrete mix, the form is vibrated to eliminate any air pockets. This will ensure a dense, and uniform concrete element.
- **Curing:** The elements will be left to cure after the casting phase.
- **Transportation:** After the completion of the curing phase, the elements will be transported from the factory to the construction site. This part requires careful planning of transportation routes (for large/long elements that would be problematic to transport in dense areas/traffic), total weight and placement of the elements need to be considered for each batch of transport.
- **Assembly:** When the elements arrive at the construction site they are lifted and placed into their affixed position (following the assembly plan/ construction plan). The elements are connected using methods of welding, bolting and use of concrete.

Table 2 shows the main advantages and disadvantages of using prefabricated concrete construction. The following section will turn its attention to a critical aspect of modern construction, sustainability. The forthcoming chapter will discuss how prefabricated concrete construction more specifically the use of HCSs will promote sustainable building practises.

Table 2- Advantages and disadvantages of prefabricated concrete construction

Advantages	**Disadvantages**
Material and time efficiency [12]	Higher initial costs [13]
Construction efficiency [14]	Not eligible for changes contrary to standard design
Helps achieve environmental sustainability [14]	Additional planning needed for transportation and handling
Reduction in pollution [14]	Not possible to do changes in design later
Makes construction site more workable	
Better quality [15]	

3.3 Prefabrication for waste reduction

Precast concrete is a versatile construction method where components are produced in a controlled factory environment instead of at the final construction site. The production process involves pouring concrete into reusable moulds or forms and then subjecting them to a controlled curing process. Once the precast elements reach the desired strength and maturity, they are transported to the construction site for assembly.

Two benefits mentioned in section 3.2 that are relevant here are improved quality and reduced waste generated by construction. According to data from Dodge & Data Analytics, 90% of users cited that they experienced improved quality when using prefabricated concrete, 81% of the same users cited that they experienced a greater reduction in waste generated on construction [15]. Resource conservation and waste reduction are increasingly important factors of sustainable construction, it does also correspond with the UN rules mentioned above.

According to The Planning and Building Act, reducing greenhouse gas emissions must be given top priority in planning processes [7]. During the pre-construction phase, companies have the opportunity to carefully plan and strategize their resource usage for the upcoming project. This involves analysing the project requirements, identifying potential limitations, and developing effective solutions to minimize waste and ensure optimal utilization of resources. By investing time and effort in this phase, companies can significantly improve their overall project outcomes and reduce unnecessary costs. 33% of construction waste can result from failure to reduce waste during the design process [16].

Additionally, the precast method guarantees the production of high-quality and uniform products by maintaining controlled manufacturing conditions. Important factors such as temperature, humidity, and curing time are closely monitored, resulting in consistent and superior structural properties. Achieving this level of uniformity is challenging with on-site casting, where environmental factors can unpredictably affect the concrete [17].

When constructing buildings that involve repetitive designs, such as residential complexes or commercial buildings, the same moulds and designs can be used multiple times, resulting in cost savings due to economies of scale and waste reduction. An example of achieving minimal construction waste is the T30 Tower Hotel in China. This project generated only 1% construction waste compared to cast-in-situ [18].

The next section presents a pre-case study based on Hong Kong, amplifying the practical benefits of prefabrication in construction to minimize waste. As part of the literature review on resources, this real-world example underscores the effectiveness of prefabrication in improving resource efficiency and reducing environmental impacts in densely populated urban settings.

3.3.1 Pre-Case: Hong Kong (Waste reduction)

The ongoing population growth increases the need for expansion in the urban areas. Efficient resource allocation and planning will become crucial to prevent unnecessary surpluses and usage of materials when building. Currently, as of mid-2023, the population of Hong Kong is 7,498,100 [19]. As shown in Figure 9, 70,2% of the land area in Hong Kong falls under the protected area category, which makes it crucial to efficiently plan the building projects on the remaining land [19]. Consequently, the developed area only accounts for 25,5% of the available land. To accommodate the growing population, Hong Kong has adopted a high-density development strategy which mandates the use of high-rise buildings. This pre-case study aims to examine how the waste reduction achievements in Hong Kong's construction industry might inform and potentially be replicated in Norway´s urban expansion in cities such as Oslo.

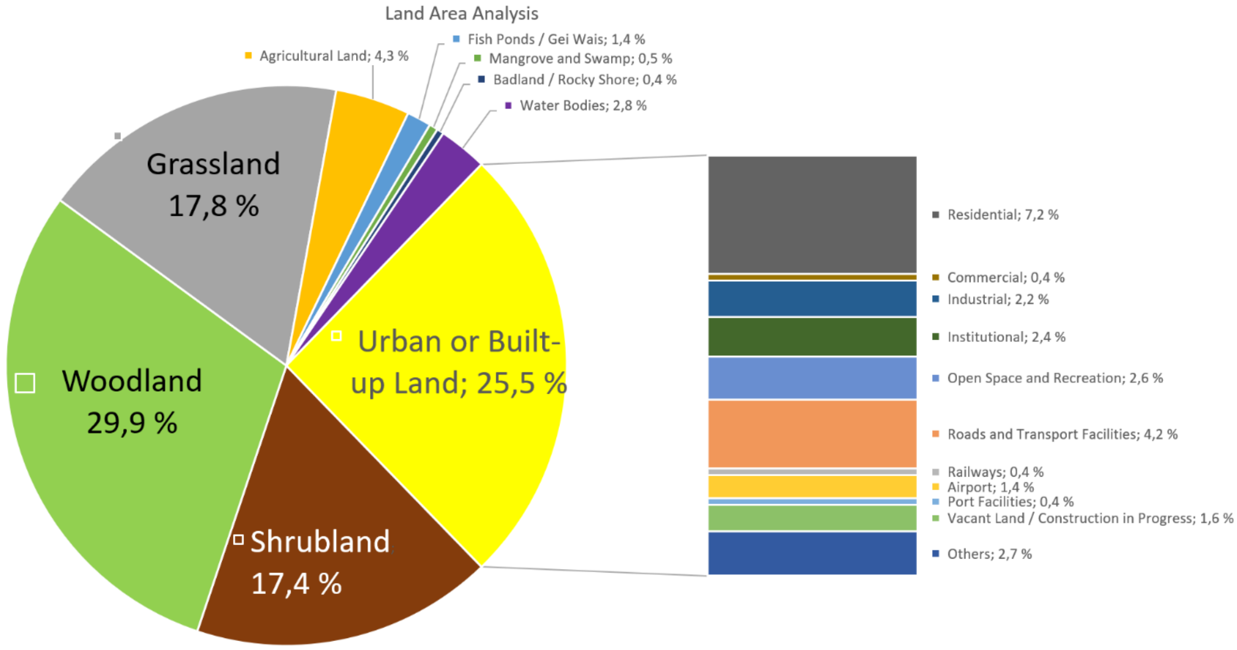


Figure 9- Land Area Analysis, Source: Planning Department, Hong Kong [77]

Due to Hong Kong's compact and densely populated nature, construction projects require methods that are suitable for small and constrained cities. Often, these sites are surrounded by developed areas. Prefabrication can be utilized in such areas to mitigate the environmental impact affecting the nearby community, such as notable noise, dust, and vibrations. Just like in Norway, construction waste plays a big part of the overall building waste in Hong Kong. The average daily quantity/ tonnes per day of overall construction waste for 2022 in landfills is 4,128 tonnes in Hong Kong [20]. Comparing this against the overall construction waste in 2012, which was on 3,440 tonnes (TPD), there is an increase of 20% [21]. Landfills are a major contributor to environmental problems as they take up valuable space and release harmful greenhouse gases like CO2 and methane. By reducing the amount of waste sent to landfills, we can help reduce the negative impact on our environment [22]**.** Since space in Hong Kong's landfills is limited, using sustainable building practices such as prefabrication would be greatly beneficial. Hong Kong has embraced the challenge and conducted multiple studies to determine the benefits of prefabrication. The results from some of these studies have been discussed below.

A case study was conducted on two building projects in Hong Kong. The first case, HKCC HK, was a 17-storey tower where 47% of the project was prefabricated. The second case, HKCC WK, was a 14-storey tower where 40% of the project was prefabricated. A project-oriented questionnaire survey was sent with the task of ranking the benefits and limitations of prefabricated construction using numbers ranging from 1 to 5 (5 being the highest). The respondents agreed upon three major benefits according to the results. These were the reduction of construction waste, improved quality control, and reduction of material use. The mean scores of these benefits were 4.25, 4.25 and 4.00. The respondents also claim that the use of prefabrication reduced the construction time by 3 months [23].

In 2019, a research paper was published that aimed to re-evaluate the impact of prefabrication on waste reduction in construction. The study used data from 114 high-rise building projects in Hong Kong and concluded that the use of prefabrication leads to a reduction in average Waste Generation Rates (WGR) compared to conventional building practices. Specifically, the average WGR for prefabrication was found to be 0.77 tonnes/m2, which is lower than the average WGR of 0.91 tonnes/m2 for conventional building practices. According to the paper, the waste production decreased by 15.38% on average. However, it's important to note that this decrease was not statistically significant. This suggests that other factors, such as project management, time, site, and technologies, could also have an impact on the performance of the CWM (Construction Waste Management) process [24]. The paper continues by stating that “small amounts of precast volumetric components yield nearly no effect on waste minimization” [24].

A study on the sustainability implications of precast concrete was done by analysing various building projects spanning two decades. The study analysed 38 building projects spanning from 1998 to 2022. It aimed to evaluate the interrelationships between construction methods, construction modularity and sustainability. The study states that an increase in prefabrication has been noted in the later decade (2011-2022), specifically 31% on average. The study continues to evaluate key metrics such as carbon emissions, waste volume, project cost, and construction period. These metrics were then collected to calculate a composite sustainability index (CSI). The results indicate that the use of prefabrication in building projects decreases carbon emissions and waste generated (in tonnes per m2) with higher levels of prefabrication. The study continues to evaluate the overall CSI of the projects. The results suggest a positive relationship between construction modularity and sustainability. The study states that the increased percentage of prefabrication correlates to a better overall CSI. It is worth noting that the study emphasizes building categories medical, and hospitality are negatively associated with CSI, this is due to special requirements for the elements. Finally, the project with the highest percentage of prefabrication such as project YCS, 87,76% prefab, has achieved the highest CSI of 84,40%. This study shows that the amount of prefabrication in a project could potentially yield environmental benefits [16].

A study was conducted using both a survey and data from fourteen building projects. The building projects used for this study were built in 2002 and 2004. The data from the case studies showcased an overall reduction in waste levels up to 52% by implementing prefabrication. The statement indicates that they were able to reduce the usage of timber formwork by 70%. It is also worth mentioning that the study revealed that the waste generation quantities varied based on the project site. The survey was sent out to 354 professionals, with a response rate of 24%. As the response rate is low, one cannot completely conclude that the overall benefits of using prefabrication were thoroughly studied. Of the respondents, the number one benefit mentioned by all was the reduction of construction waste [25]. One key takeaway from this study is the reduction in the usage of timber. This is also an important factor to consider when opting for prefabrication.

The use of uniform moulds in the fabrication of concrete elements for extensive construction projects markedly contributes to waste minimization and the achievement of scale economies. Such projects typically involve repeated or standard design features, allowing factories specializing in prefabrication to use the same moulds to produce multiple elements repeatedly. This consistency not only refines the production process but also significantly curtails material wastage. Unlike traditional construction approaches, where every new design or variant typically requires a distinct set of formworks, leading to surplus material use and additional waste, the practice of utilizing identical moulds for recurring designs markedly diminishes the volume of surplus material. Moreover, the repeated use of moulds facilitates economies of scale, as the cost associated with mould manufacturing and material procurement is distributed across a higher volume of units. Factories can buy materials in larger quantities and maximize the use of each mould, which results in reduced costs per unit. This practice is not only environmentally beneficial due to its waste reduction capabilities but also enhances the cost efficiency and resourcefulness of the construction process, especially in big projects with repetitive design elements.

This pre-case underscores the potential for prefabrication to significantly reduce construction waste in densely populated urban areas. Taking cues from Hong Kong's success, Oslo, with its emerging high-density challenges, stands to benefit from the prefabrication techniques from Hong Kong's high-rise projects. Embracing prefabrication could yield not just environmental gains in terms of waste reduction but also enhance economic and resource efficiency. While the direct transferability of data and practices across different urban contexts presents challenges, the strategic insights gathered from Hong Kong provide a valuable framework for Oslo to consider in its quest for sustainable urban development. This pre-case thus sets the stage for a deeper exploration within the thesis, aiming to consolidate prefabrication as a pivotal approach to urban construction and sustainability in Norway.

3.4 HCS- sustainable design

Incorporating hollow-core slabs can be highly beneficial in advancing the construction industry's goal of creating sustainable building designs. By using these slabs in building designs, the industry can take significant steps forward in creating more eco-friendly structures. As previously mentioned, the design of prefabricated buildings aims to meet the UN's sustainable goals, particularly those related to industry innovation (goal 9), sustainable cities and communities (goal 11), and responsible consumption and production (goal 12) [26].

The Norwegian government has made it a priority that buildings where people live, or work **must** be climate-friendly both in the construction phase and in use [7]. The hollow core slabs have been crafted with a view to minimize resource usage and waste. The design of the slabs offers multiple benefits, including lower material consumption, reduced transportation costs, and faster construction times [27]. By using these slabs, builders and contractors can significantly reduce their environmental impact while also improving the overall efficiency of their construction projects.

The Norwegian Climate Action Plan indicates that achieving national and international climate targets is impossible without reducing greenhouse emissions from buildings and construction. Compared to Europe, where the largest source of greenhouse gas emissions from buildings is the use of fossil fuels for heating, in Norway the largest remaining emissions are from the actual construction process such as emissions from the production of components and transport [7].

To effectively incorporate hollow-core slabs into a project, it is crucial for the engineer to carefully plan and design all aspects in advance. The choice of structural design, spans, and cross-sectional dimensions are critical factors that influence the amount of necessary concrete [28], [29]. By conducting thorough planning at an early stage, the engineer can accurately determine the exact amount of concrete required for each element, resulting in a more efficient and successful material usage and project outcome.

Additionally, the continuous voids in the design of the hollow core slab minimize the required concrete level compared to in-situ cast concrete [30]. The voids constitute 40-55% of the cross-section to the hollow-core slab [31]. This will yield benefits since the required amount of concrete will be less compared to an in-situ cast slab.

Using some calculations one can find the difference in area and volume in a hollow-core slab and an in-situ cast slab, assuming the same size and strength factors. For the majority of SIS-Velferdsbygg hollow core slabs in thickness 265 mm were used. The model will be called HC265. The front cross-section of the hollow core slab can be seen in Figure 10. A simple calculation on the amount of concrete, for a 1-meter slab, can be seen below. Similarly, a calculation for amount of saved water for 1 ton of HCS can be seen below.

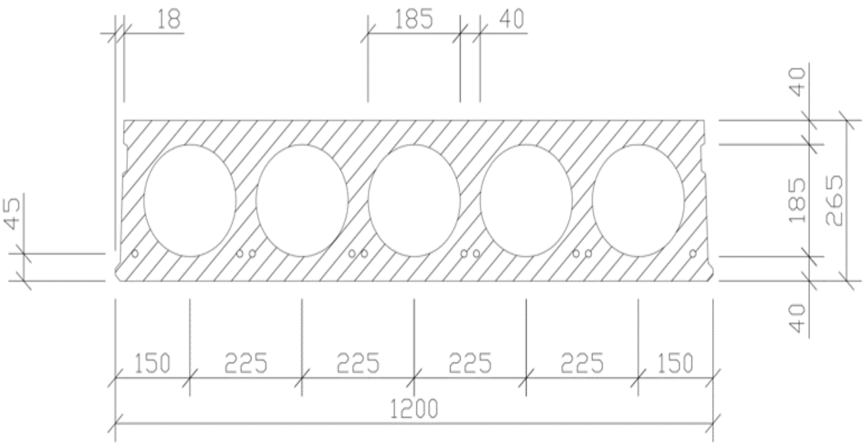


Figure 10- Cross section of HC 265, Source: Veidekke

$$\boldsymbol{Calculation\ for\ Hollow\ core\ slab\ 265\ mm}:$$

$$Total\ Volume\ (TV_{265}) = 1{,}2m\ x\ 0{,}265x1m = 0{,}318m^3$$

$$Void = \pi\ \ x\ \ r^2\ x\ h$$

$$V_{265,void} = \ \pi\ x\ (0{,}0925m)^2\ x\ 1m = 0{,}0269m^3$$

$$number\ of\ voids = n_{265} = 5$$

$$Net\ volume = NV_{265} = TV_{265} - \left(n_{265}\ x\ V_{265,void}\right) =$$

$$= 0{,}1835\ m^3$$

$$Total\ concrete\ saved = TV - NV = 0{,}1345$$

$$\approx 42\%\ saved$$

$$\boldsymbol{Total\ concrete\ needed\ compared\ to\ 1000kg\ HC}:$$

$$M_{in-situ} = \frac{1000\ kg\ x\ 100\ \%}{42\%} \approx 2381\ kg$$

$$Water\ saved:$$

$$W_{in-situ,water} = 2381kg\ x\ 5{,}62\% = 133{,}8\ kg$$

$$Water\ saved = 1 - \left(\frac{W_{HC,water}}{W_{in-situ,water}}\right)$$

$$= 58\%$$

The findings from the calculations above indicate that hollow-core slabs result in higher salvage of materials compared to in-situ cast methods. The reduction of materials when making HCSs will lead to a significant reduction in water usage. The required amount of water and materials will depend on the size of the project and concrete class. Specifically, Veidekke's production of one ton of hollow-core slab requires only 56.18 kg of water, which corresponds to 5,62% of the mix [31].

According to the EPD from Veidekke for the hollow-core slabs, 1 ton of hollow-core slab consists of 78,67% aggregate, which is 786,71 kg [31]. In 2022, the United Nations Environment Program (UNEP) published a report highlighting the issue of overconsumption of gravel and sand across the world. The report revealed that the amount of gravel and sand used annually is as high as 47 to 59 billion tons, with natural sand and gravel accounting for 68% and 85%, respectively [32]. The report continues stating that sand, gravel and crushed rock will be the construction materials dominating resource consumption in fast-growing economies [32]. As a step to decrease resource consumption, Veidekke has chosen to only use blasted rock materials and recycled aggregates instead of natural sand to decrease the consumption of the resource [30]. This is a good choice according to the UNEP as the report emphasizes that sand is the second most exploited resource next to water, and by using other materials for aggregates such as Veidekke, the firm can minimize its environmental footprint.

3.4.1 CO2-emissions

The levels of global warming have become critical due to the high amount of greenhouse gases, particularly carbon dioxide (CO2). The strength and cost of concrete has made it the most widely used building material. The yearly global production rate of concrete is one cubic meter per capita [29]. The cement industry is responsible for about 8% of the world's total carbon dioxide emissions [33]. The demand for concrete and cement will continue to rise as this is an easily acquirable material. To meet this demand while reducing CO2 emissions, it is necessary to explore cost-effective, durable, and sustainable mixtures. To get on track with the Net Zero emissions goal by 2050 the CO_2 intensity must decline by 4% through 2030 [34]. IEA states that as of now, the sector is not on track, latest data mentions that the cement production has increased the intensity by 1% instead of decreasing [35].

In addition to higher salvage of material, HCS production releases less greenhouse emissions compared to in-situ cast concrete. The total amount of concrete saved mentioned earlier results in an even better reduction in carbon emission. Veidekke-Prefab states the following on their website, “Hollow Core slabs delivered from us in Low-Carbon Plus, corresponds to in-situ cast slabs in low-carbon extreme measured per m^2 slab.” To put the numbers into perspective, see Figure 11 [30]. As a company standard, Veidekke Prefab uses Low-Carbon Class A.

A recent study compared the carbon footprint of three different construction materials: cross-laminated timber (CLT), solid concrete, and hollow-core precast concrete. The study found that hollow-core concrete has the lowest CO2 emissions from cradle to grave. Solid precast concrete had 25% higher CO2 emissions than hollow-core concrete. The difference is mainly due to the higher percentage of carbon emissions from concrete, mortar, and cement in solid precast concrete (36%) compared to hollow-core concrete (12%). Interestingly, even though both the hollow-core system and the in-situ cast system used the same material with the same embodied energy, the hollow-core system emitted only 4 tons of CO2, while the in-situ cast system produced 6.6 tons [36].

A study comparing the environmental impacts of in-situ cast concrete and HCSs for residential buildings revealed that HCSs offer a 12,2" reduction in environmental impact relative to in-situ cast concrete. However, the analysis also indicated that HCS-solutions are 17,9% costlier than their in-situ counterparts. It is important to consider that these findings are based on data from 2008, and since then, advancements in the production of HCSs have likely enhanced their efficiency [37].

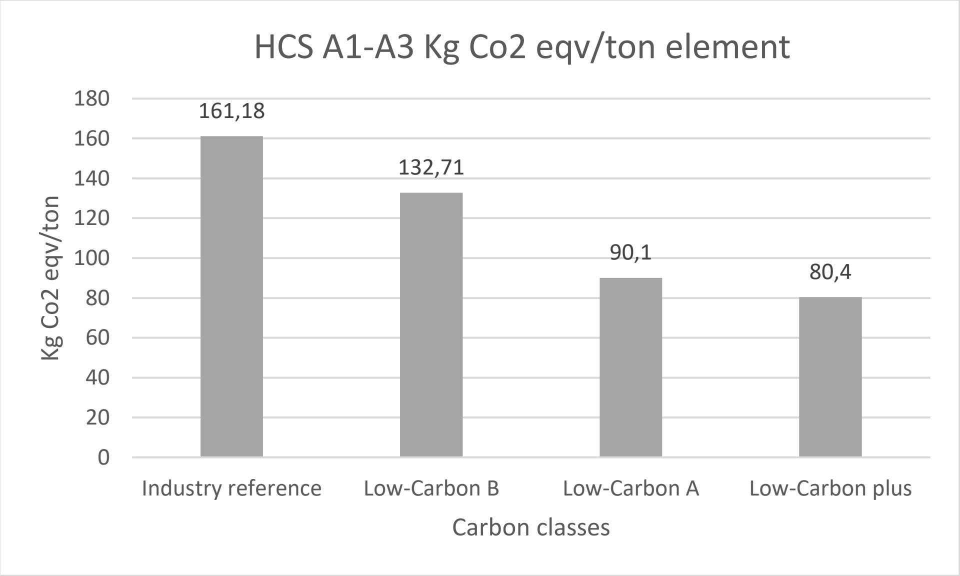


Figure 11- Veidekke-Prefab Hollow Core emission, Adapted from: [17]

3.4.2 Cement

The Norwegian Concrete Association (NB) states that cement can be responsible for up to 90% of greenhouse gas emissions [28]. As the focus increases on carbon emission, NB has worked out a definition for low-carbon concrete, with different classes. The concrete composition is assumed to meet the requirements set out in NS-EN 206+NA. The hollow-core slabs used in this thesis are made according to Veidekke Pre-fab's latest EPD. The hollow-core slabs are made in low-carbon concrete class A [31]. The NB´s guidelines for low-carbon concrete state that the limits for low-carbon class A represent what is practically achievable for structural concrete with the binders available today in the Norwegian market [28].

The Low-carbon classes are defined with a maximum allowed greenhouse gas emission value as seen in Table 3.
According to the EPD the emissions for HC265 and HC320 are defined as:
Emission pr kg $C0_2$ eqv/m^2

- **265 – 33,687 kg $C0_2$ eqv/m^2**
- **320 – 36,418 kg $C0_2$ eqv/m^2**

Table 3- Maximum allowed greenhouse gas emissions

Values follow module A1-A3 in NS-EN 15804:2012+A2:2019/7/. The choice of class should be done according to chapter A2.							
Strength classes and Low-carbon class	B20	B25	B30	B35	B45	B55	B65
Maximum allowed greenhouse gas emission (kg CO_2-eq pr m3 concrete)							
Industry standard	240	260	280	330	360	370	380
Low-Carbon B	190	210	230	280	290	300	310
Low-Carbon A	170	180	200	210	220	230	240
Low-Carbon Pluss			150	160	170	180	190
Low-Carbon Extreme			110	120	130	140	150

Replacing cement in the concrete mix is not as easy as it sounds. When exploring different environmentally friendly materials as a replacement, one must also ensure the strength, durability, and performance of the concrete are maintained.

Portland cement is holding the pivotal role of being the primary binder in the realm of concrete construction. Attributions such as adaptability, longevity, and cost-effectiveness make this a popular choice for the construction sector. The Portland cement is still a favoured material; when compared to materials such as gas, oil and coal, the production of 1kg Portland cement emits 0.6 – 0.8 kg of CO_2 [29]. Despite its relatively lower emission rates, the cement industry's environmental footprint is significantly amplified by the sheer volume of cement demand worldwide. This vast consumption of cement production renders the environmental implications more pronounced than those of other sectors (that are traditionally recognized as energy-intensive)

A promising approach to the reduction of resource depletion and CO_2 emissions is to integrate alternative materials into the concrete mix, which will help reduce the reliance on cement. Materials such as fly ash, steel slag, resin, wood waste and recycled plastics can serve as partial or complete substitutes for cement [29]. In addition to reducing the carbon footprint, these materials have been observed to not only retain but in some cases enhance the properties of the concrete. This can result in improved durability and performance of the concrete structures.

3.4.3 Recycled Concrete Aggregates (RCA)

90% of the waste generated from construction comes from the demolition phase [38]. Multiple studies have been conducted to reduce concrete waste through the use of recycled concrete aggregates (RCA). The studies state that the RCA won’t be able to showcase the same properties as natural aggregate concrete (NAC). The main problem with RCA is the attached mortar component; as the mortar component sits on it, impurities such as glass, metal, dirt, plaster, gypsum, and other building waste will occur [38]. These impurities, combined with the weak quality of the bond between the original aggregate and the attached mortar residue, the small cracks from crushing, and the dispersed size of the RCA increase the porosity, and decrease the mechanical strength of the recycled concrete [28], [39]. When using RCA, firms must carefully remove the contaminants by water cleaning or air sifting [40]. The cost-benefit ratio of using RCA falls short, as the use requires additional labour, and the aggregate does not propose improved mechanical strength. Further research and improved results are needed for firms to start using RCA’s. According to NB, using crushed concrete as a 20% substitute for natural aggregates would lead to more cement usage. Therefore, using RCA as a sustainable solution currently isn't feasible.

The construction industry needs to explore other alternatives that are sustainable and can replace both cement and aggregates. As of today, multiple studies are being conducted on finding replacements for both cement and aggregates, such as the use of slag as raw material [41], cement with low lime saturation factor [42], cement and construction materials centred on magnesium oxide [43], geopolymer cement [44], fly ash and recycled materials in cement [45], and nanotechnology in cement and concrete production [46]. As RCA’s are not a viable choice, firms must put their focus towards waste minimization, which again confirms what NHP stated. Waste prevention will be the most vital step for the reduction of resource waste. As mentioned earlier prefabrication has the added benefit of thorough pre-planning which ensures waste prevention.

Based on the data in Figure 6, the demolition phase is the main contributor to waste production. As explained in the RCA section, it is important to focus on repurposing concrete elements at a different level. Instead of opting for crushing and recycling concrete, which is not a sustainable solution, a more circular option is needed. One such option in the construction sector should be to prioritize the reusability of concrete elements.

3.5 Promoting a circular economy

The term circular economy can be described as an economic system with a main purpose to eliminate waste and reduce the ongoing resource depletion. EU defines circular economy as: *"A model of production and consumption, which involves sharing, leasing, reusing, refurbishing and recycling existing materials and products as long as possible"* [47]. Implementing circular economy practises can potentially extend the lifecycle of products and will focus on repurposing the materials when the structural elements come to their End-of-Service-Life (EoSL), this will further improve the resource efficiency thus reducing the environmental impact of resource depletion and cement production mentioned above.

The term **resource flow** is an important part of the circular economy. The resource flow refers to the movement and utilization of both materials and resources through the economic system. The goal is to optimize and enhance their values and reduce the wastage. Unlike the traditional approach, which can be described as a "take-make-waste" pattern, the circular model's objective is to maintain the active use of the resources for an extended period. This will ensure that the resources will be used to their fill potential during their lifetime. A study on circular economy strategies for concrete separates resource flow into four main categories [48] [49] [50]:

1. **Narrowing:** This category targets the reduction of material volume consumed within the economy.

2. **Slowing:** This is a strategy which aims to prolong the lifecycle of the resource between production and the end-of-use.

3. **Closing:** This category aims to reduce the "material leakage" from the end of the resource's lifecycle back to the production stage.

4. **Reintegrating:** This category involves the return of materials back into their natural environments. It is worth mentioning that this category focuses on achieving this goal without the risk of damaging or reducing the natural capital.

As mentioned earlier, the prefabrication construction method proves to be a source for waste reduction, thus emphasizing the first category, **narrowing**. By using prefabrication in construction project firms can reduce the total material volume needed to produce the elements. This gives prefabrication an added advantage because it has already achieved one of the categories. The next target for the prefabrication method is to **slow down and prolong the lifecycle** of the produced elements. A study from Deloitte identifies construction as a sector with opportunities for enhanced circularity given the Norwegian industry structure and resource base [51]. The current approach for dealing with End-of-Service-Life (EoSL) can be described as linear [52]. As the numbers for concrete waste from SSB state (Figure 6), demolition is the main reason for concrete waste. When considering the growing need for buildings and the increase in population, the prospect of demolishing and disposing of large quantities of concrete needs to be taken seriously. A more circular option needs to be assessed as demolition proves to be a "fundamental design flaw" [52].

3.5.1 Cradle-to-Cradle (CtC)

Crowther states that the existing model of life cycle assessment for EoSL elements and materials can be described as “Cradle-to-Grave”. This linear model is illustrated in Figure 12. Crowther demonstrated an alternative model he called the “Cradle-to-Cradle” approach. This approach proved to help with the reduction of CO2-emission, energy consumption, waste and air pollution problems associated with the production of concrete [53]. The cyclic model of CtC proposes a new method for the “deconstruction” of a building. Instead of demolition, a new term called “design for disassembly” (DfD) is proposed as a solution by Durmisevic. The new cyclic method can be seen in Figure 13. As the figure shows, design for disassembly has been incorporated into each step up until demolition (which was the last step of the CtG-method). This method will be further discussed in section 4.

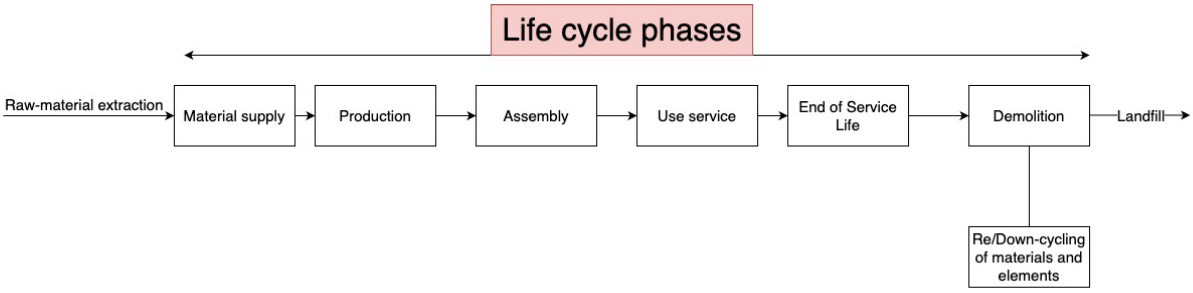


Figure 12- Linear model (CtG), Adapted from: [79]

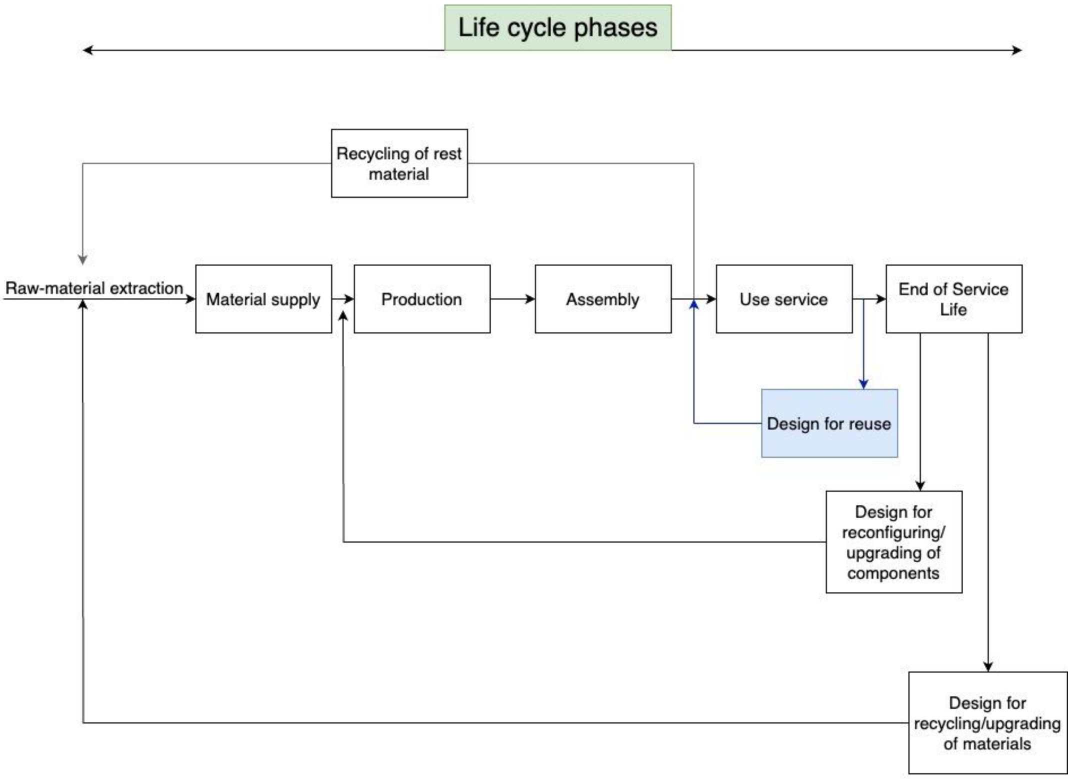


Figure 13- Cyclic model (CtC), Adapted from: [79]

4 Reusability

According to SSB, a significant portion of the concrete waste is generated from the demolition process (as shown in Figure 6) [10]. Materials from buildings will continue to accumulate, and as section 3.4.3 mentioned: recycling these concrete elements at their end of service life will downgrade its structural properties. As the blue box in Figure 13 shows, design for reuse is an essential step to prolong the lifecycle of the already produced element. Improving resource productivity will help the construction sector achieve a circular economy. Reuse is the second step in the waste hierarchy (as shown in Figure 7). Reusing concrete elements will reduce both CO_2 emissions and resource wastage. This strategy will help promote material efficiency and should therefore be a key research topic according to IEA [34]. Most research papers set their focus on recycling the concrete rather than recovering the product and directly reusing it. Current regulations and standard publications have been limited to the design and production of elements and materials.

ISO 20887 defines reusability as the following [54]:

"Ability of a material, product, component or system to be used in its original form more than once and maintain its value and functional qualities during recovery to accommodate reapplication for the same or any purpose".

4.1 Previous case studies

Poland

Laboratory tests were conducted on 45-year-old reinforced concrete (RFC) hollow-core roof slabs in Poland [55]. The test consisted of both a mechanical and chemical part. The mechanical part consisted of a load-carrying capacity check, followed by a deformability check. The deflection limit was set according to EN 1992-1-1. The study used a load equal to 6 kN/m^2, and the deflection limit was set at 13 mm. The test was conducted with the purpose to see if the RFC hollow-core slabs could be reused and loaded with e.g., ventilation equipment placed on them. Linear and concentrated loads were applied to the middle of the slab. The results state that the first observed cracks were in the middle of the span. The loading was 4kN and the crack width was 0,05mm. At maximum load capacity, 8kN, the crack width was noted as 0,2mm. As the crack width at maximum loading is way lower than the limit, the hollow core slabs prove to still be able to be in service. The study states that the usability of elements should be checked with site investigations and laboratory tests.

KA13

Kristian Augustus Road 13 is a pilot project where reused hollow-core slabs were used. Ca. 160 m^2 of reused hollow-core slabs were taken from Regjeringsbygg R4. The HCS were cut to a length of 6,5 m and had a width of 1,2m. The reused HCS were used as floor separators for the top 3 floors (floors 5-7 in the building). Entra ASA has published an experience report on the project. The report states that the lack of knowledge about the rules and regulations for reused HCS posed an issue at the beginning of the project. The reused HCS was documented according to TEK. The environmental analysis states that reused HCS had 89% less CO_2 emission compared to newly produced HCS. The procurement of reused HCS was stated to be 5-6 times more expensive compared to a new HCS. The increased cost was a result of the disassembly process, testing of elements, transport, and redesign. The structure used cross sections such as I, H and hat for the steel beam, these beams was the bearing element for the building project.

The HCS had a length of ca. 11m in their original use case. They rested on top of prefabricated L-shaped concrete beams. The height of the HCS were 265 mm (HD265) and concrete topping was applied with a height of 8mm. The added topping made the reuse process more complicated as the removal process was more costly the firm chose to let it stay on the HCS which as a result reduced the floor height of the original building plan.

Entra gives recommendations for future projects; better planning of the “donor construction” for stability and safety should be focused on before/during disassembly, proper documentation should be worked alongside the respective disciplines, and sufficient storage space must be available to work on the reused HCS [56].

Oslo Storby Legevakt (OSBL)

OSBL is another pilot project where HCS from Regjeringsbygg R4 were reused. Compared to the KA13 project, the OSBL project used the rules and regulations most relevant for the HCS, these were reported to comply with the standard for new HCS, NS-EN 1168. The EPD for the reused HCS by Contiga states that the total CO_2 emissions in phases A1-A4 is 19,98 kg-eq. Reports on the project state increased costs around the reuse concept of the project. Factors such as narrow land for disassembly, additional support for the stability of the “donor-construction”, and necessary cleaning and redesign of HCS were stated to cause increased costs. Recommendations such as reversible connections for the HCS and the reduction of reinforced casting have been noted [57].

FutureBuilt Circular

FutureBuilt has published a guideline for making the construction industry more circular. The goal of the guidelines is to motivate firms and the sector towards more circular solutions for the rehabilitation, demolition and construction of new projects. Steps for increasing the adaptability of a project have also been added to the report. FutureBuilt states that the design for adaptability involves planning the design of a building in such a way that it can change its function and use without too many material interventions. A minimum of 10 different elements used in the construction should be designed with reuse, reusability, recycle, and recyclability in mind. A minimum of 10 elements has been set to ensure that a broad number of elements in a project are made with circular measures. The criteria given on the reusability of a component (point 2.2.6 in the document) have been taken into consideration for the next sections [58].

Norwegian firms survey

A national survey was conducted aimed at understanding the reuse of construction products within the Norwegian construction industry. The survey consisted of 260 participants. Majority of the respondents had either intermediate, limited or no experience with reuse. It identifies the primary driver for material reuse as the reduction of emissions, reflecting a broad commitment to environmental sustainability across various industry stakeholder. However, it also highlights significant barriers to reuse, including lack of proper documentation, regulatory hurdles, and high associated costs. These barriers can be attributed to inadequacies in the current economic and regulatory frameworks. The study highlights effective planning and industry wide collaboration as crucial success factors for reuse. The study states that there is a varied level of optimism about the future of reuse, particularly regarding the availability and cost of reusable products. While many are optimistic about the short-term availability of reusable products, there is less optimism about their affordability in the near future [59].

The transformative use of HCS in new projects as the ones mentioned in KA13 and OSBL are living testaments to the potential that lies in reconsidering the lifecycle of concrete elements. Although the environmental benefits are clear, economic challenges are hindering the broader applicability of these practices. These case studies and the experiences noted from the disassembly process will be used for the developed guidelines in section 6. Figure 14 shows a summary of the advantages and disadvantages highlighted in the case studies. The subsequent section will dissect and differentiate the two key concepts of reusability: remanufacturing and refurbishment. These practices, while linked, diverge in intentions and outcomes.

Advantages

- Often longer technical life span
- Environmentally friendly
- Resource efficient
- New market

Disadvantages

- Costly procedure (high initial cost)
- Lack of proper documentation
- Technical challenges
- Current regulations for reuse
- Lack of clear and harmonized definition of reuse

Figure 14- Advantages and disadvantages of reuse

4.2 The role of reusability

In the context of reusing structural components, two main end-of-use strategies are often considered to extend their lifespan. These strategies are known as remanufacturing and refurbishment, and they both apply to the reuse of HCS. This section will delve into both strategies and emphasize their distinctions.

Remanufacturing entails taking elements from their original construction and processing them, so they are restored to a condition of comparable or improved functionality for reuse in new construction projects [48]. This method aligns closely with the circular economy and sustainability principles discussed in this thesis and will be the focal point of the case study in section 5. The benefits of remanufacturing are particularly noticeable in the context of buildings. The continued evolvement of architectural trends and occupancy makes remanufacturing an effective solution for the adaptability of existing structures. Some examples of the applicability of remanufacturing can be seen in:

- Modular and adaptive construction: Increasing the sustainability of modular/prefabricated construction by allowing for the ease of swapping, updating or reconfiguring elements in the structure.
- Sustainable development initiatives: Using remanufactured elements presents a way to minimize the environmental footprint through the reduction of resource extraction and waste production, thus becoming an attractive option for projects seeking to be more environmentally friendly.
- Innovative urban development: Using remanufactured elements in urban spaces that undergo renewal can improve the sustainability of urban growth. The project will "blend the old with the new".

Refurbishment on the other hand focuses more on "updating" or repairing the elements while they remain a part of the original construction [48]. The difference in application has been illustrated in Figure 15 and Figure 16. The primary difference between the two strategies is the end goal. Remanufacturing prepares the elements for a new life in a different construction project from the one it was originally in as reached its EoSL. Refurbishment on the other hand focuses on maintaining and extending the life of the actual structure as the elements might have reached their EoSL or are damaged. The refurbishment strategy has the potential to be a vital part of infrastructure management, particularly for utilities that serve critical functions in society and can't be easily replaced or subjected to longer downtime. The refurbishment strategy could prove to be a vital part of the preventative maintenance approach. It could mitigate the higher costs and logistical challenges associated with extensive repairs and full-scale replacements.

Some examples of the applicability of refurbishment can be seen in:

- Historic preservation: Refurbishment can often be seen as an important step to prolong the lifetime of historically/culturally important buildings, often called heritage buildings. The strategy respects and maintains the original craftmanship while also ensuring structural safety and compliance with modern codes and regulations.
- Operational Infrastructure: Refurbishment can be used to extend the service life of critical structures such as bridges without disrupting their functions.
- Cost-Effective Upgrades: Budlings and facilities in need of updates can benefit from refurbishment as this might achieve safety, efficiency and aesthetic goals without the higher costs associated with full rework.

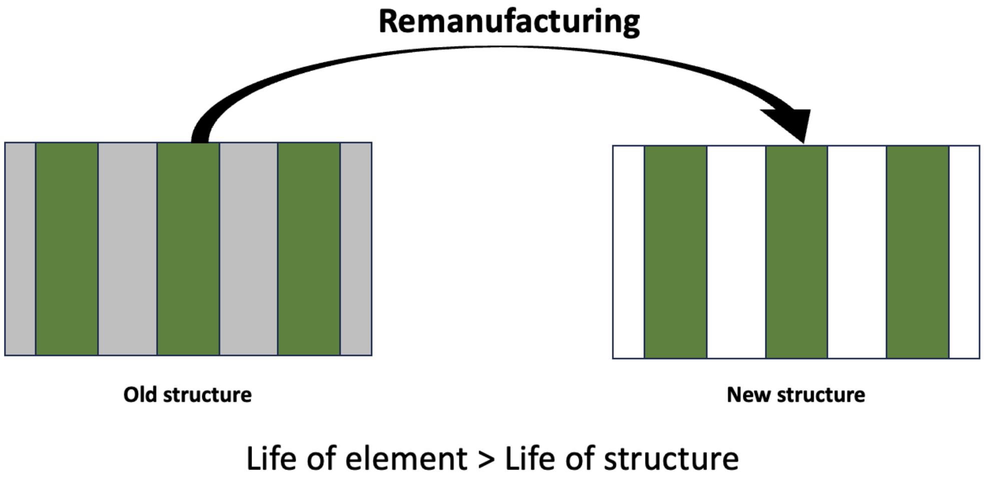


Figure 15- Remanufacturing of elements, Adapted from: [50]

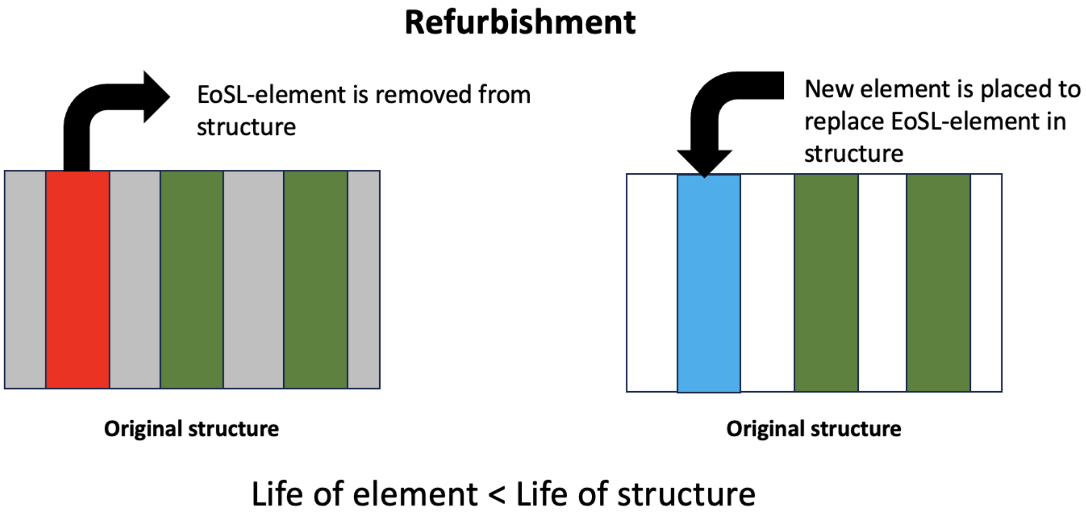


Figure 16- Refurbishment of elements, Adapted from:[50]

5 Project Case study: Reusing HCS from SIS-Velferdsbygg

Reuse proves to be a potential strategy to minimize environmental impact while maximizing resource efficiency. This option will not only conserve material but also reduce waste and lower carbon footprint of new construction projects. The following section will introduce the case study for this thesis. It will focus on the potential of repurposing HCS from the SIS-Velferdsbygg into a new student housing project at its EoSL. The donor structure, SVB, serves as a source of HCS which are repurposed to form the backbone of the reuse case- new student housing project. To ensure proper safety and structural integrity of the new building careful considerations must be given to the load cases that the slabs experienced in their previous use.

5.1 Donor structure- SVB

The SIS project comprises three building projects: the sports hall, the connecting building, and SIS-Velferdsbygg (SVB). Figure 18 shows the whole project from different perspectives. The front-facing building shown in the upper picture is SVB. All the concrete elements produced in this project are prefabricated and made by Veidekke-Prefab. This thesis will focus on the HCS (hollow core slabs) used for the SIS project, primarily on the third floor. The following section will go through the relevant loads and calculations for the design of the HCS. Calculations and designs for the HCS elements chosen for reuse will also be shown.

5.1.1 Project Overview

The SVB project comprises four floors. The floors have been named and sorted into phases as shown in Table 4. The floor plans are attached In Appendix B. 92% of the HCS used for SVB were 265 (560 HCS-elements), with the remaining 8% being HD320 (48 HCS-elements). The total area of HD265 and HD320 used for SVB is approximately 4920 m^2 and 326,51 m^2. The total mass of HD265 and HD320 for SVB is 1767,7 tonnes and 130,51 tonnes. Figure 17 shows the distribution of the HCS on each floor.

The basement floor work involves cast-in-place foundations beneath load-bearing structures and ground-level floors for both buildings. The main support system for SVB includes precast concrete walls, columns, beams and HCS. The basement uses both precast columns and cast-in-place cellar/interior walls. Stabilization is accomplished by using concrete elevator and staircase shafts, as well as load-bearing concrete walls on the lowest level.

The project states the following requirements for the project based on NS-EN1990:2002+NA:2016:

- **Consequence Class:** CC2
- **Reliability Class:** RC2
- **Seismic Class:** II
- **Fire resistance class:** REI90
- **Dimensioning service life:** 50 years

Table 4- Divided floor plan for SVB

Floor	Phase
Basement floor (U1)	HK1
	HK2
1st floor (1)	H11
	H12
2nd floor (2)	H21
	H22
3rd floor (3)	H31
	H32

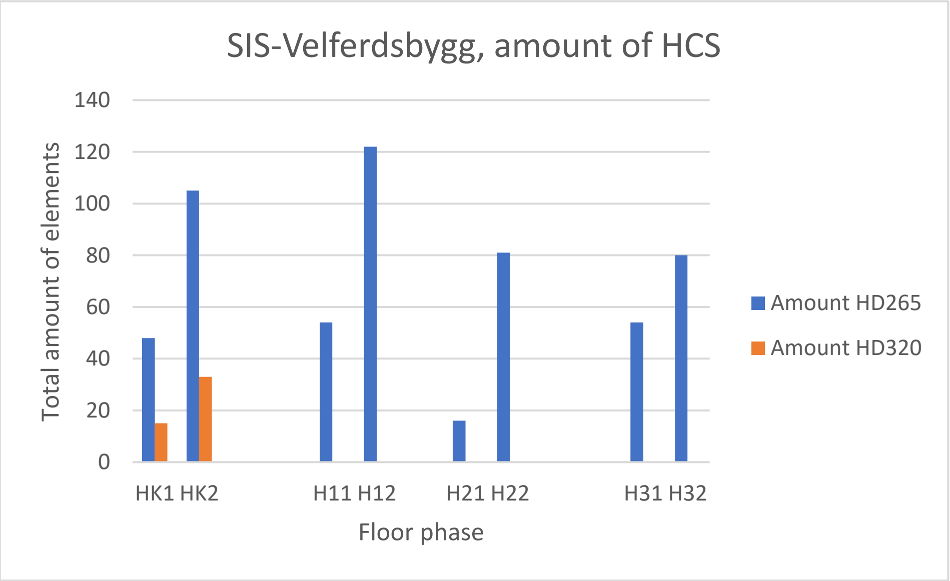


Figure 17- Amount of HCS for each floor.

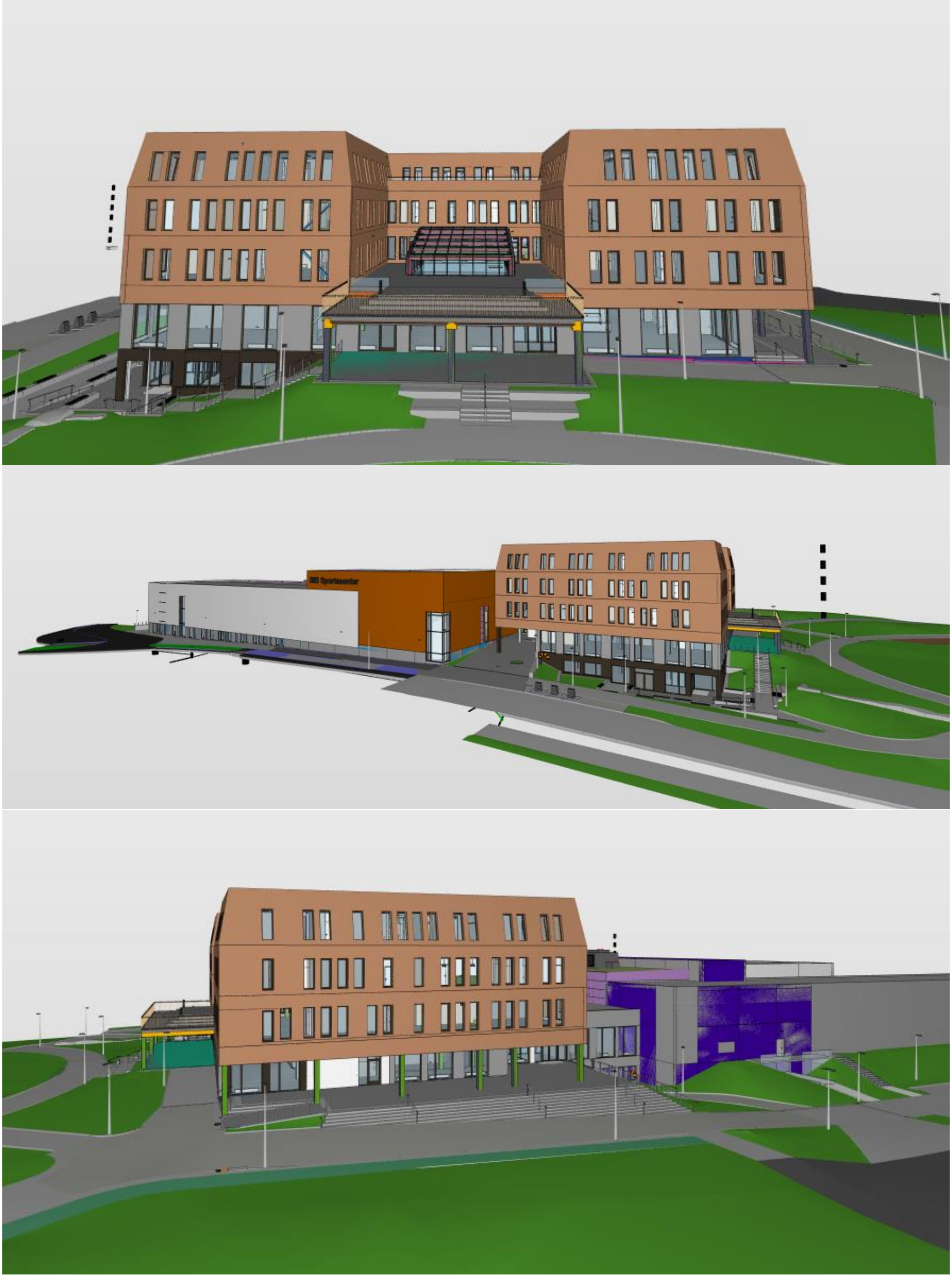


Figure 18-Different perspectives of SIS Velferdsbygg, Source: [80]

5.1.2 Applied loads (from RIB)

Understanding various types of loads- dead, self, and imposed- will be pivotal to analyse the construction. The loads used for the SVB-project are given in the tables below. Table 5 shows the dead load for the HCS used, Table 6 shows the self-load of the elements, and Table 7 shows the imposed loads. These tables will serve as the “basic loads” for the designs of the HCS.

Table 5- Deadloads for SVB

Deadload for construction element	Applied over floor	Dead load (kN/m^2)
HD265	1-3	3,9
HD320	U1-1	4,3

Table 6- Self loads for SVB

Applied self-load	Applied over floor	Self-load (kN/m^2)
Office	1-3	2,0
Common area	U1	4,0
Roof terrace	1,3	3,0
HCS-outside	U1	10,0

Table 7- Imposed loads for SVB

Area	Applied over floor	Category	Imposed load (kN/m^2)
Office	1-3	B	3,0
Common area	U1	C3	5,0
Roof terrace	1,3	C3	4,0
HSC-outside	U1	C3	5,0

5.1.3 Possibility for reuse (earlier loads).

When considering the possibility of reuse, ease of disassembly plays a vital role in the decision of which elements to reuse according to the experiences mentioned in 4.1. It is crucial to evaluate the design of the HCS to gain a better understanding of potential links between the slabs and the loads they bear. The connections between the slabs may need to be severed, and a thorough review of each element is necessary to ensure its suitability for reuse. Specifically, when considering the third floor, some loads require attention. These include distributed loads from cast-in-place, line loads from the façade, and point loads from the roof. The probability of being able to reuse slabs can be increased by avoiding HCSs with significant design changes due to load arrangements. As the following examples will show, simplicity will be key when judging the possibility of reuse. The load cases must be examined before determining the eligible HCSs for reuse.

5.1.3.1 Cast-in-Place

The floor plans for SVB show that some cast-in-place concretes have been used as there are plate covers in the floor plans. The plate covers are marked with an orange box in figures Figure 62. The HCS are connected using either a shear connector or a structural dowel as shown in Figure 19. The loads from the cast-in-place will be equally distributed between the HCS with ID numbers 2245 and 2244 (50% on each). These connectors play a crucial part in the multi-slab arrangement to transfer shear forces and align and distribute the loads between the elements. The connection can be seen as "Tverrhull" in Figure 19. Thorough planning is necessary to separate and cut elements that work as one. The additional load from the cast-in place can be calculated as shown below.

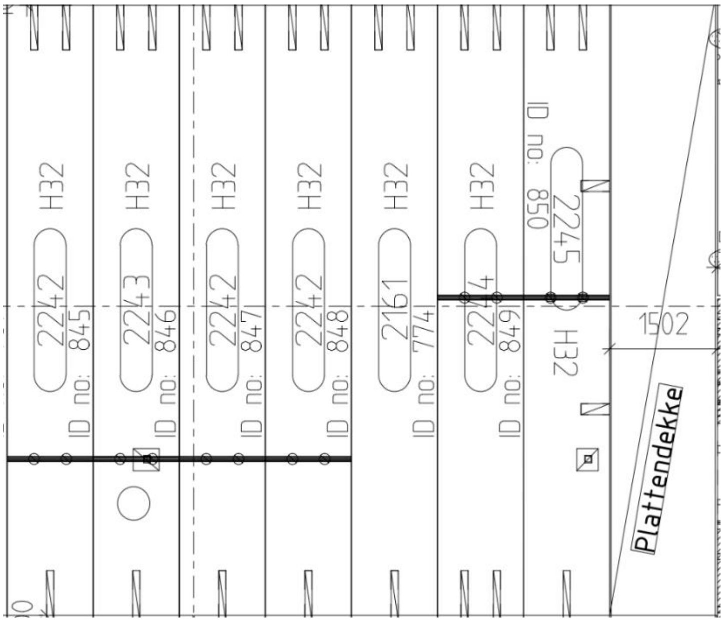


Figure 19- Section from floor plan for 3rd floor, source: [80]

$$\boldsymbol{Deadloads}:$$

$$Selfweight = 25\frac{kN}{m^3}\ x\ 0{,}265\ m = 6{,}625\frac{kN}{m^2}$$

$$Common\ Area = 4\frac{kN}{m^2}\ x\frac{1{,}502}{2}\ m =\ 3\frac{kN}{m}$$

$$\boldsymbol{Imposed\ load}:$$

$$Common\ Area = 5\frac{kN}{m^2}x\frac{1{,}502}{2}m = 3{,}755\frac{kN}{m}$$

$$\boldsymbol{Loads\ on\ each\ HCS}:$$

$$Dead\ load = 9{,}625\frac{kN}{m}\ x\ 50\% =\ 4{,}81\frac{kN}{m}$$

$$Imposed = 3{,}755\frac{kN}{m}\ x\ 50\% = 1{,}878\frac{kn}{m}$$

5.1.3.2 Line load

The façade shown in Figure 20 will contribute to additional loads on the edge of the HCS. The value of the line load is 6,8 kN/m^2. Due to the increased load, certain HCS will undergo design changes to withstand it. The red arrows shown in Figure 62 symbolize the line load. The distribution of the line load between the HCS is done according to point 3.1.2.1 in *Betongelementboka* [60]. When designing HCS (ID: 2235 and 2236), the distribution of the line load applied as shown in Figure 21 needs to be calculated.

Figure 20- Section of SVB to show line loads, source: [80]

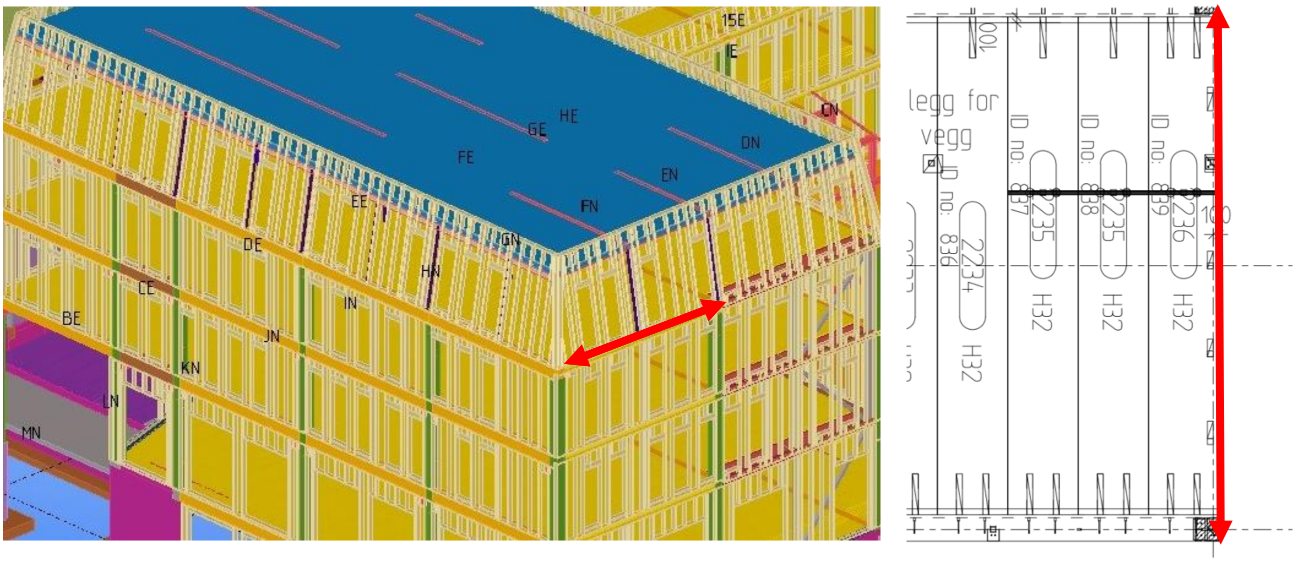


Figure 21- Line load example, 3rd floor, source: [80]

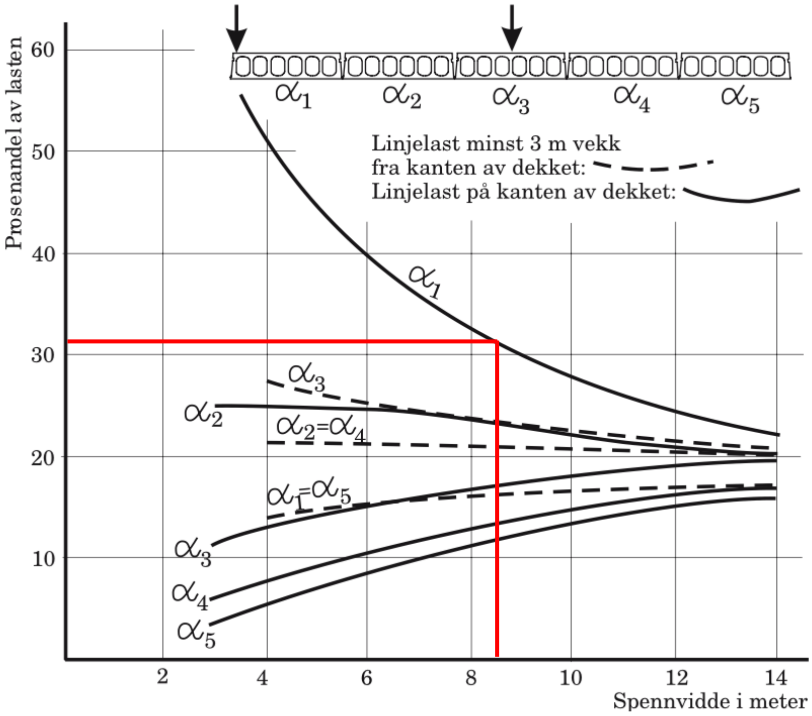


Figure 22- distribution of line load, alpha value, Source: [59]

As the line load is positioned at the edge of the HCS the normal line will be used for the alpha calculation. The guidelines states that if no cast-on (påstøp) is used on the HCS, the HCS with the applied load will have to increase the alpha value by 25% and the remaining will have to decrease accordingly. The length of element 2236 is 8,4 m. As the red lines in Figure 22 shows the percentage for the alpha 1 value will be approximately 32-33%. The value obtained from Figure 22 is then multiplied according to the guidelines with 1,25 and the remaining alpha values have been calculated as shown below. The HCS is at the end of the assembly, the value for distance to edge "e" will therefore be 0 m. The distribution will be done accordingly to the calculated alpha values. Figure 64 shows the alpha-calculation in detail.

$$\alpha_1(new) = 32{,}5\ x\ 1{,}25 = 40{,}6\% \Rightarrow 2{,}76\ kN/m$$

$$ratio\ for\ a = \frac{59{,}4}{67{,}5} = 0{,}88$$

$$\alpha_2(new) = 23\ x\ 0{,}88 = 20{,}3\% \Rightarrow 1{,}38 kN/m$$

$$\alpha_3(new) = 18{,}2\ x\ 0{,}88 = 16\% \ \Rightarrow 1{,}09\ kN/m$$

$$\alpha_4(new) = 14{,}4\ x\ 0{,}88 = 12{,}7\% \ \Rightarrow 0{,}86\ kN/m$$

$$\alpha_5(new) = 12{,}4\ x\ 0{,}88 = 10{,}9\% \ \Rightarrow 0{,}74\ kN/m$$

$$Control = \ \Sigma a = 100\%$$

5.1.3.3 Point load

Unlike the distributed load, the point load will apply a concentrated force over a small area. These specific loads/ stress concentrations can be seen in Figure 63. The point load applied on the HCS is calculated according to the procedure mentioned in *Betongelementhåndboken*. One point load has been emphasized with a value of 38 kN in permanent load and 102 kN in variable load close to axis 3N-EN in Figure 63. The graph shown in Figure 23 illustrates the various alpha values required to multiply with the actual point load for the calculation process. In Figure 24, the orange star identifies HCS 2243 and is positioned as alpha-3 in the calculation. As the point load is not centred the alpha value will have to possibly be interpolated. Information from Figure 25 has been used to calculate the alpha values for the distribution of loads.

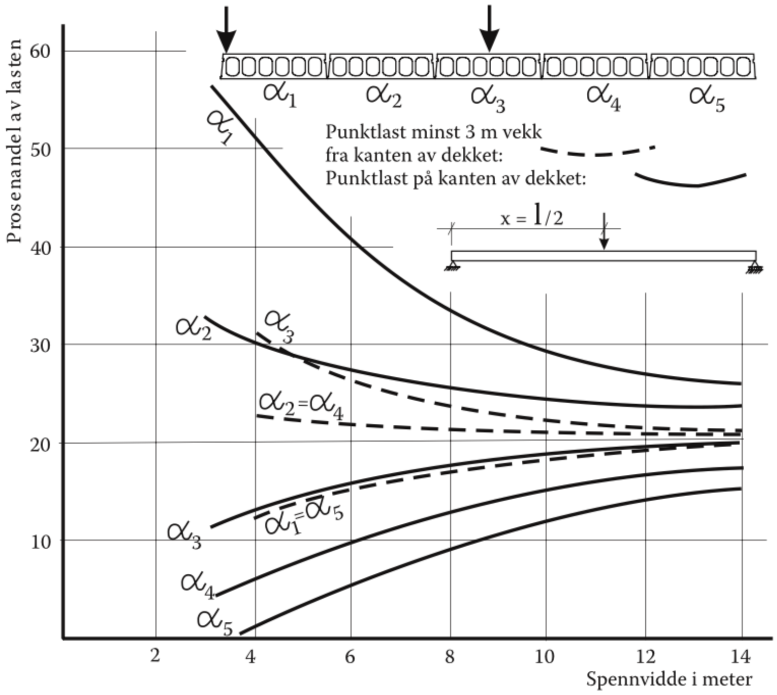


Figure 23- alpha value for distribution of point load, source: [59]

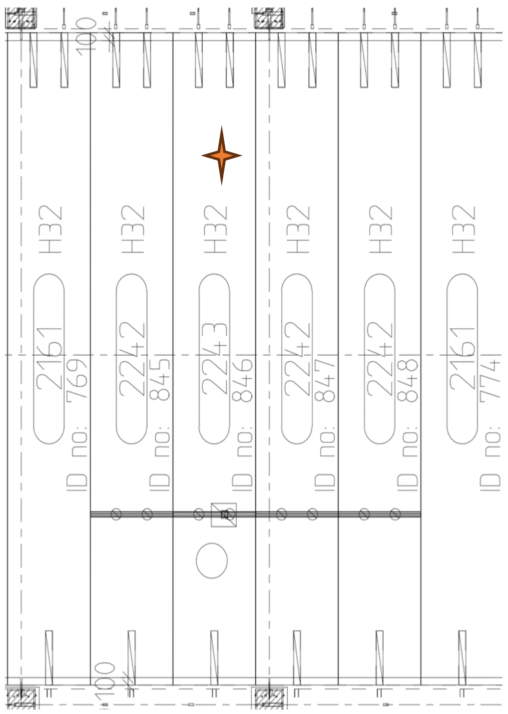


Figure 24-Position of HCS 2243, source: [80]

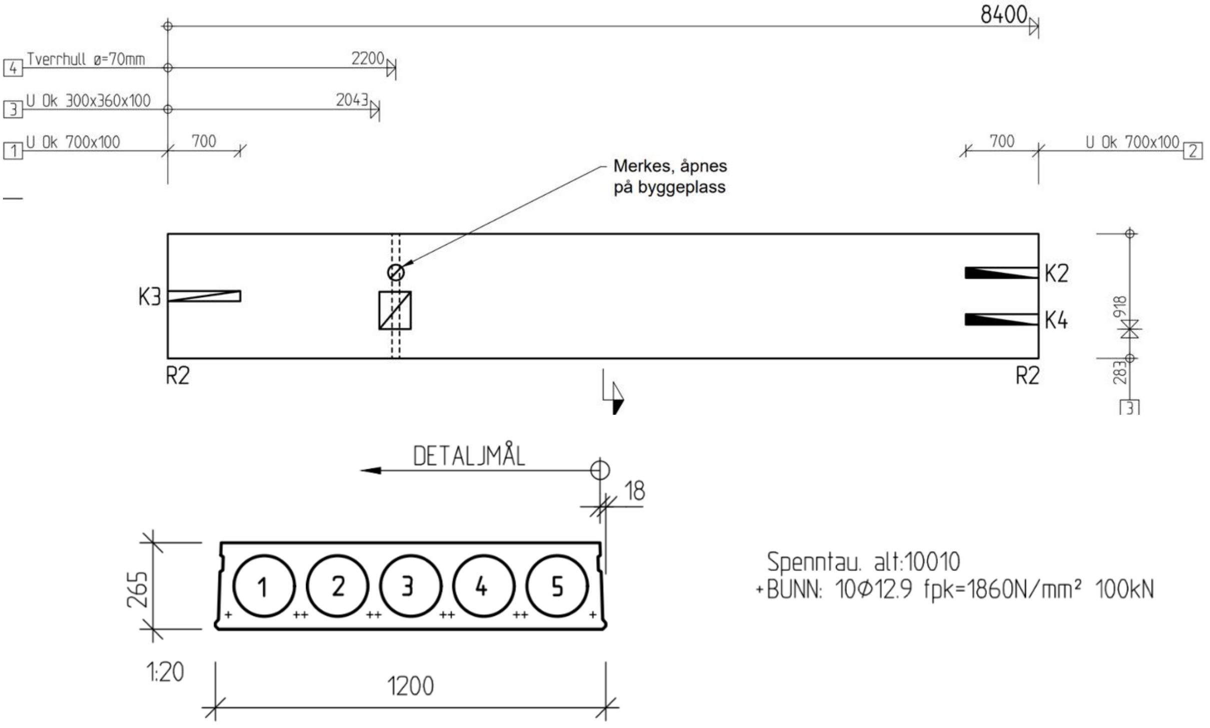


Figure 25- Detailed drawing for element-ID 2243, source: [80]

Before calculating the alpha values, the same check done for the line load has to be done here as the point load is not centred at L/2. The check written below shows that the dotted line can be used for the alpha calculations. The design data from E-bjelke states that the dead load will be 14,91 kN and the variable load will be 40,10 kN.

$$Lenght\ of\ HCS\ 2243 = L = 8400\ mm$$
$$Distance\ from\ end\ of\ HCS\ to\ point\ load = x = 2043\ mm$$
$$As\ the\ length\ for\ the\ load\ placement\ x \neq \frac{L}{2}\ following\ check\ needs\ to\ be\ done:$$
$$If\ x \leq \frac{L}{20}, all\ loads\ will\ be\ carried\ by\ element\ in\ placement\ a_3$$
$$If\ 2 < \frac{L}{x} < 20, interpolation\ should\ be\ done\ using\ straight\ line$$

Check:

$$x \leq \frac{L}{20}$$
$$\Rightarrow 2043 > {}^{8400}/_{20} = 420$$

$$2 < \frac{L}{x} < 20$$
$$\Rightarrow {}^{8400}/_{2043} = 4{,}11$$
$$2 < 4{,}11 < 20$$

5.1.4 Connections in SVB

The HCSs in the donor structure SVB uses two main connection types as depicted in Figure 26 and Figure 27. The opened slots shown in the figures will be filled with concrete thus making them irreversible. This must be considered when choosing the eligibility of reuse. Connection possibilities for the reusable HCSs will be discussed in detail in section 7 and 9.2. Creative solutions will be needed for the HCS to Wall connections since the original connection type Figure 27 won't be applicable for reusable HCS.

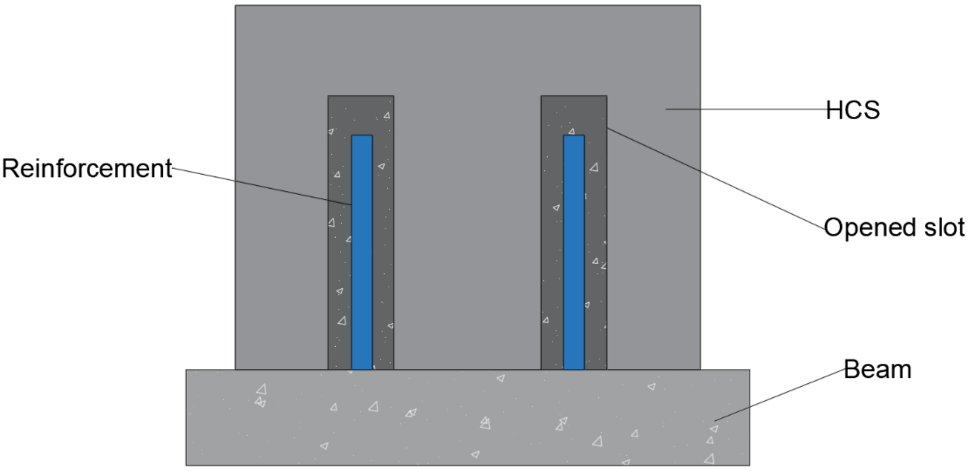


Figure 26- HCS to Beam Connection

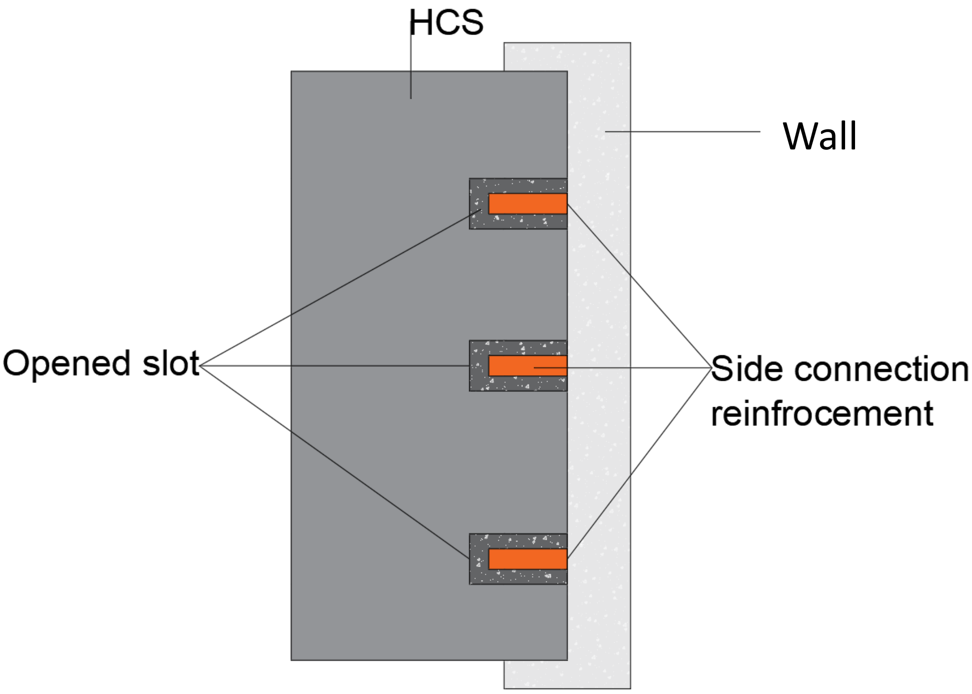


Figure 27- HCS to Wall Connection

5.2 Reuse Case

The load combinations mentioned in section 5.1.3 will propose some challenges when choosing HCS for disassembly. The cross holes made for the load distributions will be filled with cement making them permanent, removing these slabs could damage the concrete. Potential weakening or cracking could happen in the areas around the connectors. These connections are often tailored to specific load combinations and requirements. Reusing these HCSs might limit their potential in new projects as the requirements, specifications or load conditions may differ.

The elements in Table 8 will be used for the case study of the thesis. The total volume of the HCS is 56,41% less compared to the solid slab volume. The total area of the elements is 396,5 m^2. As mentioned earlier, higher possibility for reuse will come by choosing elements with little to no design alterations compared to standard design. The chosen elements are as close to the standard design as they come, making them a great fit for the reuse case. Some new HCSs will most likely have to be created to satisfy the connection needs for elements such as the walls. Standardized HCSs made in common dimensions and specifications will fit into a wide range of building designs without the need for extensive alterations. The focus on standardization gives the benefit of interchangeability, which allows for rapid assembly and disassembly. A challenge worth noticing is the connection between the cores and the elements. As the HCSs used in this case are reused, some of the cores might be sealed shut due to the cement poured over the steel rod connections between the HCSs and the beams. Therefore, alternatives for the connections needs to be considered.

The choice for the reusable HCSs was done based on the following factors:

- Compatibility in dimensions and characteristics between the reused slabs and the requirements in the new project. The potential for adjustments in dimensions should also be thought of.
- The reusable slab must comply with the appropriate technical specifications for the building project,
- Evaluate the topping layer, its nature and intended purpose must be assessed. Compatibility of the HCS might be affected by the topping due to the amount of work that could be needed to remove it.
- Connections to beams, walls, and adjacent slabs (in original/donor construction)
- The overall structural integrity of the HCS

The target of this case is to analyse the possibilities and challenges of reuse. The environmental aspect, procedure for disassembly and testing of elements will be analysed.

Table 8- HCSs for reuse case

	Total element	Solid Slab volume	Total Volume HCS	Material saved
Element ID		(m3)	(m3)	(%)
2006	1	2,671	1,447	54,17 %
2075	25	66,780	36,177	54,17 %
2076	1	2,671	1,447	54,17 %
2084	14	37,841	20,502	54,18 %
2100	2	5,406	2,923	54,06 %
2108	15	40,545	22,013	54,29 %
2122	4	10,812	5,858	54,18 %
2161	11	29,383	15,918	54,17 %
2163	5	13,356	7,235	54,17 %
2165	5	13,356	7,235	54,17 %
2176	4	10,812	5,858	54,18 %
2178	4	10,812	5,858	54,18 %
2181	4	10,812	5,858	54,18 %
2213	2	5,406	2,929	54,18 %
2215	8	21,624	11,740	54,29 %
2225	1	2,703	1,464	54,18 %
2230	2	6,080	3,296	54,22 %
			AVG-%	**54,19 %**

5.2.1 Floor plan

A design proposal for the floor plan has been made, as shown in Figure 29 and Figure 30. The floor plan consists of all the HCS elements chosen in the reuse case as shown in Table 8. The reuse case has a total length of 68,45 m and a width of 18,5m. The total area of all the HCSs used for the reuse case is 1098,37 m^2. Each of the rooms shown in Figure 30 is a student apartment, with a total area of 20 m^2, each bathroom is 3m^2. In addition to the student apartments, a common area, a laundry room and a storage/ stall has been placed. As mentioned, some of the voids were already used. The placement of the HCSs will be more restricted because of this. Section 3.2 mentions some of the benefits of pre-fabrication, one important one for waste reduction was the pre-plan phase. This phase will also be crucial for the reuse case as the placements of the HCSs needs to be carefully assessed here.

The floor plan consists of HCSs from both the third and second floor of SVB. All elements which were longer than 8,4 m was cut to the length of 8,4m. The width of the HCSs is 1,2m and they are all HD265 (height equals 0,265m). The proposed solution uses newly produced L-shaped beam and inverted Tee-Beam, these beams can be seen in Figure 28 and Figure 29 (blue colour). The HCS are all numbered (green numbers) using the same IDs as the ones used in SVB. The end cuts for the used voids have been characterized using the red colour, the end cuts for the voids chosen for the reuse case uses the cyan colour.

As the close up on Figure 28 shows, the usage of voids must be carefully chosen. The connection between the Inverted Tee beam and the HCS uses either anchorage or an iron rod. Placing HCSs with the same used voids (first-use case) on the opposite of each other, gives the added benefit of using the available voids for an easy connection using an iron rod. An example for this connection can be seen on the bottom two HCSs in Figure 28 (element ID: 2108 and 2075). The pre-planning the placement of the reused HCS will save time in the production phase of the beams for the proposed floor plan. When placing the HCSs the target must be to eliminate unnecessary use of anchorage as this demands additional labour during production.

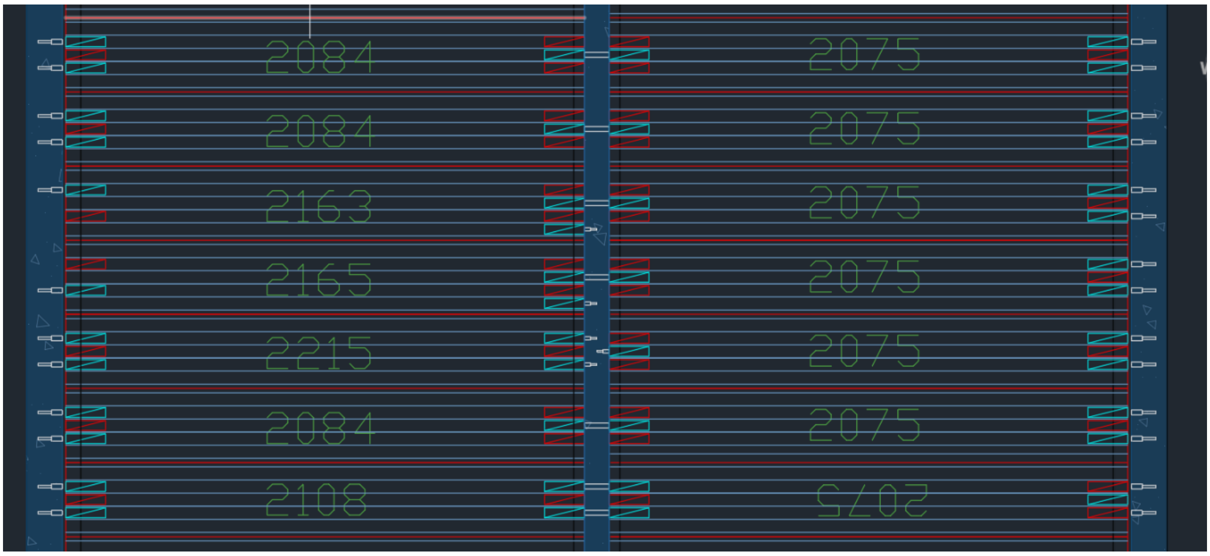


Figure 28- Closer look at the floor plan

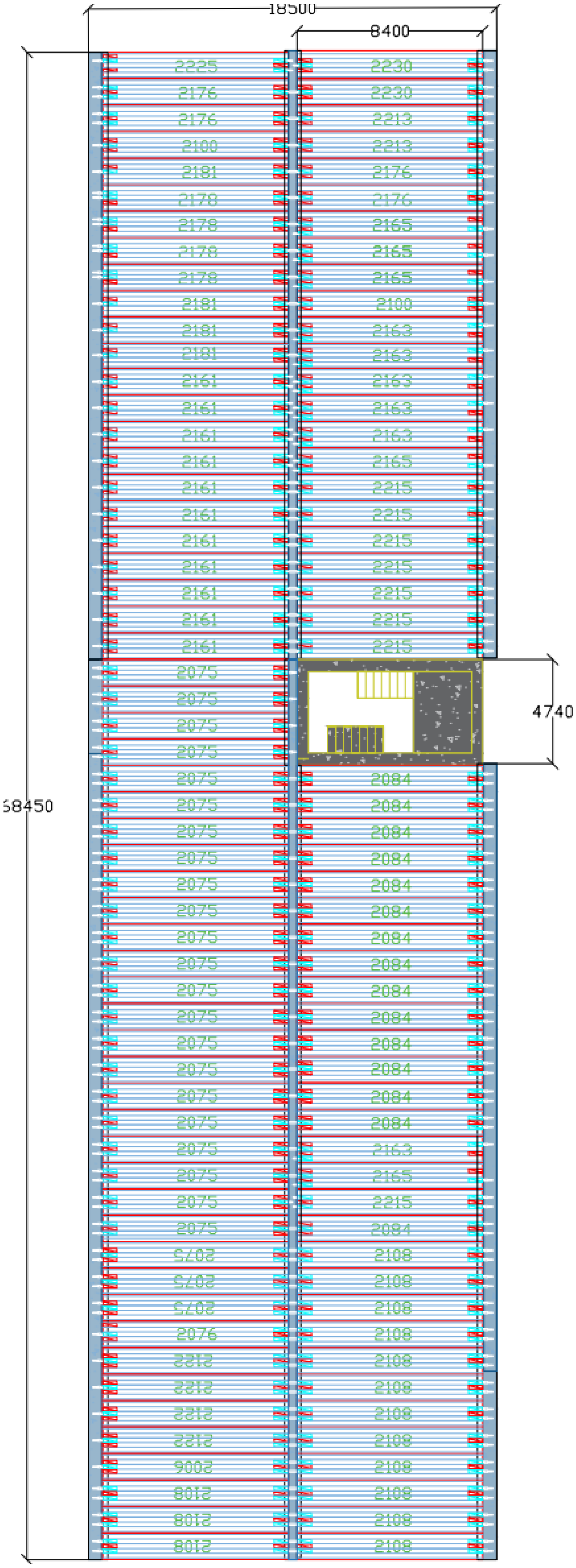


Figure 29- Floor plan used of the reuse case

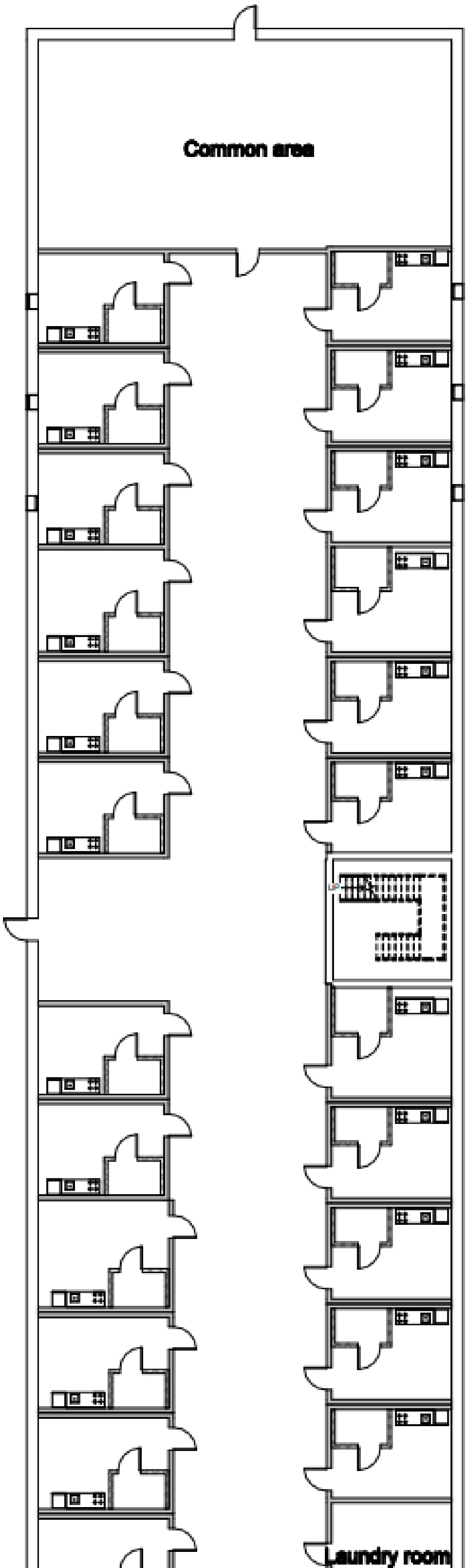


Figure 30- Floor plan w/rooms

5.2.2 Loads and regulations.

The reuse case will be presented as a student housing. The category of the building according to NS-EN-1991-1-1 is “A” as the usage is for domestic and residential activities. The main loads considered for the reuse structure can be seen in Table 9. The information for the imposed loads comes from Table NA.6.2. The self-weight of the elements will remain the same.

Table 9- Type of loads for reuse case

Type of load	Element	kN/m2	Category
Deadload	HD265	3,9	A
Imposed load	HD265	2	A

Reducing the imposed load may enhance the longevity and effectiveness of a reusable elements. Office buildings typically require higher load capacities due to heavy equipment, extensive storage, and increased occupancy. Applying HCSs in student housing could be beneficial, leveraging their excess capacity to improve durability and minimize overload risks. These HCSs, initially designed to withstand substantial loads over their service life, may experience extended operational life when used in less demanding environments, potentially improving the building’s lifecycle performance. However, it is crucial to assess the structural integrity of these elements at the EoSL following the testing guidelines outlined in section 6.3.

Furthermore, an additional dead load will have to be calculated according to the additional flooring and insulation placed on top of the HCS. The sound insulation requirements are much higher as the reuse case is a residential building instead of an office building. This change will require additional insulation to enhance the comfort and privacy within the building. The next section will discuss the most noteworthy regulations and changes that needs to be done on the HCS.

5.2.3 Sound insulation

Achieving adequate sound insulation is critical, especially when adapting structures for different uses. This is particularly relevant when converting spaces intended for offices into student housing. Table 10 shows the differences in required sound insulation based on data from Byggforsk. The limits are from NS 8175. The insulation must satisfy sound class C to satisfy the need for adequate insulation.

TEK 17 chapter 5, § 13-6 point 2 states that a minimum of 45 dB for the sound reduction figure (R'w) must be measured in a field-measure test. Allowing a lower R'w limit will improve the freedom in design for the floor plan. As the HCSs were made for the office category it will have a low flank transfer degree. The floor plan solution given in Figure 30 for the reuse case would make it seem as if it will have a middle flank transfer degree, but due to the length of the HCS being longer than 8m it will be low. A 265 mm HCS will have a satisfying R'w value of 56 dB, but the L'nw value is 76 dB which is way too high.

A simple calculation check can be done to assess the insulation quality of different designs, these are as follow:

$$R'_w = R'_{w,basic} + \Delta R'_{w,floor} + \Delta R'_{w,ceiling} \geq 45$$

$$L'_{n,w} = L'_{n,w,basic} - \Delta L'_{w,floor} + \Delta L'_{w,ceiling} \leq 53$$

Table 10-Sound insulation limits [61]

Building Category	Class C R'_w (Lowest allowed value)	Class C L'_{nw} (Highest allowed value)
Housing: between housing units from common areas/communication routes such as common corridors, hallways, stairs etc.	55	53
Offices and restaurant buildings: Between offices	37	63

Two options can be used to satisfy the sound insulation need for the student housing. Figure 32 and Figure 31 shows these two options. Option 1 will be a cheaper and less time-consuming option compared to option 2. The reduced sound reduction figure makes both of the designs applicable for the reuse case. but the weighted normalized impact sound pressure level (Ln,w) must be reduced further in option 1. Although option 1 has its economic benefits it will not satisfy the limits shown in Table 10.

The sound insulation values for both options are shown in Table 11 and Table 12. Although both of the options satisfy the R'w regulation, option 1 is on the maximum limit according to Table 10. Option 2 will be a better option to satisfy the sound insulation requirements. The decision-making must take the economic perspective and required insulation level into consideration when choosing.

Table 11- Rw-values for option 1 and 2

	$R'_{w,basic}$	$\Delta R'_{w,floor}$	$\Delta R'_{w,ceiling}$	R'_{w}
Option 1	56	0	5	61
Option 2	56	4	3	63

Table 12- Ln,w- values for option 1 and 2

	$L'_{n,w,basic}$	$\Delta L'_{w,floor}$	$\Delta L'_{w,ceiling}$	$L'_{n,w}$
Option 1	76	21	-2	53
Option 2	76	31	-3	42

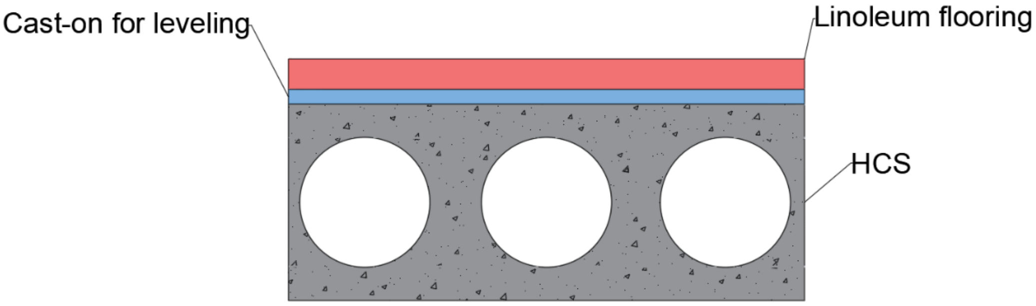


Figure 31- Flooring Option 1

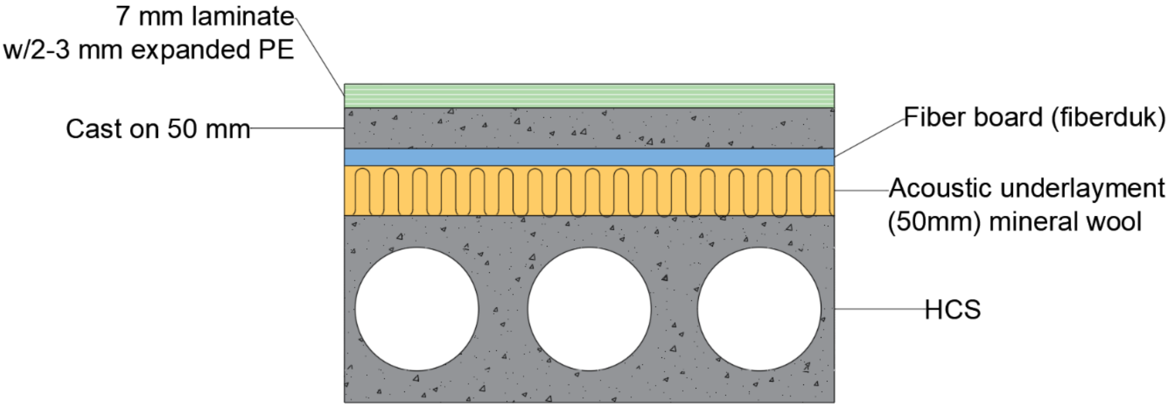


Figure 32- Flooring option 2

5.2.4 Fire resistance

Calculations for the fire resistance ability of the HCS must satisfy NS-EN 1991-1-7. It is crucial that the reuse case satisfies the fire safety regulations and requirements. TEK 17 §11-1 states "Buildings must be designed and executed in such a way that satisfactory safety is achieved in the event of fire for people staying in or on the building, for material values and for environmental and social conditions.". Adequate fire resistance is critical to accomplish the reuse case. Without achieving the safety requirements such a project cannot be done.

TEK 17 states that a student housing falls under risk class 4. The requirements for risk class 4 can be seen in Table 13. The HCS from SVB were designed with the fire resistance class REI90. This will make the fire resistance requirements quite achievable. As shown in Table 14, a building with risk class 4 will be in fire class 2 (BKL 2) up to 4 stories. The required fire resistance for such a building is REI60 as shown by Table 15.

Table 13- Risk class table, adapted from: [62]

Risk Class	Construction only intended for occasional occupancy	People in the construction known the escape conditions*	Constriction intended for accommodation	Assuming the use of construction results in little fire risk
1	Yes	Yes	No	Yes
2	Yes/ No	Yes	No	No
3	No	Yes	No	Yes
4	No	Yes	Yes	Yes
5	No	No	No	Yes
6	No	No	Yes	Yes

*Including escape routes, and (people) can bring themselves to safety

Table 14- Fire classes, adopted from: [63]

	Number of floors			
Risk Class	1	2	3 and 4	5 or more
1	-	BKL 1	BKL 2	BKL 2
2	BKL 1	BKL 1	BKL 2	BKL 3
3	BKL 1	BKL 1	BKL 2	BKL 3
4	BKL 1	BKL 1	BKL 2	BKL 3
5	BKL 1	BKL 2	BKL 3	BKL 3
6	BKL 1	BKL 2	BKL 2	BKL 3

Table 15- Fire resistance requirements for building parts in BKL 2, adopted from: [64]

Building part	**Fire class 2 (BKL 2)**
Main load-bearing system	R 60
Secondary load bearing building parts	R 60
Separating construction elements	
Fire cell limiting construction (branncelle)	EI 60
Part of building that encloses stairwell, lift shaft and installation shafts over several levels	EI 60

Table 16- Required dimensions for fire resistances, adopted from: [65]

Standard Fire resistance	**Minimum required dimension**	
	Equivalent slab thickness h_{ekv} (mm)	Reinforcement depth of bars (mm)
REI60	80	35
REI90	100	45

As the HCSs were designed with REI 90 in fire resistance for their first use case, the dimensions will be satisfactory for REI 60. As Table 16 states the required minimum slab thickness for REI 60 is 80mm. The calculation done below shows that h_{ekv} is higher than 80mm. The reinforcement depth of the bars is 45mm which satisfies REI 90. As the fire resistance is higher than the required amount these slabs could potentially be used in the reuse case. It is essential to note that given the HCS's EoSL, detailed testing is required to confirms its fire resistance. This aspect will be further discussed in section 6.3.2.

$$h_{ekv} = \frac{A}{B}$$

$$A = Net\ cross\ sectional\ area\ of\ the\ element$$

$$B = Element\ width$$

$$A = \ (1200\ x\ 265) - \left(5\ x\ \left(\pi\ x\ \frac{185^2}{2}\right)\right)$$

$$A = 183598{,}74$$

$$B = 1200mm$$

$$h_{ekv} = 152{,}99\ \cong 153\ mm$$

6 Produced guidelines

This section introduces a set of guidelines developed for assessing and facilitating the reuse of HCSs in existing structures. While existing standards such as ISO 20887 provide comprehensive methods for the disassembly of new buildings, they fall short when applied to structures not originally designed with disassembly in mind. Similarly, NS 3682 provides a comprehensive framework for the testing of reusable HCSs, but it does not address several crucial aspects that are vital for the practical implementation of reuse in existing buildings. NS 3682 focuses mainly on the post-disassembly testing, leaving a gap in the guidelines for earlier stages of the reuse process.

This section aims to bridge this gap by providing a set of tailored guidelines that adapt the principles of ISO 20887 and NS 3682 to the specific context of existing buildings. These guidelines are designed to assess the feasibility of disassembly and reuse of structural elements, ensuring that such activities are both practical and sustainable. The following guidelines will be introduced:

1. **Pre-Disassembly Evaluation:**
   This section addresses these gaps by introducing a pre-disassembly evaluation guideline that anticipates potential challenges in the reuse of HCSs. This guideline ensures a thorough assessment of the structural integrity and suitability for disassembly before any physical intervention takes place. It will thereby streamline the entire reuse process and ensure that only eligible elements reach the testing phase.

2. **Disassembly Guidelines:**
   The disassembly guideline formulated in this thesis offer a detailed and systematic approach for safely dismantling existing structures in a way that preserves the integrity of the HCSs. This enhancement is particularly crucial as NS 3682 provides only vague details on the actual disassembly process. The disassembly guideline was crafted with a vision to fill this critical information gap, ensuring a clear and actionable process.

3. **Testing Guideline:**
   The testing guideline serves as a condensed and focused version of NS 3682. It focuses on the most critical testing points necessary for evaluating the reuse of potential HCSs. This approach will not only simplify the testing process, but it will also make it more accessible and practical for implementation. Summarizing NS 3682 into a more applicable model will make it fit seamlessly into the developed flowchart.

4. **Documentation Guideline:** The documentation guideline provides a more comprehensive outline of the required documentation for reusable HCSs, offering greater detail than NS 3682. This guideline addresses the documentation deficiencies identified in the case studies discussed earlier.

These guidelines will be integrated into a single flowchart presented in Figure 40. It covers the entire process from initial assessment through to the final testing in one cohesive framework, thereby enhancing usability and efficiency. This flowchart combines the key points from the guidelines, offering a visual reference that aids in the practical application of reusing HCSs. The flowchart will essentially be a tool that ensures that users can quickly grasp essential processes and refer to detailed points in the guidelines for further information.

6.1 Pre-disassembly evaluation (feasibility of reuse project)

As the experiences mentioned from the case studies for KA13 and OSBL in section 4.1 state, the lack of knowledge in the reuse of HCS resulted in making the disassembly and testing of the elements a quite expensive process. Point 5.3.1 in ISO 20887 mentions several key principles that need to be assessed before planning the actual execution of the disassembly process. By satisfying these principles the firm can ensure both a safe and possibly cost-effective disassembly process. 6 steps will be introduced and discussed in detail for the first process in the reuse case called the pre-disassembly evaluation. In addition to explaining the key areas to consider during the pre-disassembly evaluation, a chart has been made to summarize the key steps and the most important parts in each of them in Figure 33.

6.1.1 Access to elements

The first critical step in the evaluation is assessing the access to elements. This stage involves an examination of how the components and systems within the building are installed. This examination is critical to evaluate the disassembly and reuse possibilities. A systematic approach is recommended to ensure efficiency and thoroughness in the assessment. This step can be structured in the following way:

- **Initial assessment of building blueprints and documentation:** A thorough review of the building's blueprints, construction documents, and maintenance records is required. By organizing these documents in chronological order, a timeline of the building´s evolution and interventions can be seen. This is necessary to identify the locations of all major systems and components, including structural connections, utility runs, and service modules. Understanding the placement of these elements and their integration into the construction system is essential for assessing the feasibility of disassembly.

- **Visual inspection and access mapping:** The visual inspection and access mapping will serve as the bridge between the documentation and the building´s present reality. The inspection route should be planned to cover all areas of the building. Signs of wear and tear, damage, and altered or replaced components (differing from the documents) should be noted. Findings of hazardous materials must especially be taken seriously as the discovery of such materials might necessitate the involvement of specialists and potential legal and health considerations.

  The information gathered during the visual inspection must be utilized to develop an "access map". All access points that will be utilized during the disassembly process must be noted on this map, as it will serve as a guide. Obstructions or modifications should be noted precisely, this could be for example a wall that has been added which could cover an accessible duct system. Cases like these should be noted and marked on the access map so potential removal strategies can be further discussed before the actual disassembly begins. Additionally, the condition of materials should also be considered. If there are any signs of material failure or compromise, they must be noted. This will be important as these components will most likely indicate areas which require special attention during disassembly.

6.1.2 Independence

ISO 20887 defines independence as: “(…) the quality that allows parts, components, modules and systems to be removed or upgraded without affecting the performance of connected or adjacent systems.” [54]

Focusing on the independence of components is a crucial part of the pre-disassembly evaluation for several reasons, such as enhanced reusability, cost efficiency and minimized structural impact. Integrating these points into the pre-disassembly evaluation will help firms establish a clear plan which will align with the sustainability and circular economy goals.

Using independent components in construction facilitates easier disassembly, thereby extending their lifecycle and minimizing damage risk. This approach also offers significant cost advantages, as it requires less labour and simpler machinery, reducing the overall disassembly costs. Such savings are crucial in projects involving selective remanufacturing or refurbishment of building elements. Moreover, the use of independent components lessens the impact on the structural integrity of the building during disassembly, ensuring that removing components does not compromise the entire structure. This makes the process economically and structurally more feasible.

When focusing on the disassembly of HCS the following points should be focused on closely in the pre-disassembly evaluation:

- **Structural connectivity:** During the inspection, the joints between HCS and its connection to the building frame should be investigated. This is to check if the connections can be easily cut for disassembly or if additional tools and labour would be needed to cut these connections. The most typical joints/connections are grouted. The HCSs are most often connected to the beam using connection rods in the voids which are connected to the anchorage in the beam, steel plates and angles could also be used. Connections for the disassembled HCSs are discussed further in section 9.2. Additionally, the points where loads are transferred from the HCS to other structural elements should be identified. The identification of these load transfer points will be crucial to determine the ease of disassembly. The disassembly process will depend on how these load transfers can be “reversed” without the comptonization of the structure’s stability.

- **Material bonds:** Three key areas must be investigated in the realm of material bonds or adhesions, grout and sealants, and corrosion. The visual inspection mentioned above will give relevant information on the adhesives used to bond the HCS to other elements. These adhesives could complicate disassembly, as they are typically permanent. Secondly, the use of grout or sealants in the joints between the slabs must be evaluated. The grout/sealant must be cut/removed to free the HCS for disassembly. Lastly, in some connection cases, corrosion may occur, which must be checked, as it could affect the integrity and ease of disassembly.

- **Component layering:** In some construction cases, the HCSs may be integrated with other building systems such as electrical, plumbing, or HVAC. It's important to review the HCSs chosen for disassembly to determine if these systems are not integrated into them, as this could hinder the disassembly process. Ideally, these systems should operate independently of the slabs. Additionally, surface treatments applied to HCSs, such as finishes and floor toppings, should be inspected. These treatments add complexity to the disassembly process and require special consideration to ensure an efficient disassembly.

6.1.3 Treatments and finishes

Point 5.3.4 in ISO 20887 discusses the importance of limiting the use of finishes especially with hazardous materials on elements. The types of treatments and finishes applied to components such as HCSs will dictate the ease of disassembly later for these components. Some examples are sealants and waterproofing membranes, they are typically used to protect materials from moisture and environmental damage which will extend the life of the components. They can also get into the porous surface of concrete to create strong bonds. Additionally, adhesives are often used to attach finishes and materials to the slabs. This can be particularly challenging to remove as they often work as a permanent bond. Lastly, finishes that add to the aesthetic and functional quality of a building such as paint, plaster, or cladding materials could also make the disassembly process more laborious.

The removability of treatments and finishes should be a key consideration before disassembly. It's important to consider that certain treatments and finishes can create strong chemical and physical bonds, which may pose obstacles during disassembly. Additional steps might be necessary in the disassembly process, such as applying heat or solvents to weaken these bonds. This additional work could be time-consuming, resulting in additional costs, and it also has the potential to be harmful to both the components and labourers.

Ideally, finishes that can be easily stripped or peeled away, such as certain types of paints and detachable cladding, are preferred. Chemical removal processes can be problematic, as they may leave harmful residues and damage the component surface, compromising the structural integrity and aesthetic quality of the component. Moreover, traces of the finishes left by the chemical removal process may hinder the reuse of the elements in a new building project.

If treatments and finishes are not removed, ensuring their compatibility with the new application of the reusable HCS should be a top priority. If removal is not feasible, the finishes would need to be maintained in good condition throughout their lifecycle and disassembly process or be easy to refurbish to meet the standards required for the new use case. Additionally, these finishes (if not removed) should be aesthetically pleasing, or measures should be taken to refresh or repaint them.

6.1.4 Standardisation

The next point in the pre-disassembly evaluation is standardization. There are four main aspects associated with uniformity in components, these are dimensions, components, connections, and modularity (explained in detail in point 5.3.7 in ISO 20887). The benefits of focusing on standardization in the chosen HCSs have multiple benefits which will be mentioned below, but firstly the main three checks needed in the standardization step will be explained:

- **Component uniformity:** The first step involves a detailed assessment of the component uniformity. This evaluation includes verifying that elements (panels, beams, slabs etc.) are manufactured to standard dimensions and tolerances. The uniformity check should not just be limited to size, but form and functionality should also be included. Consistency in the component profiles gives valuable benefits which will be discussed in detail below. The evaluation must document the type and dimensions of all components relevant for reuse, and it should be cross-referenced with industry standards to determine uniformity. The cross-reference will aid in determining if the chosen components can be reused in other constructions or if additional customization will be needed, such additional work can be costly and time-consuming.

- **Connection methods:** The next step involves evaluating the methods of connection between the components of the building. It is important to document the types of connections used and ensure that they are standardized throughout the building. Additionally, the connections must be checked for reversibility. The evaluation should document each type of connection, identify the necessary tools and procedures for disassembly, and evaluate the likelihood of damage to the component during the process. The goal of this step is to ensure that the connections do not damage the separation of the reusable components. If non-standard connections are found, specific protocols should be developed to address the unique tools and methods needed for disassembly.

- **Material consistency:** The last step is assessing the material consistency of the elements chosen for reuse. Ideally, the building should only employ a limited variety of materials and these materials should possess uniform characteristics. The evaluation must document material properties such as strength, bonding, and reactions to different loads and stresses as this is essential to predict the behaviour of the components during disassembly. Components with differentiating materials will have inconsistent properties which may require varied disassembly methods, thus complicating the process. In addition to cataloguing all the materials used, the evaluation must also note any treatments and finishes done on the components as this could affect the disassembly process.

The standardization of building components is instrumental in achieving an efficient disassembly process as it improves efficiency, safety, cost-effectiveness, and environmental responsibility. Choosing HCSs which have the same design and features brings a multitude of benefits to the disassembly workflow, the key benefits are as follows:

- **Efficient workflow:** Using standardized components for disassembly helps to create an organized workflow, like a reverse assembly line. This approach establishes a predictable series of steps for disassembly, saving time by minimizing the need for distinct methods to disassemble each component, thus streamlining the process. A standardized workflow also decreases the margin of error, as the process is familiar and well-rehearsed by the workers. Furthermore, standardized sizes will give the added benefit of making transportation to the factory simpler as the method for lifting and stacking will be similar for each component.

- **Tool and equipment optimization:** Focusing on standardized components proves its worth in the topic of choosing tools and equipment as well. The variety of tools needed for the disassembly process is reduced when the components are uniform. This will not only lower the inventory costs but also boost efficiency as the workers have more knowledge of the tools being used, thus speeding up the process. This will result in cost savings as the procurement and maintenance of specialized tools is reduced, thus making it less resource intensive.

- **Worker training and safety:** The focus on standardized components for disassembly will improve worker training and safety. By using standardized components, the need for different disassembly methods for each component will be reduced. This simplifies the training for workers and minimizes the required skills. Standardization will also create a consistent safety protocol, ensuring uniform and strict safety measures to minimize workplace accidents. Concentrating on a core set of disassembly skills will enhance worker competency, job satisfaction, and overall efficiency.
- **Predictable outcomes:** Choosing standardized elements leads to more reliable outcomes. Accurate cost estimations will allow for better financial planning and predictable timeframes for firms.

6.1.5 Economic appraisal

Performing an economic appraisal will serve as a critical step in the pre-disassembly evaluation, especially for the firm and the stakeholders of the reuse project. It will serve as a “final judgment” on the feasibility of the project and the disassembly process. The steps described below will help with the appraisal to determine whether the benefits outweigh the costs and if the project is economically viable. The economic perspective of reusability in the construction sector is further discussed in detail in section 9.4, this part focuses on the pre-disassembly evaluation. The steps that should be included are:

1. **Cost estimation:** All direct and indirect expenses of the disassembly process must be accounted for to estimate the costs. The main expenditures relevant here are:

    a. Direct Labour cost: The number of workers needed, estimated time of disassembly and wage rates must be considered when calculating the labour costs.

    b. Equipment costs: It is necessary to consider the purchase or rental price of the required equipment. The cost analysis should also encompass the depreciation and potential resale value of the equipment if it is purchased. If there are additional relevant use cases for the equipment, purchasing it may be more economically advantageous than renting. However, if there are no further use cases, the decision should be based on estimating depreciation and resale value to determine the most financially beneficial option for the company.

    c. Transportation costs: The cost of transporting disassembled elements needs to be estimated, whether it's to a storage facility or a new construction site. If the storage and construction sites are far apart, transportation costs could increase significantly due to factors such as fuel costs, vehicle wear and tear, labour costs for drivers, and potential tolls and fees. A detailed analysis of transportation costs could reveal the need for a temporary storage facility closer to the new construction site. However, the feasibility of this option should be considered based on the cost of leasing land, site preparation, security measures, and the cost of moving.

    d. Storage Costs: The cost of storage space and duration should be estimated. If a temporary storage site as mentioned above is established the additional costs associated with this must also be estimated.

    e. Worker safety and insurance: The cost estimation must also factor in the cost of safety equipment, insurance premiums for workers, and the liability coverage of the project.

2. **Revenue forecasting:** This step demands thorough market research to accurately determine the demand and pricing for the reusable components. An assessment of the current market rates of reusable components must be done, this will require a deep dive into the pricing structures and market valuations of similar construction projects and components. In addition to analysing the current rates, the broader market of reusable elements must be analysed. This may vary due to factors such as overall economic conditions, emerging trends in sustainable construction and the latest technological innovation in the construction sector. The accuracy of pricing and demand forecasts can be further refined in accuracy by comparing them with historical sales data of similar components. Using the collected insights, a comprehensive revenue forecast can be created. This revenue forecast will provide an expected revenue figure, this will be crucial as it forms the backbone of the Cost-Benefit-Analysis.

3. **Cost-Benefit Analysis (CBA):** The CBA is a comprehensive evaluation that compares the estimated costs against anticipated revenues and potential savings. This will provide a robust framework for decision-making as it allows the project stakeholders to ascertain whether the economic benefits outweigh the costs.

    a. Avoided Costs: The financial savings from not having to purchase new materials, the number of hours and wage payments saved on the production of elements, due to the reusable elements must be calculated. The valuation of the avoided costs requires both a detailed understanding of the market prices and demand for new elements and reusable elements. It also requires an assessment of the quality and quantity of the disassembled elements to meet the needs of subsequent projects.

    b. Environmental Incentives: Tax benefits, grants, or subsidies must also be accounted for as they could have a financial impact on the project. This requires a detailed investigation of identifying and quantifying any local, regional, and national environmental policies that support sustainable construction.

4. **Net Present Value (NPV) calculation** [66]**:** This financial tool will be used to evaluate the profitability and financial feasibility of projects; this also includes the disassembly and reuse process of components. The key aspect of this calculation is its ability to consider the time value of money. This concept acknowledges that money used today holds greater value than if used in the future due to its potential earning capacity. This principle is especially crucial in reuse cases, where costs and revenues are spread over time. Consequently, it allows for a comparison of immediate expenses with future benefits.

   The process of deriving the NPV includes identifying cash inflows and outflows expected to be realized over the life of a project. Some probable cash inflows include the sale of reused elements/materials and savings due to avoided purchases. Probable cash outflows may involve the initial disassembly costs and ongoing expenses. All the chosen cash flows should be discounted to present value with the help of a chosen discount rate. This discount rate will be used as a benchmark for evaluating the project's return.

   The NPV calculation will provide a singular figure by summing the present values of all future cash flows. It will represent the project’s overall value, adjusted for the time value of money. A positive NPV indicates that the disassembly project is financially viable and is likely to generate a net gain over its duration. Conversely, a negative NPV suggests that the project´s costs outweigh its benefits when viewed from a present value perspective. This signals a potential financial unfeasibility. “C_0” is the initial investment, “C_i” is the cash flow, “r” is the discount rate, and “T” is the time.

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{C_i}{(1+r)^T}$$

5. **Internal Rate of Return (IRR)** [67]**:** IRR is the discount rate that makes the NPV of all cash flows from the project equal to zero. The IRR is the break-even interest rate at which the present value of expected cash inflows equals the outlays on investments. The calculation consists of an iterative process where the exact discount rate to cut the NPV to zero over the project´s timeline is ascertained. This rate represents the possible average annual return for the project over its lifecycle. A project should be viewed as financially viable if its IRR exceeds the cost of capital to the project. An IRR greater than the project´s cost of capital would represent an IRR at which the project can at least recover its investment and operating costs. However, the IRR should not be looked at alone, it is something to be looked at together with other financial metrics. The IRR will be a valuable tool to optimize resource allocation for sustainable profitability.

6. **Payback period:** This metric will calculate the time when 100% of the initial investment made in a project is completely recovered from cash inflows which the project yields. This measure will give the stakeholders an intuitive clarity to the liquidity aspect of the investment. A shorter payback period is ideal as this generally means the investments return earlier. A shorter payback period reduces the different exposed project risks for the invested capital, in shorter terms it helps with addressing the project´s short-term financial resilience. The payback period should consider the timing and magnitude of expenses such as labour, equipment, and transport costs, and inflows from the sale, salvage, saving of costs etc.

7. **Risk assessment:** The risk assessment is an important part of the economic appraisal in addition to cost and profitability calculation. Its focus is to identify, quantify and plan for the various potential financial uncertainties related to the project. Some examples include the price risk in volatility of the salvaged material market, and sudden expenses due to project complications and delays. This will be a helpful tool to assess the impact on the financials of the project. A robust contingency plan should be made based on the risk assessment. This could be done by setting up a risk mitigation fund to cushion against any unforeseen challenges. Another possibility is to use the risk assessment to program the project timeline and workflow in such a flexible manner that despite unforeseen challenges the project won't get derailed.

8. **Sensitivity analysis:** The sensitivity analysis will supplement the financial model by experimenting with the robustness of the financial project outcomes against variations in critical assumptions. This can be done by targeting some critical variables such as labour costs, the resale value of disassembled components, or the project´s timeline. It can further test the robustness by impacting the project´s NPV, IRR, or payback period. The sensitivity analysis will show the stakeholders the most critical variables to which the project's success is sensitive. Potential weak points of the financial plan can be identified and information on the range of possible results due to variations in scenarios can be attained. This will help decision-makers make informed judgements on which focus areas to prioritize in risk management and strategic planning.

6.1.6 Environmental impact

Including an environmental impact assessment into the pre-disassembly evaluation offers several benefits and will serve as a critical component to evaluate the sustainability of reusing building materials in a project. By conducting an environmental assessment, firms can analyse and quantify the environmental benefits and drawbacks associated with the disassembly and reuse process, this will facilitate more informed decision-making. Incorporating this point in the evaluation will promote a more inclusive process allowing for a more transparent evaluation framework, fostering public concerns. Producing an environmental impact assessment will underscore the firm's commitment to reducing the environmental impact associated with construction projects. This evaluation consists of 2 key points:

1) **Environmental impact and savings assessment:**
    a) GWP: This evaluation will measure the potential reductions in greenhouse gas emissions achieved by bypassing the need to manufacture new elements. The GWP-evaluation should assess the emissions associated with the product from cradle to grave, in other words from raw material extraction to demolition. These values should be compared against the estimated emissions associated with disassembly and reuse. A lifecycle comparison will give a clear picture on the environmental benefits with the project, which can be used as a selling point for the project.

    b) Energy and resource conservation: This assessment considers the potential energy savings and resource conservation achievable in the reuse project compared to producing new structural elements. Key areas to consider are energy and water usage, and the impact of non-renewable resources.

    c) Toxicity: Identify potential toxic emissions that could be avoided by not processing new materials. This evaluation should especially focus on human health such as direct effects on respiration, and indirect effects such as the long-term impact on water quality or soil contamination. The accumulated data should be used to find the number of toxic emissions that can be reduced by reuse.

2) **Material and waste management**
    a) Quantify the waste generation: An estimation of the waste generated from demolition should be calculated. This includes all materials that would end up in landfills or require processing in waste management facilities.
    b) Reduction of waste from reuse: Following the waste generation calculation for demolition, the firm should calculate the potential reduction in waste through the planned reusability strategies. This calculation should consider how much material can be diverted from waste streams by reusing.

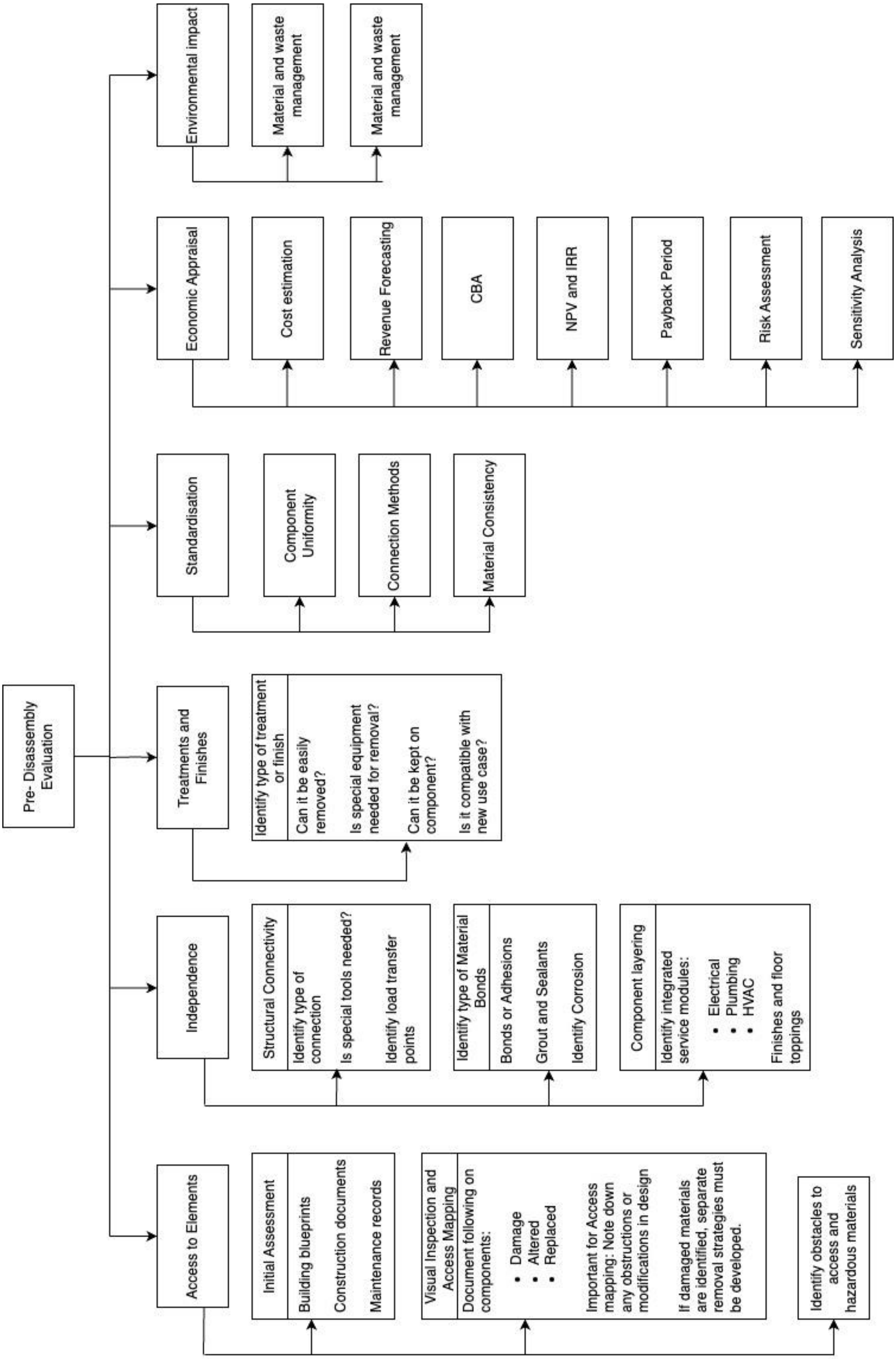


Figure 33- Pre-disassembly evaluation chart

6.2 Disassembly

Disassembly is the building procedure but in the opposite direction. To optimize resource efficiency, the focus should be to dismantle the elements without damage to ensure future use. When seeking to prioritize sustainability, the disassembly process proves to be a more favourable option compared to demolition. However, there remains a notable obstacle to its continued implementation as mentioned in the cases from section 4.1. This process requires careful planning, appropriate equipment, and precise execution. It is worth noting that the procedure should be considered for each building project, as there cannot be a one-size-fits-all approach to strategies for sustainable construction. Assuming that the criteria mentioned in section 6.1 are satisfied the next step in the project planning can be started.

6.2.1 Planning before executing

The planning phase is a critical stage in the process of dismantling the HCS. Thorough planning will ensure that the operation is conducted safely, efficiently, and with minimal environmental impact. Firms must survey the building and focus on the specific areas where HCSs are to be dismantled. Assessing the structural integrity of the building, understanding the layout, and identifying potential hazards are important parts of the planning phase. Relevant documents for the project must be obtained by the firm per points 5.1 and 5.2 in the NS 3682. This information can provide valuable insights into the dimensions, weights, and installation details of the slabs, as well as the connections and supports used.

It is necessary to determine the appropriate type and specifications for equipment such as cranes, lifting gear, cutting tools, safety gear, and shores (for the stability of the construction) based on assessments and document reviews. When cutting the elements, it is recommended to cut the elements straight rather than diagonally. The straight cut proves to be better for reducing the damage probability during the process. The HCS should be lifted according to section 5.3 of the NS.

To ensure an efficient disassembly process, the strategy should mirror the initial disassembly. The disassembly process should mirror the component level at which the structure was assembled. This approach focuses on disassembling individual components rather than larger sections, which not only facilitates handling and transport due to reduced weight and size but also minimizes the need for specialized heavy lifting equipment. Effective planning for the sequential dismantling of components like HCSs are crucial. This involves understanding the structure’s design, component interdependencies, and load distributions to establish a logical and safe removal sequence. It’s essential to prioritize the removal of slabs that least affect the structural integrity, progressively moving towards more critical ones, with the implementation of temporary supports to maintain stability throughout. Before removing each slab, assessing the need for temporary shoring or additional supports is imperative to manage the loads and prevent structural deformations or collapses during disassembly.

Keep complete documentation of the disassembly sequence. Documentation such as structural analyses, the removal order of the slabs, and any modifications applied during the dismantling process should be kept. This detailed record-keeping is crucial for adhering to safety regulations and facilitating the planning of future disassembly projects. Additionally, it's important to accurately document the identification details of HCS assigned for reuse. This should involve the categorization of each slab according to a unique identification system, as outlined in section 5.2 of the NS standards, ensuring that these components can be easily traced and correctly integrated into subsequent construction projects.

The proper lifting equipment needed for the reusable HCS should also be noted in the plan. The upper cast-on layer on the HCS makes it unfeasible to reuse the existing lifting hooks, therefore alternative strategies must be considered. Options like hoist chains, cables, straps and lifting clamps can be used for secure lifting. Figure 34 and Figure 35 illustrates how the HCS will be connected to the clamps. Securing and lifting of the element should be done by point 5.3 in the NS.

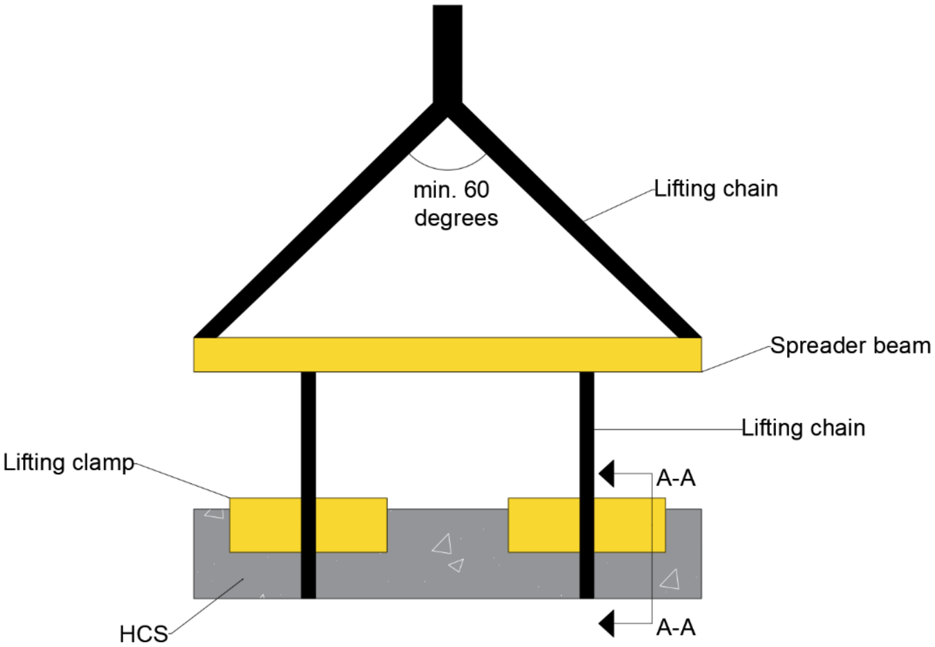


Figure 34- HCS connected to lift side view

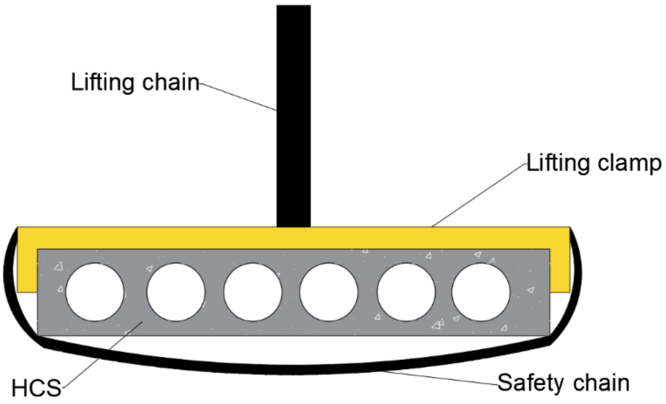


Figure 35- Section A-A, HCS connected to lift, front view

6.2.2 Crane placements

Three factors need to be prioritized when considering the placement and choosing of the cranes used in the disassembly phase of SVB. These three factors are crane capacity and reach, and disassembly sequence. Placing the cranes strategically is crucial for a seamless execution of the disassembly phase. This section discusses important points worth considering in the pre-planning phase. Thorough planning is important to ensure safety, efficiency, and the preservation of structural integrity. The proposed crane placement shown Figure 36 has been made considering the points noted below. Only the weights of the HCSs have been considered for the choice of which crane to use. The crane placements were made using data given by Nordic Crane for the mobile crane Demag AC 200-1 [68].

Crane capacity

Before choosing a crane, it is essential to map out all the weights of the various components considered for disassembly. The walls will have to be disassembled to make the HCSs easily accessible for disassembly. The chosen crane must be able to lift the heaviest elements safely. A safety margin must be considered when choosing a crane. The safety margin should be above the heaviest load, this will account for any unplanned circumstances of error in the weight calculation. The risk of failure will reduce with the safety margin due to the increased ability to handle the weight without being overstressed.

Crane reach

The positioning of the crane must be in a way so that the boom can reach all the components considered for disassembly. The maximum radius for each of the cranes with the corresponding maximum weight has been given Figure 36 (yellow coloured text and lines). The maximum radius needs to be calculated to ensure proper placement of the crane, the layout of the site and the location of the elements within the building must also be considered. The radius for crane 1 at 30 m does also overlap the outer area of the lower floors, this can be seen by the radius line (in yellow) for crane 1. In addition to the horizontal height, the vertical height must also be considered. The crane of choice must be able to be tall enough to lift the elements over any obstacles or existing structures.

Disassembly sequence

The crane must be placed strategically to minimize the need for repositioning. Placing the crane at an ideal position gives it the possibility to maximize the number of elements disassembled without the need for repositioning. This will save both time and resources. Figure 36 does also show the disassembly of SVB divided into zones, zone 1 in pink, and zone 2 in blue respectively. By dividing the project into zones one can allow for a more organized disassembly process.

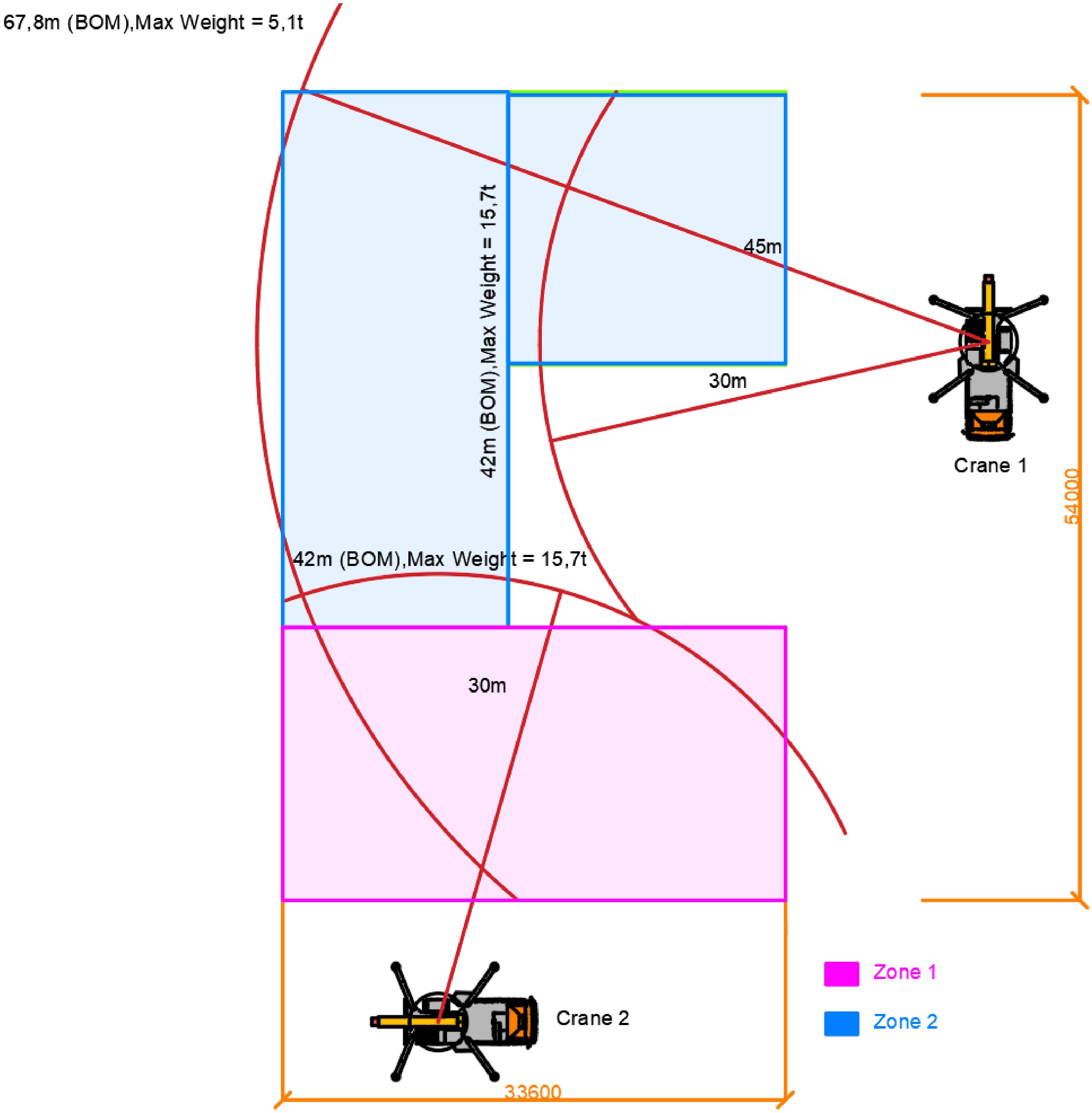


Figure 36- Proposal for crane placement

6.3 Testing

Once the HCS are dismantled/disassembled proper tests need to be conducted. According to section 6 in NS 3682, specific tests are mandated for reusable HCSs to ascertain their integrity and functionality. ULS and SLS standards must be assessed for the elements with respect to their geographical limits. This guideline proposes a more performance-based testing system. Evaluating the second lifespan of the HCSs will require a more detailed testing procedure. This guideline will include both the requirements from NS 3682 and practical experiences for the HCSs. This guideline will cover three aspects as shown in Figure 37. The key points from each category have been highlighted in Figure 38.

To deem a HCS reusable and viable for its second lifecycle, it is essential that its technical lifespan- the period during which it can maintain structural integrity and functionality- exceeds both its functional and aesthetical lifespans. Prioritizing the technical lifespan ensures that the HCS remains safe and structurally sound, preventing potential failures that could lead to safety hazards.

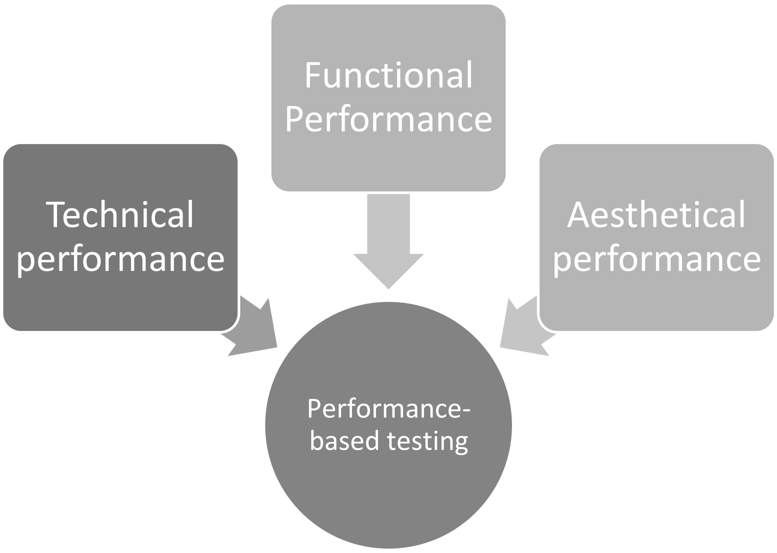


Figure 37- Testing categories of reusable HCS

6.3.1 Technical performance

The technical performance focuses on the engineering and structural aspects of construction elements. It evaluates whether the structural components meet the specified standards necessary for safety and stability. This evaluation will be a key factor when deciding if the HCS are compatible for the reuse case. The following tests must be done to evaluate the technical performance:

1. Chemical degradation

The chemical aspect of the technical performance encompasses three key areas. These are carbonation, chloride penetration and alkali reactivity. NS 3682 gives the requirements for the maximum allowable amount of chemical degradation in points. 6.3.3-6.3.6. Additional details regarding the chloride level are given in NS-EN 14629, and details regarding the carbonation depth are given in NS-EN 14630.

2. Load-bearing capacity tests

Relevant tests must be conducted according to points 6.4.1-6.4.4 in the NS 3682. The load-bearing capacity tests should involve gradually applying the relevant loads to the slab until it reaches its design load (ULS and SLS should be checked) or until failure. If loaded until failure, the test must comply with point 6.4.4 in NS 3682. The results should be compared with the original design specifications, and it should be checked if it complies with NS-EN 1992-1-1 or for simplified calculations NS-EN 1168.

3. Deflection

The deflection check must satisfy the requirements for the desired second lifespan. The HCS will not be serviceable if it does not satisfy the deflection limit. The calculations must be done according to NS-EN-1992-1-1.

6.3.2 Functional performance

The floor system from the donor structure must meet the requirements set for the reuse case. The functional performance assesses how well the building performs its intended functions. This part of the guideline ensures that the building meets all operational requirements. Key factors to consider for the functional performance:

Compatibility assessment

The compatibility of the elements must also be assessed. This implies checking if the dismantled HCS can be integrated into the new structural system. The slab´s fit should be evaluated within the overall design. This includes load distribution, support conditions, and the ability to connect with new structural elements. The compatibility of existing connection details in the HCS should also be analysed here. It should be considered if special connectors or adjustments are necessary to secure the slabs to the new structure. Changes done to the dismantled HCS must be documented by point 5.4 in NS 3682. When reusing HCS, the future flexibility and adaptability of the structure should also be studied. This entails assessing how easily the HCS can be removed, modified, or replaced following the building´s use or requirement changes over time.

Fire resistance

Following point 6.4.5 in NS 3682, the fire resistance ability must be chosen according to NS-EN 1168:2005+A3:2011. The HCS must also satisfy the requirements sat by TEK 17 in section 11.

Sound insulation

The HCSs must be designed with sufficient sound insulation for the reuse case. It must satisfy section 13.6 from TEK 17 and NS 8175:2012. This point is especially important in reuse cases where the functionality of the donor structure differs from the new use case.

6.3.3 Aesthetical performance

Before testing the strength of the HCS a visual control must be assessed (point 6.3.2). A visual control involves a detailed examination process to identify any defects or issues that might compromise the structural integrity or suitability for reuse. The visual control will provide a foundational understanding of the current condition of the HCS, this is crucial to assess the process for further detailed structural assessments or tests. The aesthetical performance evaluates the visual aspect of the construction. This includes the design appeal, quality of finishes, the choice of materials, and overall appearance. Two key factors to consider during the visual inspection are:

1. Damage

Assessing any damage to the HCS is an essential step when evaluating the reusability. The damage can range from minor issues, which might affect the aesthetic value, to major structural defects that could impact the slab’s integrity and safety. Additionally, spalling should also be examined. If concrete has chipped away it will expose the reinforcement bars which can lead to corrosion of reinforcements and deterioration of concrete strength over time. If any previous work was done on the HCS this must also be noted. The damage evaluation will help determine if any healing measures might be needed to restore both the function and appearance of the HCS.

2. Pre-tensioned wires

The condition of the pre-tensioned reinforcement must be assessed as their ability to bear loads and maintain structural integrity will be affected. Signs of corrosion or breakage must be examined. Following point 6.4.3 in NS 3682, the tension of the wires must be assessed through a visual inspection at both ends. The standard notes that the loss of tension can also be seen through abnormal deformation of the HCS. A new protective layer must also be applied to the exposed reinforcement.

3. Connections

The voids of the HCSs must be carefully assessed to ensure that they have not been compromised. Debris accumulation, internal damage, or structural deformation within the voids can affect both functionality and aesthetic appeal, particularly if the voids are used to house electrical wiring or plumbing in the new construction context. Furthermore, it is important to visually inspect the connections for damages as the ones mentioned above. If damages or any issues considering its structural integrity and reusability is found, appropriate repair and reinforcement strategies should be employed. This may include using concrete repair materials that are consistent with the original surface to maintain visual continuity. Additionally, applying finishes or coating can help conceal repairs and unify the appearance.

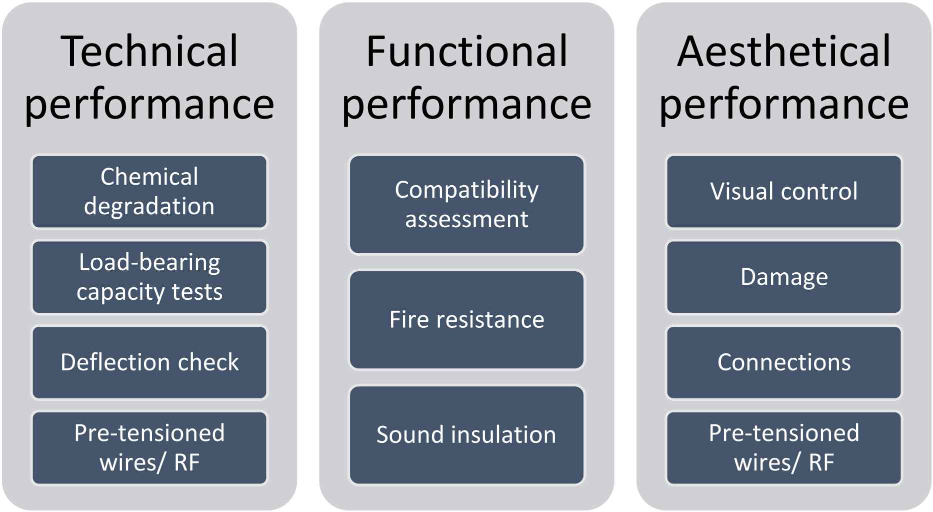


Figure 38- Key points for each category of testing guideline

6.4 Documentation of Assembly Ready HCS

Upon completion of testing, the HCSs must be documented properly. The case studies mentioned in section 4.1 states, the lack of proper documentation has been the biggest barrier for the increased efficiency of reuse. The following section provides a guideline on proper documentation of reusable HCSs. The guideline does also include the required documentation from NS 3682. Table 17 shows the minimum information needed for the documentation according to NS 3682.

According to NS 3682, point 7, reusable HCSs that meet the requirements of NS EN-1168 are deemed to have an equivalent or comparable CE-marked products as their CE-marked counterparts. NS-EN 1168 also mandates verification through a third-party body to ensure compliance with the set standards. DOK §12 requires that the third-party body carrying out tasks related to assessment and verification must be accredited. This is crucial as it guarantees the reliability of the organ. The assessment must be conducted with competence, impartiality, and independence.

In alignment with §11 of the Documentation Regulations for Construction Products (DOK), it is required that non-CE marked products, serving the same functions as their CE-marked counterparts, be thoroughly documented [69]. This documentation assesses whether the products meet the necessary standards for integration into construction projects. The responsibility for ensuring the essential characteristics of the products are well-documented lies with manufacturers, importers, and distributors. Documentation must be satisfactory and available before the marketing, sale, or utilization of these construction products at site.

Table 17- Required documentation of reusable HCSs, adapted from [70]

Characteristic	Unit
Dimensions of HCS	mm
Weight	Kg/m^2
Concrete compressive strength	Class
Characteristic moment capacity	kN/m
Exposure class	Class
Any hazardous substances to health or environment?	Yes/No
Fire resistance class	Class
Manufacturer	Name
Time of verification	Date
Control body	Name

The documentation requirements specified for non-CE marked products are not applicable to reused construction products. However, principles like those outlined in §14 of DOK are applicable. These principles state that if a construction product is legally sold in one European Economic Area (EEA) country, it must be accepted in Norway without the need for new testing or controls, provided that no significant differences in protection levels are evident.

The primary objective when crafting the documentation template shown in Figure 39 was to enhance the flow of information and establish a standardized method of documentation applicable to various actors across the value chain. While some of the data may primarily serve specific stages of the production or life cycle, the comprehensive collection of details ensures the availability of all necessary documentation for the element. The given template considers both NS 3682 and the material passport discussed by BAMB [71].

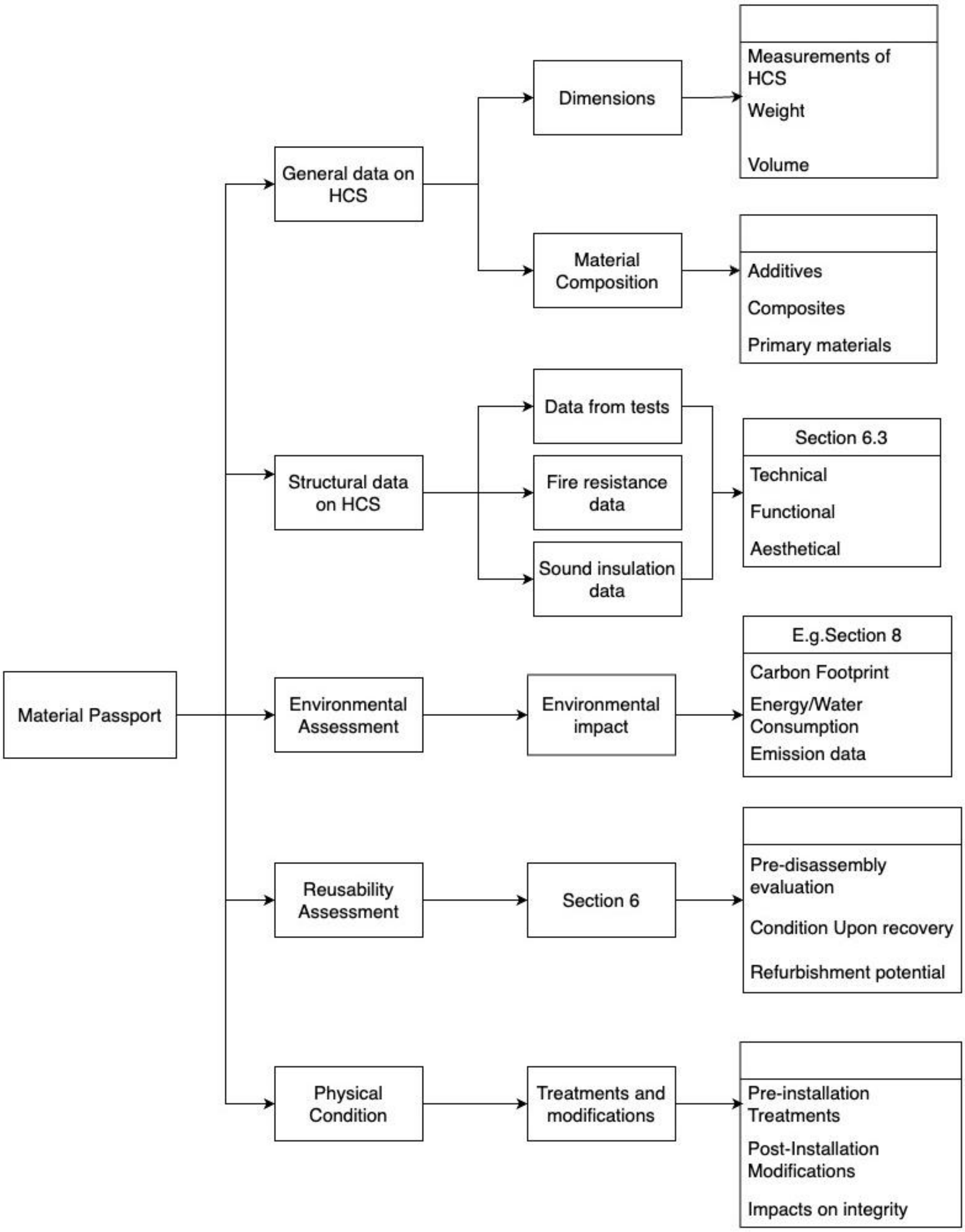


Figure 39- Ideal content for material passport

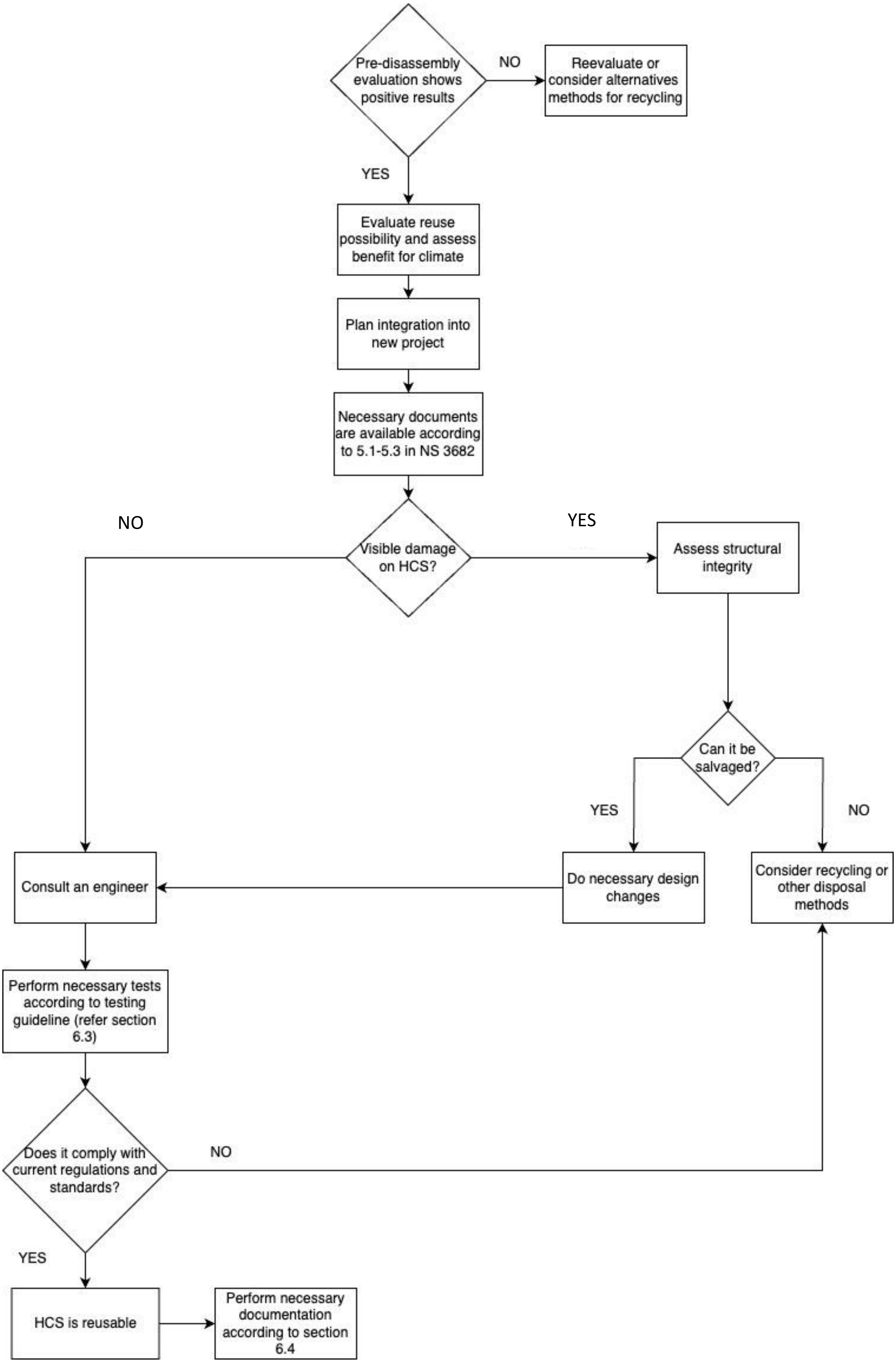


Figure 40- Flowchart summarizing guidelines

7 Connection possibilities in reuse case

When reusing HCSs one must also consider the connect. It is presumed that the disassembly and testing process has been completed according to the guidelines mentioned and the elements have been cut and fixed to the desired level, this also includes removing the topping. Various design concepts for the connections will be mentioned with their possible advantages and disadvantages focusing on the HCS for the reuse case. A principal sketch (meant for conceptual visualization) and a simple outline of the procedure will be presented of the concepts. It is worth noting that all alterations done to the HCSs must be documented as mentioned in section 6.2.1 and 6.3.

Durmisevic discusses the reversibility of connections made in a structure. Figure 41 shows the most normal types of connections used in a building project. The connections are ranked from reversible to irreversible. As the figure shows most of the current connection trends are irreversible. These connections make it problematic for further reuse as the disassembly process most likely will damage the components. Creative solutions must be developed, and the available voids must be used to their full potential.

As mentioned in section 5.2, some of the voids will be filled up with cement making them unavailable for usage. The similarity in appearance between the reusable HCSs and the newly produced allows for the same connection methods to be used. The methods mentioned below give an overview of the principles for the connection. The proven reliability through years of usage coupled with the familiarity of the connections, will allow for an easy re-assembly process. Three connections will be presented here: HCS to the wall, HCS to LB/RB- Beam and HCS to inverted Tee-beam.

7.1.1 HCS to wall

It's important to note that the lateral connections originally used must be installed during the production of the elements. It won't be possible to use the lateral connections that were originally used between the HCS and the wall due to the mortar poured over the connection in the first use case. As a result, alternative solutions for connections need to be considered. While the design concepts mentioned here are feasible, the disadvantage is that the HCS won't be reusable after the connection has been installed.

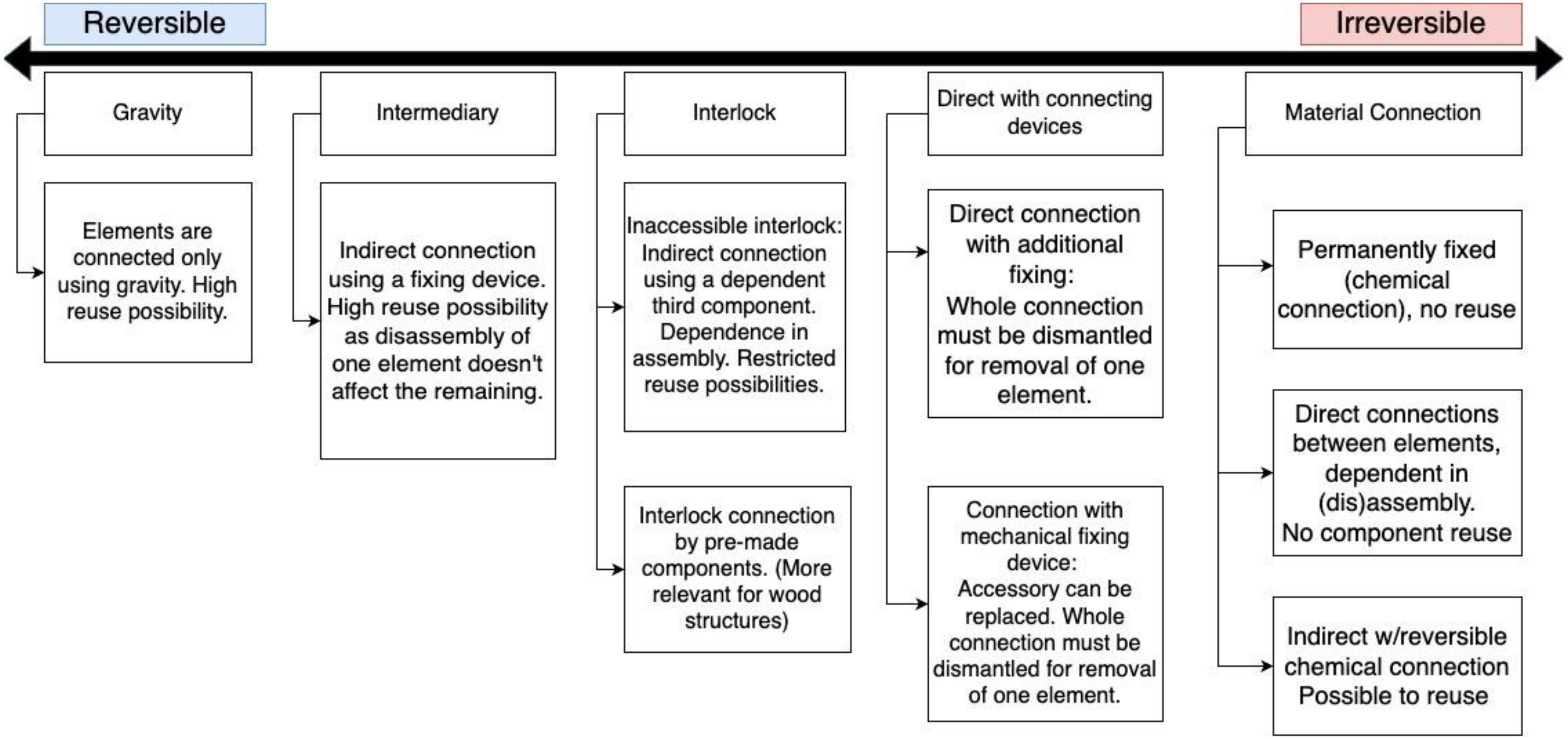


Figure 41- Connection type rankings, (adapted from Durmisevic)

7.1.1.1 Drilled bar through HCS

Photo must be fixed, iron rod

The connection model shown in Figure 42 shows a potential solution to the HCS-Wall connection. The idea consists of a bar drilled through each slab to the middle section of the bearing concrete wall. A bond beam has been placed on top of the bearing wall. Using the bond beam gives the advantage of having a given place to grout the bar.

Testing: what kind of relevant tests? Tests should be done with the HCSs at least one in the series to see if it gives sufficient strength.

Procedure:

The concept assumes the use of a new wall and bond beam, both of which should be strong enough to meet the required guidelines. The position of the bar should be determined in advance, while the HCS is still in the factory. When placing the HCSs near the wall, additional struts should be placed underneath them to ensure perfect alignment. It is essential to position the HCS precisely over the bond beam and the bearing pad. The bar should be drilled in the designated position. After the completion of drilling on both HCSs on each side of the wall, the connection must be grouted. Once the connection has fully cured, the next wall can be placed on top.

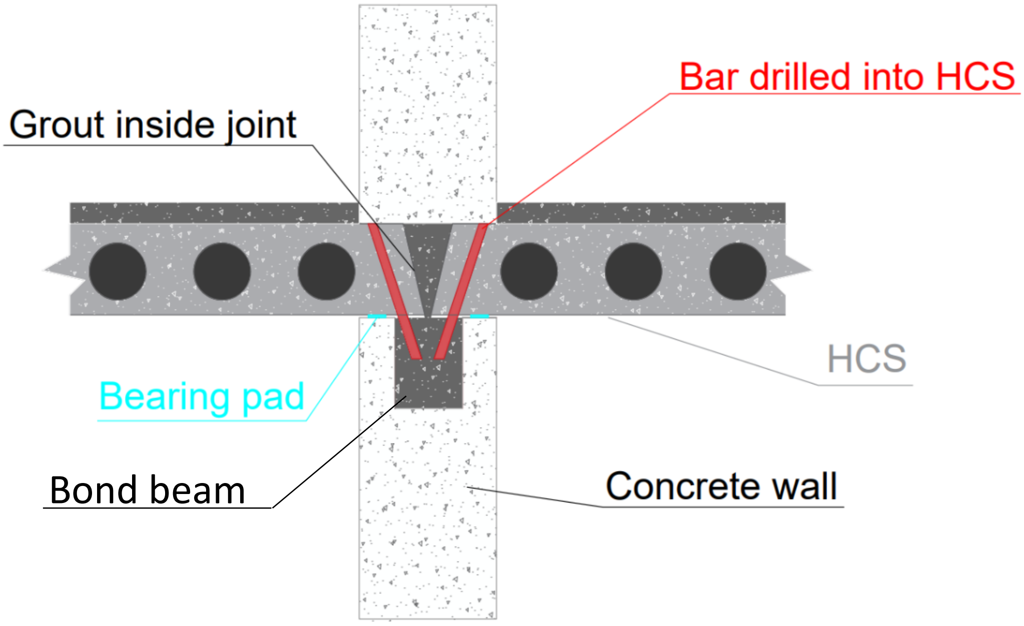


Figure 42- Illustration of HCS-Wall connection w/drilled bar

Advantages	**Disadvantages**
Practical solution	Not reusable /DfD friendly
Quick Assembly (only one alteration)	Requires additional tests
Increases design freedom	Potential increase in cost (due to tests)
	Might damage the sides of HCS

7.1.1.2 HCS to wall-- L-profile

Unlike the design mentioned above, this one uses the voids of the HCS for the connection. The design concept is based on the presumption that the wall is new. This presumption is made because the anchor must be placed when the element is cast. The L – shaped steel plate has been bolted to the wall as shown in Figure 43. The design also consists of using a connection bar which is attached longitudinally to a threaded coupler. The design concept can be seen as an interpretation of the LB-Beam-HCS connection (section 7.1.3). Unlike the LB-beam, the L-profile gives the added advantage of being placed on any given height. This gives the potential for additional architectural freedom. Some additional labour may ensue due to the need for dimensioning (thickness and positioning of holes) of the steel profile.

Procedure:

The upper part of the HCS needs to be broken and preferably two voids should be used for each slab, if possible. The end slot has a specific length for anchoring the connection bar, this should be included in the detail drawing. Once the upper section is broken, and the excess waste has been cleaned from the void, the targeted void should be sealed with a red plastic cup, as shown in Figure 43. This cup will ensure that the intended grouting length is followed and prevent it from filling the entire void. After making these changes, gently place the HCS on top of the bolted L-plate. Then, connect the threaded coupler to the anchor and the connection bar to the coupler. Finally, fill the gap with grout. The connection will be complete after the curing process is done.

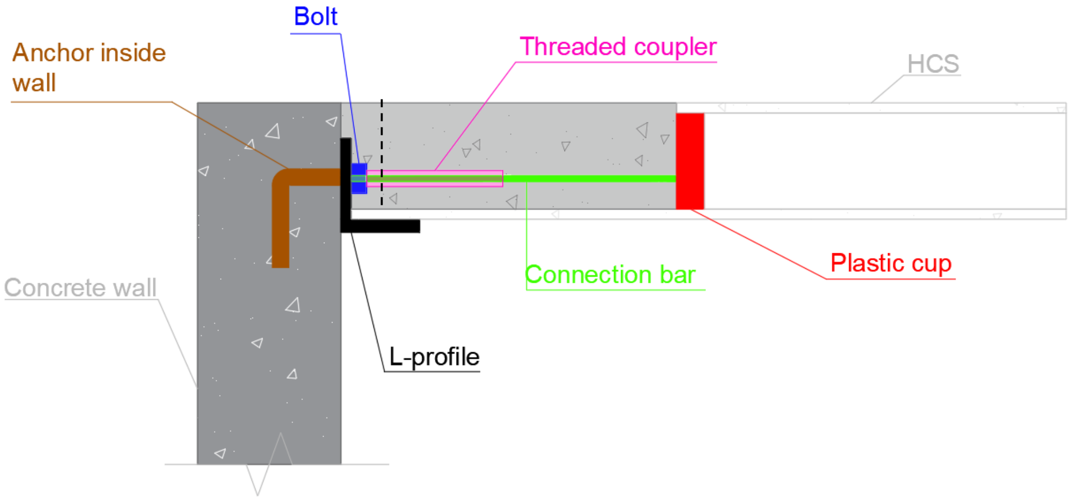


Figure 43- HCS to wall, L profile connection

Advantages	Disadvantages
Known design method	Requires potential new wall
Increases design freedom	Additional work required for steel profile
Coupling method and anchor = no need for welding	Need to reconsider floor plan (section 5.2.1)

7.1.2 HCS to Inverted Tee-Beam

The following section discusses the connection shown in Figure 44, which is between two HCSs (one on each side) and an inverted tee beam. This is a traditionally used connection principal which has also been used a lot for SVB. Bearing (preferably neoprene) has been used to ensure rotation for the slab without impacting the flanges of the beam.

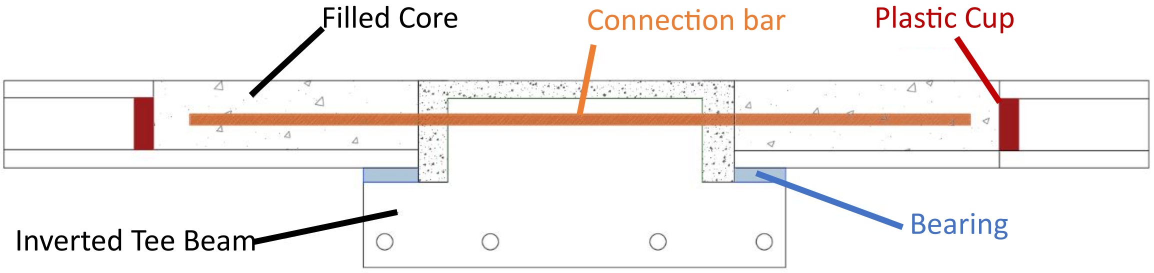


Figure 44- Connection HCS-Inverted Tee beam

Procedure:

To implement the floor plan for the reuse case, it will be necessary to break the upper portion of relevant cores/voids where the anchors are to be placed. Usually, two cores will be used for the connection per slab, but the need should be assessed based on the load case. The plastic cup is used to ensure that the poured grout only fills up the desired length achieved when breaking the upper portion. The bearing must be placed at the designated spots and the slab must be carefully positioned so it rests on the bearing, ensuring proper alignment. If a new beam is used, the connection bar will be inserted through the HCS and threaded through the beam. When the connection bar is properly placed, the cores containing the connection bars and the voids between the beam and the slab must be filled with grout. The connection will be solidified when the grout is fully cured.

Advantages	**Disadvantages**
Time efficient	Need for potential newly produced beams
Well known method	Not suitable for further reuse
No special equipment will be needed	Not suitable for DfD

7.1.3 HCS to L-shaped beam

Although not DfD friendly, the design concept shown in Figure 45 proves to be the most feasible solution for the used void problem. The connection uses a newly produced L-shaped beam, the anchoring inside the beam must be placed according to the floor plan for the reuse case, a proposed solution with anchoring has been given for the reuse case in Figure 29. This option is a traditionally used connection method in the prefab industry, which as a result will make this option less time-consuming compared to the others. The procedure mentioned below must be followed for both sides of the HCS.

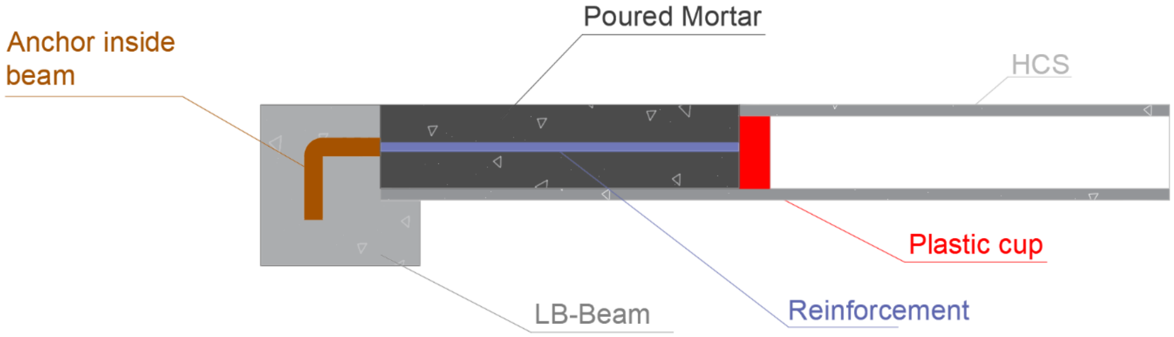


Figure 45- Illustration of LB-beam to HCS

Procedure

The alteration phase of the HCS consists of breaking the upper section of the selected voids for use, preferably two. The required length of the end slots must be given in the detailed drawing. After breaking and cleaning the end slots, a plastic cup must be placed. The plastic cup is used as a seal to ensure that the grout poured inside only fills up the desired length. Before installing the HCS, the neoprene bearings must be placed on the L-shaped beam at their designated areas. The neoprene bearing will ensure that no spalling of the edges will occur to the beam. The HCS can then be carefully placed on top of the bearing, the voids used for the connection must be aligned with the anchors of the beam. Insert the steel rod into the end slot and connect it to the anchor. Finally, pour mortar/grout into the broken section. When the poured mixture is cured, there is a positive connection between the two elements.

Advantages	**Disadvantages**
Well known method	Not reusable/ DfD friendly
Quick installation	Placement is dependent on available void

7.1.4 Longitudinal connection (for adjacent slabs)

The longitudinal connection between the adjacent slabs must also be considered. The longitudinal connection transfers the vertical and horizontal shear forces acting between two slabs. The horizontal shear component will mostly be subjected towards to the structural system (bracing walls). As the focus of this thesis is on HCSs it will focus on the vertical shear force, which will be dead and various imposed load applied vertically on the slab will be of interest in this case as shown by the red arrow in Figure 46.

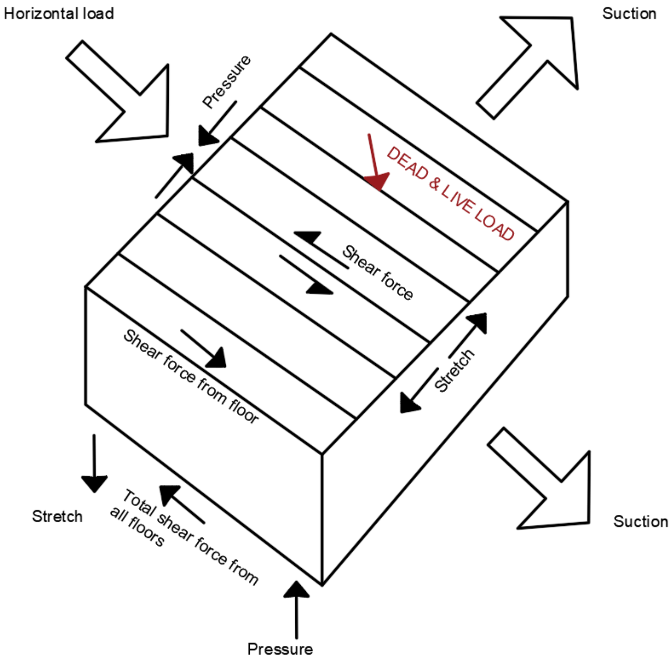


Figure 46-Shear forces due to horizontal load, adapted from: [78]

The traditional method of inserting a connection bar in the grouted joint between slabs is widely used due to its straightforward application and effective load transfer capabilities (refer Figure 47). This technique involves placing a connection bar within the space that runs longitudinally between adjacent slabs, which is then filled with grout to secure the bar and enhance the connection. This method's primary advantage is its ability to facilitate a robust and direct transfer of shear forces, ensuring the structural consistency of the connected slabs. However, this solution will present challenges when reusing HCSs as they will lack the lateral void (refer Figure 48).

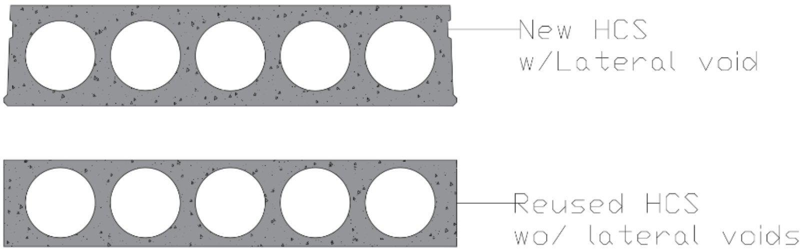


Figure 47. Comparison of new vs reused HCS lack of lateral void

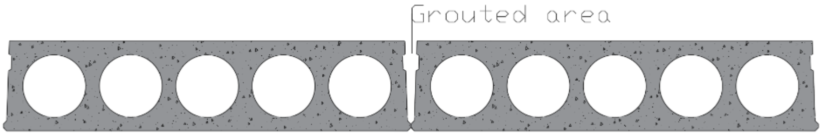


Figure 48- Longitudinal joint for new HCSs

Figure 49 shows the first option where the HCSs have been cut in its nearest core. The cut will create a precise connecting point for both HCSs with a natural grouting and connection bar position. Although it might be very practical, the connection will require a lot of work as the cut must be very precise. The reusability of this connection method will be very low as it cannot be reversed.

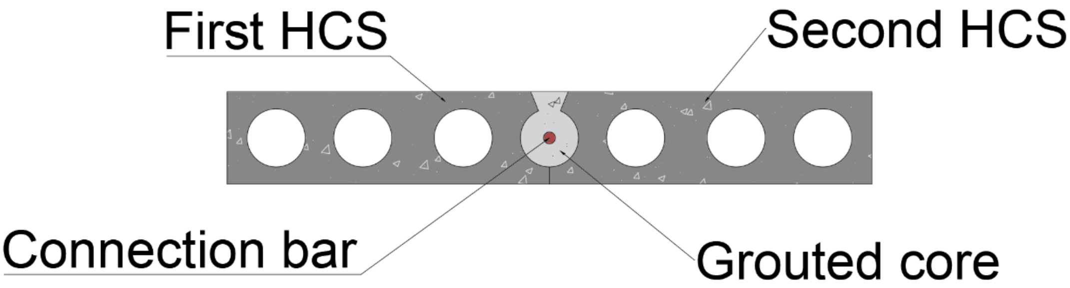


Figure 49- Longitudinal joint, Option 1

Figure 50 illustrates a connection method utilizing continuous longitudinal steel plates. This approach involves a simpler vertical cut for the grouting and placement of the connection bar. These plates are affixed to the exterior of the HCSs and anchored using mechanical fasteners. Both cores/voids must be filled with grout once the steel plate and anchor have been fastened. Although this method demands precise drilling and is not aesthetically pleasing, it significantly improves the reuse potential of the HCS. The steel plates will not only provide a durable means for transferring shear forces but also offer greater adaptability for future adjustments or disassembly, making this a practical choice for sustainability,

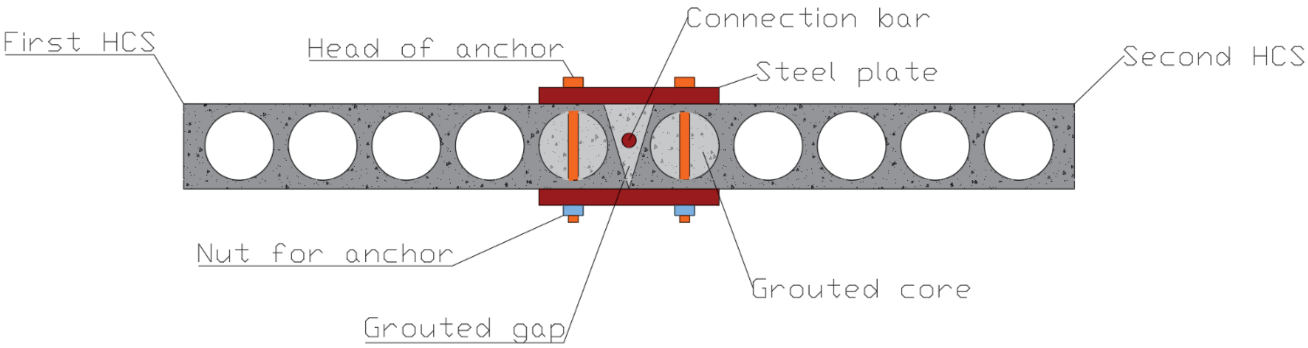


Figure 50- Longitudinal joint, Option 2 with steel plates

8 Environmental impact

The environmental impact of the construction sector commands significant attention. The sector's substantial contribution to global CO2 emissions as mentioned in section 3.4.1, and the waste production as mentioned in section 3.1, proves that the quest for sustainable development must be improved.

This section delves into an in-depth examination of the environmental footprint associated with the use of HCS in the construction of the original building project, identified as SVB. Initially, a detailed analysis of the environmental gains achieved in SVB through the use of HCS will be presented, focusing on three key aspects:

- the amount of material saved (section 8.1)
- the reduction in GWP (section 8.1.1)
- optimization of water usage (section 8.1.2)

The data will be used to compare the environmental benefits of using HCS to solid slabs. The calculation for the solid slab assumes that both the HCS and solid slab use the same concrete mixture. This assumption was made to ensure a more accurate and comparable data analysis. The volume of the solid slab was calculated by simply including the volume of the voids which were originally not included in the HCS calculation.

Following the analysis, the narrative transitions to explore the potential for further reducing the environmental impact associated with the construction sector through innovative reuse of HCS. The reuse case presented in section 5.2 will be used for the environmental assessment here. This section aims to enlighten the dual benefits of the HCS; in addition to its original benefits highlighted from the SVB data, its potential for reuse presents a forward-thinking circular strategy to sustain these environmental benefits over time. The reuse section is divided into the following sections:

- CtG analysis of elements chosen for reuse focusing on GWP and WDP (section 8.2 and 8.3)
- GWP total and WDP total for reuse method (section 8.4)
- Difference in GWP and WDP between new versus reused HCS (section 8.5)

8.1 Resource conservation- SVB

A thorough data examination of the SVB project has been conducted. This in-depth review involved a detailed review of material usage records, architectural plans, and construction phase reports. The accumulated data on the amount of concrete needed for HCS, was compared to the amount of concrete needed for in-situ solid slabs. Figure 51 shows the material savings achieved in SVB by using HCS. The examination revealed significant material savings when using HCS compared to in-situ solid slabs. The average amount of concrete saved across each floor section can be seen in Table 18**.** The results confirm the conservation of resources associated with prefabricated elements as mentioned in section 3.3. This conservation of resources is a key principle of sustainable construction. The results indicate that the use of HCS instead of in-situ solid slabs will reduce the demand for new raw materials, thus minimizing waste.

Procedure:

The calculation for the solid slab was done using the same dimensions as the HCS without retracting the volume of the voids. The same density used for the HCS was used for the solid slab as well, 2,4 tonnes/m3. Table 18 shows the max and min values for the average amount of material saved on the SVB project. The standard deviation was also calculated for each floor.

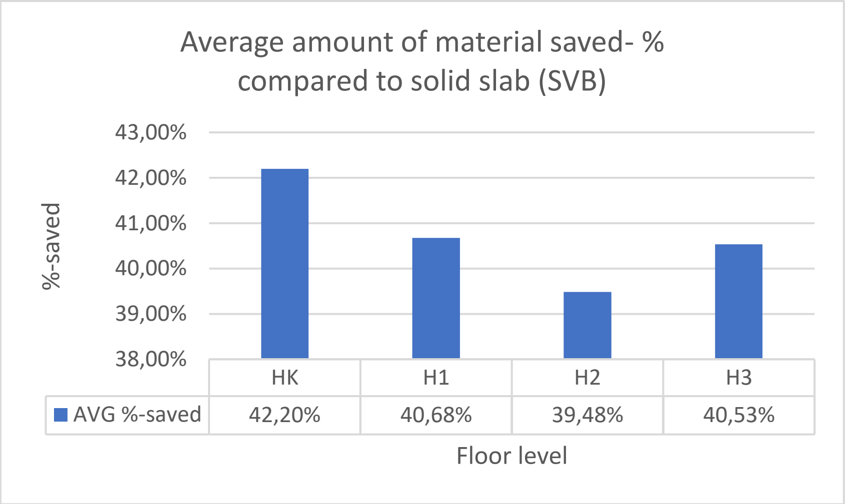


Figure 51- Material saved using prefab. HCS in SVB

Table 18-Average, standard deviation, max and min values of material saved in each floor section

Floor	AVG %-saved	Standard deviation.	Min. value	max value
HK	42,20 %	4,21 %	37,99 %	46,41 %
H1	40,68 %	3,88 %	36,80 %	44,55 %
H2	39,48 %	5,24 %	34,24 %	44,72 %
H3	40,53 %	4,16 %	36,37 %	44,69 %

8.1.1 GWP-total for saved material-SVB

In parallel with identifying the material savings related to the usage of HCS in SVB, the analysis extended to evaluating the environmental implications of these savings. This was found by calculating the Global Warming Potential (GWP) for the saved mass of concrete. This calculation considered the full lifecycle (Cradle-to-Grave), encompassing extraction, manufacturing, transportation, demolition, and recycling/landfill. The GWP total for the saved material was derived using the provided EPD by Veidekke. The calculated values give the analysis a clear and quantifiable insight into the environmental benefits of using prefabricated HCS.

The calculated GWP of the saved mass shown in Figure 52 underscores the environmental benefits of opting for HCS. By significantly lowering the GWP, the HCS will contribute to the reduction of greenhouse gas emissions associated with construction activities.

Procedure:

The mass difference (MD_x) between the solid slab and HCS was calculated for each floor section. A CtG analysis was done to calculate the total GWP value for each mass difference in each floor section. These values were based on the system limits from the EPD provided for the HCS. The calculated values can be seen in Table 19**.**

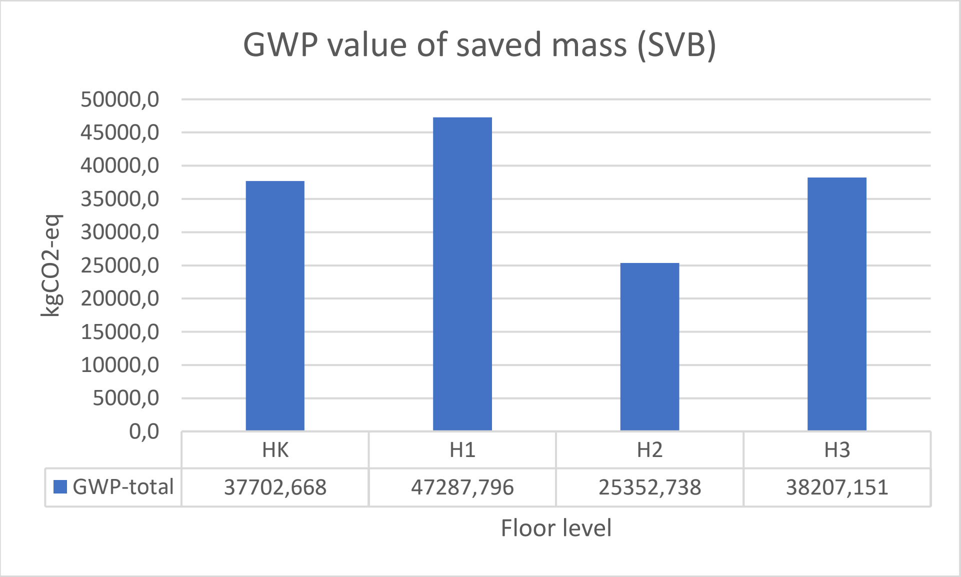


Figure 52- GWP value for saved mass in SVB

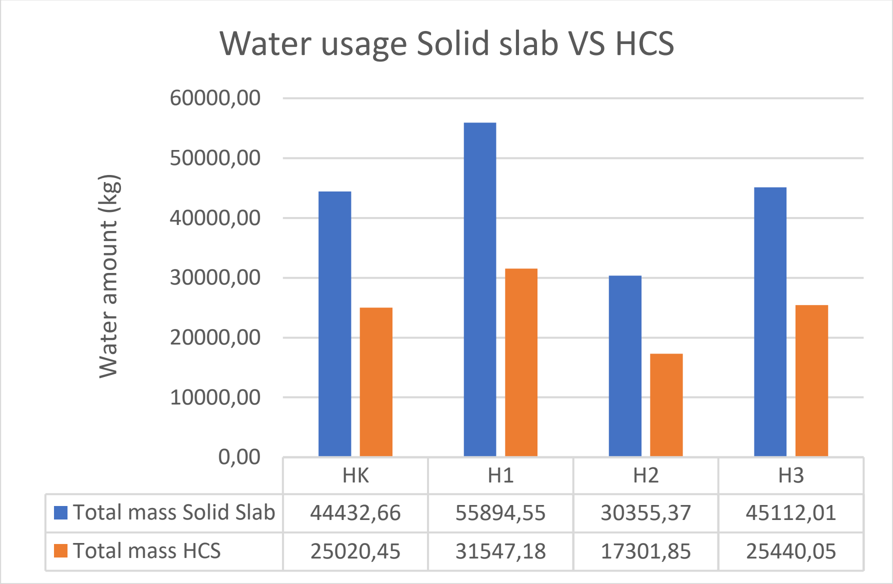
Table 19- Mass data for each floor section

	Total Mass solid slab	Total mass HCS	Mass difference (MD)	GWP-total for MD
Phase	(tonnes)	(tonnes)	(tonnes)	(kgCO2-eq)
HK	790,898	445,362	345,536	37702,668
H1	994,919	561,538	433,381	47287,796
H2	540,323	307,972	232,352	25352,738
H3	802,991	452,831	350,159	38207,151

8.1.2 Water saved-SVB

As mentioned in section 3.4, the management of resources in the construction industry can become more efficient by using HCS. Water, as a vital resource in the production of construction components, offers a significant area for improvement. This analysis will compare the total volume of water needed for SVB using HCS compared to if it were made with solid slabs. The aim is to underscore the water conservation benefits of using HCS, aligning with the sustainability objectives outlined in the UN sustainable development goals (refer section 3.1).

Figure 53 shows the reductions in water consumption by adopting HCSs against in-situ solid slabs in the SVB project. The compiled data undoubtedly shows that HCSs require significantly less water than solid slabs across all sections analysed (HK, H1, H2 and H3). This result was certain due to the reduced volume of concrete needed to produce one HCS compared to a cast-in-situ solid slab covering the same area.



	HK	H1	H2	H3
■ Total mass Solid Slab	44432,66	55894,55	30355,37	45112,01
■ Total mass HCS	25020,45	31547,18	17301,85	25440,05

Figure 53- Water usage difference between HCS and solid slab

Leveraging the environmental benefits realized from the initial application of HCS in construction projects lays a compelling foundation for advocating for their reuse. The benefits achieved through the adoption of HCS in the original case underscore the potential to extend and amplify these benefits by reusing these elements.

The decrease in resource consumption due to the use of HCS in the first project (SVB) shows the potential of prefabrication as a means for sustainable construction. The savings on the amounts of concrete will prove to reduce the demand for raw materials significantly in the long run. This will in turn diminish the environmental footprint associated with material extraction and processing mentioned in section 3.4. Furthermore, the GWP reduction achieved through the initial use of HCS plays a vital role in mitigating the climate change impacts. Focusing on the reuse of HCS emerges as a logical next step. Reusing HCS will be beneficial for environmental gains as the proven benefits can be sustained over multiple project lifecycles, thereby compounding the positive impact it has on the environment.

8.2 GWP result for CtG analysis of SVB

The total CO_2 – emission for the HCS in SVB have been calculated using the EPD provided by Veidekke Prefab. The system limit considered for the CtG analysis, and the processes involved for each system limit have been shown in Figure 56, the relevant system limits for the case have been colour-coded as well. Table 20 shows the GWP total for 1 ton of HCS for each system limit. This was used as a reference for the elements produced for SVB. Detailed data for the elements can be seen in Appendix B. As mentioned in section 3.4.2, the production of cement stands for the highest emission rates in concrete production. The cement production in addition to the depletion of natural resources makes A1 the system limit with the highest GWP total (kgCO_2-eq). Figure 54 shows the results of the cradle-to-grave analysis of SVB. 80,37% of the GWP comes from A1 which makes it the biggest contributor to the total GWP for all the elements produced in SVB.

Table 20-GWP value for system limits

GWP for 1 ton of HCS (unit: kgCO_2-eq)	
A1	87,7
A2	0,62
A3	2,76
A4*	0,549
A5	10,4
C1	4
C2	1,23
C3	0,485
C4	1,37
*The system limit A4 has been given in the EPD for the distance of 50km with a value of 1,23. The length from the factory to construction site is 22,3km (google maps). The value for A4 (for 1 ton of HCS) is 0,55 for the given distance.	

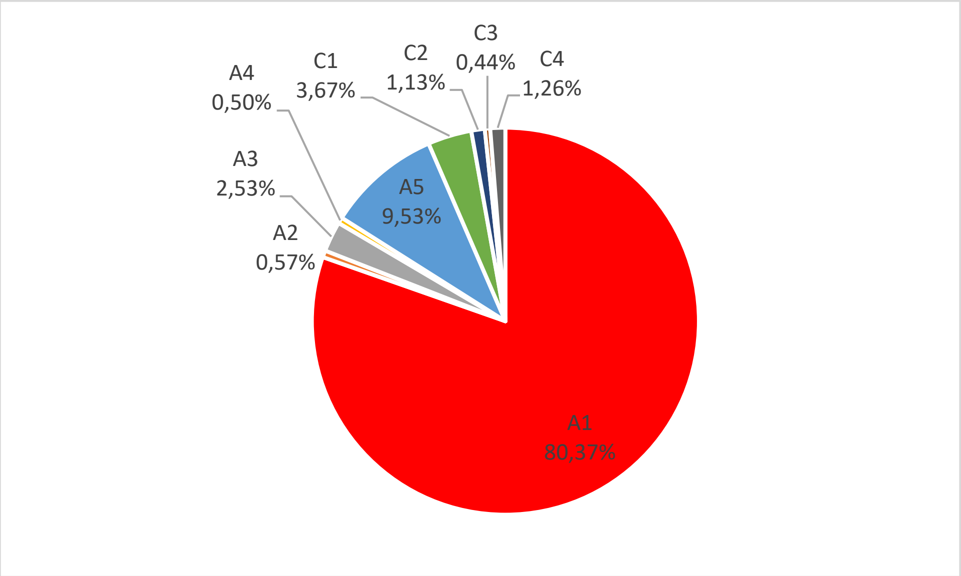


Figure 54- Total GWP for SVB

8.3 WDP results for CtG-analysis of SVB

Water Deprivation Potential (WDP) serves as a crucial environmental performance indicator in assessing the impact of water consumption throughout the lifecycle of construction materials/components. This indicator is calculated using the inverse ratio of water availability to water demand per area. This indicator provides a detailed understanding of the impact different phases have on water resources [72].

Given the significant water saving demonstrated using the HCS in SVB, it is important to examine the whole life cycle of the HCS. This analysis is pivotal in pinpointing the stages within the system limits that most significantly impact the WDP. For the purpose of this analysis, the system limits defined by the EPD shown in Figure 56 were employed. The WDP values for 1 ton of HCS is given in. As highlighted in the table, system limit A1 from the production phase and C3 from the end phase are the biggest contributors to WDP.

Table 21-WDP values for system limits

WDP for 1 ton of HCS (unit: m3)	
A1	1600
A2	16,40
A3	831
A4	55,30
A5	567
C1	11,70
C2	55,30
C3	1640
C4	93,10

Figure 55 shows the results following a CtG analysis of SVB. Identifying A1 and C1 as the most impactful system limits is important for evaluating the potential benefits of reusing HCSs. Reuse can substantially diminish the water footprint in these critical limits by reducing the demand for new materials, thus conserving water that would have been expended in the production of new HCSs.

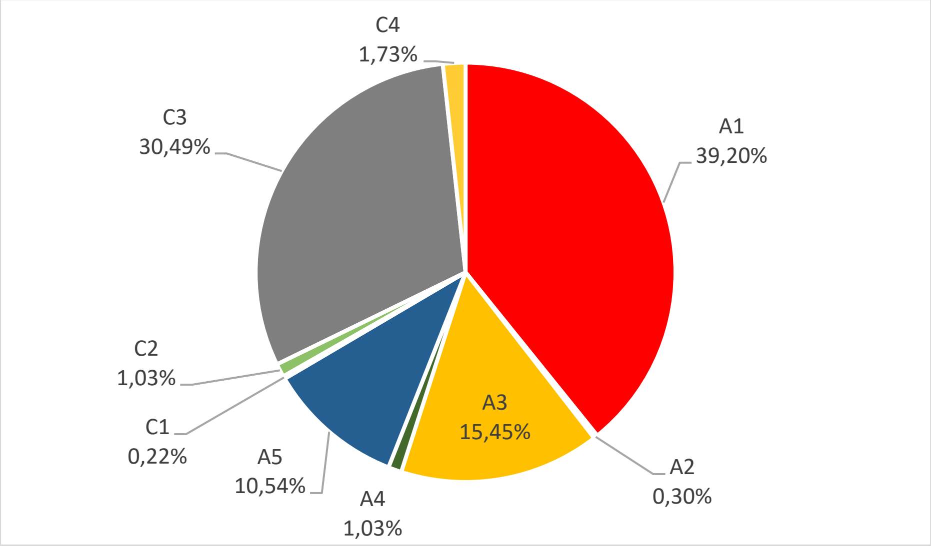


Figure 55- WDP total SVB

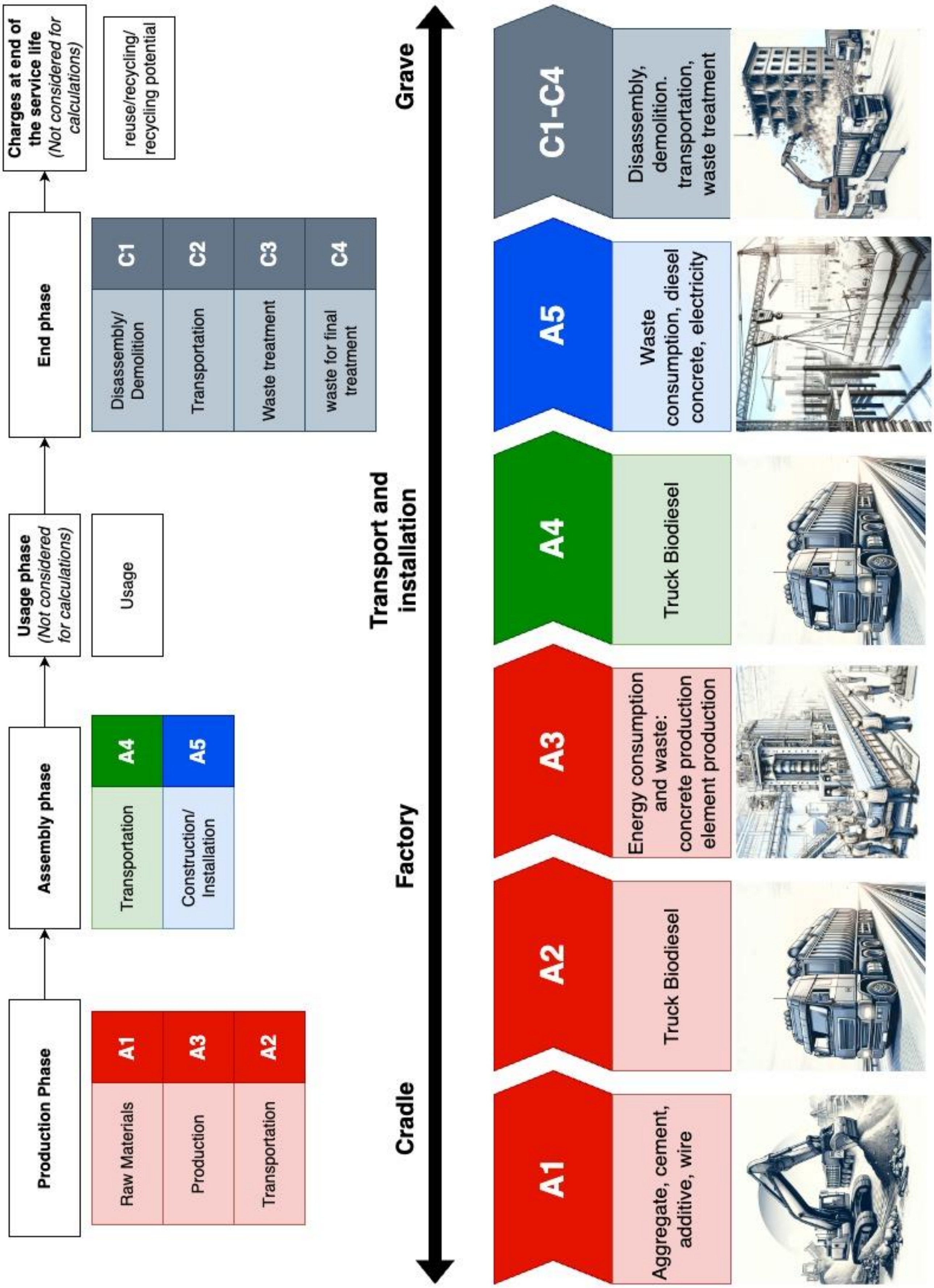


Figure 56- System limits for traditional approach (CtG), adapted from EPD

8.4 Reuse case results

The procurement phase emerges as a main contributor for the GWP- and WDP- total due to energy-intensive requirements for material extraction, processing, and transportation. However, reusing HCS proves to be a compelling solution to the challenge. Reusing HCS does not only circumvent the process of new component production, but it also extends the lifecycle of existing components. This will result in further reducing the demand for resource extraction and processing, benefitting the challenges mentioned in section 3.4.2. The analysis uses data from the HCSs chosen for the reuse case (refer section 5.2 and Appendix A). The reuse case consists of 108 HCS in the size HD265 (265 mm thickness).

The following approach for reuse is based on the cradle-to-cradle design approach mentioned in section 3.5.1. The approach shown in Figure 57, shows the new system limits implemented to calculate the total GWP for the reuse method. System limits such as A1-A3 and C1-C4 will be cancelled. System limits A1-A3 will be cut out since elements will be reused instead of being demolished, so no new HCS will be produced. System limits C1-C4 will not be needed as demolition of the building will not be an option for this case study. The elements will be disassembled, transported, and tested before either being stored or transported to the construction site.

New system limits will be introduced for the reuse method. The disassembly process, E1, will consist of the same procedure and construction level as the one used during the assembly process (A5). This assumption has been made since the disassembly process will ideally follow the same procedure as the assembly phase (for details refer section 6.2.1). The disassembly phase of the HCS can be assumed to generate carbon emissions comparable to the assembly phase. Following this theory E1 will have the same value as A5. Figure 57 shows the process with the respective system limits for this approach. The system limit values used for the reuse case can be seen in Table 22 and Table 23.

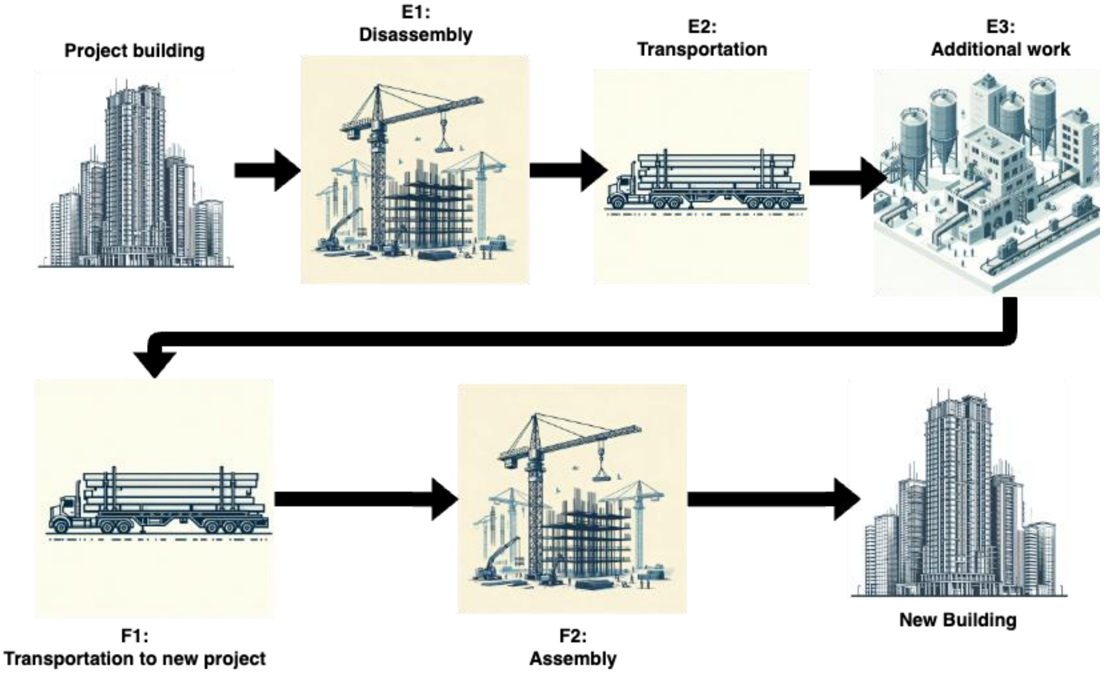


Figure 57- System limits for reuse

Table 22- Reuse case GWP values for 1 ton of HCS

GWP for 1 ton of HCS (unit: kgCO$_2$-eq)	
E1	10,4
E2	0,549
E3	2,76
F1	0,549
F2	10,4
*The system limit E1 and F1 have been given in the EPD for the distance of 50km with a value of 1,23. The length from the factory to construction site is 22,3km (google maps). The value for A4 (for 1 ton of HCS) is 0,55 for the given distance.	

Table 23- Reuse case WDP values for 1 ton of HCS

WDP for 1 ton of HCS (unit: m3)	
E1	567
E2	55,30
E3	831
F1	55,30
F2	567

GWP results:
The result states that the disassembly phase has a bigger pollution risk compared to the demolition process (C1-C4) as shown in Table 24 and Table 25. The GWP total for C1-C4 is 2794,286 kgCO2-eq compared to the higher value of 4101,705 kgCO2-eq for E1, the disassembly phase. The results from the CtG analysis state the total GWP for the selected HCSs are 43033,98 kgCO2-eq. The highest GWP total comes from A1. The reuse method mentioned in Figure 57 gives a total GWP result of 9724,984 kgCO2-eq. Although the pollution during the disassembly phase is higher, the results for the reuse method show a 71,88 % decrease in the total GWP when compared to A1 in the CtG analysis.

The reuse solution will maximize the utility of the embodied energy and materials used in A1-A3 by extending the lifecycle. Reducing the production of new elements by reusing proposes added benefits, such as diminishing the strain on the manufacturing facilities. The approach shown in Figure 57 will therefore align with the circular economy principles mentioned in section 3.5 and mitigate the environmental impact associated with initial production.

Table 24- GWP total for reusable elements, traditional approach

System Limit	GWP-total (Unit: kgCO2-eq)	Percentage (%)
A1	34588,412	80,37
A2	244,525	0,57
A3	1088,529	2,53
A4	216,523	0,50
A5	4101,705	9,53
C1	1577,579	3,67
C2	485,105	1,13
C3	191,281	0,44
C4	540,321	1,26%

Table 25-GWP-total for reuse case

System Limit	GWP-total (Unit: kgCO2-eq)	Percentage (%)
E1	4101,705	42,18%
E2	216,523	2,23%
E3	1088,529	11,19%
F1	216,523	2,23%
F2	4101,705	42,18%

WDP results:
In addition to the GWP-total a noteworthy reduction in the WDP value can also be seen. The difference between the WDP values for both methods can be seen in Table 26 and Table 27. When analysing the total impacts, it is observed that although the WDP total for the reuse process is 15,3% higher than that of the demolition phase (covering the phases from C1 to C4), this increase is counterbalanced by its efficiency in other aspects. Specifically, the WDP total for the reuse process, despite being higher in comparison to the demolition phase, is still 60% less than the WDP total associated with the traditional approach to construction material handling. Even though the reuse process is 29,75% higher than A1 it is still a more favourable option compared to demolition. This is due to the extended lifespan and reduced frequency of new component production, which greatly diminishes the cumulative water usage across multiple lifecycle stages.

Table 26-WDP total for reusable elements, traditional approach

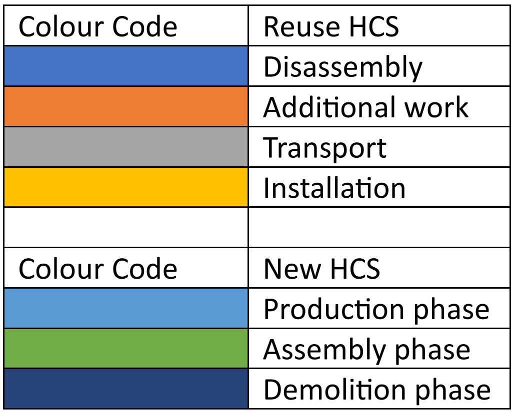
System Limit	WDP-total (Unit: m3)	Percentage (%)
A1	631031,470	32,86%
A2	6468,073	0,34%
A3	327741,970	17,06%
A4	21810,025	1,14%
A5	223621,77	11,64%
C1	4614,418	0,24%
C2	21810,025	1,14%
C3	646807,257	33,68%
C4	36718,144	1,91%

Table 27- WDP total for reuse case

System Limit	WDP-total (Unit: m3)	Percentage (%)
E1	223621,777	27,32%
E2	21810,025	2,66%
E3	327741,970	40,04%
F1	21810,025	2,66%
F2	223621,77	27,32%

8.5 Difference in GWP, transport

The chart provided demonstrates a comparative analysis of the environmental impacts, specifically focusing on GWP and WDP, for new versus reused HCSs. The data for both charts were calculated using the values from the analysis above. The values were averaged across the assessed lifecycle stages and presented in a colour-coded chart format for clarity and ease of interpretation. The colour-codes can be seen in Figure 58.



Colour Code	Reuse HCS
🟦	Disassembly
🟧	Additional work
▨	Transport
🟨	Installation
Colour Code	New HCS
🟦	Production phase
🟩	Assembly phase
⬛	Demolition phase

Figure 58- Colour codes for GWP, WDP chart

Figure 59 and Figure 60 gives a clear picture of the significant reduction in emission and water usage through the elimination of the production phase. By reusing HCSs, environmentally impact heavy processes are entirely bypassed. The absence of the production phase in reused HCS results in a drastic decrease in carbon emissions, as there is no need for energy-intensive manufacturing processes. Similarly, reusing HCSs will substantially lower the water footprint. This major reduction comes from avoiding water-intensive activities such as the production and demolition phase.

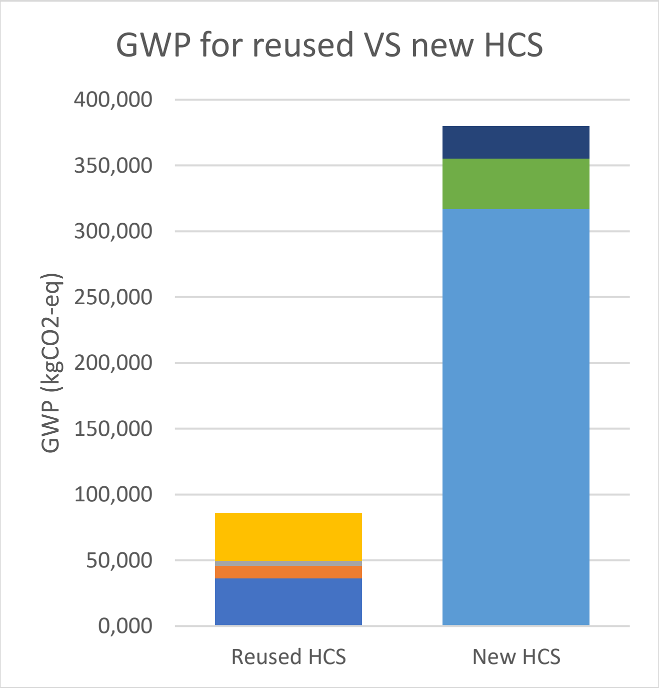


Figure 59- GWP difference between new VS reused HCS

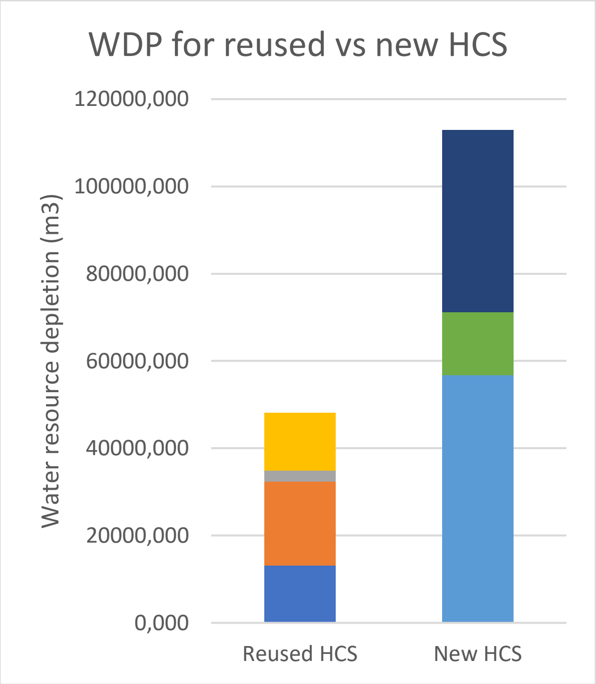


Figure 60- WDP difference between new VS reused HCS

9 Discussion

This chapter critically evaluates the findings from the study on the use and reuse of HCSs within sustainable construction practises. Key topics of discussion include the produced guidelines for HCS reuse, the technical and structural possibilities for connecting reused HCSs, and the environmental benefits with their use and reuse. Additionally, the chapter identifies necessary improvements and proposes strategies to overcome the existing barriers, aiming to enhance the effectiveness of reuse.

9.1 Usage of guidelines

The three guidelines introduced in section 6 could if implemented correctly, improve the environmental and economic efficiency within the construction industry and reuse practise. The implementation will further increase the already achieved environmental benefits mentioned in section 3.3. Each set of guidelines will serve as a cornerstone in optimizing the lifecycle of modular construction components, especially hollow core slabs. These guidelines bridge the gaps in the existing standards, such as ISO 20887 and NS 3682, which are very helpful for disassembly friendly projects, but they are inadequate for buildings without initial disassembly considerations. The production of the guidelines necessitated a thoughtful and systematic approach which could be adopted to various projects and conditions. The produced guidelines will act as a standardized model which can be used to achieve a higher rate of reuse. This section of the discussion will highlight the benefits achievable by using the guidelines.

The produced guidelines are tailored to the unique challenges of disassembling elements from a project with no intention of disassembly in its original design, making a substantial contribution to sustainable construction practises. The pre-disassembly evaluation is a pivotal feature which will ensure a thorough assessment of the structural integrity and feasibility of reuse before any physical interventions. This strategy will minimize risks, promote safety, and enhance cost-effectiveness.

An application of these guidelines is demonstrated in the planned reuse of HCSs from SVB for the new student housing project. This project serves as a practical example, it illustrates how the guidelines can be directly applied to assess the structural integrity and suitability of the HCSs for reuse in the student housing framework. This included checking for material fatigue or damage that could compromise the safety or functionality of the slabs. Upon determining the suitable HCSs for reuse, the disassembly protocols outlined in the guidelines provide a detailed procedure for safely dismantling the existing structure. This process is designed to preserve the integrity of the HCSs. Strategies such as precise cutting techniques, disassembly sequence, and the use of specialized lifting equipment is critical to prevent stress and damage to the component. Subsequently, the guidelines detail targeted testing procedure to confirm that the HCSs meet safety and performance standards appropriate for their new application.

The broader adoption of these guidelines could create a shift towards more sustainable practises within the construction industry. By providing a reproducible, systematic model for reusing building components, the guidelines not only enhance the efficiency and safety of reuse projects but also promote the integration of circular economy principles into building design and construction.

9.2 Connections for reusable HCS

While there are established methods for connecting HCSs to beams which seem achievable and reliable, the challenge arises significantly when considering connections to walls. The original connection method which often involve irreversible processes like mortar pouring, do not lend themselves well to the concept of reuse. The inherent limitation in the current connection trends necessitates exploring creative solutions to ensure the viability of reusing HCSs in construction without significant alterations to their structural integrity.

Current methods in construction predominantly employ irreversible connection techniques, which although stable, often damage structural elements during disassembly, thereby complicating their potential for reuse. For example, while connections between HCs and beams are technically feasible. They generally involve methods that do not allow for the components to be reused, which contradicts the principles of sustainable and circular construction practises.

The practical methods for reconnecting HCSs to beams have proven effective and can be adopted with minor adaptations to fit the specific requirements of the project. However the connection between HCSs and walls presents a complex challenge, which is to create an applicable connection between the HCS and wall. As mentioned in section 5.1.4, the original connection method used in SVB between the HCS and wall, lateral connections, cannot be used in the reuse case. Once these elements are integrated into structures and covered with materials like mortar, they are not only difficult to access during disassembly, but nearly impossible to reuse without compromising the material integrity. The connection proposals given for this problem can be used but will still have their limitation. Thus, complicating the reuse process. The alternative solutions for the HCS-wall connection must consider the lack of reusability of the existing connections and the need to avoid drastic changes to the HCSs themselves. For example, while the idea of drilling bars through each of the slab into a newly constructed bond beam offers a potential workaround (refer Figure 42), it highlights the need for additional structural supports and precise alignment during installation. This method, though providing a practical connection, does not support the principles of DfD, as it potentially renders the HCSs non-reusable after their connection.

Both longitudinal connections presented in section 7.1.4 brings its distinct advantages and considerations. Option 1 (refer Figure 49) is a straightforward and efficient method which primarily focuses on direct shear transfer. It is ideally suited for projects where permanent and durable connections are required. On the other hand, option 2 (refer Figure 50) offers more flexibility. This connection method allows for easier modifications and disassembly, making it a better option for projects prioritizing reusability and sustainability. The choice of option 2 will create an increase in the labour costs due to the additional work needed on the HCS.

The necessity for such creative solutions indicates that the connection possibilities will significantly influence the overall success of any HCS reuse initiative. It becomes crucial to not only evaluate the structural feasibility of these new connections but also their economic and environmental impact relative to the benefits of component reuse. Developing connection methods that are both reversible and robust enough to meet building standards will be a key factor in realizing the full potential of HCS reuse, aligning with the broader goals of sustainability in the construction industry.

9.3 Environment

The pre-case study from Hong Kong provides a valid example of how prefabricated concrete elements, like HCS, have been instrumental in reducing waste sent to landfills. When drawing parallels to Norway, where landfill usage and material wastage are also a pressing concern, the adoption of HCSs can offer similar benefits. The efficiency and pre-designed nature of HCSs make them ideal for projects looking to minimize on-site waste and environmental impact.

The current environmental state of the construction sector in Norway was discussed in the theory section of the thesis (refer section 3.1). This section highlights the demolition phase as a significant contributor to material wastage, as evidenced by Figure 6. The inherent design efficiency of HCSs reduces the consumption of raw materials by optimizing the use of each element through precise manufacturing processes. This not only narrows material consumption but also establishes a lower baseline for GWP and resource usage compared to traditional in situ cast slabs (refer sections 8.1.1 and 8.1.2).

The potential for further improving the resource efficiency lies in the reuse of HCSs, as recycling concrete into aggregates is shown to be a suboptimal option for sustainability, as discussed in section 3.4.3. By repurposing these components, the lifecycle can be significantly slowed down/ prolonged. Thus, enhancing circularity within the construction industry. The environmental impact results, specifically the reuse case result (refer section 8.4) provides a detailed analysis of the benefits achievable through reuse. In summary reusing the HCSs from SVB in a student housing project will give clear environmental benefits.

While the results are promising, it is crucial to acknowledge the potential errors and limitations that might affect the validity and generalizability of the findings. The analysis relies heavily on theoretical models and assumptions about the condition and integrity of the HCSs upon reuse. In reality, factors such as material degradation, contamination, or technical changes can affect the feasibility and environmental benefits of reusing HCS. Moreover, the additional work required post-disassembly varies depending on the condition of the HCS, which could affect the overall sustainability metrics. Furthermore, the metrics used to measure GWP and WDP are based on standardized calculations that may not capture all nuances of the environmental impact, such as local dust and sound pollution during disassembly.

The previous reuse cases mentioned in section 4.1 states that the economic costs are the main factor hindering the reuse practise. However, the environmental benefits outlined in section 8 should be emphasized as a strategic approach to offsetting these costs. By prioritizing environmental gains, stakeholders can justify the initial economic outlay, potentially leading to long-term savings and sustainability advantages. The upcoming sections will explore strategies to enhance the economic and social viability of reuse practises.

9.4 Economic perspective

Although reusing HCS are sustainable, its economic inefficiency complicates its widespread adoption. Several factors contribute to this inefficiency: (i) the time and labour costs associated with the disassembly and refurbishment process, as opposed to demolishing, (ii)transporting, and (iii)refurbishing these materials, as well as (iiii) a general lack of experience regarding such cases. Consequently, the financial benefits of reusing HCSs do not justify the costs compared to purchasing new materials. For companies to prioritize reuse projects, the cost-benefit ratio must become more favourable. Implementing a multifaceted approach that includes incentives and supportive measures is essential to promote the reuse of HCS.

9.4.1 Environmental Impact

While the case studies from section 4.1 highlighted a higher initial cost, this should not be considered as the only cost parameter for decision. Assessing the economic viability of reusable HCSs demands a broader perspective of the economic framework. The initial costs, although high, should only be viewed as a portion. The economic viability of reusable HCSs should focus on the long-term benefits beyond the initial higher costs. Benefits such as waste minimization, reduction in environmental harm, decrease of waste and reliance on landfill sites should not be taken lightly as they contribute to a better ecosystem for the construction sector. These benefits should be weighted alongside the initial costs when deciding on reuse projects.

Additionally, reflecting the hidden environmental costs in the market price for newly produced elements could prove to be of benefit to show the economic viability of reusable HCSs. The reusable HCSs propose a more sustainable solution aligning with the UN goals and the Paris Agreement by promoting a more sustainable and circular economy. This market failure could be rectified by government intervention. The cost difference between newly produced and reusable HCSs could be bridged by internalizing the environmental externalities. A carbon tax can catalyse change towards a more cyclic model approach. Implementing a carbon tax on the newly produced elements will potentially increase the cost of materials, thus reflecting the actual carbon footprint. Conversely, a financial incentive should be offered when reusable elements such as HCSs are used. Such incentives will make reuse projects more attractive to both customers and contractors.

9.4.2 Green building Certifications

Green building certifications should be used both as an environmental tool and as a marketing tool to evaluate and recognize environmentally friendly buildings. The target of the certifications is to evaluate the whole lifecycle of the components/building. Some key green building certifications are LEED, BREEAM-NOR, and the Swan mark (svane merket). These certifications evaluate the resource consumption during the procurement phase, design for sustainability, pollution, transportation emissions, waste generation and water consumption [73] [74] [75]. Buildings with these certifications often evolve into a higher market value project, thus making them more attractive to investors and customers. These certifications serve as a mark of quality and sustainability. Furthermore, buildings certified according to the green building initiative are designed to be more energy and water efficient. This will result in a significant reduction in utility costs. Additionally, achieving a certain level of green building certification could become a regulatory requirement, implementing these certifications early on can minimize the risk of additional changes to the buildings if these requirements become stricter.

9.4.3 Government Policies

The government should lead by example by using reusable components in their projects, influencing industry standards towards sustainability. The government can increase the demand for reusable HCSs and other components by requiring them in public projects. This will result in an increase in demand of reusable HCSs. This approach will help change how the construction sector views component reuse. Focusing on reuse in public projects and policies ensures steady demand, encouraging suppliers and manufacturers to invest in necessary technology and processes for sustainable reuse. Making reuse a common practice could significantly shift the construction industry towards sustainability in the long run.

Furthermore, offering financial benefits like tax breaks, subsidies, or grants for projects using reused building components can help reduce initial costs. Updating building codes and regulations to include reusable components can make it easier to incorporate them into new projects and streamline the approval process, thereby enhancing the economic appeal of reusing.

9.4.4 Innovation and job creation

Emphasizing reusability and rewarding sustainable practises through policies can drive the industry towards innovative and sustainable building techniques. This focus will encourage research and development in key areas such as material recovery, refurbishment techniques, and adaptable designs for DfD.

Moreover, prioritizing component reuse can catalyse economic growth and job creation within the construction sector. The demand for skilled workers will rise, necessitating expertise in logistics of collection, sorting, redesigning, refurbishing, and certifying. Additionally, a shift towards sustainability can generate new opportunities in both existing companies and startups focused on innovative sustainable practises. This not only fosters job creation but also leads to the expansion of the construction sector and the emergence of new markets, encouraging traditional construction firms to adopt sustainable practises.

9.4.5 Partnerships with environmental organizations

Collaborating with construction firms, environmental organizations and academic institutions can be a key strategy to develop practical and evidence-based guidelines for reusing these elements. Such partnerships will bring a wealth of knowledge and a strong advocacy platform for sustainable practices. This knowledge will ensure that environmental considerations are at the forefront in the development of sustainable building practices/guidelines. The collaborative effort between academic institutions and construction firms will allow for the development of practical, evidence-based guidelines for the reuse of construction elements. The academic institutions can provide a thorough analysis of the lifecycle, structural integrity, and performance of the reused elements. Construction firms on the other hand can provide practical insights into the logistical and economic aspects of incorporating the analysed elements/materials into a new project. The construction firms do also provide years of experience which is beneficial to determine the feasibility of new construction techniques.

The combined effort can ensure that the reuse projects are sustainable, practically feasible, and economically viable. Finally, these partnerships can be crucial in influencing policy development related to sustainable construction. Presenting a united front and a coherent set of recommendations could advocate for policies that support the reuse of construction materials/elements.

9.5 Social perspective

It is worth noting that the decision-making process involves more parameters than just environmental and economical. Incorporating social dimensions into the circular economy assessment will give the added benefit of capturing a broader spectrum of impacts and benefits. This section will delve into

9.5.1 Company perception (the sources mentioned here are from a document)

When compared to other sectors, the construction sector is quite risk averse. (Source) states that this could be due to the financial stakes, potential for errors, and the high costs and complexities issues once a building is in use. (Source) states that the motive behind risk-aversion is a key motivator for the hesitation related to the implementation of reuse by construction firms. A firm will choose the most optimal choice to ensure a proper reputation. The lack of guaranteed success and safety makes reuse a risky option for firms right now. Further work to improve the perception of reusable elements in the community is needed.

9.5.2 Consumer perception and acceptance

Public perception and acceptance are detrimental to the broader adoption of sustainable construction practices, including the reuse of HCSs. The way reuse is perceived by the public will dramatically influence the market demand, regulatory policies, and the industry´s willingness to adopt new sustainable building practices. Concentrated efforts on further education and transparency are required to ensure a positive perception.

Educational campaigns*:* Highlighting the environmental benefits, such as the ones mentioned above (reduction in CO2-emission, waste production, and water usage) could potentially help enhance public acceptance. Additionally, using success stories and case studies demonstrating the successful integration of reused HCSs can further strengthen public confidence and support for new sustainable practises. Finally, the development of comprehensive educational campaigns will play a major role in educating the public. These campaigns should highlight the benefits and safety of reuse. Information such as the process for quality assurance, processes that ensures the safety and integrity of reusable elements, and the relevant documentation for quality assessment in accordance to building codes should be included here.

Transparency*:* The public needs to feel safe with the reuse techniques. Transparency between the industry/firms and the consumers will be key to build trust. Firms should be open to share information about the process involved in reuse such as: sourcing, processing, testing, and integration of reused components. Providing clear information about the benefits and process of reuse could help alleviate concerns regarding the building practise.

9.5.3 Community Impact

Incorporating reusable elements into construction projects offers tangible benefits for the local communities, thus improving the consumer surplus. The utilization of reusable elements can improve the sustainability of the construction sector by reducing the waste in landfills, conserving natural resources, and decreasing environmental pollution.

Furthermore, incorporating reusable elements could reduce construction costs substantially. Cities such as Oslo have experienced an increase in housing prices. This cost-saving aspect will directly impact the affordability of housing, thus making it a pivotal strategy to increase the accessibility of housing for lower-income families and mitigate homelessness. The most immediate impact of reusable HCS (and other elements) is the reduction in material costs. Procuring new material constitutes a significant portion of construction expenses (source), reusing elements will cut these expenses and lower the financial barrier for constructing new housing units. By transferring these cost savings to consumers, housing can be offered at reduced purchase prices or lower rental rates, thus elevating the consumer surplus.

Additionally, lowering expenses through the use of reclaimed components allows for the reallocation of funds towards the improvement of public areas and communal facilities, thereby elevating the living standards of residents and strengthening the bonds within the community.

9.6 Improvements needed

Reusing HCS as a sustainable construction technique still needs improvement. If reusing HCS were to become a possibility, firms must emphasize and integrate the reuse aspect into all stages of a building cycle. Figure 61 shows the possible stages to consider when implementing reusable components. As mentioned earlier, the planning phase is still the most crucial part of a building project to ensure sustainable practices.

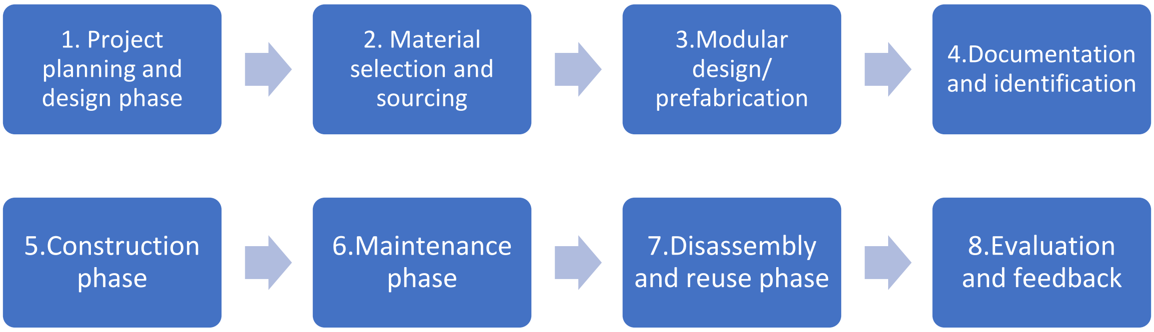


Figure 61- Workflow of construction project focused on reuse

9.6.1 Project planning and design phase

The planning phase should integrate the design for disassembly principles from the start. Implementing these principles from the beginning will ensure a safe and cost-effective disassembly process when the time comes. A modular or prefabricated design approach should be made possible, as using prefabricated components results in an easier assembly and disassembly process. The design should also plan for the possibility of both adaptability and future modifications if needed. The connections should also be designed to be reversible, if possible. The use of mechanical fasteners can prove to be more efficient for reuse instead of permanent adhesives or welds.

9.6.2 Design for disassembly (DfD)

The pre-disassembly evaluation (refer section 6.1) underscores independence and standardisation as crucial design aspects for the HCS. Prioritizing these two points during the design process not only makes HCSs viable for future reuse but also enhances their marketability and supports the adoption of a circular economy model where components are continuously reused rather than discarded.

Designing for independence allows for simpler disassembly, as components can be easily detached or replaced without compromising the structural integrity or functionality of the overall system. This facilitates the reuse of HCSs, thus reducing construction waste and environmental impact. In parallel, standardisation ensures that the HCSs are interchangeable, allowing seamless integration into various projects without the need for extensive modifications. By standardising the design of HCSs, they can be effectively utilized across different types of buildings, such as offices and residential buildings (assuming regulations are met). This will enhance the utility and economic value. While it may not be feasible for firms to produce in bulk without assured demand, having a standardised design means that once produced, these elements can be deployed flexibly across multiple projects.

9.6.3 Documentation

Due to variations among suppliers, proper documentation will be critical to reduce the uncertainty regarding the quality of the reusable materials and components. The implementation of documentation techniques such as the ones mentioned in section 6.4 would enable a more confident and widespread adoption of sustainable reuse practices.

A multifaceted approach could resolve this by considering the following points:

- **Comprehensive material tracking:** Using digital tools such as QR codes or RFID tags attached to the HCS, would allow for easy access to a digital database containing all the relevant information necessary to determine the potential for reuse. The tags or codes could provide the company with the history of the HCS, including its production details, usage history, and any refurbishment or repairs it has undergone.

- **Material Passports:** The concept of using "Material Passports" represents a forward-thinking approach to enhancing the sustainability and efficiency of construction practices. These passports will serve as a detailed record of construction components, and they will provide data on their characteristics, material composition, history, and potential for reuse. Architects, engineers, and contractors can use these passports during the pre-planning phase to evaluate the suitability of elements for reuse in new projects. Although the table (refer Table 17) provided in NS 3682 encapsulates the most relevant and crucial data, it is imperative to recognize that additional data categories are essential to develop a fully comprehensive material passport. Incorporating these extra categories (refer Figure XX) would extend the utility of the passport, making it an invaluable resource for all stakeholders involved throughout the lifecycle of the construction product.

9.6.4 Workforce training and education

The successful implementation of reusable elements hinges on a well-educated and experienced workforce. In addition to the technical aspect, the social value of sustainable construction should be emphasized further in the educational system. This will further develop a mindset that targets and values a sustainable society. Educating and training the workforce are pivotal in driving the construction sector toward sustainability. A two-way development is needed to further increase the understanding of sustainability in both the present and future construction workforce.

1. **Curriculum development:** A combination of a better theoretical understanding and practical skills is needed to further implement reusable elements into projects. Sustainability and material/component reuse should be integrated as key topics in the curriculum of all disciplines of the construction sector.
2. **Professional development:** The current workforce must also be educated on sustainable building practices. Firms and governments should offer continued education opportunities for current professionals to learn about new materials, technologies, and methods related to sustainability. As classroom lectures might not be the best solution for the firm, the educational process can be taken in the form of workshops, certifications, and on-site training sessions.

9.6.5 Platform for sales

Reusable building components can prove to be a new market in the construction sector. A robust market for these components can be created through market development initiatives, such as creating a platform or exchange where builders and developers can buy or sell reused building components. This would further improve the availability and visibility of reused HCS. Options like this can prove to be of great benefit in the long run, as firms can quickly buy extra elements if needed for their project, and firms can sell off their elements if they have a surplus, making the HCS more easily accessible. INSERT is a platform made by the company Buro Boot where they have established an online marketplace for demolition companies to offer reusable building materials/components [76]. This idea should also be investigated as a possibility in Norway to streamline the accessibility of reusable building components in Norway.

10 Conclusion

This thesis explored the sustainability of prefabricated construction, focusing particularly on hollow-core slabs (HCS) within the Norwegian construction industry, The primary objective was to evaluate whether prefabrication could effectively reduce waste and mitigate the environmental impact associated with the construction sector. Through this exploration, the research has not only reinforced the viability of prefabrication as a sustainable practice but has also unveiled the substantial potential of reusing HCSs in extending the lifecycle of construction components.

A rigorous methodological framework was applied, integrating an extensive literature review with an in-depth case study of SIS-Velferdsbygg (SVB), to investigate the environmental and practical advantages of reusing HCSs in prefabricated construction. The case study conclusively illustrates that prefabricated HCSs can be effectively repurposed in new construction projects, highlighting the substantial benefits of prolonging the lifecycle of construction components. Such reuse practises will not only bolster environmental sustainability through significant reductions in material waste and carbon emissions but also enhance economic efficiency by eliminating both material and labour costs associated with the production of new elements.

The findings from the case study confirmed the initial hypothesis that prefabrication significantly reduces waste production and carbon emissions. However, the study also brought to light new questions in the realm of reuse. The feasibility of reusing HCSs and the importance of early planning and innovative design for connections to facilitate easy disassembly and reassembly were underscored. These insights suggest that the full benefits of prefabrication, particularly from a circular economy perspective, can only be realized through systemic changes in the construction industry's approach to project design and material lifecycle management.

This dual approach allowed for a robust analysis of both theoretical frameworks and practical outcomes, contributing significantly to our understanding of sustainable construction practises and the pivotal role of prefabrication and component reuse in advancing environmental and economic efficiencies in the construction sector.

The feasibility of reusing HCSs pivot critically on the design of connection systems that facilitate easy disassembly and reassembly. This thesis has developed comprehensive guidelines that standardize the reuse, disassembly, and testing of HCSs, aiming to assure their structural integrity and extend their serviceability. To overcome the existing barriers to the widespread adoption of these practises, such as cost concerns and industry resistance, this study proposes enhanced governmental incentives and robust educational programs to cultivate an industry-wide appreciation for sustainable practises.

While the research findings are promising, the study is not without its limitations. The focus on a single case study, although in-depth, provides a snapshot that may not capture all contextual and technical variables applicable to other projects or regions. Additionally, the adoption of new construction technologies and practises such as those advocated in this thesis requires changes in regulatory framework and market acceptance, which were outside the scope of this analysis.

This thesis marks a significant contribution to the constructional engineering field by elucidating the environmental and practical advantages of prefabrication and the reuse of HCSs. It calls for a paradigm shift from traditional construction methods to innovative reuse strategies, which not only reduce environmental impacts but also promote sustainability in the built environment. By advancing these practises, the construction industry can significantly diminish its carbon footprint and lead in the global pursuit of sustainable development. The insights gained from this study should pave the way for future research and action, setting a foundation for a more sustainable construction industry.

11 Further research

There are several key areas where future research could significantly enhance the understanding and implementation of prefabricated construction methods. Particularly concerning HCSs. The following sections discusses potential avenues for future research, each addresses a critical gap in the current knowledge and practise.

Innovative reusable connections:
Future studies should delve into the design and development of innovative connection systems tailored for prefabricated components, particularly focusing on reuse. This research should focus on creating modular connection designs that maintain structural integrity while allowing for easy disassembly and reassembly. Such designs would facilitate the reuse of components across various building projects. The designs should also adapt seamlessly to different architectural requirements and construction purposes.

Lifecycle analysis of reused prefabricated elements:
Future research should focus on making LCAs based on reuse projects. Such targeted LCAs can identify crucial intervention points that significantly reduce the carbon footprint. Additionally, this research would help develop system limits for reused HCSs and establish new standards for the EPD. These standards would be based on a CtC-principle, specifically tailored to reused elements in prefabricated construction.

Enhanced durability and maintenance strategies:
Future research should focus on strategies to extend the service life of prefabricated elements. This would involve creating self-healing concrete, advanced coatings, and additional protective measures. These advancements are designed not only to increase the durability and longevity of prefabricated components but also to decrease maintenance costs over time.

Adaptability prefabricated systems:
Research into the adaptability of prefabricated systems to various architectural styles and building requirements is crucial. This area should include studies on modular systems than can be easily reconfigured to accommodate evolving architectural and technological advancements.

Economic analysis of prefabrication reuse:
A comprehensive economic analysis of the reuse of prefabricated elements is essential. Such studies should encompass key economic metrics such as the one mentioned in the pre-disassembly evaluation. A CBA-analysis that consider not only the direct savings from reduced material use and waste but also the broader environmental impacts. This would help strengthen the business case for adopting reusable prefabricated elements in the construction industry.

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Appendix A- Environmental data for reuse case

Table A 1- Essential data on elements used in reuse case

	Length	Width	Thickness	Area	Mass	Total element	Total area	Total mass	Density	Total Volume HCS
Element ID	(mm)	(mm)	(m)	(m2)	(ton)		(m2)	(ton)	(tonnes/m3)	(m3)
2006	8400,00	1200,00	0,265	10,08	3,618	1	10,08	3,618	2,5	1,447
2075	8400,00	1200,00	0,265	10,08	3,618	25	252,00	90,444	2,5	36,177
2076	8400,00	1200,00	0,265	10,08	3,618	1	10,08	3,618	2,5	1,447
2084	8400,00	1200,00	0,265	10,20	3,661	14	142,80	51,254	2,5	20,502
2100	8400,00	1200,00	0,265	10,20	3,653	2	20,40	7,307	2,5	2,923
2108	8400,00	1200,00	0,265	10,20	3,669	15	153,00	55,032	2,5	22,013
2122	8400,00	1200,00	0,265	10,20	3,661	4	40,80	14,644	2,5	5,858
2161	8400,00	1200,00	0,265	10,08	3,618	11	110,88	39,794	2,5	15,918
2163	8400,00	1200,00	0,265	10,08	3,618	5	50,40	18,088	2,5	7,235
2165	8400,00	1200,00	0,265	10,08	3,618	5	50,40	18,088	2,5	7,235
2176	8400,00	1200,00	0,265	10,20	3,661	4	40,80	14,644	2,5	5,858
2178	8400,00	1200,00	0,265	10,20	3,661	4	40,80	14,644	2,5	5,858
2181	8400,00	1200,00	0,265	10,20	3,661	4	40,80	14,644	2,5	5,858
2213	8400,00	1200,00	0,265	10,20	3,661	2	20,40	7,322	2,5	2,929
2215	8400,00	1200,00	0,265	10,20	3,669	8	81,60	29,350	2,5	11,740
2225	8400,00	1200,00	0,265	10,20	3,661	1	10,20	3,661	2,5	1,464
2230	8400,00	1200,00	0,265	11,47	4,121	2	22,94	8,241	2,5	3,296
Total						108	1098,37	394,395		157,758

Table A 2- GWP data for each element from CtG analysis, reuse case

GWP, unit: kgCO2-eq									
	Production			Transport	Installation	Demolition			
Element ID	A1	A2	A3	A4	A5	C1	C2	C3	C4
2006	317,277	2,243	9,985	1,986	37,625	14,471	4,450	1,755	4,956
2075	7931,914	56,075	249,625	49,654	940,615	361,775	111,246	43,865	123,908
2076	317,277	2,243	9,985	1,986	37,625	14,471	4,450	1,755	4,956
2084	4495,011	31,778	141,462	28,139	533,046	205,018	63,043	24,858	70,219
2100	640,802	4,530	20,167	4,011	75,990	29,227	8,987	3,544	10,010
2108	4826,331	34,120	151,889	30,213	572,336	220,129	67,690	26,691	75,394
2122	1284,304	9,079	40,418	8,040	152,301	58,577	18,012	7,102	20,063
2161	3489,960	24,672	109,832	21,847	413,861	159,177	48,947	19,300	54,518
2163	1586,345	11,215	49,924	9,930	188,118	72,353	22,249	8,773	24,781
2165	1586,345	11,215	49,924	9,930	188,118	72,353	22,249	8,773	24,781
2176	1284,289	9,079	40,418	8,040	152,299	58,576	18,012	7,102	20,062
2178	1284,289	9,079	40,418	8,040	152,299	58,576	18,012	7,102	20,062
2181	1284,289	9,079	40,418	8,040	152,299	58,576	18,012	7,102	20,062
2213	642,152	4,540	20,209	4,020	76,150	29,289	9,006	3,551	10,031
2215	2574,015	18,197	81,007	16,113	305,242	117,401	36,101	14,235	40,210
2225	321,076	2,270	10,105	2,010	38,075	14,644	4,503	1,776	5,016
2230	722,739	5,109	22,745	4,524	85,707	32,964	10,136	3,997	11,290
Total	34588,412	244,525	1088,529	216,523	4101,705	1577,579	485,105	191,281	540,321

Table A 3- GWP data for each element with reuse approach

GWP, Unit: kgCO2-eq					
Reusing	Disassembly	Transport	Additional work	Transport	Installation
Element ID	E1	E2	F1	E2	E1
2006	37,625	1,986	9,985	1,986	37,625
2075	940,615	49,654	249,625	49,654	940,615
2076	37,625	1,986	9,985	1,986	37,625
2084	533,046	28,139	141,462	28,139	533,046
2100	75,990	4,011	20,167	4,011	75,990
2108	572,336	30,213	151,889	30,213	572,336
2122	152,301	8,040	40,418	8,040	152,301
2161	413,861	21,847	109,832	21,847	413,861
2163	188,118	9,930	49,924	9,930	188,118
2165	188,118	9,930	49,924	9,930	188,118
2176	152,299	8,040	40,418	8,040	152,299
2178	152,299	8,040	40,418	8,040	152,299
2181	152,299	8,040	40,418	8,040	152,299
2213	76,150	4,020	20,209	4,020	76,150
2215	305,242	16,113	81,007	16,113	305,242
2225	38,075	2,010	10,105	2,010	38,075
2230	85,707	4,524	22,745	4,524	85,707
Total	4101,705	216,523	1088,529	216,523	4101,705
AVG	241,277	12,737	64,031	12,737	241,277

Table A 4- WDP data for each element in CtG analysis, reuse case

WDP, unit m3									
	Production			Transport	Installation	Demolition			
Element ID	A1	A2	A3	A4	A5	C1	C2	C3	C4
2006	**5788,398**	**59,331**	**3006,349**	**200,061**	**2051,263**	**42,328**	**200,061**	**5933,108**	**336,812**
2075	**144709,944**	**1483,277**	**75158,727**	**5001,537**	**51281,587**	**1058,191**	**5001,537**	**148327,693**	**8420,310**
2076	**5788,398**	**59,331**	**3006,349**	**200,061**	**2051,263**	**42,328**	**200,061**	**5933,108**	**336,812**
2084	**82007,037**	**840,572**	**42592,405**	**2834,368**	**29061,244**	**599,676**	**2834,368**	**84057,213**	**4771,784**
2100	**11690,804**	**119,831**	**6071,911**	**404,063**	**4142,929**	**85,489**	**404,063**	**11983,074**	**680,259**
2108	**88051,651**	**902,529**	**45731,826**	**3043,285**	**31203,304**	**643,878**	**3043,285**	**90252,942**	**5123,505**
2122	**23430,853**	**240,166**	**12169,399**	**809,829**	**8303,309**	**171,338**	**809,829**	**24016,624**	**1363,383**
2161	**63670,870**	**652,626**	**33069,058**	**2200,624**	**22563,364**	**465,593**	**2200,624**	**65262,641**	**3704,849**
2163	**28941,304**	**296,648**	**15031,390**	**1000,284**	**10256,075**	**211,633**	**1000,284**	**29664,837**	**1684,022**
2165	**28941,304**	**296,648**	**15031,390**	**1000,284**	**10256,075**	**211,633**	**1000,284**	**29664,837**	**1684,022**
2176	**23430,582**	**240,163**	**12169,258**	**809,819**	**8303,212**	**171,336**	**809,819**	**24016,346**	**1363,367**
2178	**23430,582**	**240,163**	**12169,258**	**809,819**	**8303,212**	**171,336**	**809,819**	**24016,346**	**1363,367**
2181	**23430,582**	**240,163**	**12169,258**	**809,819**	**8303,212**	**171,336**	**809,819**	**24016,346**	**1363,367**
2213	**11715,426**	**120,083**	**6084,700**	**404,914**	**4151,654**	**85,669**	**404,914**	**12008,312**	**681,691**
2215	**46960,361**	**481,344**	**24390,037**	**1623,067**	**16641,578**	**343,398**	**1623,067**	**48134,370**	**2732,506**
2225	**5857,713**	**60,042**	**3042,350**	**202,457**	**2075,827**	**42,835**	**202,457**	**6004,156**	**340,846**
2230	**13185,661**	**135,153**	**6848,303**	**455,729**	**4672,669**	**96,420**	**455,729**	**13515,303**	**767,241**
	37119,498	**380,475**	**19278,939**	**1282,943**	**13154,222**	**271,436**	**1282,943**	**38047,486**	**2159,891**
Total	**631031,470**	**6468,073**	**327741,970**	**21810,025**	**223621,777**	**4614,418**	**21810,025**	**646807,257**	**36718,144**

Table A 5-WDP data for each element with reuse approach

WPD, unit: m3					
Reusing	Disassembly	Transport	Additional work	Transport	Installation
Element ID	E1	E2	F1	E2	E1
2006	2051,263	200,061	3006,349	200,061	2051,263
2075	51281,587	5001,537	75158,727	5001,537	51281,587
2076	2051,263	200,061	3006,349	200,061	2051,263
2084	29061,244	2834,368	42592,405	2834,368	29061,244
2100	4142,929	404,063	6071,911	404,063	4142,929
2108	31203,304	3043,285	45731,826	3043,285	31203,304
2122	8303,309	809,829	12169,399	809,829	8303,309
2161	22563,364	2200,624	33069,058	2200,624	22563,364
2163	10256,075	1000,284	15031,390	1000,284	10256,075
2165	10256,0747	1000,28383	15031,39	1000,28383	10256,0747
2176	8303,21246	809,819487	12169,2585	809,819487	8303,21246
2178	8303,21246	809,819487	12169,2585	809,819487	8303,21246
2181	8303,21246	809,819487	12169,2585	809,819487	8303,21246
2213	4151,65426	404,914428	6084,69964	404,914428	4151,65426
2215	16641,5779	1623,06748	24390,0375	1623,06748	16641,5779
2225	2075,82713	202,457214	3042,34982	202,457214	2075,82713
2230	4672,66863	455,729409	6848,3027	455,729409	4672,66863
total	223621,777	21810,025	327741,970	21810,025	223621,777
AVG	13154,222	1282,943	19278,939	1282,943	13154,222

Appendix B- SIS- Floor plan

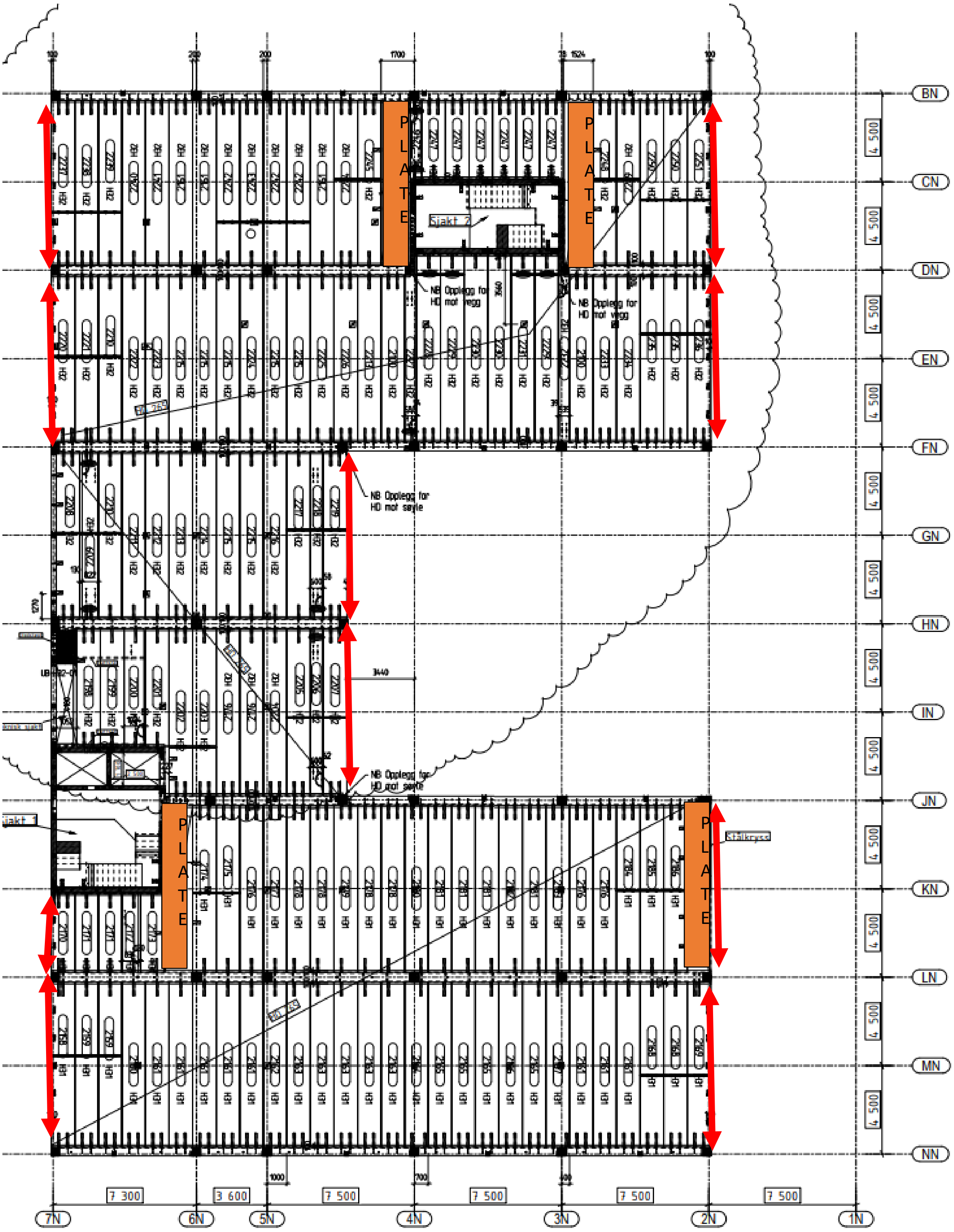


Figure 62- Additional loads on HCS above the third floor

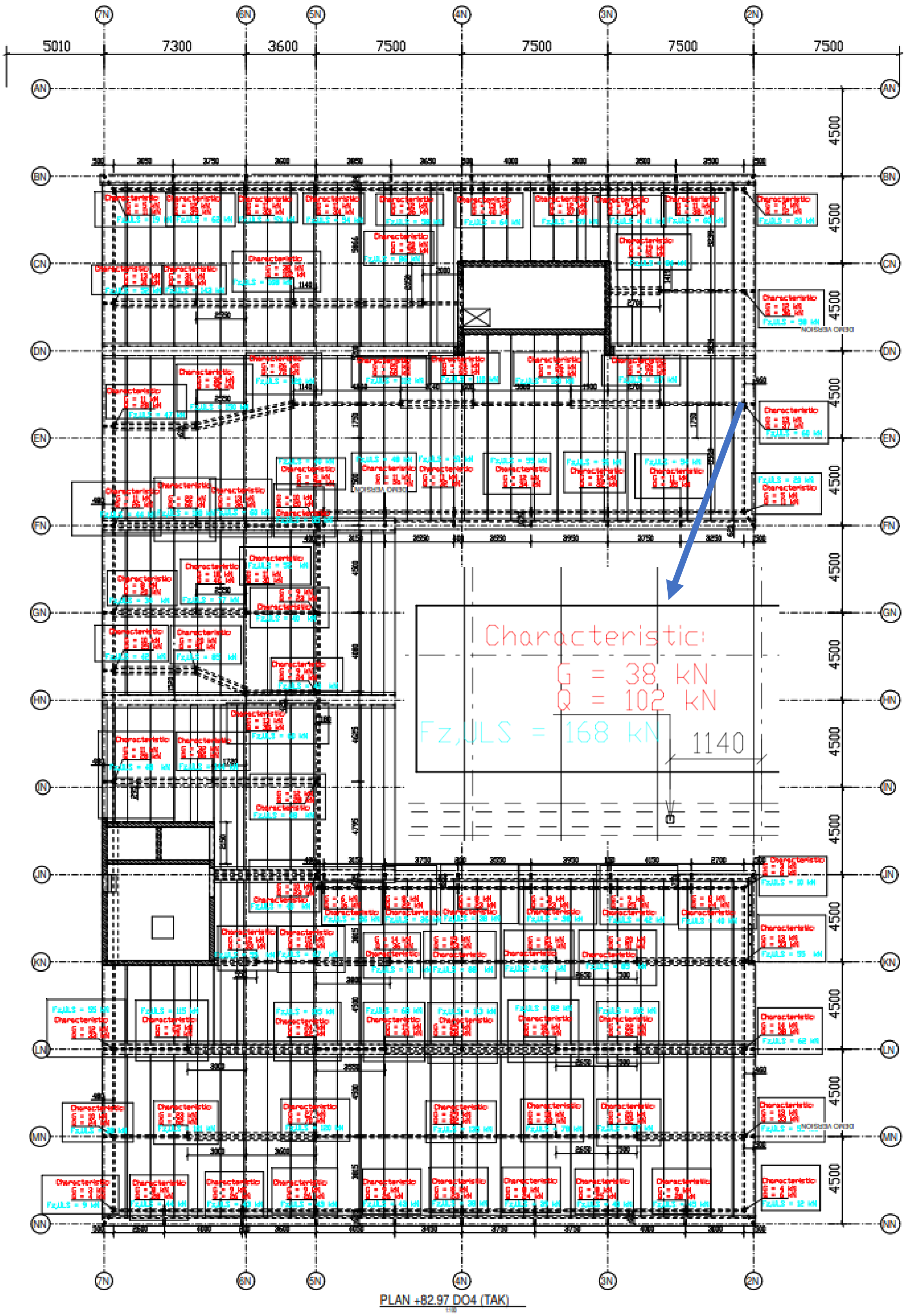
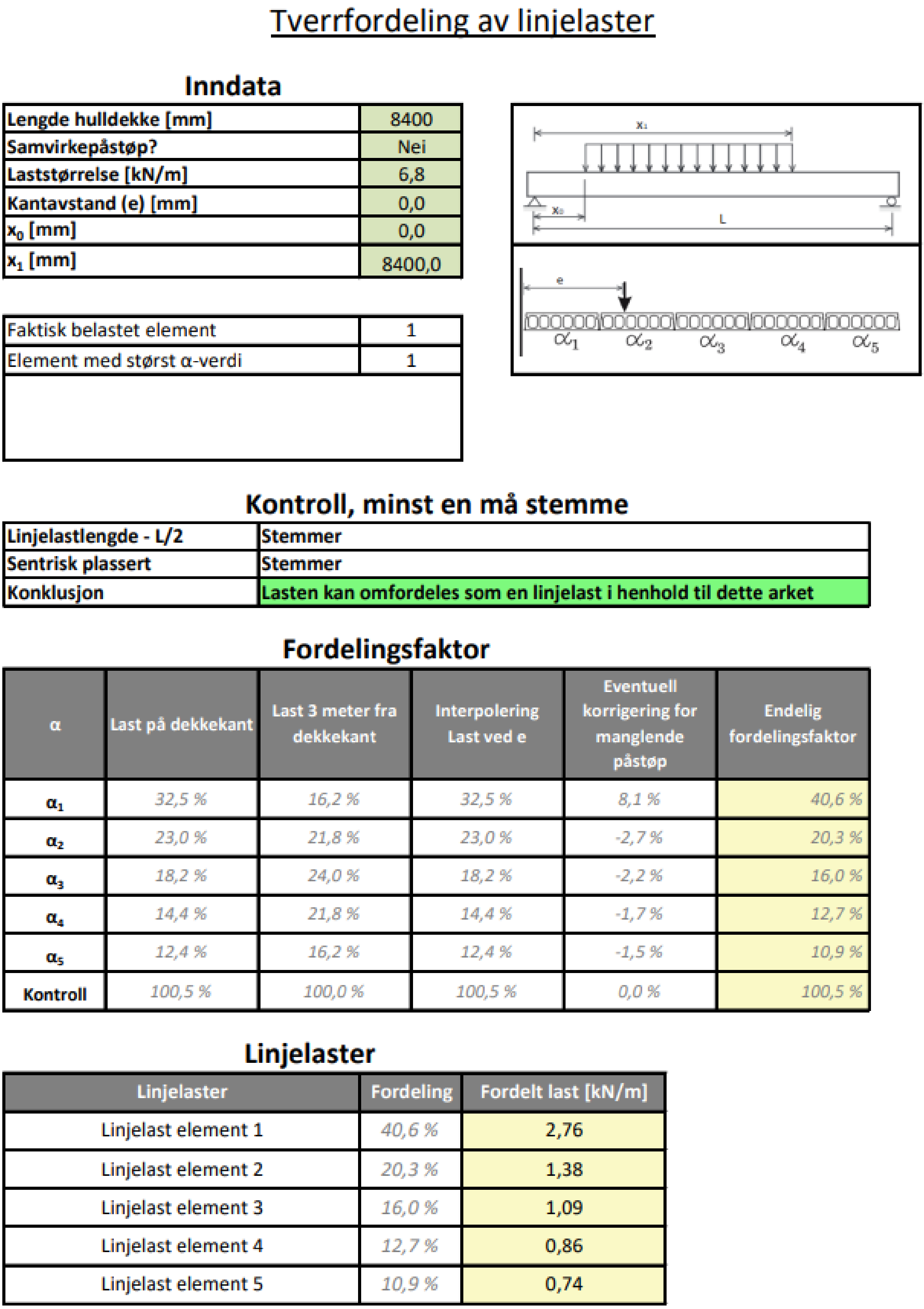


Figure 63- Point loads on 3rd floor



Tverrfordeling av linjelaster

Inndata

Lengde hulldekke [mm]	8400
Samvirkepåstøp?	Nei
Laststørrelse [kN/m]	6,8
Kantavstand (e) [mm]	0,0
x_0 [mm]	0,0
x_1 [mm]	8400,0

Faktisk belastet element	1
Element med størst α-verdi	1

Kontroll, minst en må stemme

Linjelastlengde - L/2	**Stemmer**
Sentrisk plassert	**Stemmer**
Konklusjon	**Lasten kan omfordeles som en linjelast i henhold til dette arket**

Fordelingsfaktor

α	Last på dekkekant	Last 3 meter fra dekkekant	Interpolering Last ved e	Eventuell korrigering for manglende påstøp	Endelig fordelingsfaktor
α_1	*32,5 %*	*16,2 %*	*32,5 %*	*8,1 %*	*40,6 %*
α_2	*23,0 %*	*21,8 %*	*23,0 %*	*-2,7 %*	*20,3 %*
α_3	*18,2 %*	*24,0 %*	*18,2 %*	*-2,2 %*	*16,0 %*
α_4	*14,4 %*	*21,8 %*	*14,4 %*	*-1,7 %*	*12,7 %*
α_5	*12,4 %*	*16,2 %*	*12,4 %*	*-1,5 %*	*10,9 %*
Kontroll	*100,5 %*	*100,0 %*	*100,5 %*	*0,0 %*	*100,5 %*

Linjelaster

Linjelaster	Fordeling	Fordelt last [kN/m]
Linjelast element 1	*40,6 %*	2,76
Linjelast element 2	*20,3 %*	1,38
Linjelast element 3	*16,0 %*	1,09
Linjelast element 4	*12,7 %*	0,86
Linjelast element 5	*10,9 %*	0,74

Figure 64- Calculation of line load