Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

Steinar Valbø

Investigating the Reuse of Cast-in-Place Reinforced Concrete in Load Bearing Structures in Norway

Master's thesis in MSc Sustainable Architecture
Supervisor: Gearóid Lydon
Co-supervisor: Henriette Mo Sandberg (Asplan Viak), Patricia Schneider-Marin

May 2023

NTNU
Norwegian University of
Science and Technology

Steinar Valbø

Investigating the Reuse of Cast-in-Place Reinforced Concrete in Load Bearing Structures in Norway

Master’s thesis in MSc Sustainable Architecture
Supervisor: Gearóid Lydon
Co-supervisor: Henriette Mo Sandberg (Asplan Viak), Patricia Schneider-Marin
May 2023

Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

NTNU
Norwegian University of
Science and Technology

Abstract

Concrete is the second most consumed material in the world after water, with 30 billion tonnes being used annually and a steadily increasing demand. Due to the large emissions from its production, this consumption has led to concrete being one of the main emitters of greenhouse gasses in the building industry. Therefore, in order to limit the on-going climate changes, a reduction in the emissions from concrete is necessary.

More than 22 000 buildings are demolished every year in Norway, leading to large amounts of waste. In 2021, 8% of the waste that was produced in Norway was from concrete, bricks and other heavy building materials alone. Some of this waste is recycled, primarily into crushed concrete aggregates, but a large amount is disposed of in landfills. Following the waste hierarchy set by the European Union (EU) and the Norwegian ministry of climate and environment, recycling is ranked third in preferred methods for handling waste. While reduction is the highest ranked method, some waste will likely always occur, leaving reuse as the preferred method for handling it.

Reuse of cast-in-place (CIP) reinforced concrete (RC) can be seen as challenging due to the nature of its construction, as interconnected custom-made structures. However, newer research and pilot projects show that it could be a viable practice. The research has also found that reuse could represent a significant reduction in GWP of the structure.

Designing with reused components has been stated as a challenge. To achieve an efficient design process, the components should be identified at an early stage in the design process, eliminating multiple revisions of the design. However, early procurement of the components leads to the need for storage. This can lead to additional costs in the project. Marketplaces for used building materials are now being established, and could have the potential to combat the challenge of timing between procurement and use of reclaimed components, eliminating the need for storage.

Documentation of the reclaimed components is also stated by several researchers as one of the key challenges for reuse of CIP RC. For a product to be sold in Norway, it needs to be approved in line with set requirements and standards. A used CIP RC component might have previous documentation that can be used as a basis for documenting its quality, but seen as its properties are likely altered during extraction from a donor building, tests are necessary for it to be redocumented. Such tests were outlined in the standard for reuse of hollow core concrete that was published in 2022. Hollow core concrete elements are however precast, thus being of a more predictable nature than CIP RC.

In this thesis, a questionnaire was conducted to establish what additional challenges is a project implementing reuse of CIP RC in load bearing structures in Norway likely to face compared to one that only uses virgin materials. Further, an LCA was conducted to investigate how the global warming potential could be affected when choosing reused over new CIP RC in load bearing structures. The potential implications of choosing reused over new CIP RC in load bearing structures were also investigated.

It was found that the Norwegian building industry is motivated for reuse, but that several barriers are present. Primarily, documentation of components and logistics are pointed out to be most significant. The barrier of documentation could be overcome by establishing standardized solutions for testing while logistics could be improved though establishment and use of marketplaces. Reuse of CIP RC columns was estimated to represent a significant reduction in the GWP of a load bearing structure compared to using new concrete, with reassembly being the largest contribution to its total GWP. The reuse’s potential impact on the lifespan of the building and availability of crushed concrete aggregates should however be taken into account.

Sammendrag

Betong er verdens nest mest brukte materiale etter vann, med et årlig forbruk på 30 milliarder tonn og en stadig økende etterspørsel. På grunn store utslipp under produksjonen av materialet har dette forbruket ført til at betong er en av de største utslippskildene av klimagasser i byggebransjen. For å begrense de pågående klimaendringene er det derfor nødvendig å redusere utslippene fra betong.

Hvert år rives mer enn 22 000 bygninger i Norge, noe som fører til store mengder avfall. I 2021 kom 8 % av avfallet som ble produsert i Norge fra betong, murstein og andre tunge byggematerialer. Noe av dette avfallet gjenvinnes, først og fremst til knust betong, men en stor del deponeres. I henhold til avfallshierarkiet som er fastsatt av EU og Klima- og miljødepartementet, er resirkulering rangert på tredjeplass over foretrukne metoder for avfallshåndtering. Selv om reduksjon er den høyest rangerte metoden, vil det sannsynligvis alltid oppstå noe avfall. Da vil gjenbruk være den foretrukne metoden for håndtering dette.

Ombruk av plasstøpt (CIP) armert betong (RC) kan oppleves som utfordrende på grunn av konstruksjonens art, som er sammenkoblede, skreddersydde strukturer. Nyere forskning og pilotprosjekter viser imidlertid at det kan være en levedyktig praksis. Forskningen har også vist at gjenbruk kan gi en betydelig reduksjon i konstruksjonens GWP.

Å designe med gjenbrukte komponenter har blitt beskrevet som en utfordring. For å oppnå en effektiv designprosess bør komponentene identifiseres på et tidlig stadium i designprosessen, slik at man unngår flere revisjoner av designet. Tidlig anskaffelse av komponentene fører imidlertid til behov for lagring. Dette kan føre til ekstra kostnader i prosjektet. Det er nå i ferd med å etableres markedsplasser for brukte byggematerialer, og disse kan ha potensial til å løse utfordringen med tidsaspektet mellom anskaffelse og bruk av gjenbrukte komponenter, slik at behovet for lagring elimineres.

Dokumentasjon av de gjenvunnede komponentene nevnes også av flere forskere som en av hovedutfordringene for gjenbruk av CIP RC. For at et produkt skal kunne selges i Norge, må det være godkjent i henhold til fastsatte krav og standarder. En brukt CIP RC-komponent kan ha tidligere dokumentasjon som kan brukes som grunnlag for å dokumentere kvaliteten, men siden egenskapene sannsynligvis er endret under uttaket fra en donorbygning, er det nødvendig med tester for å dokumentere kvaliteten på nytt. Slike tester ble beskrevet i standarden for hulldekker av betong til ombruk som ble publisert i 2022. Hullbetongelementer er imidlertid prefabrikkerte og dermed av en mer forutsigbar karakter enn CIP RC.

I denne oppgaven ble det gjennomført en spørreundersøkelse for å finne ut hvilke ekstra utfordringer et prosjekt som implementerer ombruk av CIP RC i bærende konstruksjoner i Norge sannsynligvis vil møte, sammenlignet med et prosjekt som kun bruker nye materialer. Videre ble det gjennomført en LCA for å undersøke hvordan GWP kan påvirkes ved å velge ombruk fremfor ny CIP RC i bærende konstruksjoner. Det ble også undersøkt hvilke konsekvenser det kan ha å velge ombruk fremfor ny CIP RC i bærende konstruksjoner.

Det viste seg at den norske byggebransjen er motivert for ombruk, men at det finnes flere barrierer. Dokumentasjon av komponenter og logistikk trekkes frem som de viktigste. Dokumentasjonsbarrieren kan overvinnes ved å etablere standardiserte løsninger for testing, mens logistikken kan forbedres gjennom etablering og bruk av markedsplasser. Gjenbruk av CIP RC-søyler ble estimert til å representere en betydelig reduksjon i GWP for en bærende konstruksjon sammenlignet med bruk av ny betong, med remontering som det største bidraget til den totale GWP. Det bør imidlertid tas hensyn til gjenbrukets potensielle innvirkning på bygningens levetid og tilgangen på knust betong.

Acknowledgments

This thesis marks the end of a two-year master of science in sustainable architecture. The program has taught me countless valuable lessons through working side by side with architects in designing sustainable buildings and the technical aspects that are included in them.

The thesis has been written over a period of five months, during which I have gotten continuous and good help from my supervisors and others.

First and foremost, I want to thank my main supervisor Gearóid Lydon for good and regular feedback. Through weekly meetings, Gearóid has guided me through the, at times overwhelming, process of writing a master thesis in a calm and supportive manner.

Secondly, I want to thank my co-supervisor Patricia Schneider Marin who gave me good guidance in setting up the LCA-part of the thesis. I also want to thank Pasi Alto for countless well-answered questions about the questionnaire that was conducted and the processes surrounding it.

Through the research project GjenOm, I got the chance to discuss the topic of my thesis with people from the industry, giving valuable insight into possibilities and obstacles with reuse of cast-in-place concrete in load bearing structures. The work that was done and thoughts that were shared gave valuable pointers to what should be focused on. A special thanks goes to Trondheim Municipality for working on setting up a case study for the thesis. Even though this did not come through all the way, due to obstacles not of their fault, the data that was supplied came to good use for the LCA that was completed in the thesis.

Lastly, I want to thank my external supervisors at Asplan Viak AS. They have been of great help since before day one and have continued to answer questions and give generous support. Asplan Viak AS also ensured a valuable connection to the industry when conducting the questionnaire. A special thanks goes to Henriette Mo Sandberg for working as my main contact person, arranging for me to work on my thesis at their office, giving me access to their LCA software and much more. Further, I want to thank Thomas Munkeby, Jill Saunders and Terje Kristoffersen among others for valuable discussions and guidance.

Steinar Valbø

Steinar Valbø

Trondheim, 26.05.2023

Table of Contents

List of tables

List of figures

Abbreviations

RC – Reinforced Concrete

CIP – Cast-In-Place

GWP – Global Warming Potential (also referred to as emissions)

DfD – Design for Disassembly

GHG – Greenhouse Gas

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

BREEAM – Building Research Establishment's Environmental Assessment Method

CO_2-eq – Carbon Dioxide Equivalent

1 Introduction

Concrete is the second most consumed material in the world after water, with 30 billion tonnes being used annually and a steadily increasing demand (‘Concrete needs to lose its colossal carbon footprint’, 2021). The cement production for this alone accounts for 5-6% of the global greenhouse gas emissions. The industry is set to focus on “clear and tangible actions for transitioning to low-carbon production”, but it has been found that the technologies needed to lower the CO_2 emissions are adopted too slowly. In 2018, it was stated in the UN climate change news that, at the current pace of implementation of the necessary technologies, the cement industry would only achieve 50% of the reduction in CO_2 emissions that is required to meet the Paris Agreement goal (UN Climate Change, 2018).

Significant changes are developing within the concrete industry, with low-carbon options cutting the emissions by up to 63% (Unicon AS, 2023), the introduction of recycled concrete using crushed concrete as aggregate (Veidekke, 2022), and experimentation with alternative materials for reinforcement (Skaar and Rambæk, 2019). While reducing the environmental impact of new concrete is necessary to reach the climate goals, a reduction in its use would be more efficient. Concrete is however, in some uses, an irreplaceable building material, making it impossible to fully eliminate its use. A solution could therefore be to build less new buildings. Harald Vaagaasar Nikolaisen, CEO of Statsbygg, states that we can’t build our way out of the climate crisis (Statsbygg, 2022). More than 22 000 buildings are demolished yearly due to lack of function or performance, outdated aesthetics, concerns about cost of refurbishment, etc., often before their technical lifespans are met (Solgaard and Th. Bramslev, 2019). Rather than demolishing, these buildings should therefore be refurbished or rehabilitated. If it is seen as necessary to demolish a building, its embodied resources could be utilized in new projects, eliminating the need for production of new building components. Due to the large emissions from production of new concrete in particular, utilizing concrete components from these buildings could contribute to a reduced environmental impact from construction of new buildings.

Reuse of building materials has increasingly become an important research topic over the past few years. In 2022, a Swiss university (EPFL) published a report on an experimental 10-metre-long footbridge made from reclaimed cast-in-place (CIP) reinforced concrete (RC) blocks, showcasing its feasibility. The same year, a Norwegian standard on reuse of hollow core concrete slabs was published. In 2023, a warehouse for selling reused building materials was also established in Oslo, Norway. These developments show that reuse of building materials is becoming more available to the industry.

Reuse of CIP RC is however not a common practise. Despite pilot projects and research that has been completed, many barriers remain. Documentation and logistics are among the barriers that are most frequently pointed out (Entra ASA et al., 2021; Gorgolewski and Morettin, 2023). Proper documentation of building materials is necessary to ensure that the products performance meets the necessary requirements in line with relevant standards. By documenting a building material according to established standards, the distributer eliminates the risk of liability if the building material does not perform as expected. Documentation of reclaimed CIP RC can be challenging. If previous documentation of the component is not available, the properties of the reinforcement and concrete must be determined, as well as their remaining lifespan. This task must be completed through testing. The standard for reuse of hollow core concrete has established a testing procedure that could be applicable to reuse of CIP RC (Standard Norge, 2022), but seen as CIP RC is a less predictable material than hollow core concrete (that are precast), the procedure is likely to need modifications.

Logistics is also pointed out to be challenging, primarily in the form of storage of components (Entra ASA et al., 2021). When planning a project, it can be beneficial for the design team that the components that are to be reused are identified at an early stage (Gorgolewski and Morettin, 2023). However, to do this, the components must be acquired and stored until the construction process can start. This additional step can lead to increased cost in the project (Gorgolewski and Morettin, 2023). To combat this, alternative solutions have been proposed, e.g. buying the donor building or establishing a market place for used building materials (Reppe, 2021; Gorgolewski and Morettin, 2023).

This report investigates the drivers and barriers for reuse of CIP RC to expand the basis for further research and eventual implementation of it in the building industry. A questionnaire was conducted to determine the current state of reuse in the Norwegian building industry, and establish the industry's motivation for reuse of CIP RC. Further, an LCA was completed to investigate the environmental impact reuse of CIP RC could have on a project.

It was found that the industry is motivated for reuse, but at the same time identifies several barriers to establish it as a common practise. The environmental impact of a reused CIP RC column was also estimated to represent a significant potential for reduced GWP of a load bearing structure.

The report will begin with an introduction to concrete and establish its environmental impact. In section 2, a literature review is presented including a state-of-the-art review on reuse and an investigation of the process of reuse. A short introduction to LCA is given before the methodology that is applied in the project is presented in section 3. The results from the questionnaire and LCA is then presented in section 4 before they are analysed and discussed in section 5. The limitations of the research that is done are also outlined in section 5 before the main conclusions are presented in section 6. Suggestions for further work are given in section 7.

1.1 GjenOm

The thesis is written as part of the research project GjenOm established by Trondheim municipality. The project is a collaboration between Trondheim municipality, Norwegian University of Science and Technology (NTNU), Sintef, Loopfront and Asplan Viak. It looks into increasing the efficiency of the process related to reuse of concrete in load bearing structures by looking at, among other things, what extra considerations must be taken in the planning process of a project including reused products compared to one only using virgin materials. Further, what parameters must be calculated, tested and/or verified to make recommendations on possible uses of the component based in the relevant rules and regulations. The goal of the research project is to identify necessary flow of information and decision-making in a process for reuse of cast-in-place concrete in load bearing structures.

1.2 Research question

1. What additional challenges is a project implementing reuse of cast-in-place reinforced concrete in load bearing structures in Norway likely to face compared to one that only use virgin materials, and how can these challenges be overcome?
2. How is the global warming potential affected when choosing reused over new cast-in-place reinforced concrete in load bearing structures?
3. What are the potential implications of choosing reused over new cast-in-place reinforced concrete in load bearing structures?

1.3 Goal

This report sets out to identify challenges relating to projects that reuse cast-in-place (CIP) reinforced concrete (RC) in a Norwegian context. Identifying these challenges can form a basis for further research on the topic while also informing relevant parties about what additional considerations should be taken to reduce their impact.

Further, the effects of reuse of CIP RC will be explored to ensure that the decisions made for or against reuse can be made on an informed basis. The global warming potential is among the effect that will be explored, estimating whether reuse of CIP RC can play a role in a high emitting industry facing the climate crisis.

1.4 Scope and limitations

The scope of the thesis is limited by the timeframe of an MSc thesis, which is approximately 5 months. Seen as reuse of CIP RC is a comprehensive topic with limited previous research, the focus has been on outlining the key factors that stand out compared to the use of virgin materials. Therefore, the research in this report is limited to:

- Reuse of CIP RC on a new site. For example, reuse of existing load bearing structures that are not demolished and transported to a new site are not included, nor refurbishment and rehabilitation of old structures.
- The structural engineering concerns related to reuse of used CIP RC components will not be investigated in detail.
- The testing and documentation of reclaimed components will not be investigated in detail.
- The life cycle assessment (LCA) will only be conducted for reuse of CIP RC columns.
- The LCA is only investigating the global warming potential (GWP) of the reused component.
- Possible implications will not be quantified.

2 Background and review

2.1 The sustainable development goals

The UN has set 17 sustainable development goals with the aim of urging the worlds inhabitants to take action to prevent poverty, protect the planet and improve the lives and prospects of everyone, everywhere (‘The Sustainable Development Agenda’, no date). Goal number 11, 12 and 13 can be seen in connection with what can be achieved through reuse of cast-in-place (CIP) reinforced concrete (RC).

Sustainable development goal 11 aims to make cities and human settlements inclusive, safe, resilient and sustainable. The first target within this goal is to ensure adequate, safe and affordable housing and basic services and upgrade slums (‘Cities - United Nations Sustainable Development Action 2015’, no date). This target will likely involve the demolition of old buildings that no longer meet the required criteria. The demolition, followed by the construction of new buildings will likely lead to significant emissions of greenhouse gasses, noise, fumes and waste. Disassembly and reuse of old structures could contribute to mittigating these emissions, ensuring cleaner air and less pollution in cities.

Sustainable development goal 12 aims for sustainable consumption and production patterns. Unsustainable patterns of consumption and production are stated to be among the main causes of the triple planetary crises of climate change, biodiversity loss and pollution (‘Sustainable consumption and production’, no date). The building industry contributes to more than 30% of the use of natural resources and 25% of the solid waste globally (Benachio, Freitas and Tavares, 2020). By implementing reuse of building materials as a common practise, this consumption can be greatly reduced. A lot of progress has been done on the topic the last years, but reuse of CIP RC concrete is still lagging behind.

Sustainable development goal 13 focuses on decreasing and eventually mitigating the emissions of greenhouse gasses (GHG) that causes global warming. The goal is quantified in the Paris Agreement with emissions having to decline by 43% by 2030 and to net zero by 2050 in order to not exceed the limit of 1,5^{o}C increase in temperature above the pre-industrial level (‘Climate Change’, no date). The materials and construction process needed for new buildings are currently responsible for 11% of the global emissions while, as previously stated, the emissions from cement production alone is responsible for 5-6% (World Green Building Council, 2023). The potential for making a significant contribution in the fight against climate change is therefore present through reuse of building materials. Reuse will lead to a reduced need for virgin materials, lowering the emissions of GHG from their production.

2.2 Concrete

Varying forms of concrete have been in use since the ancient Egypt civilisation. In the early 19th century, the form of concrete that is commonly used today was developed, where a mix of clay and chalk is burnt to form Portland cement. It, together with aggregates and additives, is what makes up concrete. The aggregates can be gravel, sand, or crushed rocks, among other things, and is the part of concrete that gives it its strength, while the cement acts like a glue to hold it together. Different forms of additives can be included to give the concrete special properties for certain tasks (Thue, 2023).

To create cement limestone (calcium carbonate, $CaCO_3$) is heated up to be converted into lime (calcium oxide, CaO) and carbon dioxide (CO_2). The necessary heat is often achieved through combustion of fossil fuels. It is this combustion as well as the calcination process in itself that contributes to the large emissions from cement production (Mikulčić *et al.*, 2012). The total yearly emissions from this production is estimated to be around 2,4 billion tons of CO_2-equivalents, whereof about two thirds are from the calcination process (Årtun, Nesse and Eide, 2023). To achieve the same emissions with a large petrol car, it would have to be driven around the world six times a second throughout the year (Horne, 2020).

When the concrete is poured and hardens, the calcium oxide reacts with water and is converted into calcium hydroxide (Ropp, 2013). The calcium hydroxide in the hardened concrete further reacts with CO_2 in the atmosphere to form calcium carbonate ($CaCO_3$) (Park *et al.*, 2021). This process is called carbonation and works from the surface of the concrete and inwards. The carbonation process lowers the pH-level of the concrete from about 13 to about 9. Reinforcement steel is generally an important part of concrete, and at a pH-level of 13, the concrete has a corrosion preventative effect on the steel. As the pH-level drops, this effect is reduced, leading to increased corrosion, cracking and eventually peeling of the outer layers of the concrete. This can eventually lead to a concrete structure losing its load bearing capabilities and collapsing. These effects of carbonation pose a serious threat to old concrete structures that have been exposed to the environment (Thue, 2020).

The aggregates used in concrete are, as mentioned, mainly gravel, sand, or crushed rocks. These resources has generally been perceived as endless but due to the vast consumption of these materials worldwide, the world is facing a scarcity. Especially sand is pointed out to be a threatened resource due to its use in not only concrete but also glass and silicone production. In the case of concrete production, not all types of sand can be used. Desert sand, which covers large parts of the face of the earth, is not suited seen as it has been ground down by the wind, giving it smooth surfaces which will not give the necessary binding effect that sand from quarries or rivers gives (UN environment programme, 2022).

2.3 Cast-in-place reinforced concrete as a structural material

Reinforced concrete (RC) is one of the most important materials in today's building industry, and has been so for many decades after it was first introduced in the late 19th century (Thue, 2023). Making use of the high compressive strength of the concrete together with the tensile strength of the steel makes reinforced concrete a highly efficient and versatile material.

Concrete is poured in liquid form into formworks that are built on-site and disassembled once the concrete has set. This process makes it possible to create large and intricate elements that would otherwise be too heavy for transportation. The formwork is disassembled when the concrete has reached sufficient strength, before it continues hardening until reaching its dimensioning strength after 28 days (Sørensen, no date).

In the case of cast-in-place RC, the reinforcement bars are generally put into the formwork before the concrete is poured. An exception is with fibre-reinforced concrete, where fibres of steel, plastic, metalized plastic waste or other materials are used in addition to or instead of conventional reinforcement bars (Bhogayata, 2019). The fibres are then poured together with the concrete, providing additional tensile strength without the additional work of placing the reinforcement bars.

Building with RC can be seen as a relatively efficient and straight forward process. This efficiency is due to the method of assembly. Rather than dealing with small grids of load bearing structures, RC is often implemented as bigger elements like walls and slabs, large beams and columns that are all interconnected, distributing all the forces present in a structure.

The downside of this method is that the elements must be custom made for its specific load case, meaning that its geometry and load bearing properties due to quality of concrete and rebar distribution will vary significantly. The geometry of an element is easily determined through a visual inspection, but the quality of the concrete and rebar distribution can only be identified through previous documentation and/or a series of tests and cutting the element to complete a visual inspection.

2.4 Reinforcement

RC includes reinforcement in the form of steel bars, wires or fibres taking up tensile forces that the concrete is less capable of coping with, or to provide additional strength to lower the need of concrete. This reinforcement is calculated for specific load cases, meaning that it varies greatly between elements with different purposes like walls and slabs, as well as between elements with different geometrical properties like height, thickness or width.

Steel bars, the most commonly used form of reinforcement in concrete, can be divided into categories based on what purpose they serve in an element. For columns, this is primarily longitudinal and transverse rebar (Standard Norge, 2021). An illustration of reinforcement steel in a column is shown in figure 4. The longitudinal rebar runs along the height of the column (red) with a main purpose of taking up compressive forces. The transverse rebar runs perpendicular to the longitudinal rebar (blue).

For beams or plates spanning in one direction (only supported in two ends), there are four main types of reinforcement: longitudinal, shear, torsional and surface bars (Standard Norge, 2021). The longitudinal bars runs along the length of the span (red) and takes up compressive and tensile forces in the bottom and top of the beam. The shear reinforcement are vertical bars (blue) taking up shear forces. The torsional rebar wraps around the surface of the beam, perpendicular to the length of the span (blue), and takes torsional, or twisting forces in the beam. The torsional and shear reinforcement are in figure 5 combined and placed along the surface of the concrete working also as surface reinforcement, preventing the surface of the concrete from cracking.

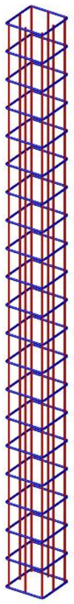

Figure 1: Concept of reinforcement of a concrete column.

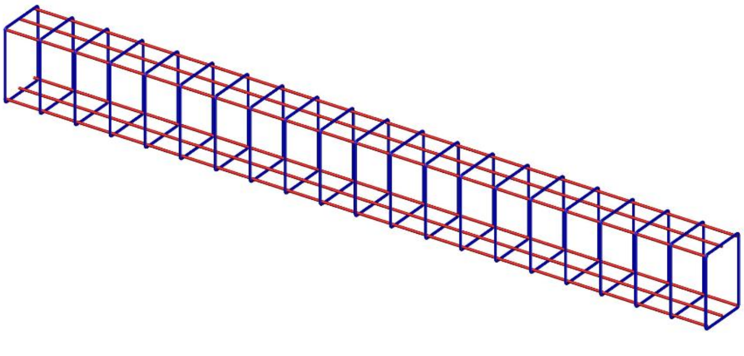

Figure 2: Concept of reinforcement of a concrete beam.

The longitudinal reinforcement of a beam or plate that takes tensile forces can also be achieved with cables. The cables are then prestressed before the concrete is put under load, leaving the concrete in compression. As load is put on the component, the prestressed cables will take up a portion of the forces before the concrete come under tension. The component can then be used over larger spans or for higher loads without the concrete experiencing tensile forces and cracking (Hannant, Venkata Siva and Rama Sreekanth, 2018).

Fibre-reinforced concrete (FRC) has gained increased attention the recent years (Lin and Yoda, 2017). FRC utilize the tensile strength of short fibres of steel or polymers to increase the flexural strength, energy absorption capacity and ductility performance, making for a more isotropic material (Mohammadhosseini *et al.*, 2020).

2.5 Concrete waste

Of all the waste produced in Norway in 2021, the building industry accounted for 25%. This amount was a 15% reduction from 2020 when the share was 40%. 38% of this waste comes from concrete waste, brick and other heavy building materials that are not contaminated, whereof 85% comes from demolition and refurbishment of buildings (SSB, 2023a). Summed up, this means that 8% of all the waste produced in Norway in 2021 came from non-contaminated concrete, brick and other heavy building materials from demolition or refurbishment of buildings, equivalent to about 590 000 tonnes. Disregarding the fact that some of this material is bricks and other heavy building materials, this would be equivalent to a more than 337 km long 200 mm thick and 3,5 meter tall concrete wall, spanning from Oslo to Dombås, or more than 36 000 concrete lorries, or "cement trucks", carrying on average 6.5 m^3 of fresh concrete.

2.6 The three R's – reduce, reuse, recycle

Both for the European Union (EU) and the Norwegian ministry of climate and environment, the strategies for handling waste to reduce emissions can be summed up in the waste hierarchy. There the preferred approaches for dealing with waste are ranked from most preferable to least preferable, whereof the three R's rank the highest. The three Rs include, from most preferable to least, reduce, reuse and recycle.

2.6.1 Reduce

The most preferable method for dealing with waste to limit emissions is simply to reduce the amount that is made of it. This strategy means less packaging material for groceries and other types of products, not throwing away food, or to use the same jacket for one more winter. In terms of the building industry, reducing waste can be done by building versatile and solid structures that last for longer than the required 60 years. The topic of reducing waste is however not relevant for this thesis and will not be further discussed.

2.6.2 Reuse and Circular Economy

Even when aiming for reduction of waste, it is not possible to eliminate it. The most efficient way to deal with the waste that inevitably forms, is then to utilize its embodied resources through reuse. By reusing waste, the lifespan of the product is expanded, while eliminating the need to produce a new product, thus eliminating its emissions and resource demand. While reuse may not completely eliminate emissions in all cases, it is an efficient approach to significantly reduce them. Reuse is today a relatively common practice both in normal day-to-day life and in industries. The Norwegian web page "finn.no" is a good example of how efficient and valuable reuse can be. In early 2023, a warehouse for selling reused building materials was also established in Oslo, Norway, showing that reuse is becoming more available in the building industry as well (FutureBuilt, 2023).

In 2022, the Norwegian Building Authority (Direktoratet for Byggkvalitet – DiBk) made the addition to the minimum requirements for new buildings that they should be designed for disassembly (DfD). After the set deadline of July 1st 2023, all new buildings should therefore be planned and built with materials that are suited for reuse in a way that is easily deconstructed, provided that it is feasible within practical and economical reason (Direktoratet for byggkvalitet, 2023a).

The effect that reuse can have in regards to its impact on the climate can vary greatly depending on in what way an element is reused. Reuse can be divided into three different levels (Küpfer, Bastien-Masse and Fivet, 2023):

Equivalent reuse:	When an element needs to fulfil the same requirements in its new use as it did in the building that it was extracted from. E.g., a column is reused in a new building as a column with equal loads as it was originally designed for.
Downcycling reuse:	When the requirements of an element are lower in its reused state compared to its original use. E.g., a column is reused as a bench where the variety and scale of loads are smaller than what it was originally designed for.
Upcycling reuse:	When the requirements of an element are greater than those of the original use. E.g., two floor dividers, previously simply supported, are sandwiched together to be used as a cantilevered slab.

If an element is to be reused with high resource efficiency, it is favourable to utilize the full capacity of the element. If an element is downcycled, a portion of the resources in it are not utilized to its full potential (or at all), meaning that the element that it potentially could substitute an element with greater requirements and resource demand. Equivalent or upcycling reuse can therefore be seen as favourable to downcycling reuse. In figure 6, Küpfer, Bastien-Masse and Fivet has illustrated how equivalent reuse fits into the life-cycle of a concrete component (Küpfer, Bastien-Masse and Fivet, 2023).

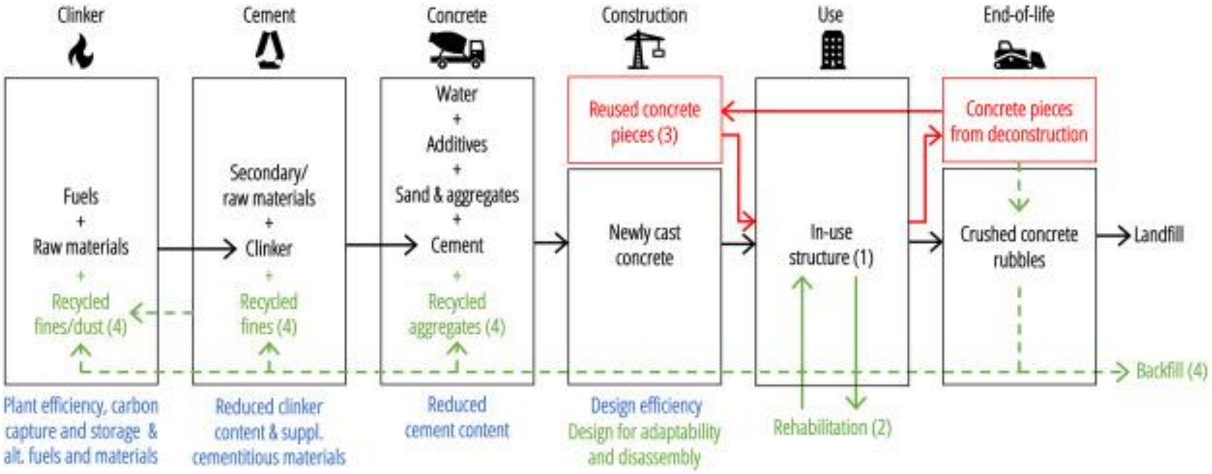

Figure 3: Equivalent reuse of a concrete component in a life-cycle perspective (Küpfer, Bastien-Masse and Fivet, 2023).

Reuse is the basis of what is known as circular economy. In a circular economy, all forms of waste are returned back to the market or used more efficiently, thus decreasing the impact on the environment through reducing waste and the use of raw materials. The United Nations Conference on Trade and Development (UNCTAD) emphasise that circular economy entails markets that give incentives to reusing products, rather than scrapping them and then extracting new resources (*Circular Economy: The New Normal*, 2018). Circular economy have been shown to several researchers to have a positive impact on the lowering of GHG emissions (Benachio, Freitas and Tavares, 2020).

2.6.3 Recycle

Recycling is the third ranked waste management strategy in the waste hierarchy and is the most common strategy in Norway (SSB, 2023b). Recycling means reprocessing of waste into new products, materials or substances. Recycling is the most efficient way of handling waste, in terms of its impact on the environment and human health, when it cannot be reused (European Parliament, 2008).

2.6.4 Energy recovery

When recycling waste is not possible due to contamination of the materials, or that the material is not suited for it, it can be incinerated. This way, the embodied energy is the resource that is recycled. If this approach is not possible, the product can be incinerated without utilizing its embodied energy, or it can be disposed of at a landfill. Neither energy recovery, incineration without energy utilization nor disposing of waste in a landfill is counted as recycling. Energy recovery is however the preferred method of the three per the waste hierarchy (European Parliament, 2008).

2.7 Reuse and recycling of concrete today

Reuse and recycling of concrete has progressed the last few years, with hollow-core concrete slabs from Regjeringskvartalet being reused in other buildings, and EPFL building a footbridge from cut concrete blocks (Entra ASA et al., 2021; Devènes *et al.*, 2022). These advances are however not a common practise, and mainly happen in research and pilot projects. In Norway, the majority of concrete waste ends up in landfills, about 54%, while about 41% is used as aggregates at work sites. About 2% of the remainders are recycled in other ways (*Avfallsregnskapet*, no date).

2.7.1 Crushed concrete

The most common form of reuse of concrete today is as aggregates. The concrete is crushed up into smaller pieces and the reinforcement is removed. After crushing it, the remaining mass must be tested for hazardous chemicals. If cleared, it can then be used as aggregates in place of conventional crushed rocks, thus falling under reuse of concrete (Jacobsen, 2018).

By crushing the concrete into smaller pieces and leaving it exposed, the surface area that is in contact with air is increased. This allows for quicker carbonation of the concrete, i.e. the concrete's consumption of CO_2 is accelerated (Jacobsen and Jahren, 2001). Jacobsen and Jahren found that total carbonation reaches a total depth of 10-40 mm (Jacobsen and Jahren, 2001). Thus, crushing concrete into aggregates might lead to complete carbonation of the recycled concrete, reversing the emissions from the calcination process during production. This does however not lead to "net-zero" concrete, seen as the emissions from burning fuels during production still represent a significant share of the total emissions from cement production.

Another way of reusing the aggregates is to use it in new concrete, often called recycled concrete. This method is becoming more conventional, with projects being planned with concrete using 100 percent crushed concrete as aggregates (Veidekke, 2022). By using crushed concrete in place of crushed rock, the use of virgin materials is reduced while also eliminating the need for disposal of the concrete. This approach contributes in relieving the high demand for sand and aggregates used in concrete, eventually preventing the sand shortage.

2.7.2 Reuse of hollow core concrete

Reuse of concrete has gained increased attention the last few years, and one instance where it has come a long way is in reuse of hollow core concrete. Hollow core concrete are precast elements with embedded reinforcement and channels running the length of the element, thus "hollow core", that are used as structural floors. These channels make the element lighter and decreases the material usage, without affecting its load bearing capacity ('hulldekke-element', 2019).

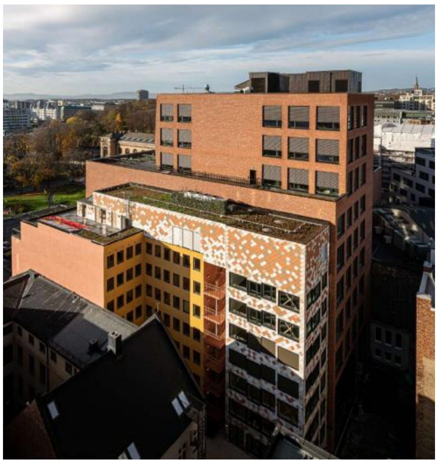

Figure 4: Kristian Augusts gate 13 (Entra ASA, 2021).

Kristian Augusts gate 13 (KA13) is one of the most ambitious and renowned projects in Norway for its high level of reuse. The project included refurbishment of an old building and the addition of an eight-story annex. In total, the project sourced materials from 25 buildings whereof 26 hollow core concrete slabs were extracted from one building (Entra ASA et al., 2021).

The process of reusing hollow core slabs was at the time not a standardized practise and work had to go into establishing procedures for extracting and documenting the components from the donor building. The original documentation of the components were not available, so testing had to be done to ensure that the quality was sufficient. The testing included visual inspection of both the surface and the core, including the reinforcement, of the element by cutting it. Further, the components were tested for carbonation and chloride content which laid the basis for calculations that showed that the quality was sufficient. The need for CE marking was also discussed, but seen as there was no harmonized standard for reuse of building materials, it was concluded that reaching the requirements of TEK17 (Direktoratet for byggkvalitet, 2023g) was sufficient (Entra ASA et al., 2021).

Figure 5: Extraction of hollow core slabs (Entra ASA, 2021).

To extract the hollow core slabs, conventional lifting arrangements could not be used due to the additional height of the screed on the components that could not be removed. Holes were therefore drilled through the slabs for bolts to be attached to a steel profile underneath, running the width of the element (Entra ASA et al., 2021).

The cost of the reused hollow core concrete slabs was estimated to be 5-6 times that of new ones, without considering the additional cost of planning and administration. It is however speculated that if the practise becomes more industrialised in the future, the cost will likely decrease (Entra ASA et al., 2021).

Calculations of the environmental impact of the reused hollow core slabs showed that the emissions were reduced by 89% compared to buying new ones. In total for the project, with 96 tonnes of reused slabs, the total savings in emissions came to 10,9 tonnes CO_2-eq (Høydahl and Walter, 2020). It was further stated by Reppe that the components could have been transported an additional distance of between 450 and 1100 km before their emissions would exceed those of new hollow core concrete slabs (Reppe, 2021).

The planning process for KA13 is described as both colourful and tough. Both decision making and planning processes were said to be more complex due to the high level of reuse. The architects emphasise the importance of a tight multi-disciplinary collaboration to make reuse possible. High level of knowledge, creativity and commitment is pointed out to be key factors that parties involved in a project with reuse should possess (Entra ASA et al., 2021).

The contractors at KA13 went into the project with little faith in that the high level of reuse was going to be realised. This opinion was due to previous experience with entrepreneurs setting similar goals without following through due to the challenges that follow. They were however surprised when the goals where not discarded. When sourcing materials, the time schedule is mentioned as a challenging factor for reuse, and the contractors were at times not certain of where to get materials from the next day. Common questions were: what is to be reused, how much and where is it going to be picked up, and are the components documented well enough? The motivation for reuse did however increase during the project, and the contractors were proud of having been part of it when it was done (Entra ASA et al., 2021).

In 2022, a Norwegian standard on reuse of hollow core concrete was published (Standard Norge, 2022). This came, in part, as a result of the work done with reusing hollow core concrete slabs from Regjeringskvartalet R4 in Kristian Augusts gate 13 and Oslo Storbylegevakt (Brekkhus, 2020; Reppe, 2021; *Rapport om KA13*, no date). The standard includes considerations for planning and logistics, as well as ways of ensuring the quality and proper documentation of the elements that are to be reused.

2.7.3 Reuse of CIP RC: The Udden project

Reuse of precast concrete can be dated back to as early as 1967 in Germany. It is not until 1997 that a documented instance of reuse of cast-in-place concrete appeared. This project took place in Sweden and reused 1850 tonnes of large concrete wall elements, floor beams and foundations from two donor buildings in Finspång, and reused the materials in a new apartment building in Linköping, 64 km away (Küpfer, Bastien-Masse and Fivet, 2023). The donor buildings were built in the 1960s and were demolished due to a vast surplus of empty apartments in the area. The decision was made to reuse parts of the building in new a new apartment building in Linköping, where there was a shortage of available housing. Both the donor buildings and the new building were government owned (Eklund, Sundbaum and Ab, 2023).

Figure 6: One of the two donor buildings in Finspång before demolition (Eklund, Sundbaum and Ab, no date).

The donor buildings contained about 50 apartments, whereas the new building had 22 smaller appartments. The buildings were constructed mainly out of cast-in-place concrete, which had to be cut with a diamond saw to be extracted for reuse. The concrete elements that were reused included wall elements, beams and foundations. Some elements were tested for load bearing capacity, although it is not specified in the report from the project how this task was completed. The technical requirements of the elements did not pose any implications for the project, whereas the logistics suffered from poor timing and a lack of storage space for the components that were taken out from the donor buildings (Eklund, Sundbaum and Ab, 2023).

Through environmental analysis of the project, the CO_2-emissions were found to be reduced by 60%, and the energy use by 40%, compared to a similar building made with new concrete (Küpfer, Bastien-Masse and Fivet, 2023). The elements could be transported a distance of 140 km before the emissions of nitrogen oxides from the truck transport would exceed that of a project using new concrete.

When concluding the paper, the importance of predictability of further use of the practise for the contractors was emphazised. If the contractor could be certain that reuse of cast-in-place concrete would be a common practise in the future, more work could be put into improving building techniques, develop relevant technology and establish common practises (Eklund, Sundbaum and Ab, 2023). Even though the cost of the project was 10-15% higher than that of a conventional one, the contractors were optimistic that this could be mitigated in future projects by gained experience and knowledge on larger scale projects (Küpfer, Bastien-Masse and Fivet, 2023).

2.7.4 Reuse of CIP RC: EPFL’s Re:Crete footbridge

Cast-in-place concrete is also being reused in various scales. One example of this is an experimental 10-metre-long footbridge built by a Swiss university (EPFL). Concrete blocks from cast-in-place walls where in this case cut from a building undergoing transformation. Following the concept of a traditional arch bridge, the blocks were placed in an arch, making use of the high compressive forces of the concrete, before they were prestressed by wires that were run through them. The wire acted as a constant load on the arch, ensuring that it did not collapse under uneven loads. This strategy resulted in a stable bridge, utilizing traditional building principles to convert what was a wall into a bridge (Devènes *et al.*, 2022).

Acquiring of materials was completed in an opportunistic way for the Re:Crete project, meaning that possible suppliers, like demolition and concrete sawing companies, were contacted in search of suitable materials from their ongoing projects. A building less than 10 years old, undergoing major transformations, was selected. The materials were cut to size before transported to the construction site of the bridge. A total of 25 blocks of 120x45.5x20cm were collected, whereof one had to be replaced due to damage from sawing and transportation (Devènes *et al.*, 2022).

Figure 7: The Re:Crete footbridge (RE:CRETE, 2021).

To test the environmental impact of the Re:Crete footbridge, an LCA study was conducted with four alternative material choices. The alternatives chosen were recycled concrete blocks, a monolithic recycled concrete structure, steel beams and timber beams. Other than changing the structure, the general form of the bridge stayed the same. The results showed that the alternatives had a 71%, 63% and 74% reduction in GWP for recycled concrete block arch, recycled monolithic arch and steel beam arch, respectively. Compared to the timber arch, the GWP was 9% higher. The largest emitters for the Re:Crete footbridge were found to be transportation and the timber support structure with 34% of the total GWP each (Devènes *et al.*, 2022).

2.7.5 Reuse of CIP RC: Reuse in point foundations

Among the data gathered by Küpfer et al. there is one instance where both the compressive and tensile capabilities of the RC is partially reused (Küpfer, Bastien-Masse and Fivet, 2023). In this instance, concrete blocks are reused as point foundations. In addition to the original reinforcement of the reused blocks, they were embedded with new reinforcement, together with a minimum concrete cover, in order to link them together and distribute the forces sufficiently. Due to a lack of time for material sourcing, one quarter of the point foundations in the project were eventually cast with new concrete (Küpfer, Bastien-Masse and Fivet, 2023).

Figure 8: Point foundations of reused concrete blocks (Küpfer, Bastien-Masse and Fivet, 2023).

2.8 Process of reuse of CIP RC

2.8.1 Disassembly process

Demolishing a building can be done in varying ways depending on the planned outcome of the building materials. Traditionally, a building is demolished with no regards for reuse, but rather to leave small and easy to manage pieces for extraction and transportation of site. An alternative approach is therefore necessary to accomplish reuse. In the collection of cases with reuse of concrete done by Küpfer et al., various techniques for dismantling concrete structures were used (Küpfer, Bastien-Masse and Fivet, 2023). Diamond saws, hydro-blasting and local impact demolition are among the techniques mentioned, whereof diamond saws are most commonly used (Devènes *et al.*, 2022; Küpfer, Bastien-Masse and Fivet, 2023).

Although selective demolition, where some building components are spared for reuse, might have a positive environmental impact compared to conventional demolition, Coelho and de Brito (2011) found that it cost up to six times more. While a conventional demolition process is highly dependent on the cost of final disposal, the cost of selective demolition also depends on cost of labour, equipment and transport to a larger degree (Coelho and de Brito, 2011).

2.8.2 Planning with reused components

Planning a building with reuse means that the building must, to some extent, be planned for the available components, rather than the components being specially made for the building. The reused components might not have been sourced at the time the planning starts. This issue could lead to multiple revisions and an increase in the time spent on planning and design of the building. The sourcing of the components also affects the time spent in a planning process. This task is related to the fact that one or more compatible buildings need to be demolished in the same timeframe as the new building is to be constructed (Gorgolewski and Morettin, 2023). Architects have also stated that reuse can be difficult to implement when assessing the environmental impact of a building while real estate developers have pointed out that reused components become more important in later stages of development (Hollberg *et al.*, 2022).

The challenge of designing and planning for reused materials could be solved by sourcing the materials early in the project. However, this strategy can be challenging for several reasons. First of all, the materials would need to be stored for a long time before they could be inserted in the new building. The storage would introduce additional cost to the project and could therefore be seen as non-beneficial and something that should be kept to a minimum. If storage is not available, Gorgolewski and Morettin state the importance of identifying the donor building early in the design process (Gorgolewski and Morettin, 2023). Today, the availability of online marketplaces is also increasing. Examples of these types of platforms in Norway are Ombygg, Rehub and Loopfront (Loopfront, 2023; *Ombygg*, no date; *Home - Rehub*, no date).

Another solution, as stated by Gorgolewski and Morettin, could be to buy the donor building (the building the used components are extracted from) or to simply reuse it on site (Gorgolewski and Morettin, 2023). Sticking to the scope of this thesis, with reuse on site, the first of these two options could be a viable solution. Buying the donor building could allow the stakeholders responsible for planning to postpone the disassembly of the building to the time when the components are needed in the new building, while being able to identify the components that are going to be reused. Again, this would introduce additional cost to the project, seen as parts of the building that are not going to be reused now have to be demolished and deposed.

Regardless of how the materials are sourced, Gorgolewski and Morettin state that it is likely beneficial to the project that contractors are involved early in the project. In this way the contractors can take part in the sourcing of materials and influence the design and techniques for installing the reused components. If the contractors were to be involved at a later stage, the risk of contractual implications or negative influence due to inexperience or disinterest might increase (Gorgolewski and Morettin, 2023).

When designing with reused components, multiple revisions are to be expected depending on when the materials are sourced. To limit the amount of additional work that has to be done, it is advisable to keep the design flexible and stick to standardised dimensions to have a higher likelihood of matching the sourced materials (Rakhshan *et al.*, 2020).

2.8.3 Reassembly process

A common practise has yet to be established for reassembling used concrete components. However, research by Mykyta Volkov emphasised the possibility for applying standardized solutions for connection of pre-cast elements in order to reassemble CIP RC components for reuse. For columns, Volkov suggested the use of coupling sleeves, where steel sleeves are embedded or holes are made in the bottom of the element and lowered onto vertical reinforcement steel sticking up from the slab on which it is mounted. The steel sleeves or holes are then injected with grout to ensure a secure connection between the elements (Volkov, 2019). The same process applies for assembly of the top of the column.

Figure 9: Precast element with coupling sleeves (Volkov, 2019).

A column that is extracted for reuse might not be of sufficient height, due to the cutting process or simply because the ceiling height of the donor building was lower than that of the new one. Inaccuracies in the cutting process might also lead to varying heights of the columns. This can be solved by casting a small extension, or reusing parts of an old column, to reach the necessary height. In order to achieve a solid splice joint between these parts, coupling sleeves can be utilized in the same way as for mounting a column to a slab (Volkov, 2019).

In order to use coupling sleeves with a cut CIP column, the holes will have to be drilled. The drilling can be completed in similar way to the process of core extraction as shown in figure 13 In addition to the sleeves themselves, venting holes at the ends of the sleeves are necessary to let air out as the grout is pumped into the sleeves. This task might be a labour intensive process if the quantity of the reused columns are high (Volkov, 2019).

Figure 11: Core extraction of concrete (Eibenstock ETN 162/3 P, 3-Speed Wet/Dry Diamond Core Drill with Built-In Dust Extraction Port - Holes up to 8", no date).

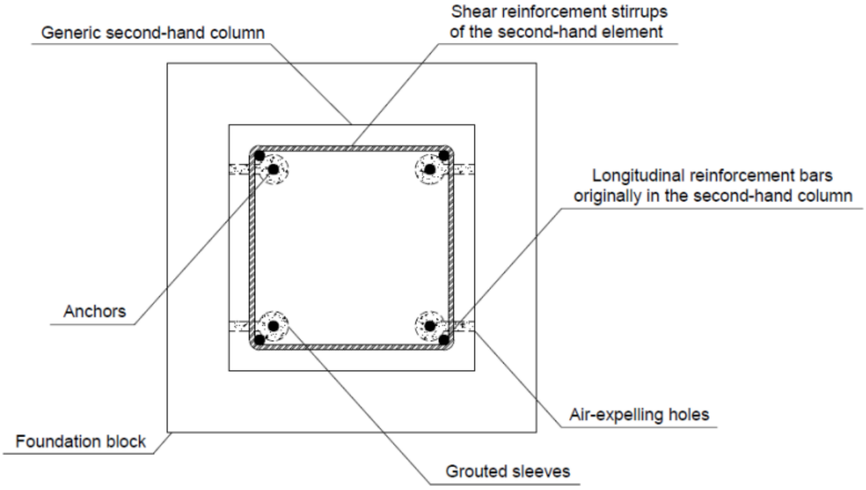

Figure 10: Top-view of reused column with coupling sleeves (Volkov, 2019).

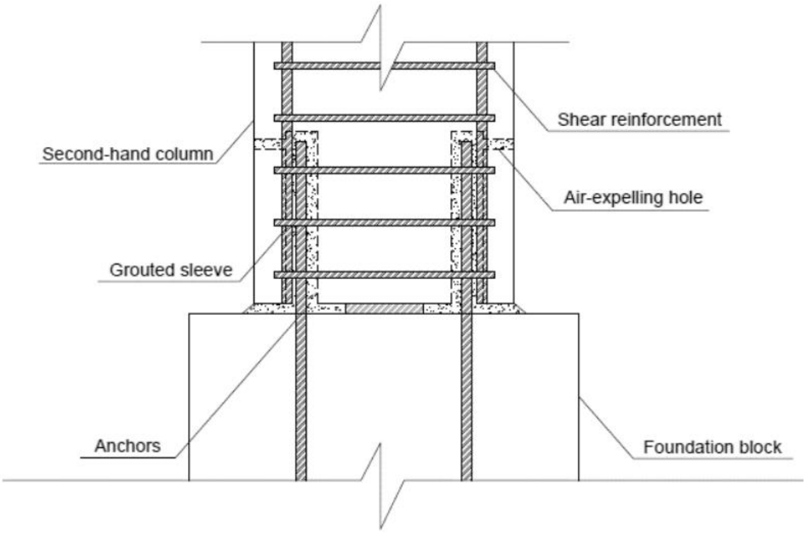

Figure 12: Side-view of reused column with coupling sleeves (Volkov, 2019).

2.8.4 Rules and regulations

To be viable for use in the building industry, a product must fulfil certain criteria. The regulation on documentation of building goods (DOK) states the following fundamental requirements, in line with TEK17 (Direktoratet for byggkvalitet, 2023b, 2023g):

1. Mechanical resistance and stability
2. Fire safety
3. Hygiene, health and environment
4. Safety and accessibility in use
5. Protection against noise
6. Energy-saving and heat insulation
7. Sustainability

To ensure that these requirements are fulfilled a product needs a CE mark and a declaration of performance (Direktoratet for byggkvalitet, 2023f, 2023e). The CE mark ensures that the product is produced and performs after a set of harmonised European standards and is approved for use in the whole of the European Economic Area (EEA). However, for building products, the CE mark only ensures that the technical specifications are made in line with the standard and does not ensure that the product meats the technical requirements of a building product on a national level (Direktoratet for byggkvalitet, 2023c). In Norway, a building product is therefore also required to have a declaration of performance, stating the products performance specifications in line with the relevant standards (Direktoratet for byggkvalitet, 2023d).

For concrete, the harmonised standards are exclusively for precast elements, admixtures and aggregates (European Comission, 2022). "EN 1992: Design of concrete structures" with its national annexes is the standard used for designing and dimensioning concrete structures but is not characterized as a harmonised standard by the European Commission (European Comission, 2015). When a product is not covered by a harmonised standard, it can acquire a European Technical Approval (ETA) instead to be able to be freely sold throughout the EEA area. This can be made by a Technical Approval Body and involves the documentation of the same relevant essential characteristics as for a CE marking (Direktoratet for byggkvalitet, 2023h).

Within Norway, a product can still be sold without a CE mark or ETA as long as it fulfils the national fundamental requirements, as stated in the beginning of this chapter (Direktoratet for byggkvalitet, 2023h). In the absence of a harmonised standard, these requirements should be based in national standards, a technical assessment of a third party or the producers own technical specifications (Direktoratet for byggkvalitet, 2023b).

2.8.5 Testing of extracted concrete

Testing of the extracted concrete is necessary to ensure that it still holds a sufficient level of quality and otherwise are suited for reuse in a new building. An estimation of the scope of testing can be done with basis in the Norwegian standard "Hollow core slabs for reuse" (Standard Norge, 2022). These tests do however rely on the elements being made at a factory as parts of known production lines. Seen as CIP concrete is made on site, there might be a greater variation in characteristics between elements due to inaccuracies during production. However, the tests do correlate to how CIP RC structures are tested on-site to determine their condition, with the exception of full-scale testing (Norconsult, 2023).

The condition assessment for hollow core slabs as described in the standard includes:

- **Carbonation depth** is determined as described in NS-EN 14630 and is tested on the underside of the element. A carbonation depth of 10 mm is accepted. A depth greater than this demands a calculation of the remaining lifespan of the element. Carbonation depth should be tested on every 20th element that is to be reused.

- **Chlorine content** is determined as described in NS-EN 14629 with a required average content of less than 0,2% of the mass of cement. This requires that the cement content is known (Standard Norge, 2007). Chlorine content should be tested on every 50th element.
- **Alkali-silica reactivity** should be tested to determine the potential for damaging reactions. The test should be done by petrographic analysis. Alkali-silica reactivity should be tested on every 50th element.
- **Compressive strength** should be tested in two ways. One includes extraction and testing of core samples in line with NS-EN 12504-1 and NS-EN 12390-3. This test should be done on every 20th element. The second is a rebound hammer test done in accordance with ISO 1920-2 on every 5th element.
- **Full scale destructive tests** full scale testing should be done in accordance with NS-EN 1168:2005+A3:2011 on every 50th element. If the tests are done on less than six elements, the results should show a capacity of 1,25 times the characteristic load. If more than six elements are tested, the requirement is reduced to 1,10 times the characteristic load.

Further description of the tests is included in the standard on reuse of hollow core concrete as well as test specific standards.

In the Re:Crete project, a ground penetrating radar was also used in order to determine the positioning of reinforcement steel and their concrete cover. In a component where the reinforcement steel is going to be utilized, determining these properties is essential to estimate the load bearing capacity and remaining lifespan of it. In the Re:Crete project, the measurements where used to determine the structures durability if it were to be placed in an outdoor location (Devènes *et al.*, 2022).

2.9 Life cycle assessment (LCA)

LCA, often called a "cradle-to-grave" assessment, is a way of assessing a products environmental impact over its life cycle. During the ongoing climate crisis, it has become an important tool for quantifying the overall environmental load of a product in order to make optimizations, or to compare products to one another (Muralikrishna and Manickam, 2017). By evaluating the product over its full lifespan, LCA also makes it possible to balance emissions with performance. The scope of a LCA can range from determining content of specific chemicals or CO_2 emissions, to a full inventory of outputs and inputs to the product.

The LCA procedure is commonly divided into four distinct phases (Hernandez *et al.*, 2019):

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation.

The goal and scope definition involves stating a goal for the analysis, setting the boundaries of the LCA, and deciding on the factors that should be included as well as the functional unit for the analysis. The functional unit is important to establish how the product is expected to perform and for how long. The functional unit is the method for which the emissions are presented, i.e. one functional unit of the product leads to a certain amount of emissions (Hernandez *et al.*, 2019).

The inventory analysis, or Life Cycle Inventory (LCI), is the part of a LCA were all materials and processes involved in making a product are collected. The LCI includes all flows to and from the product from the nature. An increasing amount of Environmental Product Declarations (EPD) have also become available. An EPD is an independently verified document stating the environmental impact of a product, meaning that it can be used in place of conducting a full LCI for a product (Hernandez *et al.*, 2019).

Following the LCI is the impact assessment, or Life Cycle Impact Assessment (LCIA). At this stage the impact categories are selected and analysed. The impact categories might include climate change, resource depletion, land use etc. The goal of the LCIA is to evaluate the significance of potential impacts within these categories (Hernandez *et al.*, 2019).

Finally, the LCIA has to be interpreted. This is done in line with the goal and scope that has previously been set. The interpretation should identify the greatest contributions to different impact categories while also analysing the uncertainty of these, giving the final results of the LCA (Hernandez *et al.*, 2019).

LCA can be used in various ways in a building project. In the early stages of the planning process of a project, goals can be set according to established classification systems like the EU taxonomy, BREEAM or FutureBuilt. The classification systems provide companies, investors and policymakers with definitions for which economic activities can be considered environmentally sustainable (European Comission, 2023). Furthermore, LCA-budgets can be set to approximate a projects environmental impact, establishing a foundation for choices of material and operations that are to be made at a later stage. When the project is completed, a detailed assessment can be done in order to determine how the building performs compared to set benchmarks. During the lifespan of a building, improvements or refurbishments can be evaluated through LCA to compare the environmental loads to the remaining lifespan of the building.

There are two main types of LCA, attributional and consequential. An attributional LCA is used to determine the environmental impact of a product and allocate emissions within its system. The system in this case is assumed to be static, and not subject to change, e.g. an environmental product declaration. In a consequential LCA, the aim is to describe changes in a system as a result of alternative decisions to be made for it, e.g. deciding on what windows to choose for a building (Dastjerdi *et al.*, 2022; Solli *et al.*, 2023).

The products life-cycle can be divided into four main phases with subdivisions (Standard Norge, 2011):

> **Phase A** includes the processes from extraction of raw materials to production and implementation of a product. Phase A is further divided into supply of raw materials (A1), transportation (A2), production (A3), transportation (A4) and building-/ assembly process (A5).
>
> **Phase B** includes the use stage of a product from its implementation to it is to be demolished or taken out of use, including use (B1), maintenance (B2), repair (B3), replacement (B4), renovation (B5), energy use (B6) and water use (B7).
>
> **Phase C** includes the end-of-life stadium of a product when it is demolished or otherwise discarded of. This phase is further divided into deconstruction/demolition (C1), transportation (C2), waste management (C3) and disposal (C4).
>
> **Phase D** is used if a product is to be reused or recycled and includes the potential advantages and disadvantages of this process.

NS 3720 is the Norwegian standard for calculating emissions of greenhouse gasses from buildings, building on the Norwegian standard for calculating environmental performance of buildings, NS-EN 15978. NS 3720 focuses on attributional LCA, meaning that it focuses on describing environmentally relevant physical flows to and from a life cycle and its subsystems, as described by Finnveden and Potting (Finnveden and Potting, 2014). The standard describes the system boundaries and prerequisites that should be used when conducting an LCA, ensuring comparable results (Standard Norge, 2018).

To interpret the output from an LCA, several assessment methods have been established. One of the first and most internationally recognised ones that use LCA in its validation and certification system is BREEAM, created by the British Building Research Establishment (BRE) in 1990 (BRE Group, 2016). BREEAM is an abbreviation of Building Research Establishment’s Environmental Assessment Method and is used to measure a building’s sustainable characteristics. The building is awarded with points within different categories of sustainability and is given a classification based on its score. A building is measured on categories ranging from project management during construction to visual comfort and adaptability. The classifications include “Pass”, “Good”, “Very Good”, “Excellent” and “Outstanding” (Grønn Byggallianse, 2022). This system helps raise awareness among owners, users, planners and others around sustainability.

BREEAM is based upon the EU Taxonomy which is a classification system that has established a list of environmentally sustainable economic activities. The aim of this classification system is to provide companies, investors and policymakers with appropriate definitions for which economic activities can be considered environmentally sustainable (European Comission, 2023).

The Norwegian Green Building Council (Grønn Byggallianse) has adapted BREEAM to the Norwegian building industry, creating BREEAM-NOR. Among the nine categories in which a building can gain points is material efficiency and reuse. Through reuse of building materials from a building that is torn down and replaced or external reuse, a building can achieve a total of three points. A weighting system is also included in BREEAM-NOR, where the material categories always give the highest impact on the final score of the building. The weighting of materials is 17%, 20% and 24% for furnished, unfurnished and building envelope including load bearing structure respectively. These factors are used to estimate the categories contribution to the final score (Grønn Byggallianse, 2022). Reuse can therefore give a significant impact on the final score of a building.

FutureBuilt is another certification system and is tightly connected to the BREEAM-NOR Excellent class and is also stated as one of the criteria for one of the reuse categories (Grønn Byggallianse, 2022; *Om oss*, no date). To be classified as a FutureBuilt project, a building must reach criteria within city environment and architecture, social sustainability, GHG-emissions, innovation and environment in addition to two or more optional criteria. Among the option criteria is that the building should consist of a minimum of 50% reused components (FutureBuilt, 2022). FutureBuilt also describes the method for calculating emissions in order to reach their FutureBuilt Zero classification which is one of the main criteria that must be met in order to be classified as a FutureBuilt project. In the method, reuse is accounted for by giving an 80% reduction in the emissions from the production phase (A1-A3) of an equivalent product (Resch *et al.*, 2021).

3 Methodology

Three main approaches have used to answer the research questions: a literature review on the field of reuse in the building industry; a questionnaire to establish the current state of the topic in Norwegian industry and the perceived barriers and solutions for reuse; and a case study to investigate the feasibility and potential environmental savings.

3.1 Literature review

The literature review was the first method used to approach the research question, but it was also important throughout the project to acquire complementary information and data. Further, it was also used in the planning of the questionnaire.

The first papers that were reviewed were found through recommendations from supervisors, as well as searches using scientific sources (e.g. Science Direct (ScienceDirect, 2023)). The key words when searching where primarily: concrete AND reuse; reuse AND building industry; design for disassembly AND concrete.

When the preliminary database was established, the web-page Research Rabbit (*ResearchRabbit*, no date) was used to further expand the collection. By adding the collected papers to the software, it found relevant works through linking citations and collaborations between authors. The search did however seem to be limited to scholar papers, and did not include other works (e.g. Book chapters). Through using the software, both later and earlier work could be easily identified, complementing the database with key papers.

3.2 Questionnaire

Based on the literature review, a questionnaire (See Appendix A) was planned to gain an understanding of opinions on reuse of cast-in-place (CIP) reinforced concrete (RC) in load bearing structures. It was implemented in Nettskjema (Nettskjema, 2023) and distributed at Asplan Viak. In addition, it was shared on the social media platform LinkedIn, including the group "Ombruk i byggebransjen" (Norwegian for "Reuse in the building industry"). The questionnaire was made up of a minimum of 21 mandatory questions, with seven more depending on what answers where given. Additionally, six more voluntary questions could be answered, whereof three had a free format for the respondent to elaborate on their thoughts on the topic. This structure resulted in a total of 34 questions that could be answered.

Four question formats were used in the questionnaire: single choice, multiple choice, linear scale and free format. The single choice questions consisted of a set of alternatives where the respondent could choose just one. In multiple choice the respondent is given a set of alternatives to a question but can choose several. A limit was in some cases set to the number of alternatives that could be chosen to ensure that the respondent had to make thorough considerations, and to make the preferred options stand out more during analysis. In the linear scale questions the respondent was asked to place a marker on a scale from one to five where the values were defined in each question. Where the respondent placed the marker would output a number in the final data extraction, making analysis of the data simpler. The free format questions asked the respondent to write an answer on a question or elaborate on a topic. These answers would give supplementing data to the previously described closed format questions, and could ensure deeper understanding on the topic.

3.2.1 Section one: Background information

The section consisted of 6-13 questions, depending on what answers were given and if elaboration of the answers was necessary. The purpose of this section was to provide an overview of the experience and background of the respondent.

The first two questions established the age and gender of the respondent, per common practice in scientific questionnaires. The age also helped to create a picture of the amount of professional experience, in addition to making it possible to see trends in attitude and motivation on the subject across demography.

In the third and fourth questions, the respondents were asked in what country and role they were currently employed. This question made it possible to relate their answers to the rules and regulations, as well as type of industry and attitude within each industry, that they are currently working under, in addition to establishing what interests they have in the industry.

The fifth question asked what types of buildings or structures the respondent had worked with, before they were asked if they had worked with reuse before in question six. Here, they were also asked what materials they had reused if they answered that they had reused materials in load bearing structures. These questions would make it possible to identify differences in motivation and attitude for reuse between people who had experience with it and those who do not.

3.2.2 Section two: Concrete as a building material

Section two consisted of two mandatory questions and one free format question for the respondent to elaborate freely. In this section the respondents' attitude and motivation for use of concrete was explored. The section established a background for how the respondent approach questions regarding reuse of concrete – if they see it as a necessity or not.

3.2.3 Section three: Reuse of building materials

The third section had four mandatory questions and investigated the respondents view on the status of reuse in the building industry today, as well as how it could work in the future.

The first question asked how the respondent perceive the building industry's view on reuse of building materials today. Even though the amount of reuse in the building industry can be seen from an objective standpoint, the question could help in mapping out how the respondents experience the ease and availability of it in their part of the industry, and possibly how it could change in the future.

Question two investigated how the respondent thought that the efficiency of a planning/building process involving reused materials would compare to one using only virgin materials. By efficiency it was referred to the use of resources in a project, in terms of time, money, materials etc. This question aimed to see how experienced people in the industry envision the practise of reusing building materials to work, and could also help with identifying the respondents motivation for reuse.

For the last two mandatory questions of the section, as well as the voluntary free form question, a scenario was introduced to the respondent. The scenario set up a case where a system for buying and selling used building components exist and is actively used in the building industry. The components would be sold out of a local storage with all necessary documentation and ready for use. The following two mandatory questions then asked how the respondents use and implementation of reused building components in new projects would change, and who should be responsible for providing such a system. These questions aimed to investigate how the barrier of availability of reused materials impacts the respondents' choices, and how effective it would be to mitigate this barrier, as well as identifying the responsibility of stakeholders. Who the respondent chooses as the responsible part for a reuse centre can also indicate who they think should be responsible for making reuse available for the industry.

3.2.4 Section four: Reuse of CIP RC in load bearing structures

Section four, the final section of the questionnaire, had nine mandatory questions, three elaborative questions and one voluntary free form question. Two of the mandatory questions were free format questions. The first question asked to what degree the respondent saw reuse of RC as feasible in today's building industry. This question could lay the basis for interpreting the following questions by establishing the respondents' thoughts on the topic from the start.

The second question asked the participant to grade 12 different categories of the building industry on a range from significant barrier to significant driver. This would give the respondent the possibility to emphasise what they see as the biggest reasons that reuse might not be applied today and what could help implement it to a bigger extent in the future.

Question three and four looked at what RC components the respondents thought to be most viable for reuse. This data would lay grounds for the further work of the thesis on life cycle assessment of reused RC components. By knowing what components are seen as most viable for reuse, it could be assumed that these components are most likely to be the first components to be reused in practice, thereby making them the most interesting for an early phase LCA.

Question five asked the respondent to give one predefined answer to ensure that they were paying attention and not answering questions at random. This question was asked to ensure that the questionnaire would give reliable data.

The sixth and seventh questions looked at what prices the respondent would expect, and what prices they would find acceptable, for used RC components. This feedback would give an indication how of how the implementation of reuse in the building industry could work, and the significance of price as a barrier.

Question eight asked how the collaboration between client, architects, engineers and contractors would change in a planning process where reused RC is being used. The respondents should all belong to these fields of work, and their opinions on how the process would change could give valuable insight into how reuse might be implemented to the planning process and how potential obstacles might be solved.

The nineth and final mandatory question asks the respondent what information about the reused RC component is necessary for them to do their part of the planning process in a project. This question helps to identify what information and documentation must be gathered to be able to reuse a RC component.

3.3 LCA/Case study

The goal of the LCA conducted in this case is to establish the potential savings of reusing a CIP RC column compared to casting a new one. The goal of the LCA conducted in this case is to establish the potential savings of reusing a CIP RC column compared to casting a new one. NS 3720 states that the lifespan of a product used when conducting an LCA should be 60 years, if not specified differently (Standard Norge, 2018). The column that is dimensioned in line with NS-EN 1992-1-1 (EC2) is however only designed to have a lifespan of 50 years (Standard Norge, 2021). Therefore, the lifespan assumed for the column in this LCA is chosen to be 50 years. During phase B and onwards, the products are assumed to perform similarly, meaning that use, maintenance, repairs, dismantling, disposal and potential recycling or reuse is assumed to be equal between the two components. Only A1-

A5 is therefore included in these calculations. Further, the process described in NS 3720 will be used as a template for conducting the LCA (Standard Norge, 2018).

Due to the current climate situation and the time frame of the project, Global Warming Potential (GWP) has been chosen as the most vital factor when comparing new and reused concrete. This decision is also backed up by FutureBuilt's method for impact assessment of reused building materials through giving a reduction in GWP of the material. Reuse also impacts the amount of waste from demolition of buildings, thus decreasing landfill usage. The disposal of building material is however not going to be compared to the reuse of it. The reused component will only be compared to the production of a new one.

The functional unit that the LCA will be conducted for will be:

One CIP RC column of 300x300x3500 mm installed and capable of fully utilizing the requirements it has been designed for, with a lifespan of 50 years.

The LCI will be completed in SimaPro and based on the ecoinvent database. SimaPro will also be used to conduct the impact assessment with use of the IPCC 2021 GWP100 method. The results will then be extracted to excel, where they will be interpreted for analysis and discussion.

3.3.1 Setup of case

The LCA was initially intended to be conducted as part of a case study supplied through the project GjenOm, with donor buildings being either Nardovegen 12 or 14 or Nidarvoll Helsehus. Sufficient data was however not available at the required time, so the decision was made to include the available data and further back it up with estimations and assumptions. This approach resulted in a realistic case study, which could be completed within the timeframe of the thesis.

The data that is carried on from the original case study is primarily the locations of the buildings. The donor building is assumed to be Nidarvoll Helsehus (figure 16 and 17) and the new building where the reused components are intended to be reused is a new storage building in Granåsen, about 8,3 km away. The approximate size of the buildings are going to be used for the calculations. Nidarvoll Helsehus is a three-story building, with a load bearing structure assumed to be made primarily out of concrete. The building has an L-shape with each leg of the L estimated to be around 50 metres. The width of the building is estimated to be 20 metres. The load bearing structure is assumed to have a standard six-by-six metre grid.

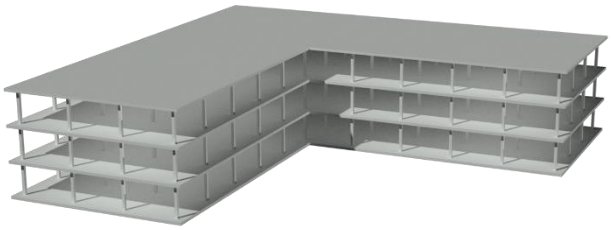

Figure 14: Assumed load bearing structure of the donor building.

Figure 13: Aerial view of donor building (Google Maps, no date).

The new building that will reuse the components is planned to be a one-story building with the same dimensions as in the initial case (figure 18 and 19). The load bearing structure will however be assumed to be made in concrete. Seen as the reused components are assumed to maintain their load bearing capacity, the structure is designed so that the columns will carry the same projected area as in the donor building. In the donor building, the columns were carrying an area of 6x6 m. The width and length of the new building is about 12 and 30 meters respectively. For the columns to be carrying the same projected area, they will have to be spaced at intervals of 6 m along the walls. A fair assumption could be that the rated load bearing capacity would be lower for the reused components compared to new ones due to safety measures taken during documentation. This issue will not be taken into account in these calculations due to the uncertainties related to it.

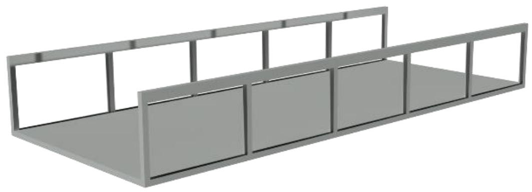

Figure 16: Assumed load bearing structure of the new building.

Figure 15: Rendering of new building (Saunders, Moe and Larsen, 2022).

3.3.2 SimaPro

The software SimaPro was used to conduct the LCA in this report. SimaPro is one of the most used LCA software solutions and has been for more than 30 years. It was chosen for these calculations due to its detailed nature, the availability of processes through extensive libraries and the transparency of these. The software is commonly used for sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators (SimaPro, 2023a). Access to the software was provided by Asplan Viak AS.

SimaPro works by making use of established life cycle inventory databases to combine activities that are included in the making of a product, creating a detailed inventory for the final product. The activities can include materials, material processing, energy use, waste, land-use etc. All processes are described thoroughly with all steps and materials that are included in it. This data makes it possible to ensure that the correct processes are included in the product analysis.

There are several methods for completing Life Cycle Impact Assessments (LCIA) in SimaPro. For this report, the IPCC 2021 GWP100 method is going to be used. The method was developed by the Intergovernmental Panel on Climate Change (IPCC) and focuses on "the Global Warming Potential (GWP) climate change factors of IPCC with a timeframe of 100 years, where carbon dioxide uptake is implicitly included". Biogenic carbon dioxide is not taken into account in this method (SimaPro, 2021).

3.3.3 Ecoinvent

The ecoinvent Database is a Life Cycle Inventory (LCI) database that has been used to model the products for this report. This database provides detailed processes that are combined in SimaPro. The ecoinvent Database contains more than 18000 activities modelling human activities or processes. The information about the activities that are modelled measure the natural resources withdrawn from the environment, the emissions released to the water, soil and air, the products demanded from other processes (electricity) and the products, co-products and wastes produced (ecoinvent, 2020a).

The activities are divided into geographical sectors to ensure that they are represented as accurately as possible for the areas where they are intended to be used. When a local dataset is not available, a dataset for the location global (GLO) or Rest-of-the-World (RoW) is made. The GLO dataset represents the global average for an activity while the RoW dataset represents the average for the rest of the world while other geographical sectors are also present (ecoinvent, 2020b). The most local dataset available will always be chosen for the calculations in this report, including Norway (NO), Europe (RER), Rest-of-the-World (RoW) and Global (GLO).

The activities are further divided into system models. These are categorized after how they deal with allocation for the activity. The different system models are "Allocation, cut-off by classification", "Allocation, cut-off, EN15804", "Allocation at the point of substitution" (APOS) and "Substitution, consequential, long-term" ('System Models - ecoinvent', 2020). For the calculations completed in this report, the system model "Allocation, cut-off by classification", or the cut-off system model, is going to be used. This model uses the underlying philosophy of "polluter pays" and builds on the system that primary production of materials is always allocated to the primary user of the material. If a material is recycled or reused, this means that no benefits are assigned to the primary user, but rather that the material that is recycled or reused is supplied burden free to the next user, apart from the processing that it involves ('System Models - ecoinvent', 2020). In terms of a reused concrete column, this means that the emissions from making the concrete and casting the column is not assigned to the building that reuses it. The emissions from extraction, transport and reassembly are however assigned to the new building. The remaining system models are not going to be described in detail.

The activities are also divided into market and transformation processes. The market process includes both inputs from production and of transport processes. The transformation processes do however not include the transport processes. SimaPro recommends users to use the market processes when data from a specific supplier is not known (SimaPro, 2023c).

The ecoinvent libraries consist of unit and system processes. A unit process is "the smallest element in the life cycle inventory analysis for which input and output data are quantified" (SimaPro, 2023b). System processes are however single cradle-to-grave systems where inputs and outputs throughout a products lifespan is compiled into one system, known as aggregated life cycle inventories (SimaPro, 2023b). To ensure an organised and thorough LCI for the reused components, the unit system is going to be preferred for use in the LCA conducted in this report.

3.3.4 New component

The calculation of the new concrete column includes transportation and material usage. The formwork is not taken into account seen as this can be assumed to be reusable, making the emissions per use negligible. The formwork can also be seen in comparison to the support structures needed when installing the reused component, where it can be assumed that the emissions would be close to equal, thus cancelling each other out.

The columns are assumed to be 300mm by 300mm square sections and 3500mm tall. In order to give a realistic relation between the amount of concrete and steel in the new column, it's properties will be determined in line with NS-EN 1992-1-1 (EC2) (Standard Norge, 2021). A minimum amount of reinforcement steel will be used to minimize the emissions from the column, seen as the emissions from reinforcement steel is higher per volume than from concrete (Unicon AS, 2022; Norsk Stål AS, 2023).

Full calculations regarding the new column can be found in appendix B. A summary of the key points will be presented here. The columns are assumed to be exposed to a mostly dry climate giving the exposure class XC1. This demands a durability class of the concrete of M60, meaning that the grade B30 concrete must be used. Seen as the forces that the column will be experiencing is unknown, the minimum amount of longitudinal reinforcement is set to 0,01 times the area of the concrete (300mm x 300mm) in line with equation NA.9.12N in the national appendix of EC2. To reach this area, eight longitudinal rebars with 12 mm diameter is chosen. The same diameter is chosen for the transverse rebars, giving a maximum spacing, per section NA.9.5.3(3) in EC2, of 180 mm adding up to 21 transverse rebars. These parameters give a minimum thickness of the concrete above the reinforcement of 25 mm in line with equation 4.2 in EC2 with a dimensioning lifespan of 50 years. The column also needs a steel connection to the floor on which it sits and the floor divider/beam above. It is assumed that this is sufficiently provided by eight reinforcement bars angled 90 degrees (one per longitudinal bar in the column) with one leg of 800 mm and the other 1100 mm, giving sufficient overlap between reinforcement while reaching the bottom or top layer of a 300 mm thick slab beneath and above the column respectively. The diameter of the reinforcement tying the column to the slabs are assumed to be 12 mm. This adds up to 0,3097 m^3 of concrete and 65,33 kg of reinforcement steel per column. The overlap of the rebar tying the column to the adjoining surfaces is not calculated in line with EC2, seen as this requires known forces on the column, but is estimated on the basis of a well-established rule-of-thumb in the building industry of and overlap of 50 times the diameter of the reinforcement.

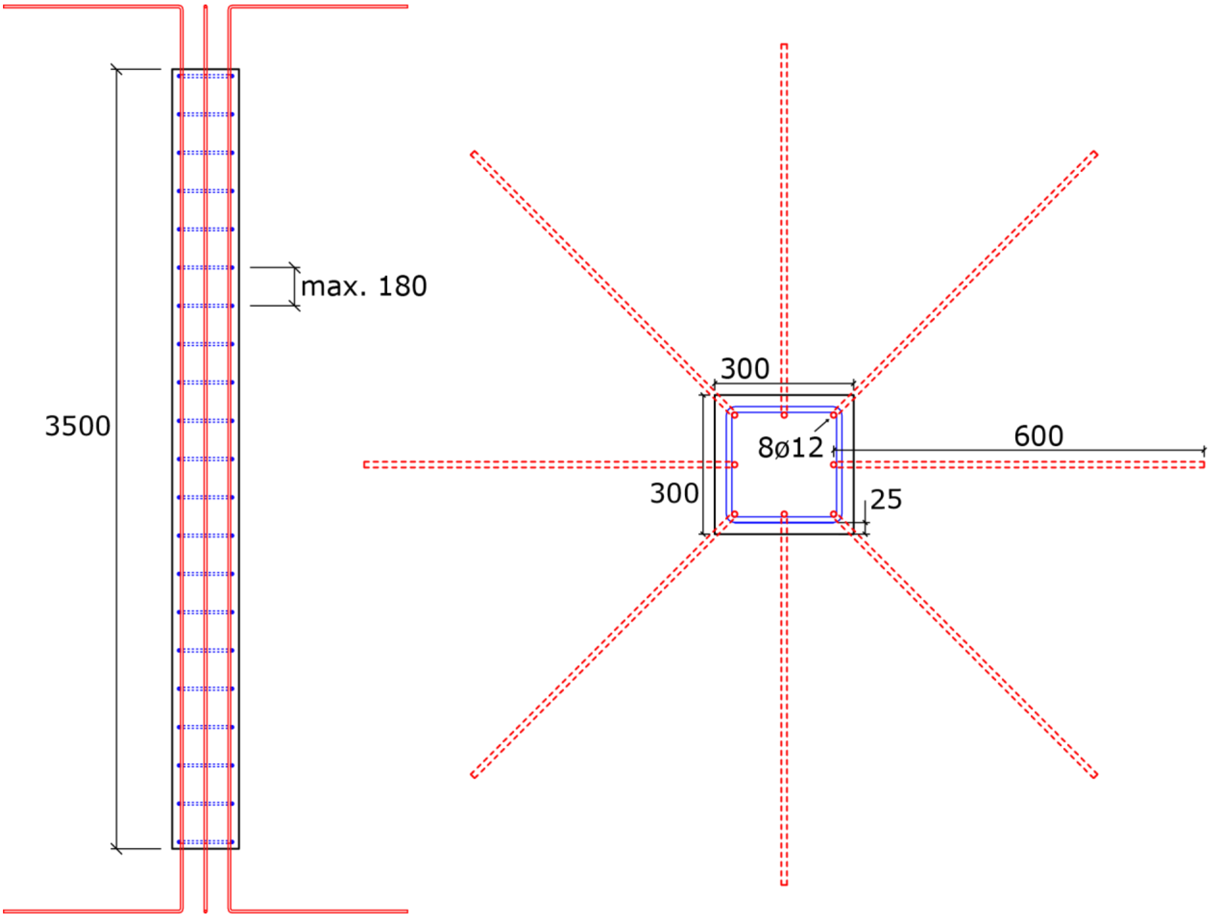

Figure 17: Estimated rebar distribution in new concrete column.

The GWP of the new concrete column will be estimated on the basis of modelling done in SimaPro. Seen as the local supplier of concrete and steel can be assumed, transformation processes are used for the materials. This step is done to ensure that the transportation is not overestimated, thus giving more realistic grounds for comparison. The closest supplier of concrete is assumed to be Betong Øst at Heggstadmyra, 8,9 km away. The closest supplier of steel is assumed to be Norsk Stål AS at Nyhavna, 11,6 km away.

The transportation is assumed to be completed by a Euro6 lorry between 16 and 32 tonnes. Euro6 is the class of lorries with the strictest requirements to emissions (Samferdselsdepartementet, 2007). The process that is used in SimaPro to model the operation includes the emissions for a lorry carrying an average load, as well as the return trip. The input needed is therefore the weight of the component and the distance it is transported in the form of tonnes-kilometres (tkm). The output is then the transported components share of an averagely loaded lorry over the given distance. For the transportation of concrete, with an assumed density of 2,5 t/m^3, the input is 6,89 tkm. For the transportation of reinforcement steel, with an assumed density of 7,8 t/m^3, the input is 0,759 tkm.

Unicon has published data on relations between GWP of production of low-carbon and conventional concrete based on the criteria set by the Norwegian Concrete Association’s (Norsk Betongforening) publication NB37. On their web-page it is stated that low-carbon B (LC-B), low-carbon A (LC-A), low-carbon Pluss (LC+) and low-carbon Extreme (LC-Ex) has respectively a 15%, 36%, 51% and 63% reduction in emissions respectively compared to standard concrete (Unicon AS, 2023). This data will be used to approximate the emissions from a column using low-carbon concrete for comparison with the reused column. It is assumed that changing to low-carbon concrete will not lead to other changes in the column.

The low-carbon concrete options have varying availability. From Unicon, LC-B, LC-A and LC+ are available in all parts of the country, but LC+ is not delivered in all strength classes. LC-Ex has to be ordered on a project basis (Unicon AS, 2023). The prices will increase the lower the carbon class is, but the difference is not stated (‘Lavkarbonbetong’, no date).

Seen as the transportation distances can be assumed, transformation processes are used to model the concrete and reinforcing steel. This assumption will ensure that the transportation distances are not overestimated, giving a realistic total GWP of the new column.

Table 1: Inputs and assumptions for modelling of new column.

Operation	Included processes	Input	Assumptions
Concrete	Concrete, 30MPa {RoW}| concrete production 30MPa | Cut-off, U	0,3097 m^3	With percentwise output of GWP: 1 100% (conventional concrete) 2 85% (LC-B) 3 64% (LC-A) 4 49% (LC+) 5 37% (LC-Ex)
	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	6,89 tkm	Transportation of 0,774 tonnes 8,9 km
Steel	Reinforcing steel {Europe without Austria}| reinforcing steel production | Cut-off, U	65,3 kg	
	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	0,758 tkm	Transportation of 0,0653 tonnes 11,6 km

3.3.5 Reused component

For the reused concrete components, the extraction from the donor building, transportation to storage, testing and documentation, preparing the component for installation, insertion into the new building and the materials used during installation is considered. This process is not a commonly practised one, thus some assumptions are made. Included in the calculations are the processes from, and including, dismantling and extraction from the donor building to installation in the new building. Only the materials used during installation will be taken into account, seen as the potential formwork and supports needed are assumed to be reusable, thus giving negligible emissions per component. The process is also assumed to be similar to that of the new component, thus not contributing to any differences between the new and the reused components.

The assumptions made will be presented in the following paragraphs. A table presenting the operations with the processes chosen to model them will be presented by the end of this section (table 2).

It is assumed that everything but the load bearing structure of the building is demolished. Due to uncertainties regarding the emissions from this process, this is not taken into account for the total emissions assigned to the reused component. It is also assumed that all of the load bearing structure is intended for reuse. This leads to the further assumption that the emissions from extracting adjacent components are exclusively assigned to the extracted components themselves.

The floor dividers and/or beams that are supported by the column that is to be extracted are assumed to be extracted before the removal of the column. The emissions from this are not assigned to the column.

Figure 18: Concrete wall saw that could potentially be used for cutting a column (Motek, no date).

To extract the component that is going to be reused, sawing and lifting of the component is taken into account. The sawing is assumed to be completed with a high voltage concrete wall saw of 20 kW (Motek, 2023b). The setup of the sawing process is not detailed in this report. The cutting process (operation of the saw) is assumed to take 30 minutes, not including the preparations and following rigging down and clean-up of the process. The cutting time includes 15 minutes for cutting the base of the column, as well as cutting of the top of the column after it is extracted. The top of the column, where the beams and/or floor dividers have been attached, is necessary to ensure predictable reinforcement distribution.

The extraction of the component is assumed to be completed by crane. It is assumed that wrapping straps around the column is sufficient for the lifting process. The crane is assumed to be run during the cutting of the base of the column (15 minutes), supporting it while it is cut. This done as a conservative measure to account for any underestimations done when assuming the process as a whole. This way the emissions should end up being higher than what is likely for the case in reality. The crane is also assumed to be running for 15 minutes in addition to the cutting process, adding up to 30 minutes of total runtime for one column. Several columns would likely be extracted simultaneously when running the crane, making this a realistic assumption. If only one column were to be extracted, the runtime per column might have increased beyond 30 minutes. The crane is assumed to be attached and run by the lorry that transports the columns, so when modelling the operation, the process of "Machine operation, diesel >= 74,57 kW, low load factor" is assumed to be an appropriate estimation. Low load factor is chosen due to the relatively low weight (ca. 800 kg) of one column compared to the capacity of an average crane of the relevant type (Nordic Crane, 2023).

The transportation of the column is assumed to be done with a Euro6 lorry between 16 and 32 tonnes to storage at the work site of the new building. Using the new column as reference it is assumed that the extracted column weighs 813,3 kg. The transportation distance is 8,4 km. The input in SimaPro is then 6,83 tkm. For the case that is looked at in this report, it is assumed that there is sufficient space at the work site to store the sourced components. This might however not be the case for other projects and sourced components might need to be stored off site. The additional emissions from transport to an unknown location and the storage itself would however need to be further assumed, leading to additional sources of inaccuracies. It is therefore decided that off-site storage is not relevant for these calculations.

Testing and documentation of the sourced components are assumed to happen during storage. It is likely that this would be done prior to transport to the work site, but seen as storage is assumed to be at the work site for the purpose of these calculations, this will not be the case in this process. Testing and documentation of a concrete component for reuse could include both destructive and non-destructive processes. The non-destructive processes are not going to be taken into account when calculating emissions, but destructive test will be accounted for by assuming some waste per reused component. The leftover materials from testing could likely be reused, but seen as this would lead to a significant increase in number of variables, the leftovers are counted as waste as a simplification. In the standard "Hollow core slabs for reuse" full scale testing of one in every 50 element is required. Due to the unpredictable nature of the quality of CIP RC a shorter interval of one in every 10 element is assumed. This assumption is not based in data but is considered a conservative assumption. The full-scale testing means that 10% of the extracted columns end up as waste. Another 10% is counted as waste due to components having to be discarded due to damages and/or poor quality. The loss will be counted as concrete and steel waste. For the chosen size of column, 20% of its total weight is equal to 163,1 kg. Given the average relation between steel and concrete in the column, that means 8,7 kg steel and 154,4 kg concrete. This amount of waste is what is assigned to one column when a set of columns are assumed to be reused. The transportation of this waste to the work site is not counted, seen as the loss would occur throughout the process, including during extraction of the components and during preliminary visual inspections after extraction.

To attach the column to the beam or slab beneath, coupling sleeves, as described on page 14 and 15, are used. The coupling sleeves are assumed to be 40 mm in diameter and 1000 mm deep. The depth is chosen to accommodate a sufficient overlap of the rebar with a diameter of 20 mm that is to be inserted. The diameter of the reinforcement bar is chosen to give a cross section of the coupling rebar equal to, or greater than that of the longitudinal rebar in the column, maintaining the load bearing capacity through the new joint. The overlap is not calculated, seen as this requires a known force in the rebar to be done in accordance with NS-EN 1992-1-1 (Standard Norge, 2021). The overlap is however estimated on the basis of a well-established "rule of thumb" in the building industry of 50 times the diameter of the rebar. When drilling the coupling sleeves, the removed amount of concrete is counted as waste, adding up to 50,3 kg for the in total 16 holes that needs to be drilled in the top and bottom of the column as well as their adjoining surfaces.

After the documentation and preparation of the column, it is hoisted into the building. The same equipment is used to insert the column as was used to extract it from the old building. The run-time of the crane is also assumed to be the same for insertion as for extraction. This should give sufficient time for placing and supporting the column.

Due to the cutting of the reused columns, it is fair to assume that they end up shorter than needed or that inaccuracies are introduced in the cutting process. Therefore, two cases of reuse are modelled. One case will include and extension of 50 mm in both ends of the column, extending the column 100 mm while also giving the ability to adjust for inaccuracies in the length of the column. The extension will be made from mortar, seen as concrete, with its aggregates, likely would not reach into the narrow spaces of the sleeves. Synthetic materials might also be used, but mortar is used as an approximation in this modelling. A case without extension is also modelled. The thickness of the mortar between the column and the slab is then assumed to be 5 mm in both ends of the column.

When installing the column, it is lowered onto rebars previously cast into the slab on which the column is going to be placed. Four rebars are used per connection (two per column, one top and one bottom). The rebar is modelled in SimaPro as reinforcement steel with a total amount per column of 41,2 kg with extension and 39,3 kg without. Input for transportation of the steel is 0,478 tkm and 0,456 tkm respectively, based on the same assumptions as for the new column. In addition to the rebar, mortar is used between the columns as well as in the sleeves. With extension, the total amount of mortar needed is 59,9 kg, while without, the amount is 38,8 kg.

Figure 19: Installation of precast concrete column with coupling sleeves ('Reinforced Precast Concrete Columns', no date).

The final setup of operations can thus be divided into the phases of an LCA that are included as follows:

A1 – Preparation for extraction and extraction

A2 – Transportation

A3 – Storage, testing, documentation and preparation for assembly.

A4 – Transportation to site (not included, seen as all transportation is assumed to be done in phase A2)

A5 – Reassembly

Table 2: Inputs for modelling of reused column

Operation	Included Processes		Input
Preparation for extraction	Electricity, high voltage {NO}| market for | Cut-off, U		10 kWh
Extraction	Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| market for | Cut-off, U		0,5 hr
Transportation	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U		6,83 tkm
Storage, testing and documentation	Process-specific burdens, inert landfill {RoW}| market for process-specific burdens, inert material landfill | Cut-off, U	Concrete waste	154,4 kg
		Steel waste	8,7 kg
Preparation for assembly	Process-specific burdens, inert material landfill {RoW}| market for process-specific burdens, inert material landfill | Cut-off, U		78,5 kg
	Electricity, low voltage {NO}| market for | Cut-off, U		4 kWh
Insertion	Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| market for | Cut-off, U		0,5 hr
Assembly	With extension (2x50mm)	Cement mortar {RoW}|market for cement mortar | Cut-off, U	59,9 kg
		Reinforcing steel {GLO}| market for | Cut-off, U	41,2 kg
		Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	0,478 tkm
	Without extension (2x5mm)	Cement mortar {RoW}|market for cement mortar | Cut-off, U	38,8 kg
		Reinforcing steel {GLO}| market for | Cut-off, U	39,3 kg
		Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	0,456 tkm

3.3.6 Scope

The reused component is assumed to perform similarly to the new component in terms of lifespan, maintenance and end-of-life. This means that phase B and C will be equal between the two, leaving the dissimilarities to phase A. Phase B and C (and D) will therefore be excluded from this LCA. Phase A1-A5 will be assessed but excluding some processes within phase A5. This includes the formwork of the new CIP RC column and the potential formwork and supports needed for the reused CIP RC column. This is seen as a fair assumption due to the similarities in these processes as well as the likely reusability of the materials and tools that are used. For both components, the formwork and supports would likely be of reusable metal profiles, thus making the emissions per component negligible.

Due to the large GHG emissions from the production of concrete and the ongoing climate crisis, global warming potential (GWP) has been deemed the most vital grounds for comparison and will therefore be the focus of this LCA. The GWP is commonly presented as kilograms of emissions of carbon dioxide-equivalents (kgCO_2-eq). This is also the unit of measurement used to present the GWP per functional unit in this report.

The results will be presented with one decimal. Due to the amount of assumptions that have been done, the results are only intended to give an approximation of how the components will perform in reality. One decimal is therefore seen as sufficient and will ensure easier interpretation of the tables and diagrams. No decimals could also be seen as sufficient for the purpose of this assessment. This could however give false impressions of some of the operations that are included, showing no GHG emissions. Limiting the results to one decimal might lead to round-off errors between processes and their totals.

4 Results

4.1 Questionnaire

Relevant results from the questionnaire will be presented per section. Single choice answers will be presented by a percentwise distribution across the alternatives, multiple choice answers will be presented as percentwise distribution or in graphs, and linear scale answers will be presented as averages in graphs. Free format answers will be presented as short summaries. Only the quantity of the responds will be presented in the report, while further analysis and connections between the results are based on the full dataset that is attached (appendix C and D).

4.1.1 Section 1: Background information

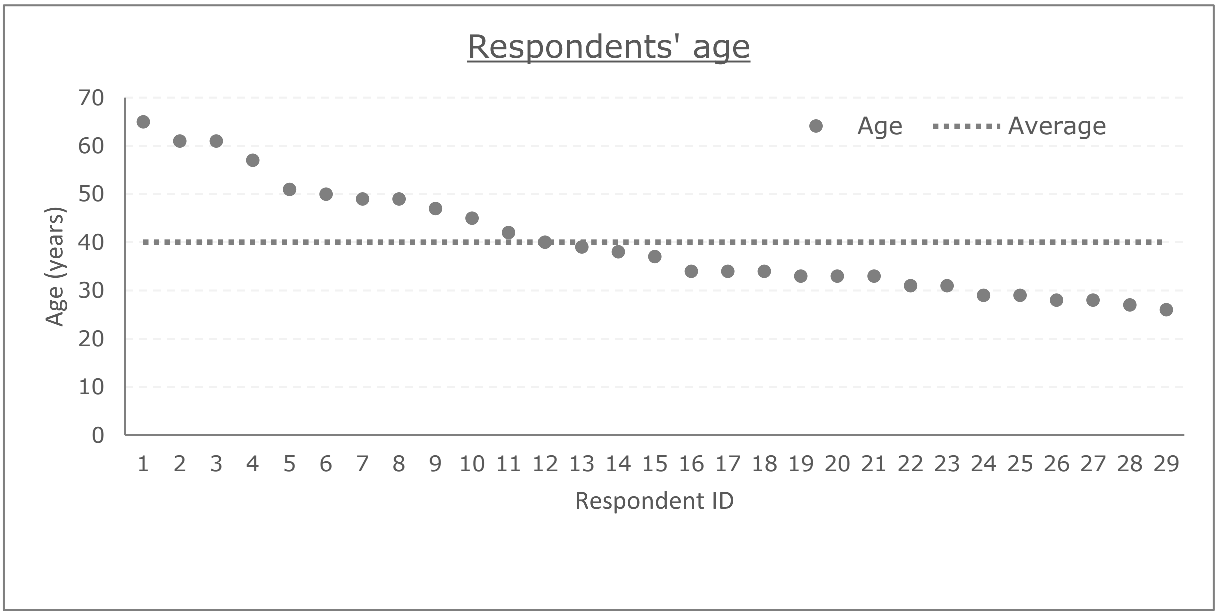

Figure 20: Graph of respondents' age with average age plotted as a doted line.

The section “Background information” shows that the average age of respondents were 40 years, with the oldest being 65 years and the youngest being 27, as shown in figure 23. In table 3, further background information is listed. 65,5% were male, 31% female and 3,5% preferred not to respond. All respondents, except one, were from Norway, whereof the majority worked in design and/or construction analysis. 20,7% had also worked in other fields, including energy calculations and advisory in energy, environment, reuse and concrete technology.

28 out of 29 of the respondents had worked on buildings under and/or over five floors, whereof commercial buildings over five floors were most common. Second after buildings where infrastructure, whereof most respondents had worked on bridges. 17,2% (5 respondents) had worked with reuse in load bearing structures before, whereof concrete was most commonly reused before steel.

Table 3: Background information

	Number		
Respondents	29		
Gender			
Male	19		
Female	9		
Prefer not to respond	1		
Country of employment			
Norway	28		
Canada	1		
Role	**Share [%]**		
Client	10,3		
Design	72,4		
Construction analysis	51,7		
Quantity surveyor	27,6		
Finance	3,6		
Demolition	3,5		
Material sourcing	6,9		
Other	20,7		
Type of structures worked with			
Buildings over 5 floors	86,2	Commercial	78,6
Buildings under 5 floors	65,5	Residential	57,1
		Mixed use	60,7
Infrastructure	34,5	Bridges	80
		Roads	30
		Large scale public works (sewers, water conduits etc.)	30
Landscaping	17,2		
Worked with reuse			
No	62,1		
Yes, but not in load bearing structures	20,7		
Yes, in load bearing structures	17,2	Wood	20
		Steel	40
		Concrete	60
		Bricks	20

4.1.2 Section two: Concrete as a building material

In the second section "concrete as a building material", the respondents were asked about their relationship to and motivation for use of concrete. When asked if the emissions from concrete worked as a limiting factor in the planning process of a project with the current regulations, the average rating (on a scale from one to five, where one was not limiting and five was very limiting) was 2,31. The average rating showed that the emissions were slightly limiting but not to a large degree. The results are shown in figure 24.

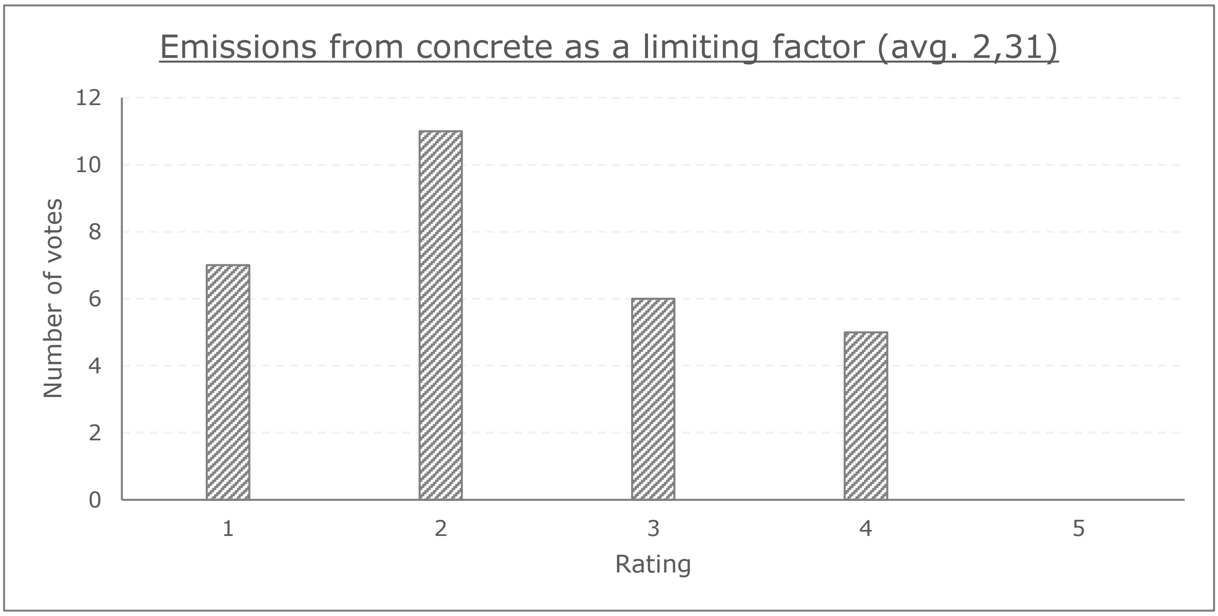

Figure 21: Responds to the question if the emissions from concrete works as a limiting factor in the planning process of a project with the current regulations.

The second question, asking to what degree concrete will be used in the sustainable building industry of the future, on a scale from one to five where one is not at all and five is a lot. The average rating of 3,28 showed that the respondents see concrete as an important building material in the future but with somewhat limited use. The results are shown in figure 25.

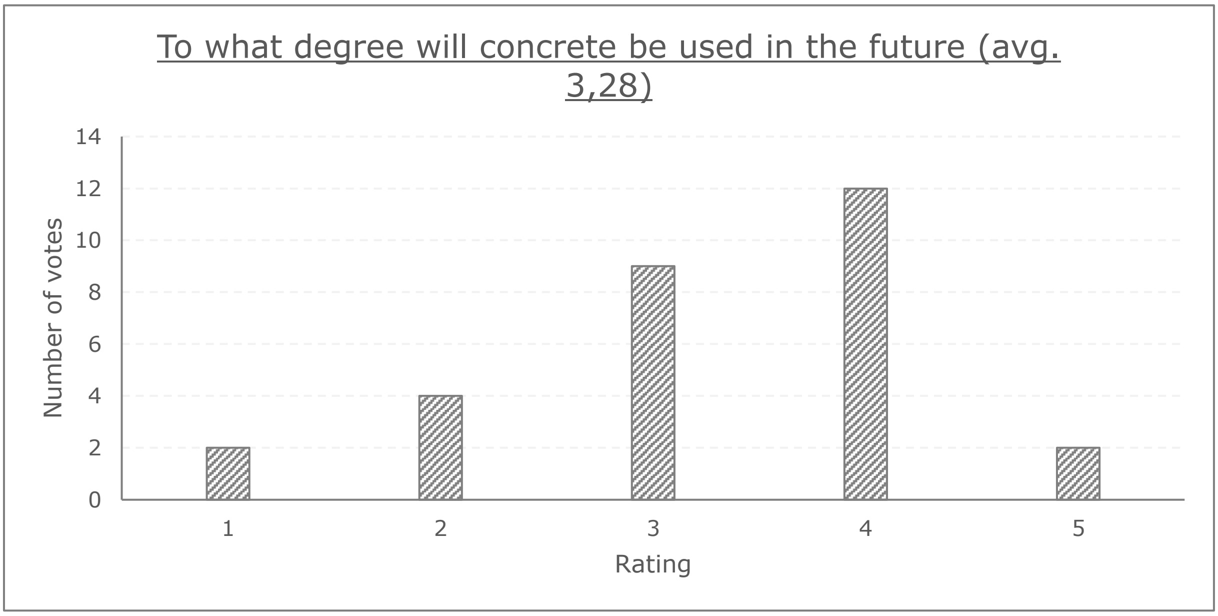

Figure 22: Responds to to what degree concrete will be used in the sustainable building industry of the future.

When given the opportunity to freely comment on concrete as a building material, the importance of concrete in the building industry was pointed out. One respondent emphasised that concrete is irreplaceable in some of the areas where it is used today, like foundations, but that its use should be limited to where it is strictly necessary. Another respondent pointed out how changes in rules and regulations might change the amount of, and how concrete is used in the future. The availability of low-carbon concretes is also pointed out to have a potential impact on the attractiveness of use of concrete. Alternative materials for reinforcing concrete is also mentioned to have an effect on the potential lifespan of concrete, further increasing its attractiveness for planners.

4.1.3 Section three: Reuse of building materials

The third section focused on the respondents' views on reuse of building materials. Firstly, the respondents were asked how they perceive the industry's view on reuse of building materials today on a scale from one to five, where one was very negative and five was very positive. The average rating was 2,76, with only one respondent answering "very negative", meaning that the industry is perceived as slightly negative to reuse of building materials. The results are shown in figure 26.

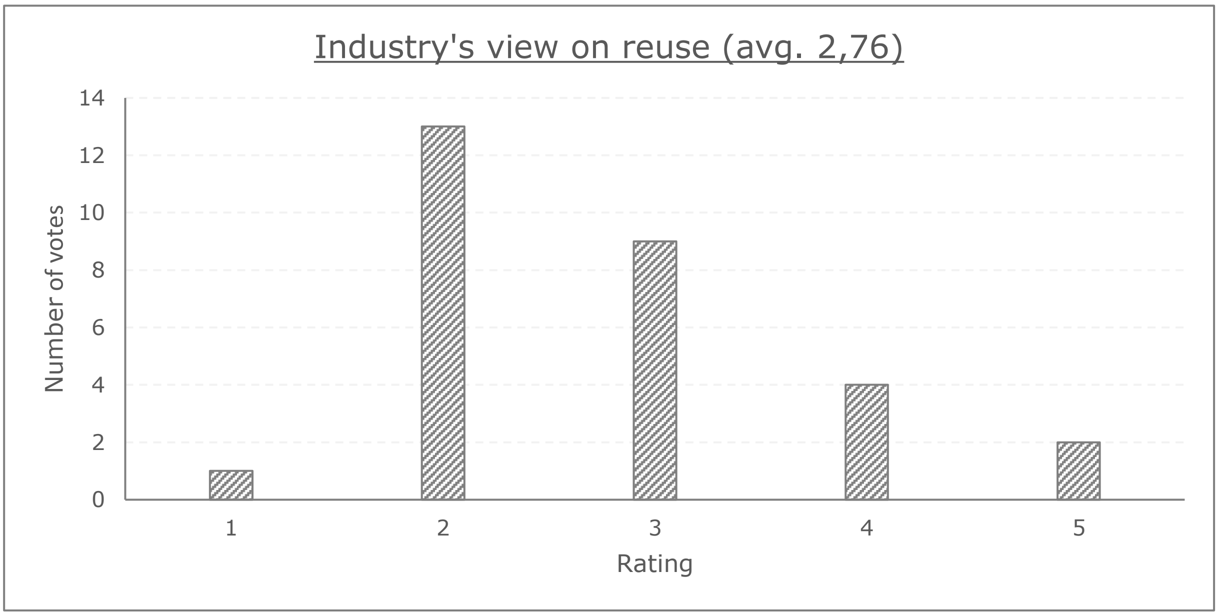

Figure 23: Responds to the question of how the respondent perceived the industry's view on reuse of building materials.

The second question investigated how the respondents thought the efficiency of planning/building with reused materials would compare to planning/building with virgin materials. By efficiency, it was referred to the resources spent on a project in the form of time, money, materials etc. The alternatives ranged from one to five, where one was less efficient and five was more efficient. With an average of 2,72, the respondents thought that the efficiency of a planning/building process would get slightly less efficient when using reused building materials compared to virgin ones. The results are shown in figure 27.

Figure 24: Responds to how the respondent think the efficiency of planning/building with reused materials will change compared to using virgin materials.

For the next questions, the participant was presented the following scenario:

> *Imagine a scenario where a system for buying and selling used building components exists and is actively used in the building industry. The components are gathered at a local storage facility and are sold with all necessary documentation, ready for use.*

When asked how this would affect the amount of reused materials they include in their projects on a scale from one to five, where one was not at all and five was a lot, the average rating was 4,0. With only one respondent answering that it would not change their amount of reuse at all, the average rating shows that the scenario would increase the amount of reuse in the building industry. The results are shown in figure 28.

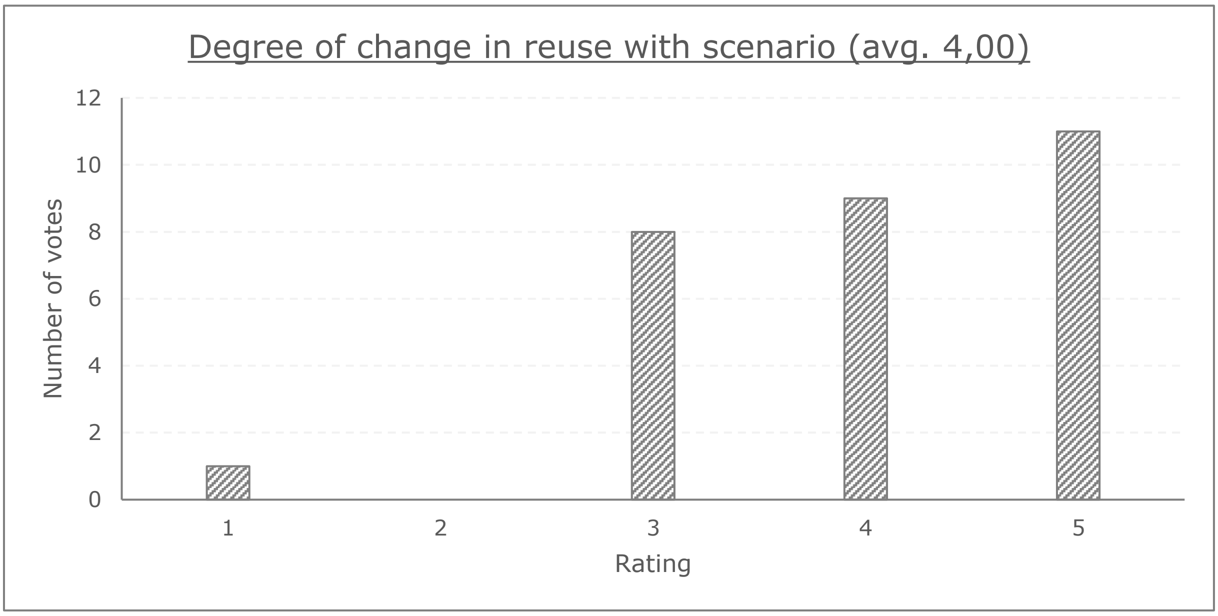

Figure 25: Responds to how the scenario would change the respondents use of reused building materials in their projects.

For the final question regarding the scenario, the respondents were asked who should be financially responsible for providing such a system. A shared responsibility between public organisation, contractors and planners was rated highest, with public organisation rated second highest. The results are shown in figure 29.

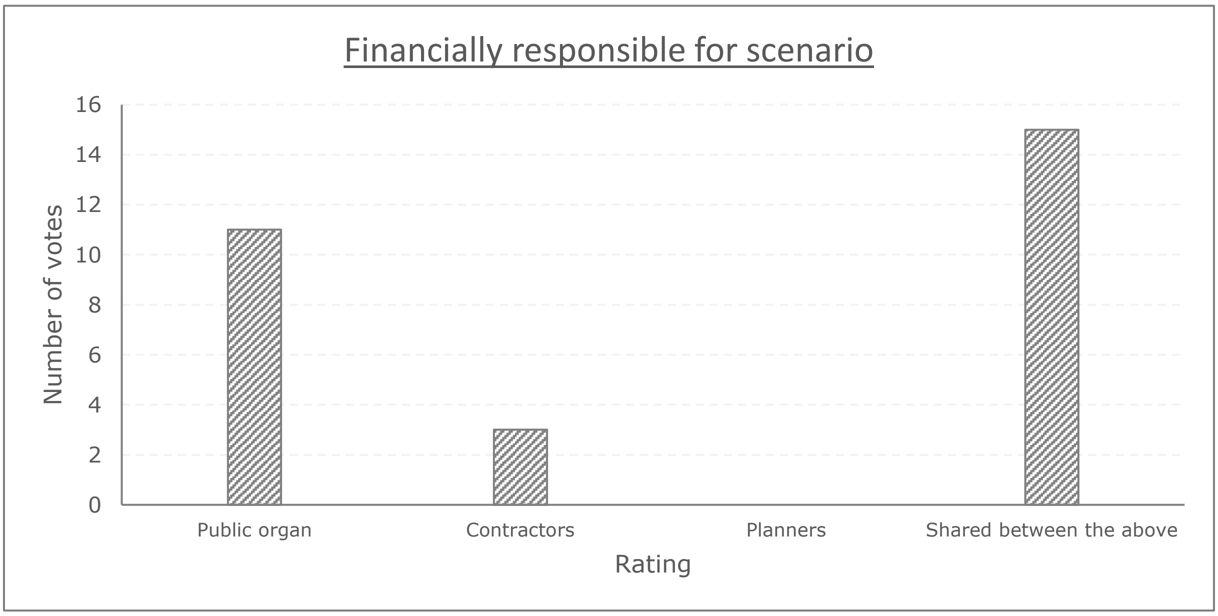

Figure 26: Responds to who should be financially responsible for providing a system as described in the scenario.

When asked to elaborate on opinions around the scenario, the importance of decentralised storage facilities with short transport distances to work sites is emphasised. Further, it was pointed out that the system should not be shielded from the common market, and be competition driven. Another respondent mentions private actors with start-up funding to be a viable solution for realising the system. A digital platform is pointed out to be an effective tool to make the system available in the industry, preferably with ID-numbering of the components. Lastly, the importance of proper documentation of the building materials is pointed out. Who should be responsible for the testing and overall quality of the components? Good documentation of building materials in new buildings is pointed out as a solution to ease the process of documentation for future reuse.

4.1.4 Section four: Reuse of CIP RC in load bearing structures

The fourth and final section investigated the respondents' views on reuse of cast-in-place concrete in load bearing structures (CIP RC). In today's building industry, most respondents rate the feasibility for reuse of CIP RC as somewhat low, with an average rating of 2,55, where one is not at all feasible and five is highly feasible. The results are shown in figure 30.

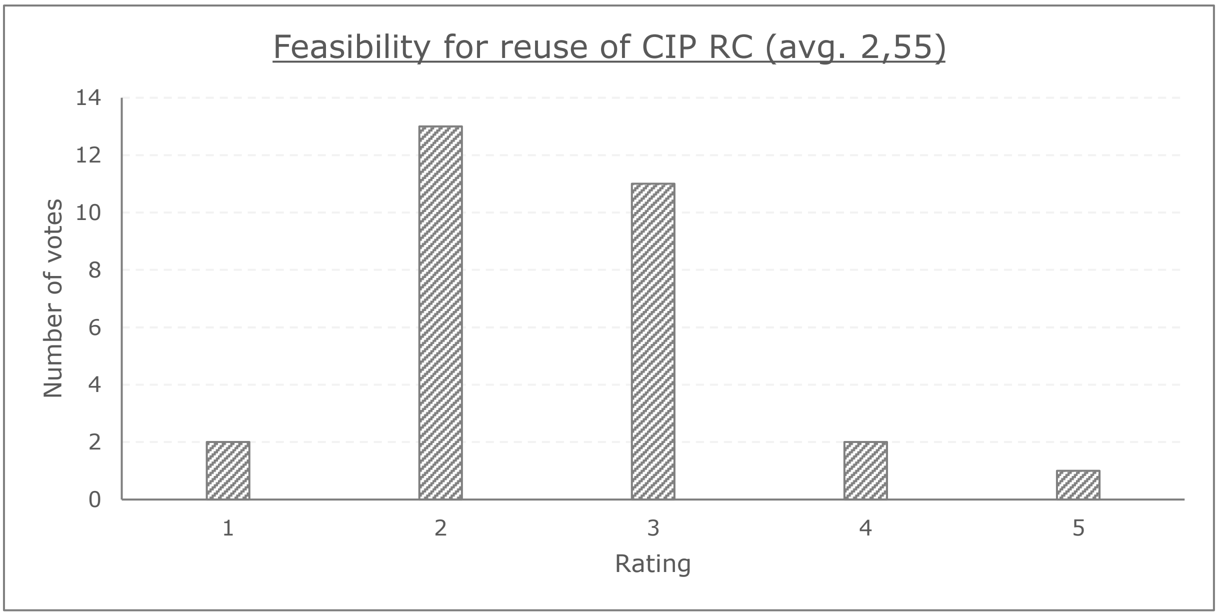

Figure 27: Responds to how the respondents see the feasibility for reuse of CIP RC.

Emissions are rated as the greatest and only clear driver by the respondents. Documentation of sourced materials is rated as the most significant barrier among the alternatives, while regulations and time being rated slightly higher. The remaining influencing factors are all rated about three, meaning neither barrier nor driver for reuse of CIP RC. The responds are shown in figure 31. Group 1, 2 and 3 refers to, respectively, respondents who have worked previously worked with reuse in load bearing structures, respondents who have previously worked with reuse, but not in load bearing structures, and respondents who have not previously worked with reuse. Their average ratings are presented to distinguish between the ratings given by respondents with different levels of experience within reuse. The data labels belong to the overall average ratings.

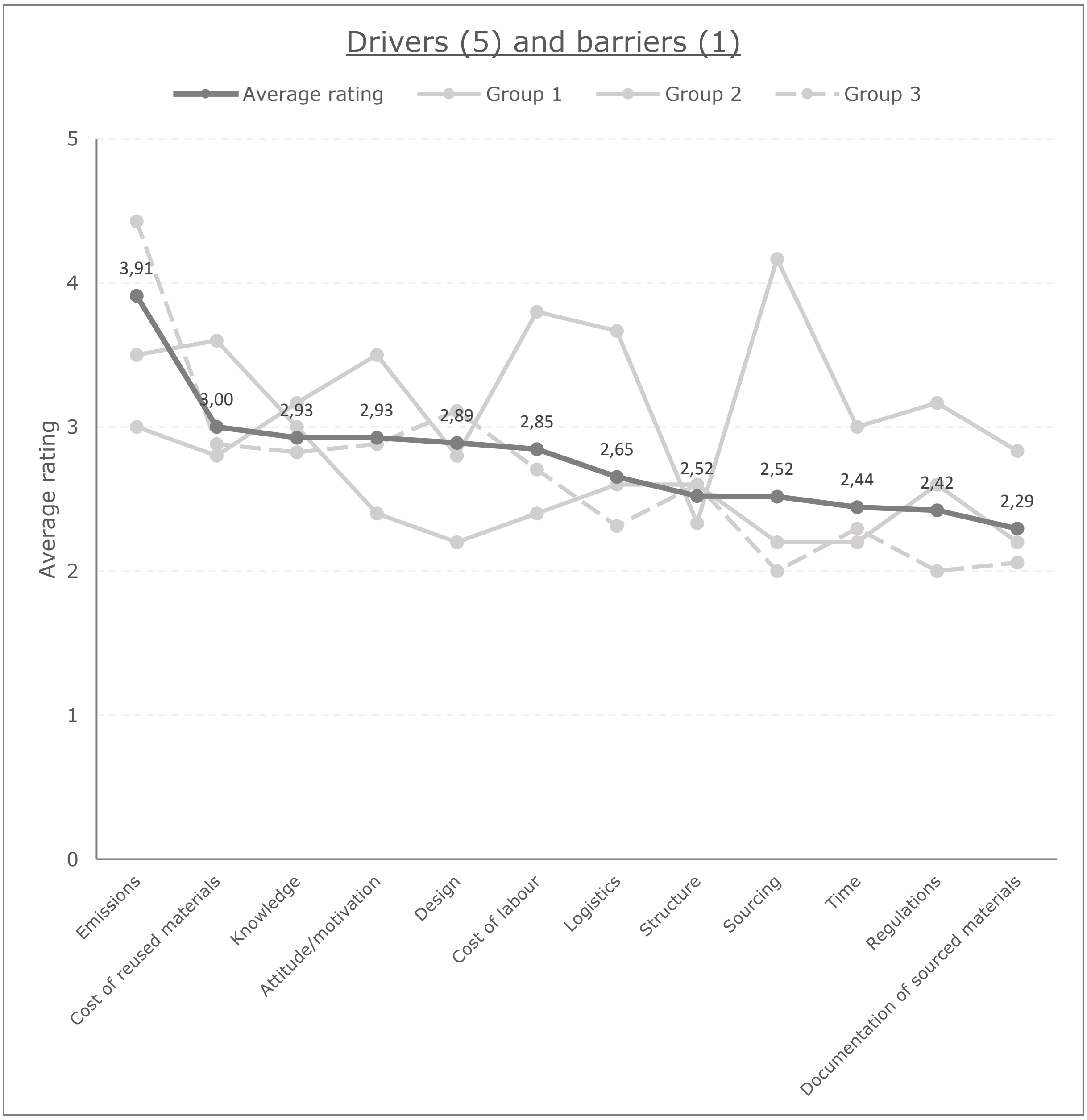

Figure 28: Average rating of to what degree different factors work as driver (5) or barriers (1) for reuse of CIP RC. The data labels belong to the overall average ratings.

In figure 32, the respondents' ratings of feasibility for reuse of different types of CIP RC components are shown. The figure contains two graphs, whereof one shows feasibility for equivalent reuse, and one shows feasibility regardless of end-use. By regardless of end-use, it is referred to a component being reused without necessarily utilizing its full potential, e.g. a floor divider being reused as a slab on ground. The scale ranges from one to five, where one is not suited and 5 is highly suited.

Regardless of end-use beams and floor dividers are rated highest by the respondents. Foundations and slabs on ground are rated lowest. For equivalent reuse columns and floor dividers are rated highest while foundations still are rated lowest. All components are rated lower for equivalent reuse compared to reuse regardless of end-use.

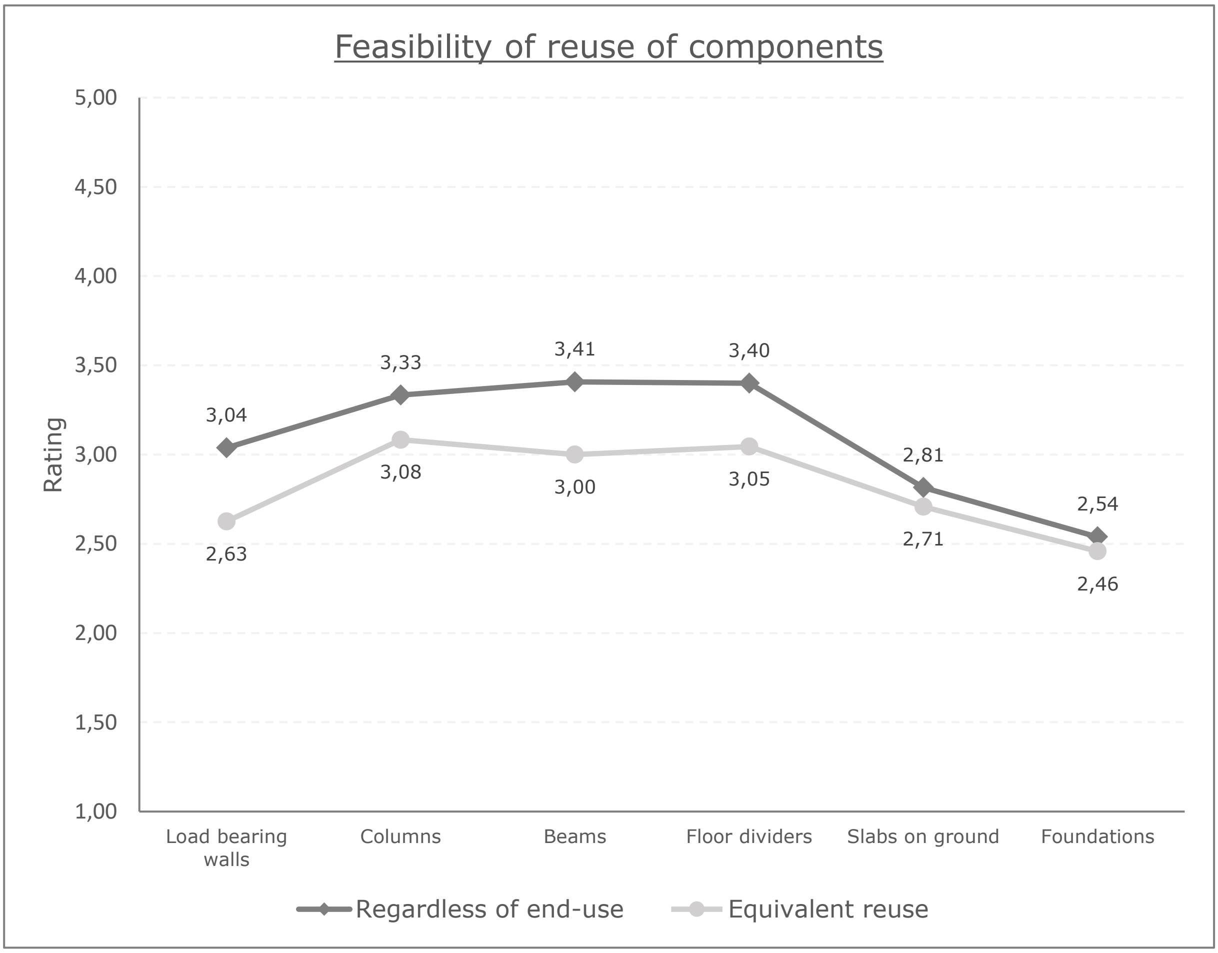

Figure 29: Ratings of feasibility for reuse of some CIP RC components. The dark line represents reuse regardless of end-use and the brighter one represents equivalent reuse.

The respondents were at this stage in the questionnaire asked to answer one specific option to a question to ensure that they were paying attention, thus validating their answers. All respondents passed this test.

In figure 33, the responds to expected and acceptable price of reused CIP RC components are presented. Expected price (left bars) were rated to be higher, up to 150%, of the price of an equivalent component cast in new concrete. The acceptable price (right bars) was rated to be equal. Rated second after equal as acceptable price was a lower price.

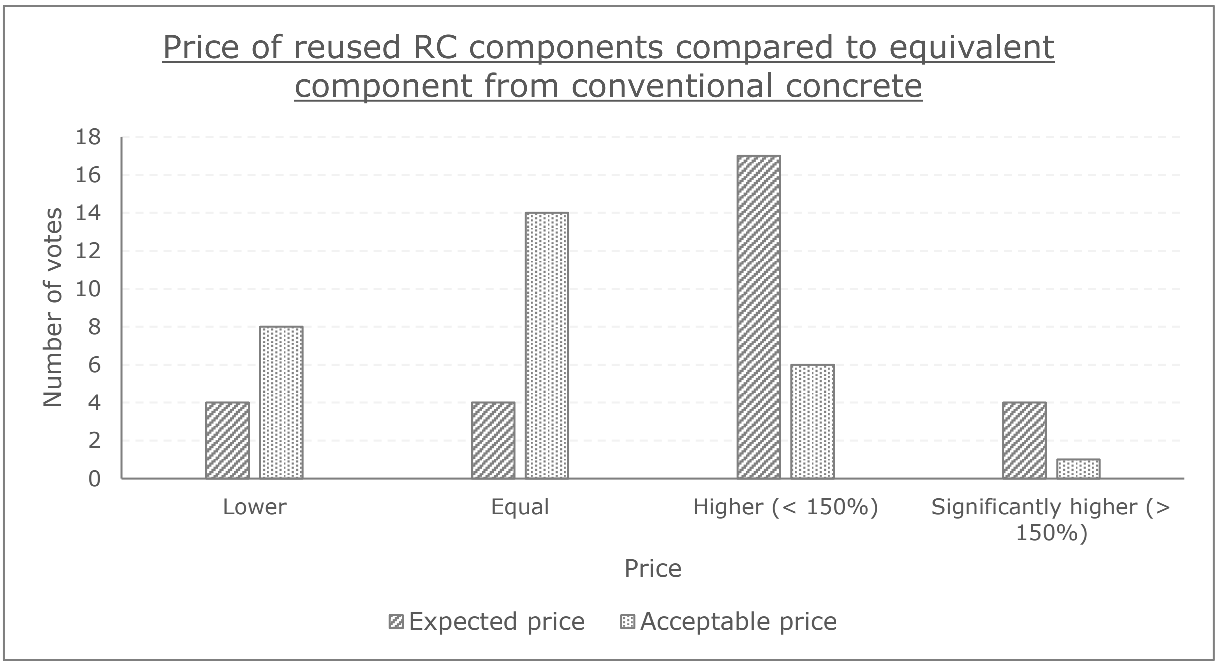

Figure 30: Responds to what price could be expected for a reused CIP RC component, and what would be acceptable. Ratings for expected price is the left bar and acceptable price is the right.

In the third to last question, the respondents were asked to elaborate on how they expected the collaboration between client, architects, engineers and contractors to change in the planning phase of a project where reused CIP RC is used. Several respondents emphasised the importance of early contracting of key stakeholders (e.g. designers, structural engineers and contractors), and increased collaboration between the different parties involved. An increased use of time was also pointed out to be expected, with several revisions of plans and designs. Fewer standardized solutions would also be applicable, one respondent pointed out.

When asked what information about the sourced CIP RC component the respondent would need to do their part of the planning process in a project, general documentation of its properties was pointed out as vital. This documentation should include history of the component (what kind of environment has it been exposed to), its dimensions, load bearing capacity, depth of carbonation, alkali reactivity, compressive strength etc. Further, sufficient information on the logistics around acquiring the components is necessary to ensure a streamlined workflow. Rules and regulations, as well as standards on reuse of CIP RC is pointed out to be a necessity for including it in a project.

Lastly, the respondents were given the opportunity to freely elaborate on the topic of reuse of CIP RC. The first of three main points that were made was the uncertainty of quality in old concrete structures. It was stated that CIP concrete generally has a lower quality than pre-cast element, thus making it less suited for reuse. Corrosion of the reinforcement was also pointed out to be a major risk factor for the quality of reused components. The uncertainty of the reused components quality affects the level of risk that the supplier of the component assumes.

The second key point that was made in the additional comments was the challenge of storing the components that are to be reused, including transport to and from the storage. This step would lead to increased cost of the components.

Finally, it was pointed out that the rate of which buildings are demolished does not correspond to the rate of which new ones are constructed. Therefore, reuse will not cover the demand for concrete structures, making new concrete a necessity.

4.2 LCA

Results from the LCA that has been conducted will be presented in the following sections. The results will be divided into two sections: one presenting the results for the new column with its low carbon options; and one presenting the results for the reused component with and without extension. The results will be presented based on the functional unit that was defined on page 23 with kilograms of carbon dioxide-equivalents per functional unit (kgCO$_2$-eq/p) as the unit of measurement. The raw data extracted from SimaPro can be found in appendix E.

4.2.1 New CIP RC column

Table 4: GWP of new CIP RC column with low carbon concrete options [kgCO$_2$-eq/p]

Type	Total	Concrete	Steel	Transportation concrete	Transportation steel
Conventional	216,6	83,5	131,8	1,1	0,1
LC-B	204,1	71,0	131,8	1,1	0,1
LC-A	186,5	53,5	131,8	1,1	0,1
LC+	174,0	40,9	131,8	1,1	0,1
LC-Ex	164,0	30,9	131,8	1,1	0,1

Table 4 and figure 34 shows the estimated emissions from casting a new CIP RC column in different types of concrete. Only the emissions from the concrete changes, affecting the total, between the different concrete options. Reinforcing steel has the greatest share of emissions for all options. The transportation processes give the smallest contribution. Figure XX shows a gradual decline in the total emissions as the emissions from the concrete decreases. From the option using LC-B, LC-A, LC+ and LC-Ex there is a decrease of respectively 5,8%, 13,9%, 19,7% and 24,3% compared to the option using conventional concrete.

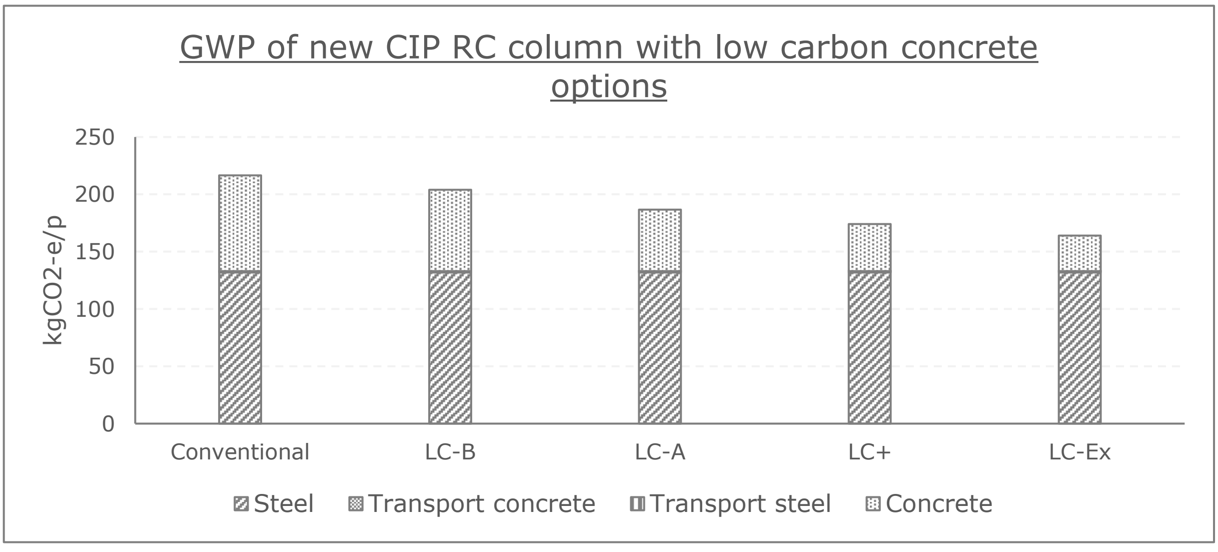

Figure 31: GWP of new CIP RC column with low carbon concrete options

4.2.2 Reused CIP RC column

Table 5: GWP of reused CIP RC column with and without extension

Operation	With extension [kgCO2-eq/p]	Without extension [kgCO2-eq/p]
Cutting	0,2	0,2
Extraction	11,7	11,7
Transportation	1,1	1,1
Testing	0,4	0,4
Preparation	0,2	0,2
Insertion	11,7	11,7
Reassembly	98,6	89,3
Total	123,9	114,7

Table 5 and figure 36 shows the GWP of a reused CIP RC column, with and without extension. All processes except reassembly have the same emissions between the two options, making the GWP of the extended option 7,4% higher. The reassembly process is responsible for the largest share of the GWP of both options. As figure 35 shows, this is mainly due to the large emissions from the reinforcing steel. Further, the extraction of the component from the donor building and the insertion into the new building gives the second largest contribution to the total GWP. The cutting, transportation, testing and preparation (drilling of sleeves) of the column all contribute with less than 1% to the total GWP.

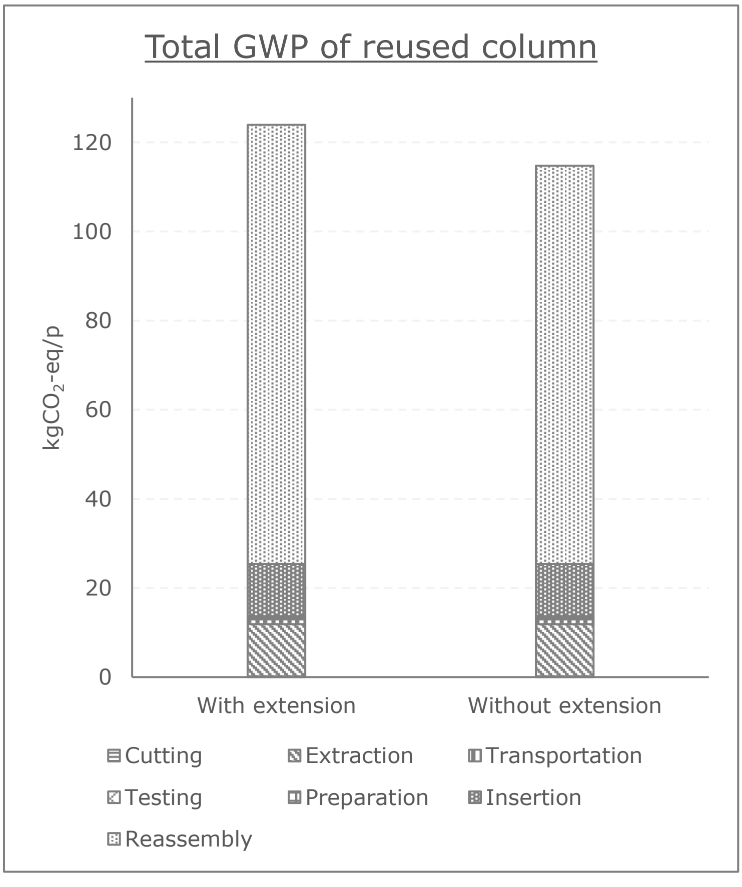

Figure 32: GWP of one reused CIP RC column with and without extension.

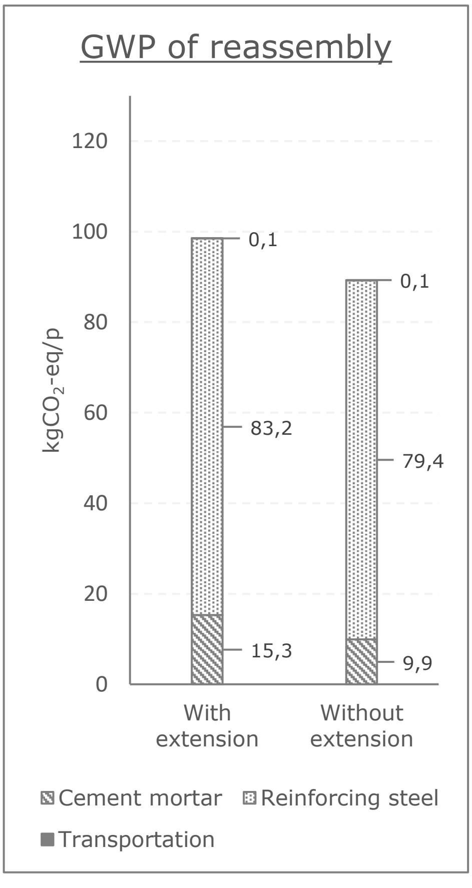

Figure 33: GWP of reassembly process of one column with and without extension.

5 Analysis and discussion

5.1 Questionnaire

5.1.1 Section one: Background information

The results from the questionnaire show that most of the respondents worked within design and construction analysis. Seen as the majority of respondents work within the same role of the building industry, further analysis will not differentiate between the replies given by respondents within the different roles.

A relatively high percentage had worked with reuse in load bearing structures previously (17,2%). The majority of these had worked with reuse of concrete. Such a high percentage was unexpected but might be explained by their connection to the topic of the questionnaire, and thus likely increased interest in sharing their opinions on it. 62,1% had however never worked with reuse before, ensuring a wide range of backgrounds for the data.

For the purpose of readability of the discussion section, respondents who have previously worked with reuse will be referred to as Group One. Respondents who have worked with reuse, but not in load bearing structures, will be referred to as Group Two. When referring to respondents who have worked with reuse, both group 1 and 2 are included.

5.1.2 Section two: Concrete as a building material

When asked if the respondent saw GHG emissions from the use of concrete was seen as a limiting factor with the current regulations, the average rating came to 2,31, meaning that the emissions were seen as slightly limiting. When sorting for the replies for who had worked with reuse and not, the ones who had worked with reuse, and especially Group One, rated the emissions as less of a limiting factor. Based on this, it can be argued that the regulations on use of concrete might not be strict enough. If the large emissions from concrete are to be reduced, rules and regulations might have a significant effect on limiting its use. This issue was also highlighted by respondents to be a vital tool to make the building industry more sustainable.

Concrete is also seen as playing a role in the sustainable building industry of the future. The average rating for the question regarding this was 3,28, showing that concrete will continue to be an important building material, regardless of the implications this might lead to. As mentioned by one of the respondents, concrete is a unique building material that is hard to replace in structures (e.g. foundations). The only viable alternative might therefore be to lower the emissions of the concrete itself. As pointed out by another respondent, the availability of and continuous research on low-carbon concrete options might help concrete to become a vital building material, on terms with the sustainable building industry of the future. As previously stated, the low-carbon concrete that is currently available on the market has a 63% reduction in GWP, making it a great option to conventional concrete. However, as the emissions from concrete are so high in the first place, a 63% reduction is not likely to be enough to reach the goals to limit climate change.

5.1.3 Section three: Reuse of building materials

The third section focused on reuse of building materials, whereof the respondents first where asked about how they perceive the industry’s view on it. The average rating of 2,76 showed that today’s industry is perceived as somewhat negative towards reuse. Even though a lot seems to be happening on the field of reuse, with marketplaces being opened and standards being developed, this might imply that the general attitude towards and motivation for reuse is not as high throughout the industry. Especially the respondents who had worked with reuse previously stated the perceived positivity for reuse as low. This could indicate that the parties that have tried to implement reuse have met resistance among other parts of the industry. Regardless, it could be speculated that as reuse becomes more available, the general view on it might turn more positive.

Further, the planning and design process is rated to get slightly less efficient when implementing reuse, with an average rating of 2,72. Group one gave a lower average of 2,20, while group two gave an average rating of 3,00. This could imply that the ones who had worked with reuse in load bearing structures had experienced a more significant decrease in efficiency in their projects compared to what the ones who had not, giving the respondents an unequal approach to the question. A more significant decrease in efficiency when designing for reuse of load bearing structures compared to non-load bearing structures can however be argued to be a natural result of the additional considerations that have to be taken. For example, the dimensions of a structural floor that is to be reused may dictate the overall layout of a building, while the dimensions of a door that is to be reused will only impact the wall that it is to be placed in. The efficiency of planning and designing with reuse will therefore vary greatly depending on what type of components are to be reused. Designing and planning with reuse in a load bearing structure is likely to lead to decreased efficiency due to additional revisions in design and general lack of knowledge with the process, as stated in several of the reviewed papers.

The majority of respondents rated the scenario that was presented as highly likely to increase the level of which they incorporate reuse in their projects with an average rating of 4,00. This further supports the theory that availability has a strong impact on how the industry’s motivation and attitude is towards reuse is.

Financial responsibility for the system for buying and selling reused components was voted by the respondents to be shared between public organs, contractors and planners. In the following free format answers, one respondent pointed out that it would be natural that today’s suppliers of building materials would be the natural choice for providing such a system. Establishing such a system might however be challenging without a wide collaboration within the building industry and the financial means to build up an inventory of components. An existing supplier of building materials, collaborating with the industry to ensure a flow and documentation of products for reuse with funding from a public organ might therefore be the viable solution. It was also emphasised that such a system should be part of the free market, with prices driven naturally by supply and demand. This could be ensured if the system was run by private actors such as today’s suppliers of building materials.

Further, the importance of having a digital platform for distributing the products is emphasised to make the products easily available for the buyers. ID-numbering of the products is stated as a way to organise the products, and would make a digital platform a more feasible solution. It would also simplify the process of documentation both before the product is sold, and if it is to be reused again at a later point.

5.1.4 Section four: Reuse of CIP RC

When asked about the feasibility for reuse of CIP RC in load bearing structures, the average rating from the respondents were 2,55, showing that the feasibility is seen as somewhat low. For this question, Group One rated the feasibility as higher, with an average of 3,00, while Group Two had an average of 2,67 and those who had not worked with reuse had an average of 2,39. Those who have experience with reuse of load bearing structures, and thus more knowledge about it, does therefore prove to be more positive to reuse of CIP RC compared to those who do not have this experience. This can be interpreted as showing that a lack of knowledge about the process of reuse of load bearing structures contributes to a less positive attitude towards it. Sharing of information and experiences can therefore be argued to be an essential step in making reuse of load bearing structures more mainstream.

Emissions is stated as the only clear driver for reuse of CIP RC by the respondents, with a rating of 3,91. This supports the hypothesis that is the basis for a lot of reuse in the building industry, and one of the main arguments going into writing this thesis. By reusing instead of producing new building materials, the emissions from phase A of a product's life-cycle should be greatly reduced while also minimizing waste. The respondents who had previously worked with reuse did however rate the emissions from reuse of CIP RC as less of a driver than those who had not worked with reuse. This might imply deeper knowledge of the emissions related to reuse, or it could indicate a more negative attitude towards it.

Further, most factors that were included in the question were rated close to or below 3,00 which represents neither a barrier not a driver. Cost of reused materials is rated at exactly 3,00. This factor can be hard to predict the outcome of, seen as the process of reusing CIP RC is not commonly known, thus making it hard to predict whether the price will be higher or lower than that of new CIP RC components. However, Group One rated cost of labour as more of a driver at 3,60. This feedback could imply that the price of reused CIP RC might be lower than commonly thought, or a confidence in a reduced price as the practise becomes more common.

After cost of materials comes knowledge, with a rating of 2,93. As previously stated, the general knowledge related to reuse of CIP RC can be seen as relatively low. However, there are large-scale projects that have reused CIP RC, or similar products like hollow core concrete, that have gained some attention. Especially the project KA13, where hollow core concrete slabs where reused, gained a lot of attention in the building industry, spreading the message that reuse of such components is far from impossible (Entra ASA et al., 2021). Group Two rates knowledge as less of a barrier, and more of a driver, with an average rating of 3,17.

Attitude and motivation is rated equal to knowledge, with an average rating of 2,93. Here, Group One gave an average rating of 2,40, significantly lower than the two other groups. The low rating might imply that the group has first-hand experience working with parts of the industry that are less willing to deal with reuse in load bearing structures. Contrarily, Group Two gave an average rating of 3,50 – highest of the three groups. This might show that the motivation for and attitude towards reuse in general is higher, but that the lack of experience within reuse in load bearing structures has not given them the same impressions as the ones that have worked with it specifically.

Design is rated as a slight barrier for reuse of CIP RC, with an average rating of 2,89. Group One gave the lowest average rating of 2,20. Again, this might imply that experience with reuse in load bearing structures has shown this group the obstacles related to designing with reuse. This finding is further supported by Group Two giving a lower average rating than the ones who have not worked with reuse. Findings from the literature review also state that designing with reuse is one of the key challenges for making it a common practise.

Cost of labour is given an average rating of 2,85 and is thus seen as a slight barrier for reuse of CIP RC. Again, this might suggest that the cost related to reuse can be hard to estimate, due to the uncertainties related to it. Group One gave the lowest average rating of 2,40, while Group Two gave the highest of 3,80. These ratings represent a significant gap in how the cost of labour for reuse of CIP RC is perceived. The difference might be based in the groups difference in experience, seen as the cost of labour for reuse, not including load bearing structures, might be significantly lower than in load bearing structures.

Logistics is given an average rating of 2,65, again ranking it as a slight barrier. Logistics is repeatedly mentioned as a great barrier for reuse of load bearing structures by researchers and in projects. Primarily, storage of components after extraction and before insertion as well as timing between demolition of donor building and construction of new building is brought up as the most significant challenges. This feedback is also stated by the respondents in free format answers, where also the cost related to storage and the transportation to and from it is mentioned.

A possible solution to the challenge of timing between demolition of a donor building and constructing the new building could be to buy the donor building, as stated by Gorgolewski and Morettin (Gorgolewski and Morettin, 2023). This might however not be favourable to the new project, seen as it would lead to additional work and cost in demolition and disposal of the parts of the building that is not going to be reused. An agreement to buy the remaining load bearing structure after majority of the demolition work is completed could also be a solution. However, this strategy could result in a lack of care during demolition, which could result in damages to the load bearing structure. An exposed load bearing structure that is exposed to the environment might also not be favourable when the components are to be reused. It could also be argued that it would not be aesthetically pleasing for end-users. Therefore, a middle-ground could be favourable, where only the building envelope and the load bearing structure is bought for reuse, leading to a minimal amount of demolition work remaining, while keeping the load bearing structure protected and leaving the most destructive parts of the demolition process to the buyers.

As this solution still has the potential to lead to increased costs in the new project, a marketplace that buys and sells used building components could be a feasible alternative that eliminates the aforementioned challenges. Such a marketplace has been proven in the previous answers of the questionnaire to have a great potential in the building industry. However, the solution does depend on the owner of a building that is to be demolished seeing the value of selling the components for reuse. It is unlikely that this can rely exclusively on the motivation for reducing the environmental impact of the building. The marketplace will therefore be able to buy the components for such a price that it becomes a financial benefit for the owner to sell components for reuse.

Structure is given an average rating of 2,52, stating it as a slight barrier. A lot of uncertainty related to the structure of reclaimed CIP RC concrete can be seen as one of the sources for this barrier, as also stated by several respondents in the free format answers. Due to it being custom made on site, cutting apart a CIP RC structure could remove integral parts of its reinforcement, thus reducing its load bearing capabilities to an unwanted or unknown state. This could be a challenge for the responsible party, seen as they will need to take on the responsibility for a structure of which the properties can be hard to identify. A system for documenting the properties of a component could be the necessary tool to overcome this challenge.

Sourcing is given an average rating of 2,52, implying that it is seen as a slight barrier for reuse of CIP RC. Group Two gave a significantly higher average rating of 4,17. This could be interpreted as the group having experience with ease of sourcing in their reuse projects. Following this logic, Group One have not experienced this ease of sourcing. Based on the groups different backgrounds, this could show how a market for reuse of building materials might already be established and working well, thus making sourcing of general materials for reuse effortless, but the market not delivering load bearing components.

Time is given an average rating of 2,44, showing that it is seen as a slight barrier. Again, Group Two gave a higher average rating of 3,00, while Group One and Three gave average ratings of 2,20 and 2,29. The relatively low rating is backed up by the literature review that was conducted in this report, where several researchers and project reports stated that an increased use of time is a significant challenge for reuse of CIP RC.

Reuse of building components in new buildings might make the task of designing a well-functioning, good looking and flexible building harder. As found by several researchers before and confirmed by the questionnaire conducted in this thesis, the time that is required to accomplish a well-designed building with reused components is a challenge. It could be argued that, in an effort to combat the increased time demand, the designers might make rushed decisions, compromising the quality of the design. Conversely, the increased use of time can be seen as a result of the designers taking extra care in ensuring a sufficient quality of design.

Regulations is given an average rating of 2,42, meaning that the respondents see the current regulations as a slight barrier for reuse of CIP RC. This can, among other factors, be tied to the current system for selling and buying building materials where extensive documentation is needed. The process for documenting a CIP RC component for reuse is currently not established, making it hard to distribute it on the market. It was also stated in one of the following free format answers that clearly defined rules and standards are necessary in order to plan and design with reuse in load bearing structures. The regulations can also be seen as a barrier in the sense that it does not limit the use of new CIP RC, making it more convenient to choose it over reuse in a project.

The barrier of documentation of sourced materials is further emphasised by its average rating of 2,29. It is further emphasised in the following free format answers to the question on what information about the components for reuse that is necessary for the respondents in their roles of a project, that proper documentation on the history, dimensions, capacity etc. is vital. Further, it is stated that the barrier of documentation also comes down to who that is going to be responsible for the reused components meeting the necessary requirements. As investigated in the theory part of this report, there are established methods for testing and documentation of concrete products for reuse. However, these methods are primarily based on pre-cast elements. For CIP RC components, the same range of tests will likely need to be included, but due to the reduced predictability of its designed properties and production quality, the methods and frequencies of testing will likely have to be adjusted. The tests are also commonly used for condition assessment of CIP RC structures, and methods and frequencies of tests can likely be adopted from this routine to work for reuse.

When asked about the feasibility for reuse of some types of CIP RC components, beams and floor dividers were rated highest for reuse regardless of end-use, followed by columns. For equivalent reuse, all components were rated lower, with columns being rated highest, followed by floor dividers and beams. The lower ratings of equivalent reuse can be assumed to based in the increased risk and the uncertainty related to the quality of reclaimed CIP RC components. Columns, beams and floor dividers are likely rated highest due to their more predictable structure and ease of extraction compared to foundations and slabs on ground. However, load bearing walls was given a lower rating even though their extraction process and predictability could be comparable to columns and structural floors. For equivalent reuse, load bearing walls are also rated lower than slabs on ground. Foundations are rated lowest for both reuse regardless of end-use and for equivalent reuse. This might be due to challenging extraction because of the size and weight that often characterizes such a component, introducing difficulties to the lifting operations, or its constant exposure to the outside environment that might compromise its lifespan. All components are rated slightly higher by the respondents that have previously worked with reuse, implying that knowledge about reuse has given an increased perception of feasibility for reuse of load bearing CIP RC components.

The expected price of reused CIP RC components was rated to have an expected price of up to 150% higher than that of a similar new component. This feedback can be interpreted as a summary of how the process of reuse of CIP RC is perceived of the respondents. The additional work that has to go into sourcing, design, documentation, logistics etc., all rated as barriers, will likely force the price to increase. It is natural that more expensive components are not chosen over the cheaper alternatives without clear incentives to encourage such a decision. The increased price might therefore be part of the explanation for why reuse of CIP RC has not become a more common practise. The respondents rating an equal price as being acceptable might indicate that reused components are not viewed as waste products, but are seen to have value equal to that of new concrete. In one of the reuse projects that were reviewed earlier in the report, the price of reused hollow core concrete slabs had been calculated to be 5-6 times that of new ones, showing that a lot of work needs to go into standardizing the process of reuse of load bearing components in order to bring the price to an acceptable level.

More collaboration between the planning parties in a project is emphasized to be a key factor to realise projects with reuse in load bearing structures. Increased collaboration would primarily ensure a more stream-lined design process. By contracting structural engineers, constructors and other relevant parties early in the design process, architects can make informed decisions on how reclaimed CIP RC components can be used both in theory and in practise. Making these informed decisions early in the planning process may lead to fewer revisions and less time use. Such collaboration will however only be fruitful if the components that are going to be reused are already identified. Sourcing components early in the process might however lead to increased cost due to the need for storage. A marketplace, where the components can be identified early in the process and retrieved when the construction process can begin, might therefore be a necessity to realise the increased collaboration that is stated as vital for the planning process with reuse.

Information and additional comments?

5.2 LCA

To analyse and discuss the results from the LCA, this section will be divided into three parts. First the results for the new and reused CIP RC columns will be analysed and discussed individually, based on the functional unit that has been set and the assumptions and estimations that have been made. The new and reused CIP RC components will then be applied to the new building that was introduced in the case study and compared.

5.2.1 New CIP RC column

The new CIP RC column was calculated to represent a realistic scenario. However, some assumptions were necessary to create the complete component due to a lack of data. The new CIP RC column is still seen as a realistic estimation.

As previously stated, the emissions from reinforcing steel gives a higher contribution to the total GWP of RC than concrete. However, the significance of this feature did turn out greater than expected, with the reinforcing steel contributing to more than 60% of the total GWP with conventional concrete and more than 80% with LC-Ex. This result shows that, even with a minimum amount, the reinforcing steel represents a significant challenge in bringing RC concrete into the sustainable building industry of the future.

Even with the high contribution from the reinforcing steel, the low-carbon concrete options gives a significant reduction in the total GWP, with up to 24,3% reduction with LC-Ex. The availability of LC-Ex might however make it a less feasible alternative. The new building that is examined in this report is only a XX m^2, one story building. The amount of concrete that would be used in this building might not be enough to bring the price down to an acceptable level, seen as it would likely cost more for the supplier per cubic meter they deliver if the amount of low-carbon cement they have to take in is not high.

The process that was chosen for modelling of reinforcement steel in SimaPro accounts for the average global mix of GHG emissions from reinforcement steel. Detailed research on types of reinforcement steel has not been done in this report, but the question could be raised whether the process is representative for the average mix of Norway. If a larger share of recycled steel is used, the GHG emissions would for example likely decrease.

5.2.2 Reused CIP RC column

Reuse of CIP RC is not a common practise. To complete an LCA on the reuse of it will therefore necessitate many assumptions and estimations. The LCA that has been conducted in this report should therefore only be seen as an approximation of how a reused CIP RC component might perform. The assumptions that have been made have also generally been conservative ones, meaning that the total emissions from the reused components are likely higher than what they would be in reality. There are however exceptions to this, mainly related to the process of preparation for extraction and storage.

Before the column that has been investigated can be extracted from the donor building, the surrounding structure would have to be removed. As previously mentioned, the demolition of the building, excluding the load bearing structure, was assumed to be demolished, leading to emissions. These emissions would need to be allocated to either the donor building's total lifespan or to the components that are extracted for reuse. It could be argued that regardless of if the load bearing structure is to be reused or not, the building would be demolished, and the emissions would occur. However, the load bearing structure being reused might lead to additional care having to be taken during demolition, leading to greater emissions than for a conventional demolition. However, assigning all the emissions to a reused component might also be argued to be wrong. If reuse is to become a common practise, in order to lower the use of resources and emissions, it is vital to encourage the building industry to do it. By assigning all the emissions from the demolition of the surrounding structure of a building to the reused components, the reduction in emissions from reuse might not become significant enough and conventional materials might be chosen instead. However, it can also be argued that the owner of the donor building should not be punished for selling parts of the building for reuse by getting the additional emissions assigned to their building. By selling some parts for reuse, especially the load bearing structure, the owner of the building does however avoid the emissions from having to dispose of large amounts of materials. A middle-ground might then have to be struck, where a percentage of the emissions, accounting for the increase due to additional care having to be taken, is assigned to the reused components. This might however be a challenging practise, both in deciding on what this share should be as well as hoe it is distributed across different components. A column might for example get a greater percentage increase in its emissions compared to a structural floor, making it an unfavourable choice for reuse compared to new products.

Another assumption that might be favourable for the GWP of the reused components is that all of the load bearing structure is assumed to be reused. If the adjacent components were not to be reused, it would be natural to assign a share of the emissions from demolishing or extracting these to the column that is to be reused. In the case study that was set up for the calculations, the donor building is significantly larger than the new building. If this new building was the only receiving structure, reusing all of the structure in the donor building would be impossible. These calculations are therefore relying on other new buildings reusing components from the same donor building. The likelihood of there being other projects in the same area that have a planned structure that correlates to the donor building can be argued to be small. One solution could be that the planners and designers working on new buildings in the area would agree on who would reuse what.

This would ensure maximum utilization of the donor building. Collaboration across projects might however lead to increased use of time as well increased cost. Another solution could therefore be a market for reused components where designers and planners could plan according to the inventory that is available.

For cutting, a high voltage concrete wall saw of 20 kW was modelled. This saw is, as the name implies, meant for cutting concrete walls. In practise, a more commonly used concrete saw might have been used for this operation. Commonly used concrete saws generally have lower power and shallower cutting depth than the one used in these calculations (Motek, 2023a). The cutting time might therefore increase but it could be assumed that the total energy consumption might decrease.

The extraction and insertion give the second largest contribution to the total GWP of the reused CIP RC columns. The process that was used to model this in SimaPro was meant to represent a crane run by the same lorry as was used for transportation. It might however be that the processes that were chosen does not match. The process chosen for transportation was a Euro6 lorry, while for the machine operation process chosen for the crane, an emission-class was not specified. Nevertheless, it can be argued that it makes sense that the emissions from the crane are greater than that of transportation, seen as for transportation, only the one column's share of the emissions from an averagely loaded lorry is counted. In the case of running the crane, the full share of the emissions from running the lorry is allocated to the one column that is extracted. The conservative assumption of the crane being run for 30 minutes might also have been too high of an estimation. While the crane supporting the column during the 15 minutes that the cutting process takes can be seen as necessary, it could be argued that 15 minutes for preparation and lifting the column out is not likely. For inserting the column, 30 minutes can be seen as more realistic due to the operations that needs to be done to install it. Even though the emissions from extraction and insertion can be perceived as high compared to other operations in these calculations, it is seen as important that these operations are not underestimated, giving unreasonably low emissions.

Further assumptions that were made for the extraction and insertion of the columns were the lifting arrangements. It was assumed that the columns would be lifted by wrapping straps around them. While this can be seen as a plausible solution, a dedicated lifting arrangement might be favourable with regards to HSE (Health, Safety and Environment). Such a lifting arrangement is however likely to be reusable, thus not making a difference for the LCA. Using lifting arrangements might require modifications to the component that is extracted, as with the case of hollow core slabs presented earlier where holes had to be drilled. If this were to be the case for columns, it would lead to added emissions in the process of modifying the components and disposing of the waste materials. However, the emissions could be assumed to be comparable to those of the preparation operation that is included in this calculation, thus being of little significance for the total emissions of the component.

The emissions from transportation of reused components have previously been seen as one of the challenges for reuse. However, the calculations that were completed in this report do show transportation to give a relatively small contribution to the total GWP of a reused column. This feature is likely explained by the short transport distance chosen, and the fact that the components were assumed to be stored on site, eliminating additional transportation. It can be estimated that based on the results that the column with extension could have been transported close to 700 km before exceeding the GWP of a column from new conventional concrete. Compared to LC-Ex concrete, it could be transported close to 300 km. For the column without extension, the transport distances could be increased further. This finding is comparable to the numbers found by Reppe for reuse of hollow core concrete slabs (Reppe, 2021), as well as those of the Udden project

(Eklund, Sundbaum and Ab, 2023). The modelling of the transportation process can therefore be argued to be realistic.

The testing and documentation of CIP RC for reuse is, as stated both in previous research and by respondents to the questionnaire, a currently uncertain process. Therefore, some assumptions were necessary in order to model an operation for it that could represent a realistic case. As an approximation to a realistic testing process for CIP RC, the standard for reuse of hollow core concrete was used. The tests that were most likely to give an impact on the total emissions of the reused components were the destructive tests. These tests were accounted for through adding waste processes. Due to the uncertainty related to the consistency of build quality in CIP RC, an increase in the frequency of testing was seen as necessary in order to mirror a realistic case. The waste process was also modelled to account for components discarded due to poor quality or damages. Accounting for the discarded and tested elements as waste could be argued to give a worse picture of the reused components than what could be the case in reality. In a project that works with reuse, thus likely focusing on reduction of waste, it could be argued that the components that are not suited for reuse would follow the waste hierarchy to the next step of recycling. However, counting the discarded components as waste was chosen in an effort to create a scenario that did not mirror an idealistic case of reuse, but rather a case that is close, or worse than, a realistic case of reuse in terms of emissions. Despite these assumptions, the emissions from testing made up less than 0,2% of the total emissions from both the reused column with and without extension.

For preparation of the column for insertion, the research completed by Volkov on reassembly of used concrete components was primarily used as the basis for estimating its GWP (Volkov, 2019). The use of coupling sleeves is a well-established practise for assembly of pre-cast columns, and is thus seen as a viable solution also for reuse of CIP RC columns. The size of the sleeves was however decided with the intention of fitting the rebar while giving space for the mortar to access the sleeve. No calculations were done to ensure that the diameter was over- or underestimated, thus being a source of inaccuracy in the LCA calculations, both in terms of the waste that is generated and the amount of mortar that is used during reassembly. Moreover, it could be investigated if only one coupling sleeve could suffice, further reducing the amount of waste generated and mortar used.

The testing procedure of hollow core concrete slabs include taking a core sample of the component for compression testing. The core drilling of the coupling sleeves could possibly supply such a core sample for each column that is reused, ensuring a high frequency of testing and increased confidence in the quality of the components. The extracted cores will however then need to comply with the specified requirements for core samples for testing in NS-EN 12504-1 (Standard Norge, 2023).

By using coupling sleeves for reassembly, the columns will gain similar properties to that of a CIP column. Although this is a desired outcome to utilize the full potential of the load bearing capacities of the component, it does not make it easily dismantlable for reuse at a later point. Repeated reuse would be favourable to further reduce the environmental impact of the component but is not facilitated through the use of coupling sleeves. However, it could be argued that further reuse would not be possible, seen as the concrete might have reached the end of its technical lifespan, meaning that it is no longer able to serve its design purpose. It could therefore be necessary to recycle the concrete rather than reusing the component at this stage.

The reassembly was modelled for two scenarios: one where the column was at the desired height and only a 5 mm layer of mortar was needed in the connection at each end of the column; and one where the column was too short, needing a 50 mm extension at each end. Volkov states that grout is to be used in the assembly of coupling sleeves (Volkov, 2019). Seen as this material was not available in the ecoinvent database, mortar was chosen as an approximation to it. Other, synthetic materials are also likely to be used for connecting the reinforcement bars in particular. Such materials might have a greater environmental impact than that of mortar, but the approximation that was done is still seen as giving a representative result.

The two scenarios that were modelled gave an understanding of how the reassembly process can affect the GWP of the final product. The results show that, if the column were to be cut 10 cm under the desired height, the total GHG emissions would increase by 8%. This increase is 2% greater than the difference in GHG emissions between conventional and LC-B concrete (6%). Therefore, an accurate disassembly process of the donor building can be seen as vital to ensure a low GWP of reused CIP RC columns.

Summing up, the GWP of a reused CIP RC column can thus be seen to have its source mainly in reassembly and lifting operations. The assumptions and estimations that were done to model the operations might however have had an impact on their perceived performance. The solutions that have been chosen, especially for the reassembly process, might also be adjustable to further lower the GWP.

Further, the testing and documentation process of CIP RC for reuse is currently not standardized, thus necessitating assumptions to estimate its impact on the GWP. Even with the conservative assumptions that were done, the operation does not have a significant impact on GWP compared to other operations in the reuse process. The way that the operation is modelled for these calculations, the testing does however generate large amounts of waste, with 163 kg per column, contributing to landfill usage. Realistically, this waste would likely be sent for recycling, further lowering the environmental impact of the column.

5.2.3 Comparison

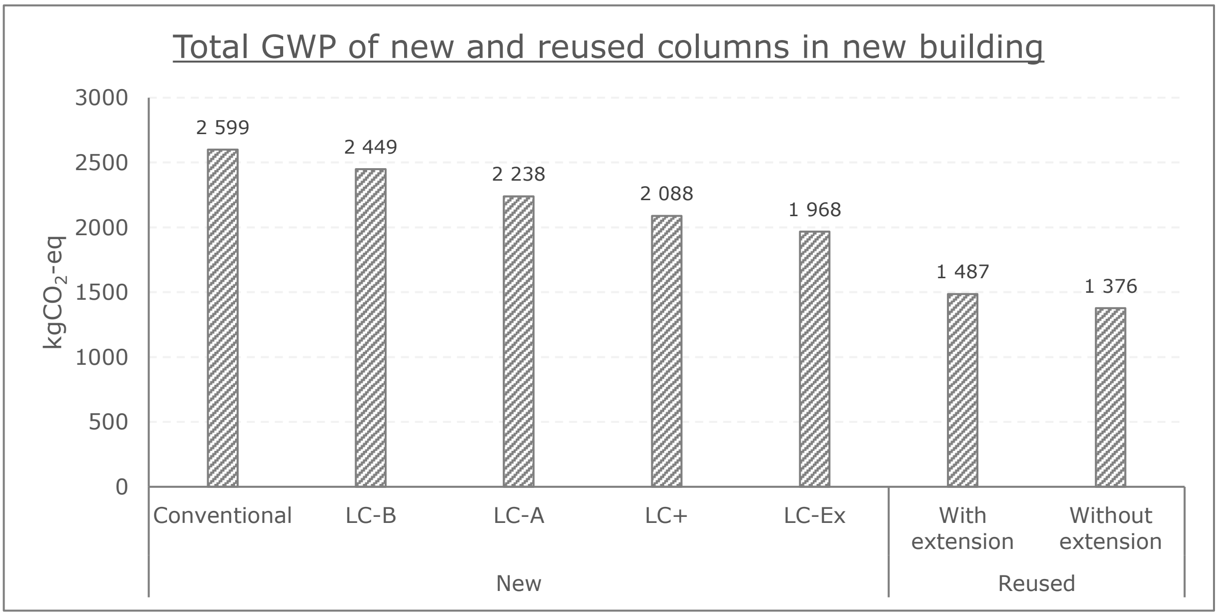

Figure 34: Total GWP of the 12 new or reused columns needed in the new building.

Figure 37 shows the total GWP of all 12 new and reused CIP RC column that are needed in the new building. Compared to new columns from conventional concrete, the reused columns represent a significant reduction in GWP. The reused columns with and without extensions give a reduction of 42,8% and 47,1% respectively. If LC-Ex concrete were to be used, the reduction would however be 24,4% and 30,1%. This difference can be argued as low compared to the additional work that needs to go into the reuse. The option of reuse might however be more favourable in terms of price if the process becomes more mainstream, but seen as the cost of LC-Ex and the reused components is not known, this is just speculation.

If leaving out the emissions from reassembly, the emissions from phase A1-A3 are left with a GWP of 163 kgCO$_2$-eq. Compared to the GWP of the new columns from conventional concrete, this represents a reduction of about 94%. Compared to LC-Ex, the reduction is about 92%. This is significantly lower than the reduction of 80% that is used for calculating emissions from reused components in the FutureBuilt method (Resch *et al.*, 2021). The operations that were included in the calculations for this report might however not be exact representations of a real reuse scenario. In spite of this, seen as all assumptions that were done were made to represent a worst-case scenario, it can likely be concluded that the realistic emissions of CIP RC columns represent a reduction greater than 80% compared to a new column.

The LCA was based on the presumption that the new and reused components would perform similarly when installed in the new building, thus only comparing the components based on phase A. An effort was put into ensuring equal performance in regards to load bearing capacity, using coupling sleeves to install the reused component. Further performance was assumed to be ensured through testing. However, despite extensive testing of RC components for reuse, it can be seen as likely that the lifespan of it is shorter than that of new RC. Primarily, the reduced lifespan might come down to carbonation of the concrete. It is inevitable that a certain amount of carbonation will have occurred in the reused component, and seen as its lifespan was predefined when it first was designed, the component will have a limited remaining lifespan. A short lifespan of the load bearing structure of a building could lead to the building having to be demolished earlier, likely before its remaining components have reached their intended lifespans. Means could however be taken to hinder further carbonation, for example by shielding it from the environment with a protective coating. Applying such a coating would however contribute to the GWP of the component.

The carbonation of concrete also contributes to a reduced GWP by consuming CO$_2$ trough the components lifespan. A reused component, where a portion of the carbonation has already happened, will have a reduced potential for further carbonation. By sealing it with a coating, the carbonation process would be stopped completely, giving no reducing factor to its GWP. This would lead to a difference in performance of the reused component compared to the new one.

As previously stated, crushing concrete into aggregates increase the surface area of the concrete that is in direct contact with air, accelerating the carbonation process (Jacobsen, 2018). By reusing concrete, rather than recycling it, less concrete will be crushed up and used as aggregates. Therefore, it could be argued that reuse could have a negative effect on the CO$_2$-consumption of concrete in the building industry. However, it must be taken into account that reuse of concrete leads to a decreased demand for new cement, eliminating the initial calcination process that is reversed in the carbonation process. Thus, the theoretical total of GHG emissions should not increase, but potentially decrease.

A decreased amount of recycled concrete can also lead to an increase in the use of crushed rock as aggregates. This increase could lead to a higher demand for what is already becoming a scarce resource (UN environment programme, 2022). However, crushed rock is also needed in the production of new concrete. Therefore, reuse of concrete could also contribute to a decreased strain on the demand for crushed rock.

As discovered in the Re:Crete project, wood could represent a greater reduction in GWP than reused concrete (Devènes *et al.*, 2022). It can be assumed that this would also be the case for these calculations. Moreover, it could be argued that concrete columns would not be necessary in a simple one-story building such as the one that was the objective of these calculations. However, if the scope is extended beyond the GWP, reuse of CIP RC columns represents a reduction in resource costs, giving relief to the demand for wood.

5.3 Limitations

Great care has been taken to ensure reliable and complete data both in the questionnaire and the LCA calculations. However, some limitations to the results have been a natural consequence of limited time and resources. The limitations will be outlined in the following paragraphs.

The questionnaire has been analysed with a main focus on who has previously worked with reuse and not. This was seen as a natural basis for analysis and discussion due to the number of respondents within the different groups. Further analysis could however be done to distinguish between the opinions of the different parts of the industry. This could identify where the focus should lie in incentivising and distributing knowledge.

The LCA calculations are based on several assumptions in order to give an estimated GWP of reused CIP RC columns. These assumptions could be seen as sources of inaccuracies for the final results and thus discussion. As more knowledge about and standardized methods for reuse are established, further assessments should be done to determine the realistic environmental impact of reuse of CIP RC.

Only the GWP of reuse of CIP RC columns were investigated in this report. Columns were voted by the respondents to the questionnaire to be one of the most feasible components for reuse, and were therefore chosen for the LCA calculations. However, assessments should also be completed for other CIP RC components that have potential to be reused, determining how it could impact the environment.

GWP was chosen to be the most important factor for comparison of reused and new CIP RC. The GWP does however only show parts of the impact that reuse might have, and further assessments should therefore be done. Some aspects other than GWP have been discussed, but further assessment could contribute to a more thorough understanding of the environmental impact of reused CIP RC.

6 Conclusion

Typically, cast-in-place (CIP) reinforced concrete (RC) structures are not built to be reused. Nevertheless, research and experiments have shown that it can be a viable practise, even on a large scale. The research completed in this project have shown that the motivation for reuse in Norway's building industry is present. The feasibility for reuse of CIP RC is however not seen as positive due to several factors. Primarily, the documentation that is needed for selling or using a reclaimed component in a building project is seen as the greatest barrier. Therefore, a well-established system for testing and documentation of CIP RC components for reuse is necessary for companies to take on the responsibility of using and providing such components.

In addition to documentation of reclaimed CIP RC, logistics are repeatedly pointed out to be a challenge for its reuse. As a solution to this barrier, several researchers and responders to the questionnaire have pointed out that a marketplace for buying and selling used building materials could be an efficient approach. Such marketplaces are already being realised, establishing the foundation for further development within reuse of CIP RC and other building materials.

Especially respondents to the questionnaire that have previously worked with reuse of building materials in load bearing structures rate reuse of CIP RC as achievable. However, they also rate potential barriers as greater, showing that today's building industry is not yet adapted for reuse. To achieve a building industry that allows for easy reuse of CIP RC in load bearing structures, it is vital that the experience and knowledge that exist on the topic is made readily available throughout the industry. Standardized solutions should also be established to lower the bar for companies that do not have the financial means to spend the added time on design, research and logistics.

Further, it was shown that reuse of CIP RC has the potential to give a significant reduction in the GWP of a load bearing structure compared to using new concrete. Despite several assumptions that had to be made due to uncertainties in the process, a reused CIP RC column was estimated to have a reduction of up to 94% in phase A1-A3, and 47,1% for the whole of phase A. Compared to the reduction that is given to reused building materials in the FutureBuilt Zero method of 80% in phase A1-A3, the reduction achieved by reuse of the CIP RC columns represents a significantly greater reduction, showing that the potential for savings in GHG emissions with reuse of concrete is present.

Different scenarios for the reused column were also modelled, where one had to be extended by 10 cm during reassembly. The GWP then increased by 8% compared to a column without extension, showing that a precise disassembly process is vital during the extraction from the donor building in order to limit the GHG emissions of the reused component. The greatest contribution to the GHG emissions from the reassembly process came from the reinforcing steel. However, the operation was based on conservative assumptions and could likely be optimized through detailed calculations.

Finally, the potential implications of reuse of CIP RC was explored. First, reusing concrete components in a load bearing structure could lead to a decreased lifespan of the building as a whole. Seen as a reused component will already have served parts of its dimensioning lifespan, the remaining lifespan will likely not match that of other components in the building, leading to the building having to be demolished at an earlier stage. Thorough testing of the reused component is therefore necessary to determine its remaining lifespan and ensure that the lifespan of the building as a whole is not compromised.

By reusing concrete rather than recycling it, the availability of crushed concrete aggregates will also decrease. This decreased availability can lead to an increase in the use of crushed rock aggregates, putting strain on an already limited resource. At the same time, new concrete also utilizes crushed rock in its production, so by reusing concrete, the demand for crushed rock aggregates is also relieved. Further, it will lead to less carbonation of the concrete, seen as crushed concrete has a higher rate of carbonation than solid concrete components. However, reuse of concrete eliminates the need for production of new cement where the calcination process that is reversed by the carbonation process originally occurs.

Reuse of CIP RC can be seen as having a significant potential to reduce the GHG emissions of the building industry. Realising this potential could give an important contribution to limiting the climate crisis. In order to establish reuse of CIP RC as a common practise, three key factors are pointed out: a standardized method for documentation of reclaimed CIP RC components is necessary; a marketplace for buying and selling reused components would greatly increase the amount of reuse in the building industry; and experience and knowledge about reuse of CIP RC must be shared within the industry.

7 Further work

Due to the limited timeframe of the master thesis, the questionnaire has only been analysed on the parameters that were deemed most essential. However, it could be of interest to further analyse the questionnaire, seen as it gives valuable data from the people that work in the industry.

This thesis has examined the feasibility for reuse of CIP RC by investigating savings in emissions. Another factor that could be valuable in estimating the impact of reuse of CIP RC is how it might affect the waste that is produced from demolishing buildings. How large is the average share of a CIP structure that can be potentially reused? It might also be interesting to map out the availability of suitable structures for reuse.

Due to time constraints of the thesis, only columns were considered in LCA calculations. A natural next step would be to make estimations for other types of concrete elements that can be extracted from old buildings, creating a solid foundation for which to conclude on the feasibility of reuse of cast-in-place concrete in load bearing structures.

A detailed calculation on the emissions from extracting a component should be done to strengthen the credibility of the estimated environmental impacts from reuse. Various approaches should be accounted for:

- Is all of the donor building reused?
- Is only the load bearing structure reused?
- Are only parts of the load bearing structure reused?

The different approaches will require emissions from necessary processes to be allocated in different ways. If all of the building is reused, emissions from extracting each component might be allocated to the component itself, while if only the columns where to be extracted, it might lead to an increased amount of work in sparing these while the rest of the building is demolished, leading to increased emissions. A share of these emissions might then be natural to allocate to the columns.

How should the emissions from demolition and deconstruction be allocated between the donor building and the reused components? How should the emissions be distributed between reused components?

It could be of interest to investigate how the level of reuse affects the environmental impact of a component. How does reuse of a structural floor as a pavement compare to it being reused for the same purpose as it was initially intended?

Comparing reused CIP RC to new precast components could be of valuable interest. This comparison could also lead to a more direct understanding of the relations between the extraction process and the production of a new component, seen as the installation process would close to identical. Furthermore, the comparison might be more relevant for what might be the options that a design-/planning team a choosing between.

A comparison of reuse of CIP RC to different alternatives for recycling is necessary to form a complete picture of how reuse should fit into a sustainable building industry. Such a complete picture could be of great importance for making informed decisions at the end of a building’s lifespan.

References

Årtun, T., Nesse, N. and Eide, I.B. (2023) ‘sement’, *Store norske leksikon*. Available at: https://snl.no/sement (Accessed: 17 March 2023).

Avfallsregnskapet (no date) *SSB*. Available at: https://www.ssb.no/natur-og-miljo/avfall/statistikk/avfallsregnskapet (Accessed: 28 February 2023).

Benachio, G.L.F., Freitas, M. do C.D. and Tavares, S.F. (2020) ‘Circular economy in the construction industry: A systematic literature review’, *Journal of Cleaner Production*, 260, p. 121046. Available at: https://doi.org/10.1016/j.jclepro.2020.121046.

Bhogayata, A.C. (2019) ‘16 - Concrete reinforced with metalized plastic waste fibers’, in F. Pacheco-Torgal et al. (eds) *Use of Recycled Plastics in Eco-efficient Concrete*. Woodhead Publishing (Woodhead Publishing Series in Civil and Structural Engineering), pp. 349–367. Available at: https://doi.org/10.1016/B978-0-08-102676-2.00016-5.

BRE Group (2016) *All about BREEAM - BRE Group*. Available at: https://bregroup.com/buzz/all-about-breeam/ (Accessed: 23 May 2023).

Brekkhus, A. (2020) *Hulldekker fra regjeringskvartalet ombrukes på storbylegevakta*. Available at: https://www.bygg.no/article/1428053!/ (Accessed: 24 March 2023).

Circular Economy: The New Normal (2018). Available at: https://unctad.org/system/files/official-document/presspb2017d10_en.pdf (Accessed: 19 May 2023).

‘Cities - United Nations Sustainable Development Action 2015’ (no date) *United Nations Sustainable Development*. Available at: https://www.un.org/sustainabledevelopment/cities/ (Accessed: 19 May 2023).

‘Climate Change’ (no date) *United Nations Sustainable Development*. Available at: https://www.un.org/sustainabledevelopment/climate-change/ (Accessed: 20 May 2023).

Coelho, A. and de Brito, J. (2011) ‘Economic analysis of conventional versus selective demolition—A case study’, *Resources, Conservation and Recycling*, 55(3), pp. 382–392. Available at: https://doi.org/10.1016/j.resconrec.2010.11.003.

‘Concrete needs to lose its colossal carbon footprint’ (2021) *Nature*, 597(7878), pp. 593–594. Available at: https://doi.org/10.1038/d41586-021-02612-5.

Dastjerdi, B. *et al.* (2022) ‘Waste to Energy Technologies’, in *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. Available at: https://doi.org/10.1016/B978-0-323-90386-8.00012-7.

Devènes, J. *et al.* (2022) ‘Re:Crete – Reuse of concrete blocks from cast-in-place building to arch footbridge’, *Structures*, 43, pp. 1854–1867. Available at: https://doi.org/10.1016/j.istruc.2022.07.012.

Direktoratet for byggkvalitet (2023a) *§ 9-5. Byggavfall og ombruk*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/regelverk/byggteknisk-forskrift-tek17/9/9-5 (Accessed: 3 May 2023).

Direktoratet for byggkvalitet (2023b) *§ 10. Dokumentasjon av vesentlige egenskaper*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/regelverk/dok/iii/10 (Accessed: 10 May 2023).

Direktoratet for byggkvalitet (2023c) *12. CE-merking*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/regelverk/dok/veiledning-til/12.-ce-merking (Accessed: 4 May 2023).

Direktoratet for byggkvalitet (2023d) *13. Ytelseserklæringen*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/regelverk/dok/veiledning-til/13.-ytelseserklaringen (Accessed: 4 May 2023).

Direktoratet for byggkvalitet (2023e) *Artikkel 4 Ytelseserklæring*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/regelverk/dok/byggevareforordningen/artikkel-4-ytelseserklaring (Accessed: 4 May 2023).

Direktoratet for byggkvalitet (2023f) *Byggevareforordningen*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/regelverk/dok/byggevareforordningen/byggevareforordningen (Accessed: 4 May 2023).

Direktoratet for byggkvalitet (2023g) *Byggteknisk forskrift (TEK17) med veiledning*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/regelverk/byggteknisk-forskrift-tek17 (Accessed: 25 May 2023).

Direktoratet for byggkvalitet (2023h) *Construction products in English*, *Direktoratet for byggkvalitet*. Available at: https://dibk.no/byggevarer/pcp-construction-norway (Accessed: 10 May 2023).

ecoinvent (2020a) ‘ecoinvent Database - ecoinvent’, 15 July. Available at: https://ecoinvent.org/the-ecoinvent-database/ (Accessed: 11 May 2023).

ecoinvent (2020b) ‘Geographies - ecoinvent’, 25 September. Available at: https://ecoinvent.org/the-ecoinvent-database/geographies/ (Accessed: 11 May 2023).

Eklund, M., Sundbaum, G. and Ab, S. (2023) ‘THE CONDITIONS AND CONSTRAINTS FOR USING REUSED MATERIALS IN BUILDING PROJECTS’.

Entra ASA et al. (2021) *Erfaringsrapport ombruk - Kristian Augusts gate 13*. Erfaringsrapport 1, p. 116. Available at: https://entra.no/storage/uploads/article-documents/1_ka13-erfaringsrapport-ombruk-20012021.pdf (Accessed: 9 May 2023).

European Comission (2015) *A Notification under Article 12 of Regulation (EU) No 1025/2012*. Brussels, p. 12.

European Comission (2022) *Summary of references of harmonised standards published in the Official Journal – Regulation (EU) No 305/20111 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC*. Brussels: European Comission, p. 61.

European Comission (2023) *EU taxonomy for sustainable activities*. Available at: https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en (Accessed: 23 May 2023).

European Parliament (2008) *DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL*. Available at: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:EN:PDF (Accessed: 20 March 2023).

Finnveden, G. and Potting, J. (2014) ‘Life Cycle Assessment’, in P. Wexler (ed.) *Encyclopedia of Toxicology (Third Edition)*. Oxford: Academic Press, pp. 74–77. Available at: https://doi.org/10.1016/B978-0-12-386454-3.00627-8.

FutureBuilt (2022) *FutureBuilt kvalitetskriterier*. Available at: https://www.futurebuilt.no/FutureBuilt-kvalitetskriterier (Accessed: 20 May 2023).

FutureBuilt (2023) *FutureBuilt*. Available at: https://www.futurebuilt.no/Arrangementer# (Accessed: 3 May 2023).

Google Maps (2023) *Google Maps*, *Google Maps*. Available at: https://www.google.com/maps/@63.3998436,10.4083384,129m/data=!3m1!1e3 (Accessed: 24 May 2023).

Gorgolewski, M. and Morettin, L. (2023) ‘The Process of Designing with Reused Building Components’.

Grønn Byggallianse (2022) *BREEAM-NOR v6.0 for nybygg*. Available at: https://byggalliansen.no/wp-content/uploads/2022/03/BREEAM-NOR-v6.0_NOR.pdf (Accessed: 20 May 2023).

Hannant, D.J., Venkata Siva, S.B. and Rama Sreekanth, P.S. (2018) ‘5.15 Cement-Based Composites☆’, in P.W.R. Beaumont and C.H. Zweben (eds) *Comprehensive Composite Materials II*. Oxford: Elsevier, pp. 379–420. Available at: https://doi.org/10.1016/B978-0-12-803581-8.03903-5.

Hernandez, P. *et al.* (2019) ‘Chapter 4 - Life-Cycle Assessment of Buildings’, in F. Asdrubali and U. Desideri (eds) *Handbook of Energy Efficiency in Buildings*. Butterworth-Heinemann, pp. 207–261. Available at: https://doi.org/10.1016/B978-0-12-812817-6.00010-3.

Hollberg, A. *et al.* (2022) ‘A Framework for User Centric LCA Tool Development for Early Planning Stages of Buildings’, *Frontiers in Built Environment*, 8. Available at: https://www.frontiersin.org/articles/10.3389/fbuil.2022.744946 (Accessed: 26 May 2023).

Home - Rehub (no date). Available at: https://www.rehub.no/ (Accessed: 8 May 2023).

Horne, T. (2020) *Den store klima-guiden*. Oslo: Forlaget Press.

Høydahl, V.V. and Walter, H.K. (2020) *Ombruk av byggematerialer og -produkter i et bærekraftperspektiv*. Trondheim: Norwegian University of Science and Technology. Available at: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2738114/Walter%20og%20H%C3%B8ydahl.pdf?sequence=1 (Accessed: 24 January 2023).

‘hulldekke-element’ (2019) *Store norske leksikon*. Available at: https://snl.no/hulldekke-element (Accessed: 24 March 2023).

Jacobsen, S. (2018) ‘Resirkulering og gjenbruk av betong’, *Byggeindustrien*. Available at: https://betong.net/wp-content/uploads/7-web-Resirkulering-og-gjenbruk-av-betong.pdf (Accessed: 8 May 2023).

Jacobsen, S. and Jahren, P. (2001) ‘Binding of CO2 by carbonation of Norwegian Concrete’, in.

Küpfer, C., Bastien-Masse, M. and Fivet, C. (2023) ‘Reuse of concrete components in new construction projects: Critical review of 77 circular precedents’, *Journal of Cleaner Production*, 383, p. 135235. Available at: https://doi.org/10.1016/j.jclepro.2022.135235.

‘Lavkarbonbetong’ (no date) *Betongsentrum.no*. Available at: https://www.betongsentrum.no/lavkarbonbetong/ (Accessed: 18 May 2023).

Lin, W. and Yoda, T. (2017) ‘Chapter Seven - Steel Bridges’, in W. Lin and T. Yoda (eds) *Bridge Engineering*. Butterworth-Heinemann, pp. 111–136. Available at: https://doi.org/10.1016/B978-0-12-804432-2.00007-4.

Loopfront (2023) *Loopfront - Resirkulering og ombruk gjort enkelt*. Available at: https://www.loopfront.com/no/ (Accessed: 8 May 2023).

Mikulčić, H. *et al.* (2012) ‘Numerical modelling of calcination reaction mechanism for cement production’, *Chemical Engineering Science*, 69(1), pp. 607–615. Available at: https://doi.org/10.1016/j.ces.2011.11.024.

Mohammadhosseini, H. *et al.* (2020) ‘12 - Production of sustainable concrete composites comprising waste metalized plastic fibers and palm oil fuel ash’, in P. Samui et al. (eds) *New Materials in Civil Engineering*. Butterworth-Heinemann, pp. 435–457. Available at: https://doi.org/10.1016/B978-0-12-818961-0.00012-0.

Motek (2023a) *Betongsag Hilti DSH 900 X-40*. Available at: https://www.motek.no/Maskiner/Diamantverkt%C3%B8y/Betongsag/Betongsag-Hilti-DSH-900-X40/p/58691 (Accessed: 18 May 2023).

Motek (2023b) *Veggsag Hilti DST 20-CA 3x400V PR*. Available at: https://www.motek.no/Maskiner/Diamantverkt%C3%B8y/Betongsag/Veggsag-Hilti-DST-20CA-3x400V-PR/p/47668 (Accessed: 12 May 2023).

Muralikrishna, I.V. and Manickam, V. (2017) ‘Chapter Five - Life Cycle Assessment’, in I.V. Muralikrishna and V. Manickam (eds) *Environmental Management*. Butterworth-Heinemann, pp. 57–75. Available at: https://doi.org/10.1016/B978-0-12-811989-1.00005-1.

Nettskjema (2023) *Nettskjema*. Available at: https://nettskjema.no/user (Accessed: 26 May 2023).

Norconsult (2023) *Vår kompetanse - Tilstandsvurdering betong - Norconsult*. Available at: https://www.norconsult.no/kompetanse/fag-og-tjenester/tilstandsvurdering-betong/ (Accessed: 26 May 2023).

Nordic Crane (2023) ‘Løftetabeller | Nordic Crane’, *Nordic Crane Kynningsrud*. Available at: https://nordiccrane.com/nb/loftetabeller/ (Accessed: 12 May 2023).

Norsk Stål AS (2023) ‘Kamstål til bruk i betong’. epd-norge. Available at: https://www.epd-norge.no/getfile.php/1332501-1683276644/EPDer/Byggevarer/St%C3%A5lkonstruksjoner/NEPD-4433-3701_Kamst-l-til-bruk-i-betong.pdf (Accessed: 11 May 2023).

Om oss (no date) *FutureBuilt*. Available at: https://www.futurebuilt.no/Om-oss#!/Om-oss (Accessed: 20 May 2023).

Ombygg (no date) *Ombygg*. Available at: https://www.ombygg.no (Accessed: 8 May 2023).

Park, S. *et al.* (2021) ‘Calcium carbonate synthesis from waste concrete for carbon dioxide capture: From laboratory to pilot scale’, *Journal of Hazardous Materials*, 403, p. 123862. Available at: https://doi.org/10.1016/j.jhazmat.2020.123862.

Rakhshan, K. *et al.* (2020) 'Components reuse in the building sector – A systematic review', *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 38(4), pp. 347–370. Available at: https://doi.org/10.1177/0734242X20910463.

Rapport om KA13 (no date) *Entra*. Available at: https://entra.no/news-and-media/rapport-om-ka13/2114 (Accessed: 20 March 2023).

Reppe, I.S. (2021) *Ombruk av betongelementer : analyse av marked, barrierer, muligheter og potensiale for klimagassreduksjon ved ombruk av hulldekker fra Regjeringskvartalet*. Master thesis. Norwegian University of Life Sciences, Ås. Available at: https://nmbu.brage.unit.no/nmbu-xmlui/handle/11250/2787600 (Accessed: 24 March 2023).

Resch, E. *et al.* (2021) *FutureBuilt Zero - Materialer of Energi, Metodebeskrivelse*, p. 24. Available at: https://www.futurebuilt.no/FutureBuilt-kvalitetskriterier (Accessed: 20 May 2023).

ResearchRabbit (no date) *ResearchRabbit*. Available at: https://www.researchrabbit.ai (Accessed: 27 April 2023).

Ropp, R.C. (2013) 'Chapter 3 - Group 16 (O, S, Se, Te) Alkaline Earth Compounds', in R.C. Ropp (ed.) *Encyclopedia of the Alkaline Earth Compounds*. Amsterdam: Elsevier, pp. 105–197. Available at: https://doi.org/10.1016/B978-0-444-59550-8.00003-X.

Samferdselsdepartementet (2007) *Euro 5 og 6 avgasskrav for lette kjøretøy*, *Regjeringen.no*. regjeringen.no. Available at: https://www.regjeringen.no/no/sub/eos-notatbasen/notatene/2007/feb/euro-5-og-6-avgasskrav-for-lette-kjoretoy/id2431385/ (Accessed: 12 May 2023).

Saunders, J., Moe, R. and Larsen, H. (2022) *Granåsen gjenbrukslager, Mulighetsstudie for lagerbygg for Bydrift i Granåsen idrettspark.* Asplan Viak.

ScienceDirect (2023) *ScienceDirect.com | Science, health and medical journals, full text articles and books.* Available at: https://www.sciencedirect.com/ (Accessed: 27 April 2023).

SimaPro (2021) 'SimaPro database manual, methods library'. SimaPro. Available at: https://simapro.com/wp-content/uploads/2021/12/DatabaseManualMethods930.pdf (Accessed: 11 May 2023).

SimaPro (2023a) 'About SimaPro', *SimaPro*. Available at: https://simapro.com/about/ (Accessed: 11 May 2023).

SimaPro (2023b) *What are unit and system processes?* Available at: https://support.simapro.com/s/article/What-are-unit-and-system-processes (Accessed: 11 May 2023).

SimaPro (2023c) *What is the difference between ecoinvent market and transformation processes?* Available at: https://support.simapro.com/s/article/What-is-the-difference-between-ecoinvent-market-and-transformation-processes (Accessed: 11 May 2023).

Skaar, B. and Rambæk, I. (2019) *Snart kan aluminium erstatte stål som armering i betongkonstruksjoner*, *SINTEF*. Available at: https://www.sintef.no/siste-nytt/2019/snart-kan-aluminium-erstatte-stal-som-armering-i-betongkonstruksjoner/ (Accessed: 24 May 2023).

Solgaard, A. and Th. Bramslev, K. (2019) 'Tenk deg om før du river'. Grønn Byggallianse. Available at: https://byggalliansen.no/wp-content/uploads/2019/11/Tenk-deg-om-f%C3%B8r-du-river.pdf (Accessed: 23 May 2023).

Solli, C. *et al.* (2023) 'Hvordan påvirker forutsetninger i analysene resultatet?'

Sørensen, S.I. (no date) *Betongkonstruksjoner: Beregning of dimensjonering etter Eurocode 2*. 2. utgave. Fagbokforlaget.

SSB (2023a) *Avfall fra byggeaktivitet*, *SSB*. Available at: https://www.ssb.no/natur-og-miljo/avfall/statistikk/avfall-fra-byggeaktivitet (Accessed: 28 March 2023).

SSB (2023b) *Avfallsregnskapet*, *SSB*. Available at: https://www.ssb.no/natur-og-miljo/avfall/statistikk/avfallsregnskapet (Accessed: 28 February 2023).

Standard Norge (2007) *NS-EN 14629:2007 - Produkter og systemer for beskyttelse og reparasjon av betongkonstruksjoner Prøvingsmetoder Bestemmelse av kloridinnhold i herdnet betong*, p. 16. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=269646.

Standard Norge (2011) *NS-EN 15978:2011 - Bærekraftige byggverk, Vurdering av bygningers miljøprestasjon, Beregningsmetode*.

Standard Norge (2018) *NS 3720:2018 - Metode for klimagassberegninger for bygninger*, p. 40. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=992162 (Accessed: 14 March 2023).

Standard Norge (2021) *NS-EN 1992-1-1:2004+NA:2008 - Eurocode 2: Design of concrete structures, Part 1-1: General rules and rules for buildings*, p. 260. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=1365301 (Accessed: 20 April 2023).

Standard Norge (2022) *NS 3682:2022 - Hulldekker av betong til ombruk*. 1.0, p. 24. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=1407012 (Accessed: 8 May 2023).

Standard Norge (2023) *NS-EN 12504-1:2019+AC:2020 - Prøving av betong i konstruksjoner, Del1: Kjerneprøver, Uttaking, vurdering of prøving av trykkfasthet*. Standard, p. 16. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=1504568 (Accessed: 8 May 2023).

Statsbygg (2022) *Bærekraft må stå i første rekke - Statsbygg*. Available at: https://www.statsbygg.no/nyheter/baerekraft-ma-sta-i-forste-rekke (Accessed: 23 May 2023).

'Sustainable consumption and production' (no date) *United Nations Sustainable Development*. Available at: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/ (Accessed: 20 May 2023).

'System Models - ecoinvent' (2020), 25 September. Available at: https://ecoinvent.org/the-ecoinvent-database/system-models/ (Accessed: 11 May 2023).

‘The Sustainable Development Agenda’ (no date) *United Nations Sustainable Development*. Available at: https://www.un.org/sustainabledevelopment/development-agenda/ (Accessed: 19 May 2023).

Thue, J.V. (2020) ‘karbonatisering’, *Store norske leksikon*. Available at: https://snl.no/karbonatisering (Accessed: 19 May 2023).

Thue, J.V. (2023) ‘betong’, *Store norske leksikon*. Available at: https://snl.no/betong (Accessed: 13 March 2023).

UN Climate Change (2018) *World Cement Association Urges Climate Action | UNFCCC*. Available at: https://unfccc.int/news/world-cement-association-urges-climate-action?gclid=CjwKCAjw0N6hBhAUEiwAXab-TVGrCDEZ7baT300-me0DTVmWYouO8-d0wVEUYZOobuFADm9T-Sp_ShoCxE4QAvD_BwE (Accessed: 13 April 2023).

UN environment programme (2022) *Our use of sand brings us “up against the wall”, says UNEP report*, *UN Environment*. Available at: http://www.unep.org/news-and-stories/press-release/our-use-sand-brings-us-against-wall-says-unep-report (Accessed: 17 March 2023).

Unicon AS (2022) ‘B30 M60 Bergen’. epd-norge. Available at: https://www.epd-norge.no/getfile.php/1328159-1671715190/EPDer/Byggevarer/Ferdig%20betong/NEPD-4078-3100_B30-M60-Bergen.pdf (Accessed: 11 May 2023).

Unicon AS (2023) *Lavkarbonbetong - Unicon.no*. Available at: https://www.unicon.no/produkter-tjenester/lavkarbonbetong/ (Accessed: 19 April 2023).

Veidekke (2022) *Veidekke: Etablerer selskap for sirkulære løsninger*. Available at: https://www.veidekke.no/aktuelt/pressemeldinger/veidekke-etablerer-selskap-for-sirkulare-losninger/ (Accessed: 23 March 2023).

Volkov, M. (2019) *Structural connections in circular concrete: A study about the connections between structural second-hand concrete elements*. Student theses. Delft: Delft University of Technology, p. 158. Available at: https://repository.tudelft.nl/islandora/object/uuid:41bd0462-cac9-4314-9682-06962df42e52.

World Green Building Council (2023) *Embodied Carbon*, *World Green Building Council*. Available at: https://worldgbc.org/advancing-net-zero/embodied-carbon/ (Accessed: 20 May 2023).

Appendixes

Appendix A: Questionnaire (questions) (attached file and included in document)

Appendix B: Dimensioning of new column (attached file)

Appendix C: Questionnaire (results English version) (attached file)

Appendix D: Questionnaire (results Norwegian version) (attached file)

Appendix E: SimaPro raw data

Appendix A: Questionnaire (questions)

The following text is extracted from an exported pdf-file from Nettskjema (Nettskjema, 2023).

Reuse of cast-in-place concrete in load bearing structures - questionnaire

The questionnaire takes about 15 minutes to answer. The deadline for answering is the 26th of March 2023.

Background and purpose

This questionnaire is part of a master thesis that seeks to investigate barriers and drivers for reuse of cast-in-place concrete in load bearing structures (RC) in a new site. The research question is part of the project GjenOm, which is a collaboration between Trondheim municipality, NTNU, Sintef, Loopfront and Asplan Viak.

What does participation in the project involve?

Participants will be asked questions about their experience, meanings and general thoughts on concrete, reuse of building materials and reuse of cast-in-place concrete. They will also be questioned on some background information to establish the participants approach to the subject.

What will happen with the information you give?

Data is gathered only on the basis of this agreement with the participant. Participation is voluntary, and you can withdraw from the questionnaire at any time without having to give a reasoning for this. After the questionnaire is sent, the data is anonymized automatically. The data can then not be traced back to a single participant, meaning that withdrawal is no longer possible.

Steinar Valbø, supervisors Gearóid Lydon and Pasi Aalto from NTNU and external supervisors Henriette Mo Sandberg, Jill Saunders and Terje Kristoffersen from Asplan Viak are the only ones with access to the raw data from the questionnaire. When published, the participants will not be recognisable by name. For questions or comments regarding data gathering, please contact NTNU's "personvernombud", Thomas Helgesen (thomas.helgesen@ntnu.no) or "databeskyttelsestjenester" at Sikt (https://www.nsd.no/personverntjenester/). Any participant can send a complaint to "Datatilsynet". The project is planned to end within 01.07.2023. After this date, only fully anonymized data is stored securely. NTNU is responsible for the storage of data. For questions regarding the project, please contact Pasi Aalto at +47 98025519 or pasi.aalto@ntnu.no.

By pressing "Send" at the end of the questionnaire you are giving your consent to the publication of your anonymized answers.

1. Background information

1.1. What is your age?

Your age, between 18 and 65, as a whole number.

1.2. What is your gender?

Female

Male

Other

Prefer not to respond

1.3. What country are you employed in?

Norway

Other:

1.3.1. If other, what country is this?

This element is only shown when the option 'Other:' is selected in the question '1.3. What country are you employed in?'

1.4. What is your role in the planning process of a project?

Choose up to three fields that are relevant for your role in the planning process.

Client

Design

Structural analysis

Quantity surveyor

Logistics

Finances

Demolition

Material sourcing

Main contractor

Sub contractor

Other:

1.4.1. If other, what role is this?

This element is only shown when the option 'Other:' is selected in the question '1.4. What is your role in the planning process of a project?'

1.5. What type of structures have you been involved with?

Buildings under 5 floors

Buildings over 5 floors

Infrastructure

Landscaping

Other:

1.5.1. If buildings under or over five floors, what type of buildings were these?

This element is only shown when the option 'Buildings under 5 floors or Buildings over 5 floors' is selected in the question '1.5. What type of structures have you been involved with?'

Commercial

Residential

Mixed use

1.5.2. If infrastructure, what type of structures were these?

This element is only shown when the option 'Infrastructure' is selected in the question '1.5. What type of structures have you been involved with?'

Bridges

Roads

Large scale public works (sewers, water conduits etc.)

1.5.3. If other, what type of structure was this?

This element is only shown when the option 'Other:' is selected in the question '1.5. What type of structures have you been involved with?'

1.6. Have you worked with reuse of building materials in a new site before?

Reuse of building materials in a new site refers to building materials that are taken from an old building that is deconstructed/demolished and reused in a new building.

Yes, in load bearing structures

Yes, but not in load bearing structures

No

1.6.1. If in load bearing structures, what materials did you reuse?

This element is only shown when the option 'Yes, in load bearing structures' is selected in the question '1.6. Have you worked with reuse of building materials in a new site before?'

Wood

Steel

Concrete

Brick

Other:

1.6.2. If other, what components or materials did you reuse?

This element is only shown when the option 'Other:' is selected in the question '1.6.1. If in load bearing structures, what materials did you reuse?'

2. Concrete as a building material

2.1. With current regulations, to what degree do you see the emissions from the use of concrete as a limiting factor in the planning process of a project?

By limiting factor, it is referred to your freedom to choose materials, the amounts thereof and how they are used.

Concrete is here referring to all forms of concrete based products (cast-in-place, pre-cast, hollow core etc.).

On a scale from 1 to 5, where 1 is no limiting factor and 5 is a significantly limiting factor.

2.2. To what degree do you believe new cast-in-place concrete will be used in the sustainable building industry of the future?

On a scale from 1 to 5, where 1 is not at all and 5 is a lot.

2.3. If you have any additional comments on concrete as a building material, please share them below:

3. Reuse of building materials

3.1. **How do you perceive the building industry's view on reuse of building materials today?**

On a scale from 1 to 5, where 1 is very negative and 5 is very positive.

3.2. How do you think the efficiency of planning/building with reused materials will compare to planning/building with virgin materials in the future?

By efficient it is referred to the resources spent on a project (time, money, materials etc.). On a scale from 1 to 5, where 1 is less efficient and 5 is more efficient.

Imagine a scenario where a system for buying and selling used building components exists and is actively used in the building industry. The components are gathered at a local storage facility and are sold with all necessary documentation, ready for use.

3.3. To what degree would this change the amount of reused building components you include in your projects?

On a scale from 1 to 5, where 1 is not at all and 5 is a lot.

3.4. Who should be financially responsible for providing such a system?

Public organ

Contractors

Planners

Shared between the above

3.5. If you can think of another solutions to the challenge of sourcing used materials, please share them below:

4. Reuse of RC (cast-in-place concrete in load bearing structures)

4.1. To what degree do you see reuse of RC as feasible in today's building industry?

On a scale from 1 to 5, where 1 is not at all and 5 is highly feasible.

4.2. As of today, to what extent do you see barriers (1) and drivers (5) in the following categories for the reuse of RC?

On a scale from 1 to 5, where 1 is large barriers and 5 is significant drivers.

Regulations

Cost of reused materials

Cost of labour

Design

Structure

Logistics

Sourcing

Documentation of sourced materials

Emissions

Knowledge

Attitude/motivation

Time

Other:

4.2.1. If other, what barriers and/or drivers would this be, and how would you range them on a scale from 1 to 5?

Seperate your barrier or driver and your grading of it by a comma.

4.3. How would the following RC elements be suited for reuse regardless of end- use?

Regardless of end-use, meaning that, for example, a floor divider could be reused as a slab on ground (down-cycling).

On a scale from 1 to 5, where 1 is not suited and 5 is highly suited.

Load bearing walls

Columns

Beams

Floor dividers

Slabs on ground

Foundations

Other:

4.3.1. If other, what building element would this be, and how would you range it on a scale from 1 to 5?

Seperate your building element and your grading of it by a comma.

4.4. How would the following RC elements be suited for reuse, where the end-use is the same as initially intended use?

End-use same as initially intended use, meaning that, for example, a floor divider is reused as a floor divider.

On a scale from 1 to 5, where 1 is not suited and 5 is highly suited.

Load bearing walls

Columns

Beams

Floor dividers

Slabs on ground

Foundations

Other:

4.4.1. If other, what building element would this be, and how would you range it on a scale from 1 to 5?

Seperate your building element and your grading of it by a comma.

4.5. If you are paying attention to the questionnaire, please choose the option four on the linear scale.

This question is asked to ensure that the participant is not answering questions at random and ensure reliable data.

On a scale from 1 to 5, where four is the only correct answer.

4.6. What would be the expected average price of a reused component compared to new RC?

100% referres to the price of one unit of new RC. Lower

Equal

Higher (-150%)

Significantly higher (150-%)

4.7. What would be an acceptable average price of a reused component compared to new RC?

100% referres to the price of one unit of new RC. Lower

Equal

Higher (-150%)

Significantly higher (150-%)

4.8. How would the collaboration between client, architects, engineers, and contractors change in a planning phase where reused RC is being used?

4.9. What information about the RC that is to be reused would be necessary for you to do your part of the planning process in a project?

4.10. If you have additional thoughts and oppinions on reuse of RC, please share them below:

By pressing "Send" you are agreeing to the following:

I have received information about the project and I am willing to participate. I agree to data being collected, analyzed and published anonymous. Further, I agree to being confidential about the project to ensure non-partial conditions for every participant.

NTNU
Norwegian University of
Science and Technology