Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Energy and Process Engineering

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Circular economy strategies for reducing carbon emissions in construction

A case study of reused materials in the design and construction of a storage in Granåsen

Master's thesis in Energy and Environmental Engineering
Supervisor: Juudit Ottelin
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Preface

This Master's thesis was written in the fall of 2023 and completed in January 2024. The thesis was written for the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU), and concludes my Master of Science in Energy and Environmental Engineering. The thesis was part of the course TEP4930 Master's thesis Industrial Ecology and represents 30 ECTS. This Master's thesis is written in collaboration with Asplan Viak and includes the project of constructing a storage in Granåsen Sports Park.

I would like to thank my supervisor Juudit Ottelin, for her valuable guidance the last semester. I would also like to thank my co-supervisor from Asplan Viak, Jill Saunders, for her insights into the project of building the storage in Granåsen Sports Park. Both of these ladies have contributed with valuable discussions and feedback.

I would also like to thank my family for supporting me during the past 5 years and always motivating me. Lastly, I would like to thank my fellow classmates for a memorable and educational 5 years.

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Abstract

Transitioning from a linear economy to a circular economy is crucial to reducing global greenhouse gas (GHG) emissions. This Master Thesis investigates the potential and environmental impact of reusing building components in the Norwegian buildings and construction sector. The environmental impact of reusing building components has been evaluated, with a specific focus on the reuse of materials in the design and construction of the storage built in Granåsen Sports Park fall of 2023. The study includes a comprehensive literature review and a detailed case study description, followed by a Life Cycle Assessment (LCA) to evaluate the environmental effects of four different construction scenarios. Scenario 0 reflects a storage built with beams and columns made of steel. Scenario 1 reflects a storage built with beams and columns made of glulam. Both Scenarios 0 and 1 are built entirely from virgin materials. Scenario 2 reflects the storage built in Granåsen and consists of a mix of reused and virgin materials. Scenario 3 reflects a storage built primarily from reused materials. Both Scenarios 2 and 3 are also made with beams and columns made of glulam.

The LCA in this study primarily considers the Climate Change indicator (GWP) in kg CO_2 eq. The results show that there is a decrease of 83% in CO_2 emissions from A1-A3 when glulam beams and columns were chosen instead of steel beams and columns (comparing Scenarios 0 and 1). Further, the results show that the total CO_2 emissions from Scenarios 1 and 2 were quite similar, due to a small use of reused materials in Scenario 2. In Scenario 3, when a considerable amount of reused materials are used, the results show that the CO_2 emissions from the production phase (A1'-A3') were reduced by almost 75% compared to Scenario 1, where virgin materials are considered.

The results also show that there are significant differences in CO_2 emissions from using combustion engine trucks to transport all the materials, compared to using electric trucks. Lastly, it is presented in the results that there are other environmental aspects than CO_2 emissions, such as material scarcity, which should be considered in reuse cases.

The thesis aims to provide insights into the current state of reuse in the Norwegian buildings and construction sector. Further, it aims to assess the environmental benefits of incorporating reused building components in construction projects. The results from the research examine the potential for reducing carbon emissions through the reuse of building components. The findings from this study contribute to developing the knowledge of circular economy strategies and provide a foundation for further development.

Sammendrag

Overgangen fra en lineær til en sirkulær økonomi er avgjørende for å redusere globale klimagassutslipp. Denne masteroppgaven undersøker potensialet og miljøpåvirkningen av ombruk av bygningskomponenter i den norske bygge- og anleggssektoren. Det har blitt utført en evaluering av miljøpåvirkningen av ombruk av bygningskomponenter, med spesielt fokus på ombruk av materialer i design og konstruksjon av lagerbygget i Granåsen idrettspark, som ble bygget høsten 2023. Studien inkluderer en grundig litteraturgjennomgang og en detaljert beskrivelse av casestudien, etterfulgt av en livssyklusanalyse (LCA) for å evaluere miljøeffektene av fire ulike bygningsscenarier. Scenario 0 gjenspeiler et lagerbygg med bjelker og søyler laget av stål. Scenario 1 gjenspeiler et lagerbygg med bjelker og søyler laget av limtre. Både Scenario 0 og 1 er bygget av kun nytt materiale. Scenario 2 gjenspeiler lagerbygget i Granåsen slik det ble bygget, og består av en blanding av ombrukt og nytt materiale. Scenario 3 gjenspeiler et lagerbygg primært laget av ombrukt materiale. I likhet med Scenario 1 er også Scenarioene 2 og 3 laget av bjelker og søyler av limtre.

LCA i denne studien vurderer primært indicatoren "Climate Change (GWP)" i kg CO_2 ekv. Resultatene viser at det er en reduksjon på 83% i CO_2-utslipp fra A1-A3 når bjelker og søyler av limtre ble valgt i stedet for stål (sammenligning av Scenarioene 0 og 1). Videre viser resultatene at de totale CO_2-utslippene fra Scenarioene 1 og 2 var ganske like, på grunn av lite ombrukte materialer i Scenario 2. I Scenario 3, der en betydelig mengde ombrukte materialer ble brukt, viser resultatene av CO_2-utslippene fra produksjonsfasen (A1'-A3') ble redusert med nesten 75% sammenlignet med Scenario 1, der kun nytt materiale brukes.

Resultatene viser også betydelige forskjeller i CO_2-utslipp fra transport av materialene ved bruk av lastebiler med forbrenningsmotor sammenlignet med elektriske lastebiler. Til slutt vises det i resultatene at det er andre miljøaspekter enn CO_2-utslipp, som for eksempel materialknapphet, som bør vurderes i ombruksprosjekter.

Oppgaven har som mål å gi innsikt i dagens tilstand for ombruk i den norske bygg- og anleggssektoren. Videre har den som mål å vurdere de miljømessige fordelene ved å inkludere ombrukte bygningskomponenter i byggeprosjekter. Resultatene fra forskningen undersøker potensialet for å redusere karbonutslipp gjennom gjenbruk av bygningskomponenter. Funnene fra denne studien bidrar til å utvikle kunnskapen om sirkulære økonomistrategier og kan bli brukt som grunnlag for videre utvikling.

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1 Introduction

Globally, the buildings and construction sector accounts for 37% of total process and operational energy-related CO_2 emissions [5]. According to Eurostat, waste from construction and demolition is Europe's most significant stream of waste by volume [6]. In Norway, the total contribution of CO_2 emissions from the buildings and construction sector accounts for 16% of the total national CO_2 emissions [7]. This percentage is lower than for Europe, which can be explained by the type of electricity mix used. In Norway, the electricity mix is primarily generated from renewable energy sources. In contrast, the electricity used in the rest of Europe is less clean than in Norway.
Due to the growth in urban areas during the following decades, there will be an increase in construction and demolition work in the future. This growth will increase the need for a circular economy to reduce construction waste, reduce the need to produce new building materials and reduce environmental impacts.

1.1 Motivation

According to the Paris Agreement from 2015, Norway has agreed to decrease the amount of CO_2 emissions by 50-55 % within 2030, compared to the level of CO_2 emissions in 1990 [8]. The 2022 Global Status Report states that despite the increased economic investment and decreasing global energy use in buildings, the total global energy use and CO_2 emissions related to the buildings and construction sector increased in 2021 [5]. Therefore, new measures must be implemented to reach the goal of the Paris Agreement. By reusing building components and materials, the life span of the materials will be expanded. Reusing building materials will avoid extracting new raw materials to produce the elements needed in a building. In addition, the reuse of materials requires little processing energy and decreases the amount of construction waste, thereby avoiding waste management. Therefore, reusing materials is a promising tool to reduce overall CO_2 emissions. The Norwegian Government presented a strategy in 2022 to reduce the overall national environmental impact of the buildings and construction sector [9]. This strategy emphasizes strengthening the focus on material efficiency, reuse of materials, and increasing the reuse of existing buildings and areas to reduce the use of resources, emissions, and waste from the sector.

1.2 Aims and Objectives

To realize and establish a circular economy in the buildings and construction sector, it is essential to map the possibilities and effects of reuse. This thesis will explore some of these possibilities and examine the environmental benefits of constructing a storage in Granåsen with as many reused materials as possible. The storage consists of two buildings, with individual areas of 299.1 m^2 and 331.1 m^2, which gives a total area of 630.2 m^2. The storage in Granåsen will store equipment used in the sports park at Granåsen.

Four scenarios will be reviewed to determine the possible environmental benefits of reusing materials in new constructions. The research question of this thesis is:

How do the life cycle CO_2 emissions of a studied storage building differ in the following building material scenarios?

- Scenario 0: a storage built with beams and columns of steel, with entirely virgin materials. This scenario reflects the initially drawn storage.
- Scenario 1: a storage built with beams and columns of glulam, with entirely virgin materials.
- Scenario 2: the storage as it was built in Granåsen, with some reused and some virgin materials, considering beams and columns of glulam.
- Scenario 3: a storage built primarily from reused materials, an optimistic case where as many reused materials and products as possible based on today's development are considered. This scenario consists of beams and columns of glulam.

1.3 Structure

Within this master thesis, an extensive literature review about reused materials in buildings and environmental impact assessments has been done. This literature review can be found in section 2. Further, a detailed case study description is found in section 3. This part of the thesis will present the storage built in Granåsen in Trondheim. Additionally, the methodology used in this thesis is presented in section 4. A Life Cycle Assessment (LCA) of the four scenarios presented in this thesis has been implemented. In this section, allocation and other assumptions are presented and discussed. Finally, the results of the LCA, followed by a discussion of these results, can be found in section 5.

2 Literature review

In this chapter, the reader will be introduced to some terminology that will give the reader a better and fuller understanding of the research conducted in this thesis. This chapter of the thesis also introduces how reused materials have been implemented in the buildings and construction sector in the past and the possibilities of how this can be further developed. Research and results from different studies are additionally presented.

2.1 Historical reuse of building materials

The concept of reuse of structural components and materials in buildings has been introduced previously. In ancient Egypt, stone architectural elements were reused in other buildings [10]. Also, the Romans reused materials in new constructions and reused building components were often preferred to new ones. Most mosques in Cairo, Egypt, from before the fifteenth century contained reused material from Roman churches and other buildings. The concept of reusing materials was highly motivated by ideological and economic concerns [11]. Raw materials like wood, metals, and semi-precious stones were expensive due to their scarcity. In addition, raw materials could be very difficult to obtain, and due to a lack of equipment and transportation methods, it was more profitable to reuse already extracted materials. Further, by reusing building components from constructions with religious and ideological meaning, it was believed that the new construction would inherit the status and authority.

There are also buildings from newer times and contemporary architecture that consist of reused materials. The 2012 London Olympic Stadium is an example of this. This stadium is, among other materials, built using materials from the demolished buildings at the site where the stadium was built. As much as 98% of the materials from the demolished buildings were used in the building process of the 2012 London Olympic Stadium [12].

2.2 Theoretical and political background

Due to population growth, globalization, and a rise in the economy on a global scale, humanity's impact on the Earth over the past century has amplified [13]. The increase in economic activity and people's standards of living actively influence the linear consumption pattern seen today. Because of this linear approach, many of the planet's natural resources are imprinted by overconsumption. The 2018 report from IPCC (The Intergovernmental Panel on Climate Change) states that ecosystems are pressed, and there is a drastic decline in biological diversity. Human activity has also increased greenhouse gases (GHG) in the atmosphere [14]. There are serious consequences that could damage our planet if no actions are taken against the global increase in greenhouse gases. IPCC also states in their report from 2018 that some of the consequences of the increase in surface temperature, due to the increase of greenhouse gases in the atmosphere, would be water shortage, reduced food production and agriculture, extreme weather, and a rise in the sea level. Therefore, the future depends on changing today's linear consumption pattern to a more circular economy.

2.2.1 UN Sustainable Development Goals (SDG)

The term "sustainable development" was first introduced by the previous Norwegian Prime Minister Gro Harlem Brundtland and the Brundtland Commission in 1987. The United Nations defines *sustainable development* as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* [15] [16]. The United Nations has developed the UN Sustainable Development Goals, which act as a common and global plan to secure sustainable development. The Sustainable Development Goals include environmental, social, and economic aspects. It is important to emphasize that understanding the connection between the three pillars is crucial for sustainable development. The UN Sustainable Development Goals are shown in Figure 1.

Figure 1: The 17 UN Sustainable Development Goals [1]

For this thesis, Sustainable Development Goal 11: "Sustainable cities and communities", 12: "Responsible consumption and production", 13: "Climate action", and 17: "Partnerships for the goals" are the most relevant goals.

Through the Paris Agreement from 2015, 194 countries, including Norway, have agreed to limit the global temperature increase to preferably 1.5°C, and no more than 2°C [17]. According to the United Nations Emission Gap Report from 2022, we are far from reaching the goals of the Paris Agreement. If no change is made, and we only follow the policies implemented since the Paris Agreement, the Earth's surface temperature will increase by 2.8°C over the twenty-first century. By implementing the current pledges, the surface temperature can increase by 2.4-2.6°C by the end of this century [18]. All of these scenarios predict a higher surface temperature increase than the Paris Agreement stated in 2015. Therefore, only urgent system-wide transformations can provide enormous cuts to limit greenhouse gas emissions.

2.2.2 Circular economy

Today's linear economy is not sustainable, and it is crucial to transform it into a circular economy. A *linear economy* is defined as a traditional model where materials are extracted and used for products, for later to be categorized and treated as waste when the product's lifetime is over. This model does not consider the environmental and ecological footprint it leaves behind, and it prioritizes economic profit over sustainability [19]. A *circular economy* is a model that includes sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products [20]. This approach decreases the need to extract new raw materials and instead focuses on extending the life cycle of products.

Figure 2 shows the difference between a linear and a circular economy. As seen in this figure, the linear approach reflects a "take-make-dispose" mindset, while the circular approach is focused on keeping the products in the loop for as long as possible.

To secure a sustainable development and future, welfare and economic growth must be decoupled from resource use [13]. This way, greenhouse gas emissions and resource use can be reduced without compromising welfare growth and obstructing other UN Sustainable Development Goals such as 1: "No poverty" and 8: "Decent work and economic growth".

Since 2015, the European Union (EU) has invested in implementing a circular economy in Europe. In 2020, they presented a new Circular Economy Action Plan to ensure a cleaner and more

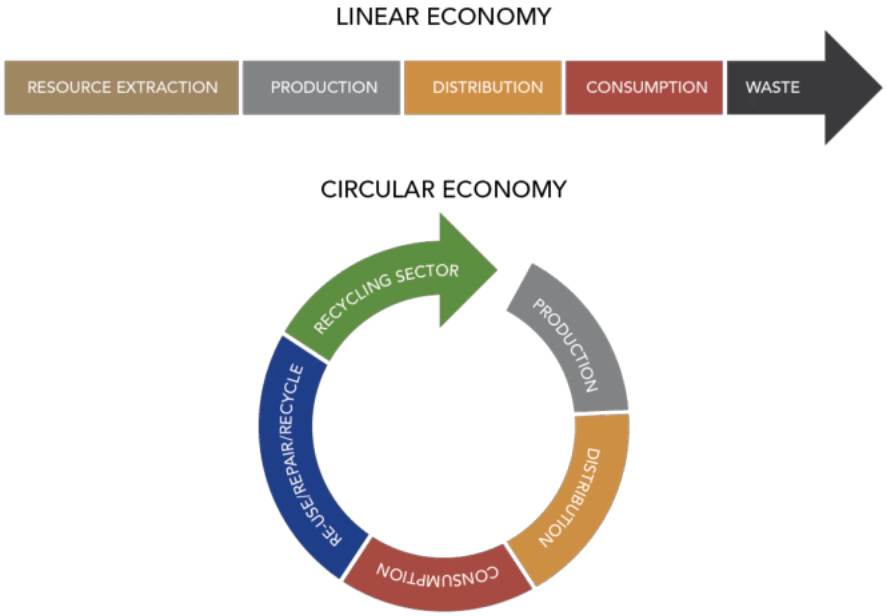

Figure 2: Comparison of linear and circular economy [2]

competitive Europe. This action plan consists of legislative initiatives toward rewarding products with longer lifetimes and an additional reward facilitating reuse and recycling [21] [22]. Many European countries have already started implementing legislative initiatives to ensure a change from a linear to a circular economy. Norway is one of those countries, and the Norwegian Government stated in its national strategy for a circular economy that Norway aims to act as a leading country in this transition [23] [24]. The national strategy serves as the groundwork for government initiatives to harness the value-creating potential within the Norwegian business sector by adopting a more circular economy model. This entails implementing specific measures targeting sectors identified as possessing significant potential for circular economy and green competitiveness in Norway. These sectors encompass the bioeconomy, process industry, the buildings and construction sector, and trade and service industries.

2.2.3 What is reuse?

The Norwegian Directorate for the Environment (Miljødirektoratet) defines *reuse* as *products or materials used again for the same purpose they were made for without being heavily processed in any particular way* [25]. Often, the terms recycling and reuse are confused. Sirken explained the differences between the two terms as follows:

- Recycling or material recycling refers to the return of materials in an industrial process. The material's structure is changed, creating a new product [26].
- Reuse refers to a new exploitation of a product in its original state. This means the material's structure is not changed before it is reused [26].

Depending on processing, the term reuse can include using building materials as building materials. The new purpose of the material can be the same as before, or the material can have a new function, either with or without processing processes [27]. This is called upcycling. Upcycling includes using building elements or materials differently than initially intended, preferably as part of a new building element or material, increasing the value of the individual components.

2.2.4 The waste hierarchy

The Norwegian Directorate for the Environment published a report in 2019 about a Waste Management Plan for the period 2020-2025. This report states that 25% of the total national waste generation is generated from the buildings and construction sector. This sector alone is accountable for the country's most significant waste generation [28]. EU's framework directive for waste demanded that 70% of non-hazardous waste from the buildings and construction sector go through material recycling or be prepped for reuse within 2020.

The waste hierarchy is illustrated in Figure 3.

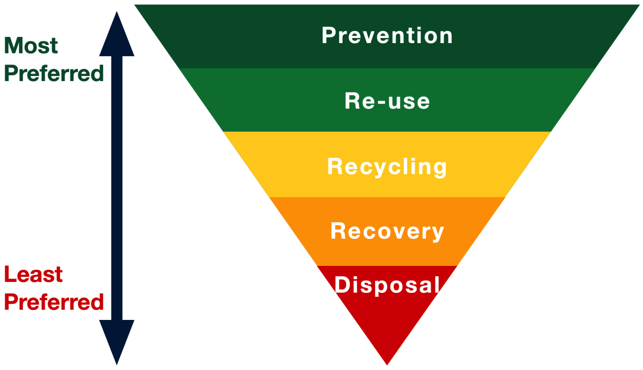

Figure 3: Illustration of the waste hierarchy [3]

This illustration shows how the waste should be treated to achieve the best exploitation of the resources. It is preferred that the waste must be treated as close to the top of the pyramid as possible. There are five different levels of treating the waste [3] [29]:

1. Prevention: Avoiding products and materials becoming waste, thereby reducing the amount of waste, is the most preferred option in the waste hierarchy.
2. Reuse: By cleaning, refurbishing, and repairing materials and products, we can prevent them from becoming categorized as waste and extend their lifetimes, and this is, therefore, the second level of the hierarchy.
3. Recycling: Recycling the waste can turn the materials or products into new ones, which can be further used. This level is below reuse in the hierarchy because the processes needed to recycle materials/products can be very energy-demanding.
4. Recovery: The energy can still be recovered from waste that cannot be recycled. The waste is incinerated, and the energy can be used for district heating or industrial use.
5. Disposal: This is the least sustainable option and is only valid if all the other levels are impossible.

2.3 Scientific review

Even though there is significant potential for reducing greenhouse gas (GHG) emissions in the buildings and construction sector, the scientific literature for the Norwegian context is limited. According to the REBUS (REuse of Building materials - a USers perspective) project, the current knowledge is mainly found in industry reports for practitioners. These reports are mainly based on anecdotal experiences [30]. Rakhshan et al. 2020 conducted a systematic review of the reuse of components in the building sector worldwide. They discovered that there has been an increase in peer-reviewed articles regarding the reuse of building components since 2014 [31]. This increase in articles points to increased interest in researching the possibility of reusing materials in the buildings and construction sector. This review presents several scientific articles and cases explaining and discussing barriers and possibilities for reuse in the sector.

2.3.1 Waste Management from building sites

A circular economy involving the reuse of building materials will also reduce the amount of waste on building sites. According to the Norwegian Green Building Council (Grønn Byggallianse), most building sites for new buildings in Norway generate around 40-60 kg waste/m^2 [32]. Even though some projects have aimed for 25 kg/m^2 waste generation or even waste-free sites, Selamawit Mamo Fufa has written an article about some challenges related to reducing the waste generation on building sites [33]. This article states that to reduce waste generation on construction sites, excessive planning throughout the project period and close collaboration between the different actors are necessary to succeed. Further, one of the reasons why the level of waste generation is this high may be that actors in the buildings and construction sector do not see the economic benefits of reducing waste on construction sites. For many building components, using virgin materials is cheaper than reusing the remaining materials. Therefore, treating the used building materials as waste instead of building components has become a more economical alternative. As described in Chapter 2.1, the reuse of building materials in the past had an economic advantage compared to virgin building materials. Today, the investment in paying working hours costs much more than before the fifteenth century. At that time, they invested more in reusing materials than the workers.

2.3.2 Barriers and possibilities for reuse

An article by Katrin Knoth, Selamawit Mamo Fufa, and Erlend Seilskjær presents and discusses barriers and success factors for reusing construction materials in Norway. In addition, the article presents perspectives from manufacturers, architects, building owners/contractors, environmental/reuse consultants, and public institutions [34]. In Knoth et al. 2022, four key themes for barriers and success factors are presented. The first key theme is mindset and knowledge, and lack of knowledge is presented as one of the barriers acknowledged by all the actors involved in the study. Lack of knowledge is mentioned as partly the reason why reusing building components is met with skepticism. The constructors and public institutions participating in the study stressed that they are still met with a conservative way of thinking regarding reusing building materials. Therefore, it is essential to change our way of thinking, which can be done by cooperation and communication throughout the whole value chain [35].

All the participants, except for the architects, also addressed reluctance to take risks or risk-sharing as a barrier. Reusing construction materials continues to be linked with elevated risks, encompassing financial implications and challenges related to documentation, material availability, and sourcing. This barrier is also discussed in Nordby et al. 2019 [35]. By increasing the cooperation and communication between all the actors, risks and experiences can be shared and learned. Hart et al. 2019 describe a lack of knowledge, interest, and skills as the crux of the problem. There will only be progress regarding circularity if there is an increase in interest, knowledge, and skills [36].

Further, Knoth et al. 2022 describe some barriers associated with the business framework as lack of market, lack of expertise, and lack of reuse research and development [34]. Current market structures make virgin materials easier to implement. Adapting a product or material to a circular economy requires changes to the existing production infrastructure. A change in the production infrastructure can be costly and it follows a high risk not many manufacturers are willing to take alone. Financial incentives and funding schemes for developing circular business frameworks would be highly motivating measures to ensure a transformation. Hart et al. 2019 and Nordby et al. 2019 describe high upfront investment costs and a lack of regulatory framework supporting sales and utilization of building materials as barriers to the circular economy transformation [36] [35]. Incorporating experts specializing in building component reuse, with their capacity to foster innovative reutilization, serves as a valuable contribution to the development of a circular economy. Through the application of creativity and the enhancement of innovation capabilities, the buildings and construction sector stands to derive advantages from the principles of circularity and sustainability in the economy [34].

Currently, there is a lack of developed and functioning markets for reused building materials. An underdeveloped reuse infrastructure is mentioned as one of the key barriers in Knoth et al. 2022 [34] and Nordby et al. 2019 [35]. The needed building materials are not always available at the desired time, which indicates that there is a clear need for physical and digital reuse infrastructure. Currently, there are a few physical marketplaces for reused materials in Norway, like Loopfront [37], Resirqel [38], and Rehub [39]. However, it is necessary to have communication and cooperation between the actors in the buildings and construction sector throughout the whole value chain. Another barrier associated with the reuse infrastructure is the timeline. In Knoth et al. 2022 it is described that demolition or disassembly of components from donor buildings don't always coincide with the time they are needed in new buildings. This results in a need for storage facilities and transportation from the demolition site to the storage before the materials are transported to the new construction site. A lack of temporary storage space and additional costs related to storage and transportation are all factors standing in the way of the reuse of building elements. It is therefore crucial to develop and establish infrastructure supporting the reuse of building elements.

The two biggest barriers related to legal framework are presented by Knoth et al. 2022 as a lack of supporting regulations and a lack of technical documentation [34]. There is a lack of a consistent regulatory framework and incentives globally, which means there is an absence of global consensus on policies regarding circular economy [36]. Currently, many Norwegian regulations are hindering the reuse of building components. Stricter requirements for reuse in building construction projects could force manufacturers to reuse, which would facilitate a wider adaptation of reused building components. According to Rakhshan et al. 2020, important drivers for reuse would be legislation and regulation. Reuse-friendly regulations and stricter requirements for reuse would play a crucial part in a wider implementation of reuse in the buildings and construction sector [31]. Lack of technical documentation is also stressed as a barrier to the reuse of building elements. Reused building materials must fulfill the requirements and qualifications described in TEK (the Norwegian building code) and DOK (Regulations on documentation on construction products), as new building materials do. Therefore, it is important to establish systems with standardized product information on health and safety, durability of the product, and material composition [40]. This tool will make the reuse of building components more predictable and less uncertain.

2.3.3 Sustainable building components

The report "Anbefalinger ved ombruk av byggematerialer" (in English: Recommendations for reuse of building materials) was published by SINTEF in connection with the research project UPGRADE, which is about mapping the potential and assessment of new solutions that can be used in upgrading existing buildings. The report presents the possibilities for reusing eight building materials and components [4]. The eight building materials and components included in the report are bricks, metal, ventilation ducts in galvanized steel, concrete, wood, glass, plastic, and electrical components. Table 1 below shows two of the eight building components mentioned in this report. Since metal and wood are the main building materials relevant to the case study examined in this thesis, the table presents these two materials.

Firstly, the report describes metal as a very robust material with a long lifetime, and the possibilities of reusing it in new constructions are very present. The price of virgin metal changes according to the changes in the price of metal on the world market. According to the IMF Blog, international metal prices have increased since pre-pandemic prices [41], which means there would be possible economic savings by reusing metals instead of buying virgin metals. In addition to the possible economic saving, metal reuse is important to fight metal scarcity. Since metal is a non-renewable source, it is important to reuse the amount of metal already available. In addition, extracting and producing metal is an energy-demanding process, and the environmental benefit of reusing the metal could be significant.

Building material	Possibilities and drivers	Barriers
Metal	A robust material with a long lifetime	It must be possible to demolish without damaging the material
	Possible economic savings	Some metal components are coated with paint and surface treatment which can contain heavy metals. These can be harmful to the health and environment.
	Contributing to fighting metal scarcity	
	Metal extraction is an energy demanding process, and there are therefore big environmental benefits from reusing metal.	
Wood	Reuse is in theory possible for all types of wood that is not coated with paint or surface treatment.	Important to check the quality of the wooden products after demolition. If there is any rot or moisture damage, the wood cannot be reused.
	Long lifetime and is dismantled relatively easily.	Normally in Norway, the wooden products are attached mechanically with nails, staples, and screws. It might take longer time to prepare the wood for reuse.
	It is beneficial to reuse wooden products for as long as possible because of the release of CO2 to the atmosphere when wood is burned. This is because wood stores carbon and is part of the carbon cycle.	Wood is a renewable resource with a high value as a biomass for energy utilization. Energy recovery of used wood may therefore be more preferred compared to reusing wood in the building sector.

Table 1: Possibilities and barriers for some building materials [4]

According to SINTEF's report, wood accounts for approximately 30-40 % of the total waste from demolishment and building sites. In general, reuse of wood in new constructions is possible for all types of wood. There is a big interest in reusing wood elements like columns, beams, trusses, doors, and other building elements of wood. This is because wood is a product with a long lifetime, and it is a material that can be dismantled relatively easily. Wood stores carbon, and is part of the carbon cycle. By burning wood, the stored carbon will be released into the atmosphere. It is therefore beneficial for the environment to reuse the wood and keep the wood elements in use for as long as possible [42] [43].

2.3.4 Previous reuse projects

There is generally a gap in the scientific literature regarding the reuse of building components, and the benefits occurring from reusing elements. The number of scientific papers regarding the reuse situation in the Norwegian buildings and construction sector is limited. There are no scientific papers regarding the reuse of building elements in storage buildings or garages in Norway. By reusing the building elements in this type of building (which is the focus of this thesis), in which the technical requirements are less strict than for residential or commercial buildings, the possibilities for reuse will increase.
Even though the reuse of building elements in the buildings and construction sector is widespread, there are some examples of projects where the amount of reused materials varies. The projects described in this section are shown in Table 2, and all projects are either commercial buildings, office buildings, or residential buildings. The projects are primarily based in Norway, however, some of them are based in other European countries like Denmark and Belgium.

Country	Study/Project	Year completed	Reused materials	CO_2 savings
Norway	KA13 [44]	2021	Concrete decks, windows, railings, stone coating for the outdoor terrace, terrace floor	70%
Norway	Sandakerveien 140 [45]	2023	Slate slabs, curbstones, benches	60%
Norway	Ruseløkka School [46]	2021	Bricks, granite blocks, wooden beams	61%
Norway	Kristinakvarteret [47]	2023	Bearing constructions in concrete	70%
Norway	KA23 [48]	2022	Foundations, exterior walls, frames, floor structures, load-bearing systems, stairwells, elevators, portion of interior walls, some technical equipment	55%
Denmark	Ressource Blokken [49]	2021	Concrete foundation	Average: 50%
Belgium	Multi Commercial [50] Building	2022	Blue limestone slabs, concrete foundation, the ventilation system, majority of the elevator machinery	Unknown

Table 2: Previous reuse projects

Kristian Augusts gate 13 (KA13)
KA13 is the first building in Norway where the reuse of building materials and circular solutions have been utilized on a commercial scale. This office building is the first in Norway to reach FutureBuilt's targets for circular buildings [44]. FutureBuilt's criteria for circular buildings state, among other things, that a circular building should facilitate resource utilization at the highest possible level and consist of at least 50% reused and reusable components. These criteria were published by FutureBuilt in 2020, with the purpose of encouraging reuse and circular principles [51]. The reused materials used in this project were sourced from different "donor buildings" nearby. Donor buildings are buildings that were supposed to be demolished or rehabilitated. For instance, concrete decks were obtained from "Regjeringsbygg R4", windows from "Kværnerbyen", and railings from "Tøyenbadet" [52]. In total, as much as 80% of the materials used to build the office building were reused building materials [53]. Because of the high rate of reused building materials, the GHG emissions from this project were reduced by 70% compared to a reference building built entirely of virgin materials. An important lesson learned from this project is the importance of prioritizing time and expertise for mapping building components and the logistics needed to store and transport them to the construction site. Experiences taken from this project have been essential to help shape future projects and regulations regarding the reuse of building materials in Norway.

Sandakerveien 140

Sandakerveien 140 is now an inviting activity park. The area was previously used as a parking area on top of a roof, which was reconstructed into a park with exercise equipment for the tenants in the building. For the client of this project, it was necessary to reuse as many materials as possible. For instance, slate slabs and curbstones were donated from "Regjeringskvartalet", while six benches were donated from "Rudolf Nilsens" square [45]. The soil used on the roof contains bricks, which effectively bind CO_2. LCA calculations carried out in connection with this project show that there was a 60% reduction in CO_2 emissions in a 60-year perspective compared to a standard facility.

Ruseløkka School

Ruseløkka School is one of FutureBuilt's pilot projects for the reuse of building materials and the use of second-generation concrete. The new school was built on the same site as the demolished school building [46]. Wooden beams, granite blocks, and as many as 4500 bricks were obtained from the old school and reused in the new Ruseløkka School. Since most of the reused materials were obtained from the old school at the same site, there was little to no transportation needed for these materials. The overall LCA calculations for this project show a 61% reduction in CO_2 emissions compared to the reference building [54].

Kristinakvarteret

Kristinakvarteret in Tønsberg in the south-east of Norway was an old office building from 1980. In 2021, the building was transformed into a pilot with ambitious environmental- and energy targets. The new office building was built using the bearing constructions in concrete from the old office building. By reusing the bearing constructions in concrete, the new office building reduced its CO_2 emissions by as much as 70% compared to a reference building built of entirely virgin materials. In addition to this reuse, the new building is also built of wood. This material was intentionally chosen because of its environmental benefits compared to other similar building materials [47].

Kristian Augusts gate 23 (KA23)

KA23 is the first protected building in Norway to be rehabilitated according to the FutureBuilt criteria for circular buildings [55]. Because of environmental considerations and because of architectural value, the goal of the project has been to preserve as much of the building's distinctiveness and its components. Therefore, foundations, exterior walls, frames, floor structures, load-bearing systems, stairwells, elevators, portions of interior walls, and some technical equipment were retained [48]. The project's total CO_2 emissions show a 55% reduction compared to the reference building. The biggest CO_2 reduction is related to transport. Because most of the reused materials come from the old building on the same site as the new KA23 building, there is less transportation needed to transport the building materials. Due to the reuse of materials, the emissions related to the materials are also reduced [56].

Ressource Blokken

Ressource Blokken is a project in Denmark that maps the possibilities for reuse for an area in Denmark. This area currently consists of residences accounting for 1 360 300 m^2. These residential buildings will be demolished in the upcoming years. The building components are going to be reused in the construction of chained housings. The majority of the public housing in Denmark was built within a period of 20 years, from 1960-1980. Most of the housings were built from a concrete foundation. Therefore, there will be environmental benefits to reusing the existing concrete foundations [49]. According to Charlotte et al. 2022, there are several possible strategies and design opportunities to reuse the old building foundations, which will have different reductions in CO_2 emissions, from 18% reduction to 86% reduction. By calculating an average of the reduced CO_2 emissions from the different designs, we get a reduction in CO_2 emissions of 50% compared to using only virgin materials [57].

Multi Commercial Building

The Multi Commercial Building in Belgium was renovated in 2020, and is a commercial building consisting of offices and a restaurant. Approximately 140 tons of blue limestone slabs from the old building were dismantled and reused in the renovated Multi Commercial Building. The blue limestone slabs were used for the cladding of some of the ground-floor interior and on the exterior of the plinth [50]. Some of the blue limestone slabs were brought from the headquarters of the BNP Paribas Fortis bank in Brussels. Therefore, there is both a cultural reason behind the reuse, in addition to an environmental reason. Additionally, the concrete foundation, the ventilation system, and the majority of the elevator machinery were reused [55]. The transportation was thereby reduced, which is environmentally beneficial. There has not been published a LCA study mapping the CO_2 savings related to this project.

3 Case study - Granåsen Sports Park

3.1 Introduction of the case

Granåsen Sports Park is a large facility designed to accommodate both everyday and elite exercisers. It should function just as well for the general public as for larger elite championships. Therefore, it is necessary to have a well-functioning operational department. Trondheim City Operations (Trondheim Bydrift) has identified the need for workshops and warehouse facilities to manage the operational equipment, outlined in a detailed functional program describing the space requirements. A maintenance building with workshops and garages for storing machines and snowmobiles, in addition to heated storage spaces, has already been constructed. However, there is a need for more storage space, and more specifically there is a need for a cold storage space. This cold storage was built during the fall of 2023, and this thesis will use this storage as a case study.

Asplan Viak has conducted a feasibility study to explore how the facilities for operational equipment in Granåsen Sports Park can be based on the reuse of materials and building components. The primary source of reused materials and building components was intended to come from dismantling buildings in the former civil defense camp 500 meters from the Granåsen Sports Park. In addition to this primary source of reused materials and building components, Trondheim Municipality's Reuse Warehouse (Trondheim kommunes Gjenbrukslager) was also used as a source for materials and building components. The municipality established this reuse warehouse to store materials intended for reuse, and it is set to be further developed. Trondheim Municipality is also collaborating with private entities to further promote reuse, including identifying and utilizing materials and building components from local buildings soon to be demolished.

3.2 Materials

The storage has a total area of 630.2 m^2, distributed over two buildings. These two buildings are intended to store operation materials and fences and, in the summertime, to store equipment, snow nets, and other materials used in the sports park during the winter. The reused materials included in the construction of the storage at Granåsen Sports Park are listed in table 3 below. The materials have been divided into the NS3451 building component sections 223 - Beams, 231 - Bearing outer walls, 261 - Primary structure for outer roof, 262 - Roof covering, 265 - Eaves, gutters, and downpipes, 337 - Fire extinguishing with handheld fire extinguisher, 364 - Equipment for air distribution, and 443 - Emergency Lights (see table 4). For the materials used in the construction, only tables 2, 3, and 4 of NS3451 are relevant. The building component sections are from the Norwegian Standard NS3451:2022 "Component table and system table for buildings and associated outdoor areas", tables 2, 3, and 4. Norsk Standard (NS) is a designation for standards established and published by Standard Norge. Standard Norge has the exclusive right to establish and publish NS and is the Norwegian member of ISO [58].

Building component	Material	Quantity	Weight/unit (kg)	Total weight (kg)
223	Glulam	40	82	3280
231	Steel door	1	60	60
231	Spruce 48x48 batten	954	0.8	763.2
231	Spruce 23x48 batten	1700	0.4	680
261	Spruce 36x48 batten	1080	0.6	648
262	Roofing sheet TP-20	27	13	351
262	Roofing sheet TP-20	26	16	416
262	Roofing sheet TP-20	163	4	652
265	Gutter drain and wall fastening	8	1	8
265	Gutter pipe bend 60	6	1	6
265	Gutter hook	18	1	18
265	Gutter	7	4	28
265	Downpipe bracket	15	0.2	3
265	Downpipe	1	1.3	1.3
265	Rafter bracket	16	2	32
265	Mortise and tenon joint	3	0.3	0.9
265	Gutter joint piece	6	0.5	3
265	Gutter pipe bend 70	4	0.2	0.8
265	Gutter bracket with spring	58	0.3	17.4
265	Ridge piece	8	3	24
265	Downpipe	2	1.3	2.6
337	Fire extinguisher	2	9	18
364	Ventilation grille	2	2	4
443	Emergency lights LED (emergency exit)	1	1	1
443	Emergency lights LED	2	1	2

Table 3: Reused materials used in the storage at Granåsen Sports Park. Information provided by Trondheim Municipality.

Table in NS3451	Main component	Building component
2	21 Ground and foundations	216 Direct foundation
		217 Drainage
	22 Load-bearing structures	222 Columns
		223 Beams
	23 Exterior walls	231 Load-bearing exterior walls
		232 Non-load-bearing exterior walls
	25 Floor slabs	252 Slab-on-grade
	26 Exterior roof	261 Primary structure for exterior roof
		262 Roof covering
		265 Eaves, gutters, and downpipes
3	33 Fire extinguishing	337 Fire extinguisher with handheld fire extinguisher
	36 Air handling	362 Ductwork for air handling
4	44 Light	443 Emergency lights

Table 4: The relevant components from NS3451:2022

The two buildings that make up the storage are two relatively simple buildings consisting of bearing constructions with roofs (see Figure 4). Because of the need to store equipment, there is a need for an open-plan solution without many columns in the area. Therefore, two different construction principles have been selected for the two buildings. Building 1, illustrated as the bottom building in Figure 5, has an area of 299.1 m^2. Building 2, which is illustrated as the top building in Figure 5, has a total area of 331.1 m^2. This building also consists of a built-in storage unit with an area of 78.6 m^2. The site layout for the project, illustrating the storage consisting of two buildings, is shown in Figure 5.

Building 1 consists of:

- Bearing outer walls that are not insulated, only consisting of windproofing and clothing
- Concrete floor on the foundation
- Doors/gates
- Windows
- Lighting

Building 2 consists of:

- Columns and steel beams with no outer walls
- A smaller built-in storage unit with an area of 78.6 m^2
- Doors/gates
- Windows
- There are no outer walls for this building, except for the built-in storage unit
- Lighting

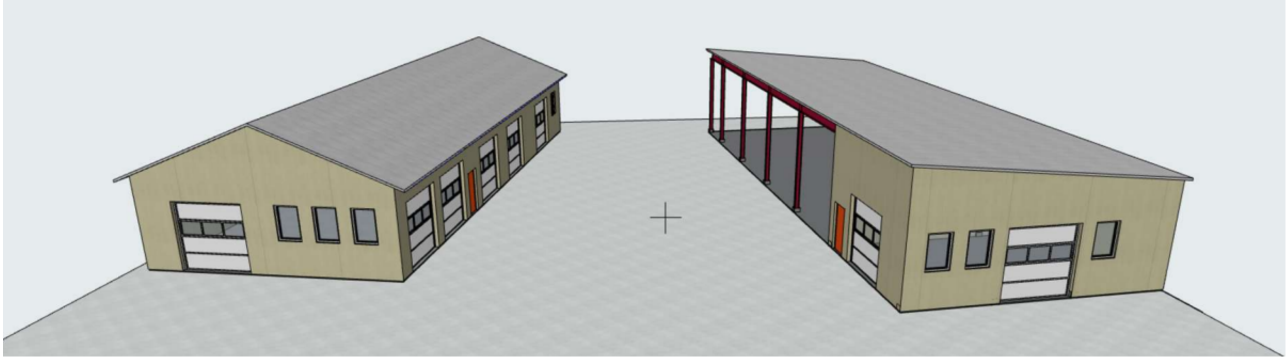

Figure 4: Illustration of the two buildings. Building 1 is to the left, and Building 2 is to the right. This illustration is from Asplan Viak's feasibility study.

Figure 5: Site layout of the storage. The bottom building illustrated in this figure is referred to as Building 1, while the top building is referred to as Building 2. The site layout is from Asplan Viak's feasibility study.

4 Methodology

4.1 Life Cycle Assessment for reused products

The methodology presented in this study is a Life Cycle Assessment (LCA) that compares different scenarios. LCA is a common method used to compare and quantify the environmental impact of a product or a service. The LCA will include all the substances exchanged with the environment, the total amount of emissions, and all the consumed resources for the production phase, use phase, and the dismissal of products at the end-of-life. The assessment quantifies the environmental impact of a product by using environmental damage indicators such as climate change, fossil and mineral resource depletion, acidification, and eutrophication [59]. Therefore, the characteristics of each material used and the effect those materials have on the environment will influence the results of the LCA. In a linear LCA approach, the production phase (A1-A5), the use phase (B1-B7), the end phase (C1-C4), and the end-of-life phase (D) are included. These phases are illustrated in Figure 6 and explained in Table 5. In a circular LCA approach, the product's life does not end with the end-of-life phase (D) like in the linear LCA approach. Instead, the product's life is extended. This study will focus on climate change (GWP - Global Warming Potential) as an environmental indicator and compare the differences in environmental impact from the production phases A1-A5 and A1'-A5'.

LCA for reused products is somewhat more challenging because allocating the environmental impact related to the product can be considered over various use and reuse options. There are no guidelines for how the environmental impact should be allocated and what appropriate allocation method should be used; therefore, different methods are applied, which makes the comparison of the environmental impact more challenging. Allacker et al. 2017 explain some of the suggested allocation approaches given by The European Commission Product Environmental Footprint (PEF) and Organizational Environmental Footprint (OEF) [60]. There are four main allocation approaches for the primarily defined end-of-life stage resulting in material reuse instead of its primary, intermediate, and final uses:

1. The cut-off approach is the first allocation approach and gives a ratio of 100:0. This means there will be *"full allocation of the reuse impact to the product using a reused material"* [60]. This means the impacts associated with phases A1'-A5' are allocated to the reused product. However, the environmental impacts of virgin production (A1-A5) are fully avoided in this approach.
2. The recyclability approach is the second allocation approach and gives a ratio of 0:100. This means there will be *"full allocation of the reuse impact to the product providing a reused material* [60]. Nothing is allocated to the reused product.
3. The third allocation method is the 100:100 approach, which means there will be *"full allocation of the reuse impact to both the product providing a reused material and the product using a reused material* [60]. Therefore, this approach is a combination of the two first approaches explained above.
4. The last allocation approach is the 50:50 approach, where *"50% is allocated to the product providing a reused material, while 50% is allocated to the product using the reused material"* [60].

Since the main objective of this study is to compare the environmental impacts of existing reuse stocks and virgin material use, and does not include possible future reuses, the cut-off approach is used in further calculations. This approach is also mainly used for similar research, like Brütting et al. 2020 [61], Buhé et al. 1997 [62], and Thormark et al. 2000 [63]. This method is also in line with the method used in EN15804. The purpose of EN15804 is to define clear guidelines for performing LCAs in EPDs for the buildings and construction sector [60] [64].

Figure 6 below illustrates the life cycle of virgin building materials and reused building materials, and how these materials can be implemented in a system flow chart. The steps in the production phase (A1-A5) are for extracting and producing new products from raw materials. Then, the product is used in the use phase (B1-B7) before it is demolished (C1-C4). The next step in a linear approach is the end-of-life phase (D). This phase includes material recovery, energy recovery, and landfilling. However, if the circular approach is included, the product can be reused. Figure 6 illustrates how the end-of-life phase can be skipped, and how the product can be reused through the steps A'-C'. The product can potentially be reused several times before it is no longer usable. Then, the product will end up in the end-of-life phase (D). When reusing an already existing product, the CO_2 emissions from steps A1-A5 are not allocated to the reused product. However, the CO_2 emissions from the reused product phase A1'-A5', involving transportation, cleaning/repairing, and storing, are allocated to the reused product.

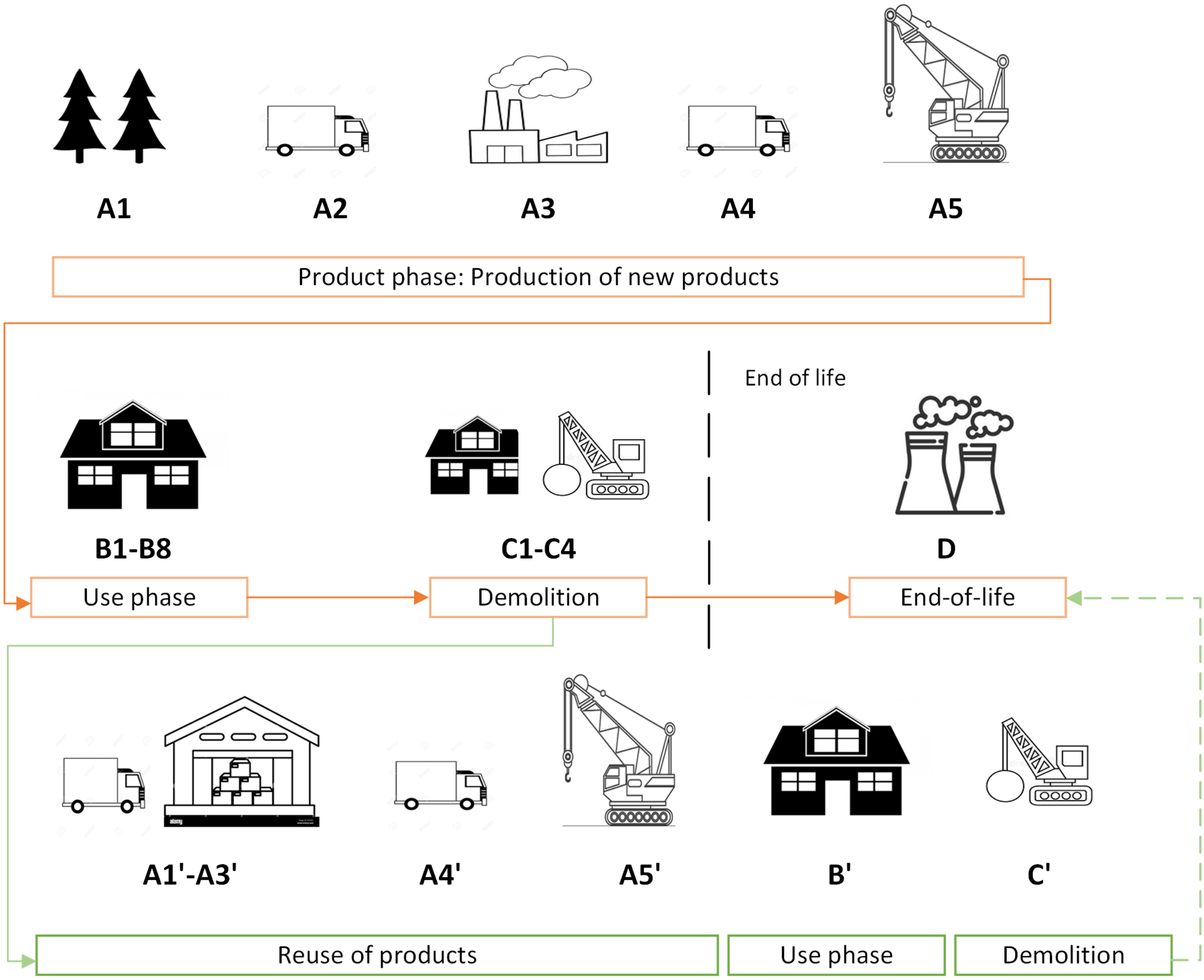

Figure 6: Illustration of LCA of virgin and reused building elements. The figure illustrates how a product can either end its life (D) or be reused (A'-C').

The phases illustrated in figure 6 are described in table 5. As seen in the illustration, the "D - End-of-life" phase is not included for reused materials. For reused building materials, there will be no end-of-life treatment like energy- or material recovery because the products are being reused instead. Therefore, this phase is not included, and moreover replaced with the phases A'-C' for reuse of products.

Phase	**Step in phase**	**Description**
A - Production phase	A1	Extraction of raw materials
	A2	Transportation
	A3	Production
	A4	Transportation
	A5	Assembly
B - Use phase	B1-B7	Use and maintenance
C - End phase	C1-C4	Demolition and waste sorting
D - End-of-life phase	D	Material recovery, energy recovery, and landfilling
A' - Reuse of products	A1'-A3'	Preparation and transportation of reused products to storage facility
	A4'	Transportation from storage to building site
	A5'	Assembly of the reused products
B' - Use phase	B1'-B7'	Use and maintenance
C' - End phase	C1'-C4'	Demolition and waste sorting

Table 5: Description of the different phases in figure 6

This thesis only examines the difference in CO_2 emissions from A1-A5 for virgin materials/products and A1'-A5' for reused materials/products. This means that the phases B/B', C/C', and D are not included in the LCA calculations. The use phase and demolition phase are both the same whether it is for a virgin material or a reused material. The same applies to phase D, the end-of-life phase.

4.2 Scenarios for Granåsen Sports Park

The aim of the project building new storage in Granåsen was to use as many reused materials as possible. However, during the planning and building process of the project, the entrepreneurs met some obstacles. For instance, the initial focus of this project was to reuse roof trusses. However, these roof trusses were damaged and did not meet the requirements to be reused in the storage. Therefore, virgin materials were used after all. Four scenarios have been created and are further studied. The four scenarios are listed below.

1. Scenario 0: The beams and columns used in the construction of the storage are made of steel. All the materials used in the storage are virgin materials.
2. Scenario 1: The beams and columns used in the construction of the storage are made of wood (glulam). The storage is built with only virgin materials.
3. Scenario 2: The storage is built with some reused materials and some virgin materials. This scenario is how the storage was actually built in Granåsen.
4. Scenario 3: The storage is built with a majority of reused materials. This scenario aims to be an optimistic, yet realistic, case.

Scenario 0 was Asplan Viak's initial design of the storage in Granåsen. This storage was designed to contain beams and columns made of steel. When Asplan Viak found out it would be possible to reuse beams made of glulam, they redesigned the storage to contain beams and columns made of glulam instead of steel. This change was done because of the availability and possibility of reusing the glulam beams. The redesigned version of Scenario 0 is called Scenario 1 in this thesis. The only difference between these two scenarios is the material of the beams and columns changing from steel to glulam. All of the materials used in the construction of the storage in these two scenarios are virgin materials. However, the transition from Scenario 0 to 1 was necessary to develop Scenarios 2 and 3.

The storage in Scenario 2 represents the storage actually built at Granåsen Sports Park. In this scenario, some materials are virgin materials, while some materials are reused. The amount of reused materials depended on the availability of reused materials matching the need for the storage built in Granåsen.

Scenario 3 is an optimistic scenario, where as many reused materials and products as possible are used in the construction of the storage. Initially, this scenario was supposed to show the results from strictly using reused materials. However, after evaluating today's possibility of reuse, some building materials did not qualify for reuse. For instance, the concrete used in this project is the Concrete B30, with a volume weight of 2400 kg/m^3. According to the report from SINTEF Community regarding recommendations for the reuse of building components [4], concrete with a higher volume weight than 1300 kg/m^3 is very hard to reuse. This type of concrete is hard to dismantle without harming or destroying it. Further, heavy machinery is needed in the dismantling processes. Due to the lack of reliable data to calculate the additional CO_2 emissions related to these processes, the reuse of concrete is not included in scenario 3. In addition, gravel and crushed stone are not reused in scenario 3. The possibilities for reusing this material are significant according to the EPD (Environmental Product Declaration) "Knust stein/pukk, Franzefoss avd. Vassjellet"; however, this would demand heavy machines to prepare the gravel and crushed stones for transportation. The reliable emission data for this process was not yet available. To make this scenario as realistic as possible for this case study, gravel/crushed stone is not included as reused materials due to a lack of data. Furthermore, a wind barrier membrane was not reused for Scenario 3. This is due to the EPD of the product stating that the wind barrier membrane was not suited for reuse. This material is not mentioned in Table 6.

It is very interesting to compare Scenario 3 with the three other scenarios and use this comparison to continue the development towards reusing more materials within the sector. An overview of what materials and products were reused in Scenarios 2 and 3 can be found in Table 6. All the reused materials/products in Scenario 3 are similar to the materials/products in Scenario 2. Therefore, the CO_2 emissions for production phases A1'-A3' are assumed to be similar to the equivalent materials/products.

	Scenario 2			Scenario 3	
Material/product	**Reused**	**Virgin**	**Comment**	**Reused**	**Virgin**
Concrete		x			x
Insulation		x		x	
Steel doors	x	x	1 of 4 steel doors was reused	x	
Steel gates		x		x	
Gravel		x			x
Glulam beams	x			x	
Glulam columns		x		x	
Structural timber	x	x	Spruce battens are reused, not the rest of the structural timber used.	x	
Roof membrane		x		x	
Asphalt		x		x	
Steel roof plates	x	x	3 of 6 roof plates in steel were reused	x	
Steel gutter system	x			x	
Fire extinguishers	x			x	
Ventilation grille	x			x	
Lighting	x			x	

Table 6: Comparison of the reused and virgin materials for Scenarios 2 and 3.

4.3 About the reused materials

Table 7 shows the reused materials used for Sceanrio 2. As seen in Table 7 below, processes needed to clarify the materials before they could be reused are presented. These processes belong to phase A1'-A3', and are needed to clarify the reused materials. In addition to these processes, the transportation routes and methods are also presented. The transportation of the reused materials to the construction site belong to phase A4’. Table 9 in chapter 4.4 presents the different transportation routes and distances of transportation. The last phase A5’ represents the emissions from the disassembly/assembly of reused materials. The emissions from the use of a crane truck for 3 hours for the disassembly of glulam have been added to the phase A5’.

Material type	**Total weight (kg)**	**Transportation route**	**Disassembly**	**Processing**	**Transport**	**Storage time (months)**	**Comment**
Glulam	3280	3	Crane truck 3 h	Manual sorting	Truck EURO 6	4	Flight Trondheim-Oslo + electric rental car Værnes-Granåsen
Steel door	60	4	Manual	None	Electric van	4	
Spruce 48x48 batten	763,2	5	None	Manual sorting	Truck EURO 8	None	
Spruce 23x48 batten	680	5	None	Manual sorting	Truck EURO 9	None	
Spruce 36x48 batten	648	5	None	Manual sorting	Truck EURO 7	None	
Roofing sheet TP-20	351	1	Manual with electric lift	Manual sorting	Truck EURO 6	4	
Roofing sheet TP-20	416	1	Manual with electric lift	Manual sorting	Truck EURO 7	4	
Roofing sheet TP-20	652	1	Manual	Manual sorting	Truck EURO 8	6	
Gutter drain and wall fastening	8	1	Manual with electric lift	Manual sorting	Electric van	4	
Gutter pipe bend 60	6	1	Manual with electric lift	Manual sorting	Electric van	4	
Gutter hook	18	1	Manual with electric lift	Manual sorting	Electric van	4	
Gutter	28	1	Manual with electric lift	Manual sorting	Electric van	4	
Downpipe bracket	3	1	Manual with electric lift	Manual sorting	Electric van	4	
Downpipe	1,3	1	Manual with electric lift	Manual sorting	Electric van	4	
Rafter bracket	32	1	Manual with electric lift	Manual sorting	Electric van	4	
Mortise and tenon joint	0,9	1	Manual with electric lift	Manual sorting	Electric van	4	
Gutter joint piece	3	1	Manual with electric lift	Manual sorting	Electric van	4	
Gutter pipe bend 70	0,8	1	Manual with electric lift	Manual sorting	Electric van	4	
Gutter bracket with spring	17,4	1	Manual with electric lift	Manual sorting	Electric van	4	
Ridge piece	24	1	Manual with electric lift	Manual sorting	Electric van	4	
Downpipe	2,6	1	Manual with electric lift	Manual sorting	Electric van	4	
Emergency lights LED (emergency exit)	1	1	Manual	None	Electric van	4	
Emergency lights LED	2	1	Manual	None	Electric van	4	
Fire extinguisher	18	2	Manual	None	Electric van	2	
Ventilation grille	4	2	Manual	None	Electric van	4	

Table 7: Overview of the reused materials, processes, and transportation needed to clarify them. Trondheim Municipality has provided the information in this table.

As Table 7 shows, a crane truck was used for 3 hours in the process of disassembling the glulam. This process was executed by Jensen Transport, who informed that the fuel consumption of the crane truck used was 1.5 liters of diesel/hour. Further, according to Cranes Today, the average CO_2 emissions from diesel-driven crane trucks are 2.67 kg CO_2/litre of diesel [65]. The calculation of the amount of CO_2 emitted from this process is shown in Table 8 below.

Hours (h)	Fuel Consumption (litres/h)	Total Fuel Consumption (litres)	CO2 emissions (kg CO2/litres)	Total CO2 emissions (kg CO2)
1	1.5	1.5	2.67	4.005
3		4.5		12.015

Table 8: Total CO_2 emissions related to the use of a crane truck for 3 hours. Information about the crane truck was provided by Trondheim Municipality and Jensen Transport.

Further, as commented in table 7, three people flew from Oslo to Trondheim to quality check the glulam intended to use in the project. The emissions related to this flight have been included in the total calculations. This is elaborated in section 4.4.

4.4 Transportation

The reused materials were transported from five different donor buildings in the area of Trondheim. The five routes have been presented in table 9.

Route	Donor building	Storage place	Donor - Storage (km)	Storage - Construction site (km)	Total distance (km)
1	Bratsbergvegen 1041	Gjenbrukslageret, Nyhavna	23.9	11.7	35.6
2	Møllestua barnehage	Møllestua barnehage	-	7.8	7.8
3	Erling Skakkes gate 59	Gjenbrukslageret, Nyhavna	3.3	11.7	15
4	Produksjonskjøkkenet	Gjenbrukslageret, Nyhavna	5.2	11.7	16.9
5	Sirken	Sirken	-	9.9	9.9

Table 9: Transportation routes of the reused materials

The distances in km are based on the shortest and most effective route for transportation. Therefore, these distances are the shortest possible distances for vehicles. Since all of the donor buildings and the temporary storages are in the Trondheim region, the transportation distances for the reused materials are reduced compared to the transportation distances of the virgin materials. There are obvious environmental benefits associated with shorter transportation distances, which was important for the actors involved in this project. Further, 72% of the reused materials were transported with an electric van instead of a combustion engine vehicle.

As commented in table 7, the CO_2 emissions related to three people flying back and forth from Oslo Gardermoen to Trondheim Værnes must be included. By using the Atmosfair Emission Calculator, flying back and forth between Oslo-Trondheim will contribute to a CO_2 emission of approximately 153 kg CO_2. This equals 460 kg CO_2 for three people [66]. The variables from this calculation are shown in table 10 below.

Number of people	From	To	Flight type	Aircraft type	Climate impact
1	Oslo Gardermoen	Trondheim Værnes	Scheduled	Boeing 737-800	153 kg CO_2
3					460 kg CO_2

Table 10: CO_2 emissions from one round-trip flight from Oslo to Trondheim

4.5 Excluded processes

CO_2 emissions from some of the processes needed to clarify the reused materials and products (see Table 7) are so small, they seem insignificant in the total amount of emissions. By using the cut-off rule, some processes are excluded from further calculations. A list of the processes excluded can be found below.

- All reused materials used in Scenario 2 are stored in cold storages for a different amount of time. Since this process contributes minimally to the total CO_2 emissions, they have been cut off from later CO_2 calculations.
- Most of the resued materials used in Scenario 2 have undergone manual sorting, while the remaining materials have not undergone any processes. There are little to no CO_2 emissions associated with manual sorting, so any potential CO_2 emissions related to this process are not considered in subsequent calculations.
- Some of the reused materials are disassembled manually with an electric lift. The possible emissions from using the electric lift are insignificant and therefore excluded.

4.6 Processes in ByggLCA

All the CO_2 emission data used in this thesis are gathered from available EPDs for various materials and products. The EPDs were selected with guidance from Asplan Viak. The LCA tool used for the calculations performed in this thesis is ByggLCA. ByggLCA is a tool developed by Asplan Viak for performing greenhouse gas calculations for buildings. The tool is verified for use in BREEAM and addresses all building components in accordance with BREEAM-NOR and NS3451 [67]. The results from the LCA calculations are shown in Chapter 5. ByggLCA provides CO_2 emissions from all phases, however, emissions from electric vehicles are not included in the tool. Therefore, manual calculations for the emissions related to the transportation A4 are included in Section 5.2.1.

5 Results and Discussion

The results from the LCA analysis are presented in this section, followed by a discussion of the findings from the impact category (Climate Change, GWP). ByggLCA was used to perform the LCA calculations, and the cut-off approach was used for the allocation of the CO_2 emissions. As mentioned in the Methodology, the cut-off approach allocates the CO_2 emissions from reusing a product to the reused product (A1'-A5'), while the emissions from the production phase of the original product (A1-A5) are not allocated to the reused product. Furthermore, emissions from phases A1-A5/A1'-A5' are the only ones evaluated because emissions from phases B, C, and D are the same for virgin and reused products. The results from the different scenarios are presented and discussed, in addition to results obtained from a limited sensitivity analysis.

The four scenarios evaluated in this chapter are:

1. Scenario 0: All the materials used in this scenario are virgin materials. The beams and columns used in the construction are made of steel.
2. Scenario 1: All the materials used in this scenario are virgin materials. The beams and columns used in the construction are made of glulam.
3. Scenario 2: This scenario reflects how the storage in Granåsen was actually built. This storage consists of some reused and some virgin materials.
4. Scenario 3: The storage in this scenario was built mainly from reused materials. This is meant to be an optimistic yet realistic scenario. Some materials used in this scenario are virgin materials.

5.1 Comparison of the scenarios

As presented earlier in this thesis, the environmental impact of four main scenarios are compared. Scenario 0 shows the storage built of beams and columns made of steel and all virgin material. Scenario 1 shows the storage built of beams and columns made of glulam and entirely from virgin materials. Scenario 2 is the storage as it was built, with some reused materials. Lastly, scenario 3 shows the storage mainly built from reused materials. The total CO_2 emissions for the four scenarios explained above are illustrated in Figure 7, and the quantitative results from this figure are shown in Table 11.

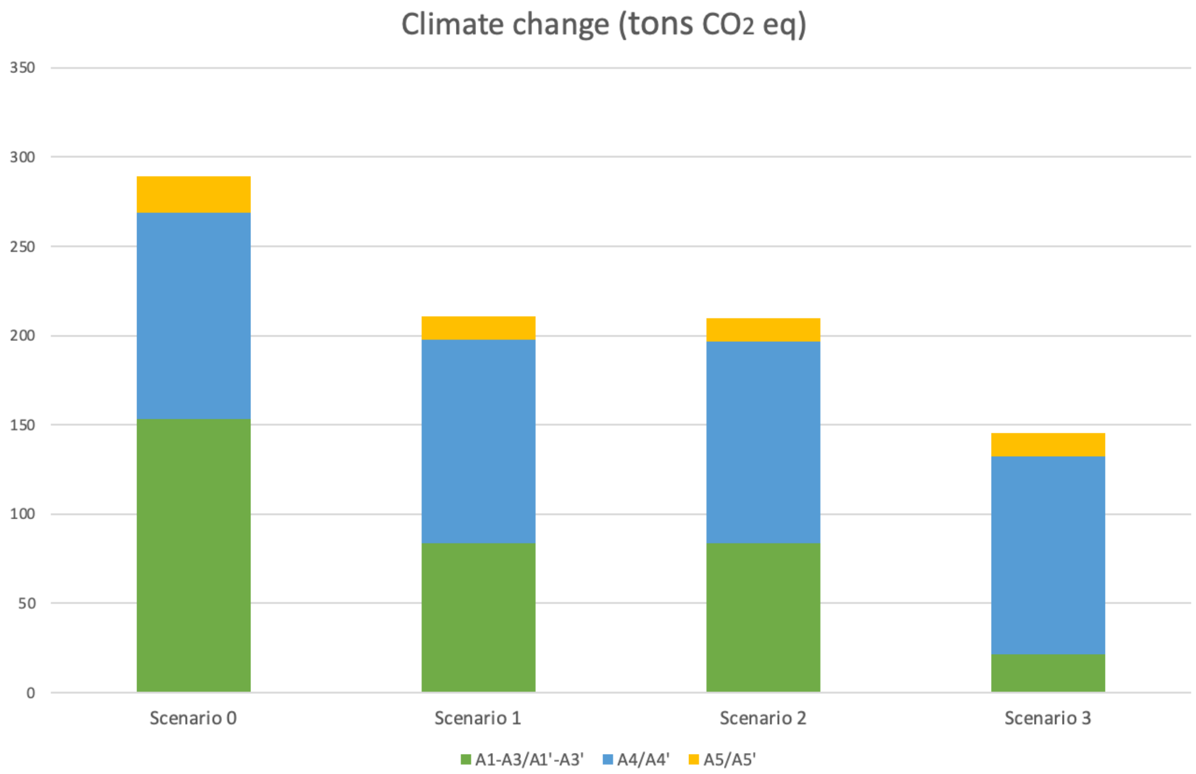

Figure 7: Results from the LCA of Scenarios 0, 1, 2 and 3. A1-A5 represents the emissions from the production phase of the virgin materials, while A1'-A5' represents the emissions from the production phase of reused materials.

Climate change (tons CO_2 eq.)				
Phase	Scenario 0	Scenario 1	Scenario 2	Scenario 3
A1-A3/A1'-A3' (Production)	153	83.7	83.8	21.5
A4/A4' (Transportation)	116	114	113	111
A5/A5' (Assembly)	20.1	13.1	13	13

Table 11: The results from LCA of Scenarios 0, 1, 2, and 3 illustrated in 7, here presented in numbers.

5.1.1 CO_2 emissions from each phase

Figure 7 illustrates the total amount of tons CO_2 eq. emitted for each of the four scenarios. The emissions from each scenario are divided into CO_2 emissions from each phase for both virgin (A1-A5) and reused (A1'-A5') materials. Phase A1-A3 represents the emissions from the production of virgin materials, A1'-A3' represents emissions from the production of reused materials, A4 represents the emissions from transporting virgin materials, A4' represents emissions from transporting reused materials, A5 represents emissions from the assembly of virgin materials, and A5' represents emissions from the assembly of reused materials. The percentage reduction or increase of emission for each phase in Scenarios 0, 2, and 3, compared to the emissions from Scenario 1, can be found in Table 12. The negative percentages represent a reduction in CO_2 emissions compared to the emissions emitted in Scenario 1, while the positive percentages represent an increase in emitted emissions compared to Scenario 1.

Phase	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**
A1-A3/A1'-A3'	82.8 %	0	0.12 %	-74.3 %
A4/A4'	1.75 %	0	-0.88 %	-2.63 %
A5/A5'	53.4 %	0	-0.77 %	-0.77 %

Table 12: Percentage reduction or increase in tons CO_2 eq. for Scenarios 0, 2, and 3 compared to Scenario 1.

The production phase (A1-A3 and A1'-A3')

As illustrated in Figure 7, the most CO_2 emissions corresponds to Scenario 0. The only difference between Scenario 0 and 1 is the beams and columns, that are made of steel in Scenario 0 and of glulam in Scenario 1. The storages from both scenarios are made entirely of virgin materials. As seen in Table 11, the CO_2 emissions from phase A1-A3 are 153 tons CO_2 eq. for Scenario 0, and 83.7 tons CO_2 eq. for Scenario 1. The change in material from steel to glulam has impacted the amount of CO_2 emitted significantly, an increase of 69.3 tons CO_2 eq., which is an increase of more than 80%. It is interesting to notice the significant difference of material selection in total CO_2 emission, an important observation that can be considered and implemented in future projects.

As Figure 7 illustrates, the difference between scenarios 1 and 2 is not very significant. Table 11 shows that from phase A1-A3, Scenario 1 contributes to 83.7 tons CO_2 eq., while the contributions from A1'-A3' for Scenario 2 were 83.8 tons CO_2 eq. This fact can be explained by the additional need for extra processes to quality check or dismantle the products intended for reuse in Scenario 2. For instance, there was an additional need to transport 3 people by plane from Oslo to Trondheim to verify the quality of the glulam before it could be reused. The emissions related to this transportation can be seen in Table 10, which are added to A1'-A3' for Scenario 2. Also, since there are not that many reused materials in Scenario 2, the environmental benefit from Scenario 2 is insignificant.

However, there is a significant amount of reduced emissions between Scenarios 1 and 2 and Scenario 3. A1'-A3' for Scenario 3 accounts for 21.5 tons CO_2 eq., a significantly lower environmental impact compared to the three other scenarios. As shown in Table 6, there are significantly more reused materials and products used in the construction of the storage in Scenario 3 compared to the amount used in the construction in Scenario 2. It is, therefore, interesting to examine the amount of CO_2 emissions from each of these product categories to discuss what products make the biggest difference in emissions from A1-A3/A1'-A3'. The total amount of kg CO_2 eq. from phase A1-A3 for virgin materials used in Scenarios 2 and 3, and from phase A1'-A3' for reused materials used in Scenarios 2 and 3, are shown in Table 13 below.

	total kg CO2 eq.		
Material/product	**Scenario 2**	**Scenario 3**	**Difference**
Concrete	1654.03	1654.03	0
Insulation	546	10.87	535.13
Steel doors/gates	1832	0.51	1831.49
Gravel	0.002	0.002	0
Glulam beams/columns	3263.77	3554.74	-290.97
Structural timber	116.17	8.76	107.41
Roof membrane	12450	2847.69	9602.31
Asphalt	0.0028	0.0028	0
Steel roof plates	63938	13420	50518
Steel gutter system	0.102	0.102	0
Fire extinguishers	0	0	0
Ventilation grille	0	0	0
Lighting	0.06	0.06	0

Table 13: The total amount of kg CO_2 eq. from A1-A3 (for virgin materials) and A1'-A3' (for reused materials) for Scenarios 2 and 3.

The CO_2 emissions related to A1' processes such as manual sorting, and emissions from A3' (temporarily storing the reused materials), are negligible. Therefore, A2' is the main contributor to the CO_2 emitted in this phase. There are no CO_2 emissions from the production of the materials included in A1'-A3'; however, for the reused glulam, there was a need to transport 3 people by plane for quality check, before the glulam could be reused. Besides that, the A2' transportation was the main source of emissions from phase A1'-A3' for the reused materials. For the materials that were actually reused in Scenario 2, the transportation distances from the donor building to the temporary storage were known (and are shown in Table 9). However, for the assumed reused materials in Scenario 3, the transportation distance A2' for each material was unknown. Therefore, a transportation distance of 25 km was assumed.

As Table 13 shows, the biggest difference in CO_2 emissions for the two scenarios is for the steel roof plates. For Scenario 2, where 3 of 6 steel roof plates were reused, the CO_2 emissions were 63 938 kg CO_2 eq. For Scenario 3, where all of the 6 steel roof plates were reused, the CO_2 emissions were 13 420 kg CO_2 eq. Further, the second biggest difference in emissions was between the roof membranes used in the two scenarios. All of the roof membrane in Scenario 3 except one was reused, while no roof membrane was reused in Scenario 2. Therefore, we can observe that there are possibilities to save CO_2 emissions by reusing roof membranes. However, the possibility of reusing roof membranes needs to be thoroughly examined. Reusing roof membranes is not widespread because they might be hard to dismantle due to them often being glued to something else. The reuse of roof membranes is included in Scenario 3 because it does not seem impossible to reuse them, and therefore they are an optimistic, yet somewhat realistic, possibility.

Moreover, the difference in emissions from doors and gates used in the two scenarios is significant. In Scenario 2, 1 out of 4 steel doors were reused, and none of the two steel gates were reused. For Scenario 3, all 4 of the steel doors and both of the two steel gates were reused. As Table 13 shows, the emissions from reusing all the doors and gates are minimal, while the emissions from only reusing one door are quite big. Reusing doors would not require a lot of extra work and is a procedure that should be implemented more frequently in the future. Moreover, wrong doors are often ordered, and there are, therefore, opportunities to include wrongly ordered doors from other projects in new constructions. This implementation could have a pretty large impact on the overall emissions from the production phase.

The difference in emissions from glulam used in Scenario 2 and 3 is -290.97 kg CO_2 eq. This difference is negative because of the biogenic carbon stored in timber products, which is not released until the wood is burnt. However, since only phases A1-A5/A1'-A5' are included in this study, the amount of carbon released when burning the wood in the end-of-life phase (D) is not presented. If the glulam was not reused and followed a linear approach ending with the end-of-life phase D, the carbon stored in the wood would be released during this phase. Therefore, reusing wooden products will store the carbon for a longer period, and the wood is then utilized to its fullest before the end-of-life phase. For Scenario 2, only the glulam beams were reused, while the glulam columns were virgin products. For Scenario 3, all of the glulam beams and columns were reused, and the negative CO_2 emissions from phases A1-A3 when producing the glulam products, are not included for Scenario 3.

Transportation (A4 and A4')

As Table 11 shows, there is an increase in tons CO_2 eq. emitted in phase A4 for Scenario 0 compared to Scenario 1. This increase equals 1.75% and is the only increasing percentage among all of the scenarios for phase A4/A4'. Phase A4 for Scenario 1 contributes to 114 tons CO_2 eq., while phase A4' for Scenario 2 contributes to 113 tons CO_2 eq. The transportation of reused materials (A4') contributes to 111 tons CO_2 eq. for Scenario 3. The small difference in CO_2 emissions between the different scenarios is due to different transportation distances between virgin and reused materials. As can be seen in the table, the reduction of CO_2 emission from the transportation of the materials to the construction site is not reduced significantly from Scenarios 0 and 1 (with entirely virgin materials) to Scenarios 2 and 3. This can be due to the fact that all materials, either reused or virgin, must be transported either way. Further, the LCA tool ByggLCA does not include electric trucks as a transportation method. Therefore, all the transportations in the calculation are based on combustion engine trucks. This is not exactly the case for Scenarios 2 and 3 since some of the reused materials in those scenarios are transported by electric trucks. It is expected that electric trucks for transportation have a positive effect on CO_2 emission. Therefore, this effect has been further examined by a sensitivity analysis in Section 5.2.1.

Assembly (A5 and A5')
Scenario 0 has the biggest contribution of CO_2 emissions from A5/A5' compared to the other three scenarios. There is an increase in emissions from this phase compared to Scenario 1, equal to almost 55%. This increase is due to the increase in emissions related to the assembly of steel beams and columns. Also, Scenarios 2 and 3 have a reduction in CO_2 emissions from phase A5' compared to the emissions from phase A5 for Scenario 1. This reduction is equal to 0.77%. The reason the difference in emissions from A5/A5' is not more significant is that most of the reused materials need the same assembly as the equal virgin material.

5.1.2 Other environmental aspects

This thesis only explores the Global Warming Potential (GWP) for the four different scenarios. This means that the amount of CO_2 emissions for the different scenarios presented are evaluated. However, other environmental aspects could be interesting to discuss. As illustrated in Figure 7, the difference in the amount of CO_2 eq. emitted is not that significantly reduced for Scenario 2 compared to Scenario 1. However, it is important to keep in mind that reusing materials and products has other benefits. For instance, reusing materials and products will help avoid material scarcity. The Earth's virgin materials are limited, and it is important to avoid scarcity to maintain the sources of today [68]. There is already a scarcity of metals around the world, and for instance, changing the materials of the beams and columns from steel (Scenario 0) to glulam (Scenario 1) will help avoid more metal scarcity. Reusing already produced products, instead of extracting virgin material to produce new products, will help avoid material scarcity.

5.2 Sensitivity analysis

This section presents the findings from the sensitivity analysis performed. The two factors included in the sensitivity analysis are transportation methods and temporary storage space for the reused materials.

5.2.1 A4 - Transportation

As previously shown in Figure 7, the CO_2 emission from the transportation phase A4/A4' were almost the same for the four scenarios, due to the lack of relevant data for electrical vehicles in ByggLCA. Therefore, it is interesting to examine the difference in CO_2 emissions from transporting all materials (regardless of virgin or reused materials) between two different transportation methods, transportation with entirely combustion engine trucks and transportation with entirely electric trucks. This comparison is illustrated in Figure 8. For the electric truck, Asplan Viak's "Klimakost tool" provided the amount of CO_2 eq./ton-km for electric trucks based on the Norwegian electricity consumption mix. This number is 0.156 kg CO_2 eq./ton-km and has been used in the calculations for the electric trucks. The distances used in this calculation are the average transportation distance for each of the materials in the case of the storage in Granåsen. An overview of these transportation distances can be found in Table 14.

			kg CO2 eq.	
Material/ Product	**Transportation distance (km)**	**Weight (tons)**	**Combustion**	**Electric**
Concrete	50	20.75	172.4	161.85
Insulation	300	1.13	93.9	52.88
Steel doors/ gates	1720	0.72	238.2	193.19
Gravel	12	1330	110544	2490
Glulam beams/ columns	300	0.77	65.02	36.04
Structural timber	115	2.93	247.11	52.57
Roof membrane	1220	2.31	141.87	440.12
Asphalt	50	0.0001	0.001	0.001
Steel roof plates	300	25.89	2151.3	1211.65
Steel gutter system	30	0.15	12.06	0.68
Fire extinguisher	30	0.002	0.17	0.01
Ventilation grille	800	0.02	5.16	2.5
Lighting	300	0.003	0.25	0.14
Sum			**113671.82**	**4641.4**

Table 14: Overview of the transportation distances, weight, and kg CO_2 eq. for combustion and electric trucks for each material

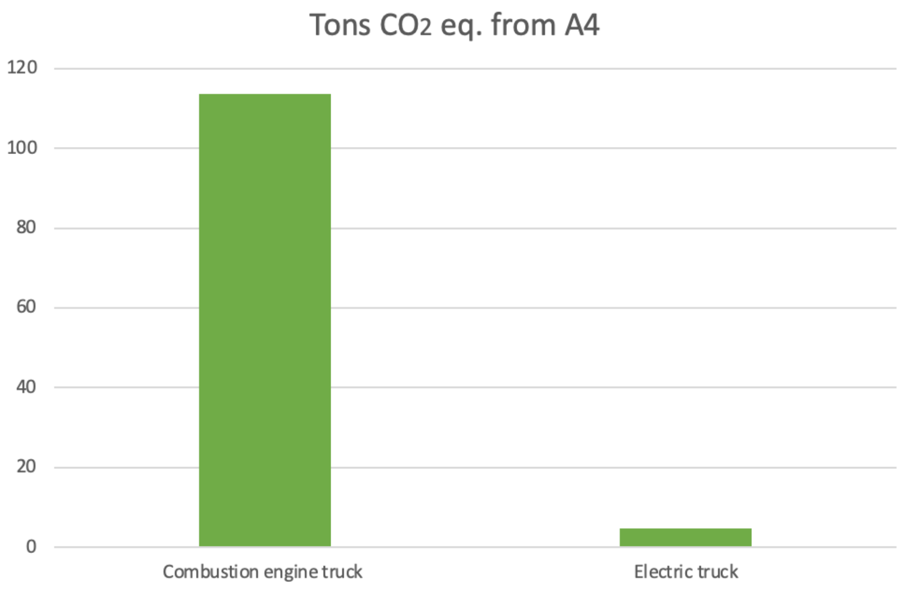

Figure 8: Total emission in kg CO_2 eq. for phase A4 for the materials used, transported with a combustion engine truck and an electric truck.

As Figure 8 illustrates, transporting all the materials with combustion engine trucks instead of electric trucks had a significant impact on the number of tons CO_2 eq. emitted from the phase A4. The combustion engine trucks emitted more than 113 tons CO_2 eq. with the assumption of the actual transportation distance. The electric trucks emitted around 4.6 tons CO_2 eq. transporting the same materials at the same distance. Therefore, choosing electric trucks instead of combustion engine trucks has a significant impact on the CO_2 emissions from phase A4.

Moreover, Table 14 shows the effect of weight of material transported matters on the amount of CO_2 emissions emitted. Gravel, with the highest weight of all the materials, contributed to 110 544 kg CO_2 eq. when transported with a combustion engine truck, and 2 490 kg CO_2 eq. when transported with an electric truck. The transportation distance for gravel was the shortest, equal to 12 km. However, the weight of the transported material had a significant impact on the total CO_2 emissions from A4. Further, steel roof plates had a significant contribution to CO_2 emitted. The steel roof plates had the second highest weight of all the materials, transported for 300 km, and contributed to 2 151.3 kg CO_2 eq. when transported with a combustion engine truck. When transported with an electric truck, the steel roof plates contributed to 1 211.65 kg CO_2 eq.

Weight and transport distance should be mapped and the use of electric trucks should be evaluated due to availability and their practical matters. This study shows that CO_2 emissions can be significantly reduced when electric trucks are used.

5.2.2 Storage space for storing reused materials

As mentioned in Table 7, the reused materials and products were stored for a short amount of time (0-6 months) in cold storage. Section 4.3 elaborates that the CO_2 emissions related to the use of cold storage are very small, and they are therefore cut off from later LCA calculations. Since none of the reused materials or products contain water, there is no need for heated storage. Products like lavatories and other sanitary products need to be stored in heated storage to prevent the water from expanding and further shattering the products. Since there are no products containing water in the case study implemented in this thesis, the materials and products could be temporarily stored in cold storage.

However, it would be interesting to evaluate the impact of using a heated storage for all reused materials. A mapping of this impact would be interesting for possible future reuse projects where some or all of the materials or products reused need to be stored in a heated storage. The emissions related to operating a heated storage are very small. These storages are normally huge, and the energy demand is allocated to all materials and products stored in the storage. Therefore, the amount of emissions allocated to each material or product stored is very small and can be excluded from the results.

5.3 Recommendations to practitioners

Since this thesis is practice-oriented, the following section includes suggestions and recommendations for practitioners. As seen from the results of this thesis, it is important to consider materials with lower CO_2 impact. Therefore, it is important to start making these changes already in the early phases of the project. Designing a construction based on materials with lower environmental impact could make a significant difference in CO_2 eq. emitted.

Further, the environmental impact of the project should be a theme in the early phases. It is important to consider the availability of reused materials and products and involve the relevant actors to map the available choices. All actors involved in the project should have the same motivation to use reused materials and products. All actors being on the same page and having the same ambitions for the projects could make it easier to carry out the ambitious plan.

The use of electric trucks as transportation should be evaluated based on the weight of the materials/products and transport distances.

It is important to evaluate the project both as it progresses and in the end. By sharing obstacles, challenges, practiced solutions, and learnings from the project within your organization, and possibly with others, the valuable experience from the project will be passed on. Reuse is a growing opportunity in the buildings and construction sector. Learning from previous projects and using previous experience are necessities for success.

6 Conclusion

To realize and establish a circular economy in the Norwegian buildings and construction sector, it is important to map the possibilities and effects of the reuse of building materials. This thesis focuses on a real case study; the storage built in Granåsen Sports Park in the fall of 2023 for Trondheim Municipality and in collaboration with Asplan Viak. This work explores the environmental impact (Climate Change (GWP)) in kg CO_2 eq. of reused materials and products in the construction of the storage in Granåsen, using Life Cycle Assessment (LCA).

Four scenarios were studied to examine the differences in CO_2 emissions for reused materials. Scenario 0 represented the storage built with beams and columns made of steel. Scenario 1 represented the storage built with beams and columns made of glulam. All materials used in Scenarios 0 and 1 were virgin materials. Scenario 2 represented the storage as it was built with some reused and some virgin materials. Scenario 3 represented the storage built primarily from reused materials, with a few exceptions.

The storage consists of two separate buildings and the construction has a relatively simple design. The materials used in the construction of the storage were concrete, insulation, gravel, asphalt, glulam beams/columns, steel doors/gates, structural timber, roof membranes, steel roof plates, steel gutter system, fire extinguisher, ventilation grilles, and lighting.

One of the main findings from this thesis is that the type of material can have a significant impact on the CO_2 emissions. The choice of material, in this study a choice between beams and columns made of glulam instead of steel, contributed to almost 83% reduction of CO_2 eq. in the production phase A1-A3. Therefore, implementing this knowledge already in the design phase of new constructions can be significant.

Using a majority of reused materials (Scenario 3) resulted in a reduction in CO_2 eq. of almost 75% for phase A1'-A3' compared to the same construction with only virgin materials (Scenario 1). Steel roof plates, roof membranes, and steel doors/gates were shown to be the main sources of reduction in CO_2 emissions when reused products were considered. Therefore, implementing reused materials in new construction can significantly impact the CO_2 emissions from A1-A3/A1'-A3'. To achieve reuse of materials/products, it is important to map out possible reused components and consider their availability in the design phase of the project.

CO_2 emissions from transportation to the construction site (A4) using combustion engine trucks for all materials were more than 25 times more than CO_2 emissions, using electric trucks for all materials. The sensitivity analysis showed the CO_2 emissions from transporting all materials, virgin and/or reused, by using the actual transportation distances for the case study in Granåsen. If combustion engine trucks had been exclusively used, the emissions from A4 would have been 113.7 tons CO_2 eq. In the case of electric trucks, the emissions from A4 would have been 4.6 tons CO_2 eq.

6.1 Future work

Future work on the possibilities of reusing building components is a necessity to successfully achieve a circular economy within the Norwegian buildings and construction sector. Since the reuse of building components is still under development, more projects exploring the reuse of materials and products are necessary for developing solutions to barriers and obstacles. The experiences gained from these projects are recommended to be shared to experience progress.

Moreover, developing a common marketplace to improve the accessibility of reused products will make it easier to choose reused products. Inspection and quality of the reused products vary depending on the product, and they need to be further developed for each product category. Routines regarding quality-checking the materials, information on required testing facilities, and expertise for inspection should be shared openly to minimize the risk of reuse. There is a lack of reliable CO_2 emissions data for the production phase of reused materials/products (A1'-A3'). Research work providing such values is recommended.

Requirements and regulations encouraging or demanding the reuse of materials/products in the buildings and construction sector will motivate the actors and contribute to the development of circular business models for reuse.

Even though there is future work that needs to be done to increase the use of reused products in the Norwegian buildings and construction sector, it is possible to solve the current obstacles. The winnings and achievements from solving today's problems would be significant and should be a motivation for future work.

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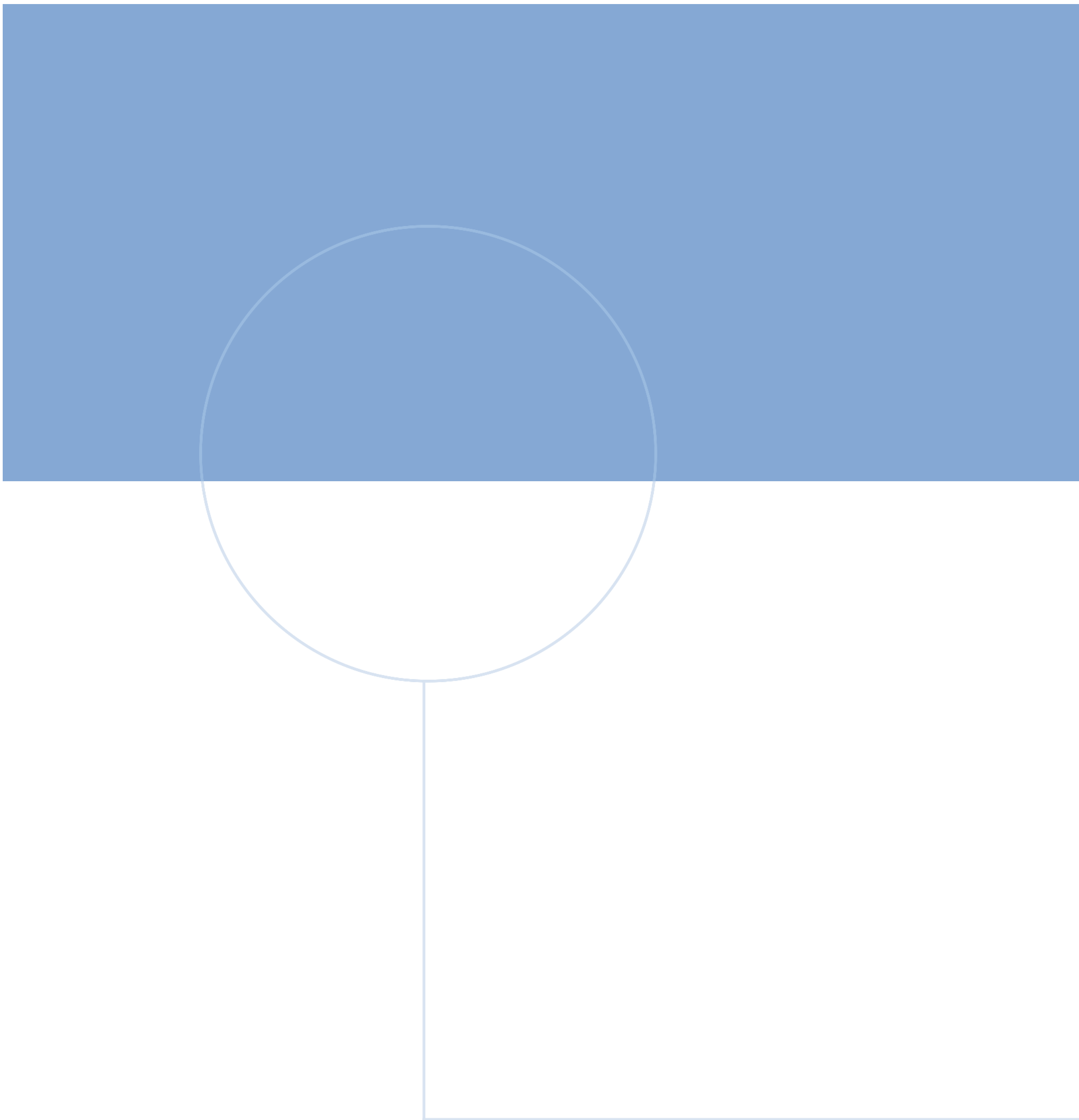
7 Appendix

7.1 Overview of all building components used in the building of the storage

Table 15 below shows an overview of all materials used in the construction of the storage built in Granåsen. The table divides the building components based on Tables 2, 3, and 4 in NS3451. The different categories can be found in Table 4.

Main building section	**Building component**	**Material/product**	**Total volume (m^3)**	**Total weight (ton)**
21 Ground and foundations	216	Concrete B30	8.6423	
	216	Rockwool insulation	8.428	
	216	Gravel		0.00014
22 Load-bearing structures	222	Glulam columns	3	0.4
		Glulam beams	7.7	12
23 Exterior walls	231	Steel door		2.4
	231	Steel gate		0.4
	231	Structural timber	3.09	
	231	Membrane		0.08
	232	Lightweight aggregate	1.07E-07	
25 Floor slabs	252	Asphalt		7.23E-05
	252	Gravel		1330
26 Exterior roof	261	Structural timber	3.24	
	261	Steel roof plate		24.44
	261	Membrane		2.23
	262	Steel roof plate		1.45
	265	Steel gutter system		0.1456
33 Fire extinguishing	337	Hand fire extinguisher		0.018
	362	Ventilation grille		0.004
44 Light	443	Emergency lights (LED)		0.003

Table 15: An overview of all the materials needed in the construction of the storage in Granåsen



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