Helene Jortveit Lauvland

# The Carbon Footprint of Furniture

Master's thesis in Energy and Environmental engineering
Supervisor: Johan Berg Pettersen
January 2021

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Norwegian University of Science and Technology
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# Summary


The building industry is considered as a key element for mitigating global carbon emissions. Furniture products are an important part of buildings, but are rarely included in environmental analysis of buildings, or mentioned in carbon mitigation strategies for the building sector. To investigate how much furniture contributes to emissions of buildings, the carbon footprint of furniture is found for six non-residential buildings. The case projects include two upper secondary schools, two university buildings and two office buildings. The results showed that furniture contributed to 4-13% of the total carbon emissions of the building considering a 15 year lifetime of furniture and 60 year lifetime of the building. This is a significant share and should therefore be accounted for as part of building emissions.

To reduce the carbon footprint of furniture, different mitigation through strategies was defined. These included increased reuse and refurbishment, prolonged usage time with maintenance, and material choice. Increasing the amount of reused furniture, as well as ensuring a long usage time for furniture products were found to be two effective measures. By only using reuse, the carbon footprint of the furniture inventory was reduced with an average of 59% compared to having only new products in the furniture inventory. Prolonging the usage time of the furniture products to 30 years, with additional necessary maintenance processes, reduces the carbon emissions from the furniture inventory by 46% on average. Additional mitigation strategies found were to ensure more furniture of low environmental impact by right material choices, as well as increased use of refurbishment and longer lifetimes.

Through literature search and conversations with managers and handlers of furniture, it is repeatedly confirmed that there is a lack of information available on the carbon footprint of furniture. Today's practices do not support the effective mitigation strategies of long usage times, reuse, and maintenance and refurbishment processes. There are no policies and few environmental analysis of furniture which reduces the incentive to reduce emission from furniture. The carbon emissions of furniture must be further communicated and mitigation strategies must be promoted to meet this challenge.

# Sammendrag

Bygningsindustrien regnes som et viktig satsingsområde for å reduse globale klimagassutslipp. Møbler er en viktig del av bygninger, men er likevel ikke inkludert i miljøanalyser av bygg eller i strategier for å redusere utslipp i bygningssektoren. For å undersøke hvor stor del av utslipp fra bygninger møbler står for, er karbonavtrykket av møbler i seks ulike bygg funnet. Dette inkluderer to videregående skoler, to universitetsbygg og to kontorbygg. Resultatene viste at møbler bidrar med 4-13% av totale klimagassutslipp fra bygg. Det er da beregnet for møbler med en levetid på 15 år og 60 års levetid for bygg. Dette er betydelige utslipp, og de bør derfor inkluderes i beregninger for klimagassutslipp fra bygg.

For å redusere karbonavtrykket fra møbler er det lagt til rette for ulike strategier. Strategiene inkluderer økt gjenbruk og oppussing av møbler, lang brukstid med vedlikehold, og materialvalg. Resultatene viser at økt gjenbruk og forlenget levetid er to svært effektive strategier. Å møblere med kun gjenbrukte møbler gav en reduksjon på gjennomsnittlig 59% sammenlignet med å kjøpe alle møblene nye. Å forlenge brukstiden med 30 år med vedlikehold underveis reduserte utslippene med gjennomsnittlig 46%. Videre bør møbler med lav miljøpåvirkning implementeres sammen med mer oppussing av møbler og lengre brukstider.

Litteratursøk og samtaler med aktører i møbelbransjen bekrefter at det finnes lite informasjon om miljøpåvirkningen til møbler. Det er ingen retningslinjer bransjen må forholde seg til, i tillegg til at det er få miljøanalyser av møbler tilgjengelig. Dagens systemer støtter ikke strategier som lang brukstid, gjenbruk, vedlikehold og oppussing. Dette begrenser insentiver for å redusere utslipp fra møbler. Klimagassutslipp fra møbler må bli kommunisert og effektive stratefier må bli promotert for å møte denne utfordringen.

# Preface

This master thesis is written for the Faculty of Engineering at NTNU department of Energy and process engineering, and concludes my M.Sc in Energy and Environmental engineering with specialization in Industrial Ecology. The thesis is the continued work of former project thesis from the spring semester of 2020.

I want to thank everyone who contributed with the case project and conversations on the furniture industry and furniture management in Norway. A big thank you to my supervisor Johan Berg Pettersen and co-supervisor Christofer Skaar for continued advise and motivation.

Trondheim 22.01.2021

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# Abbreviations

| | | |
|---|---|---|
| $A$ | = | building area |
| $b$ | = | building carbon intensity |
| $\mathbf{c}$ | = | carbon intensity vector per furniture product |
| CF | = | Carbon Footprint |
| $CO_2eq$ | = | $CO_2$-equivalents |
| CPSC | = | Consumer Product Safety commission |
| DIFI | = | Norwegian Digitalisation Agency |
| $e$ | = | exchange rate |
| $E$ | = | energy |
| EMC | = | Eco Materials Collect |
| EPA | = | Environmental Protection Agency |
| EPD | = | Environmental Product Declaration |
| EU | = | European Union |
| $\mathbf{F}$ | = | furniture intensity matrix |
| GHG | = | Greenhouse gases |
| GWP | = | Global Warming Potential |
| $h$ | = | emissions from Norwegian energy production |
| HVL | = | Western Norway University of Applied Science |
| IPCC | = | International Panel on Climate Change |
| $l$ | = | lifetime |
| LCA | = | Life Cycle Assessment |
| $\mathbf{M}$ | = | maintenance and refurbishment matrix |
| NS | = | Norwegian Standard |
| NTNU | = | Norwegian University of Science and Technology |
| $o$ | = | occupancy |
| PCR | = | Product Category Rules |
| $\mathbf{R}$ | = | reuse intensity matrix |
| $\mathbf{s}$ | = | carbon intensity vector per room |
| SMEs | = | Small and medium-sized enterprises |
| SSB | = | Statistics Norway (National statistics office) |
| $t$ | = | transport carbon intensity |
| TFK | = | Trøndelag Fylkeskommune |
| UiT | = | University of Tromsø |
| $v$ | = | driven distance for reused furniture products |
| $x$ | = | share of furniture product reused or repaired |
| $z$ | = | ZEB factor for emission intensity for electricity |
| ZEB | = | Zero Emission Building |

Chapter 1

# Introduction

## 1.1 Background and motivation

Furniture is a necessity to support daily human activities and to make a building functional. This requires great volumes of products, and in the EU alone 10.5 million tonnes of furniture is consumed every year. Furniture is an assembly industry of several different materials which leads to a complex value chain of many processes. With such large volumes of consumption and a complex value chain, large environmental impacts to furniture follow. Despite this, there is little information on the environmental impact of furniture (Forrest et al., 2017).

The EU has set goals of 40% reduction in emissions by 2030 compared to 1990 levels. The building industry is the largest single energy consumer in Europe, and both EU and IPCC recognize reducing emissions associated with buildings as a key measure to achieve the 2030 goal (Esser et al., 2019; Ürge-Vorsatz et al., 2014). Subsequently, Europe has set many requirements for buildings that demands low emissions from new and renovated buildings. However, in certifications and investigations of the environmental impact of these buildings, the furniture inside of the buildings is rarely included (Hoxha and Jusselme, 2017). Additionally, furniture is not included in carbon emission mitigation strategies from buildings by the IPCC (Ürge-Vorsatz et al., 2014) Knowledge around furniture's contribution to building emissions and following climate change is necessary, as furniture is an important part of buildings and their functionality. Furniture consumption among offices and households across Europe is of great dimensions. Furniture is getting cheaper and ever more accessible, and thereby becomes easier to exchange. Furniture has become fashionable articles with frequently declining life cycles (Kharazipour and Kües, 2014). Quality of furniture products decreases with decreased cost of furniture, and leads to shorter usage time and increased consumption (Fremtiden i våre hender, 2011). Increased consumption leads to increased production and emissions, and calls for a bigger need to properly map the carbon emissions and raise awareness of the following impacts of furniture. Finding the carbon impact of furniture is not a trivial task. Furniture products come in great varieties, are consumed in large volumes and there are limited data and literature available. The whole value chain must be assessed, and using life cycle thinking and integrated assessment is essential (Mirabella et al., 2014).

Only a couple of published studies includes furniture in the environmental analysis of a building. Hoxha and Jusselme (2017) included furniture and electronic appliances in an LCA of a Swiss building and found furniture was responsible for 10% overall environmental impacts of this building. McCoubrie et al. (1999) found in their analysis that furniture represented 31% of the total embodied energy delivered throughout the building's lifetime. Energy is an indicator of environmental impact (Askham et al., 2012), and following this contribution is substantial. It is clear from these assessments that the environmental impacts from furniture in buildings are significant, and emissions from these products should be given focus. Mitigation strategies to reduce emissions must be targeted. To detect the environmental impact of furniture, and locate mitigation strategies, environmental assessments must be undertaken. Inclusion of furniture in environmental assessment is a comprehensive task which demands a comprehensive amount of information, and several studies address the need for better access to environmental information on furniture (Antov and Vasileva Pancheva, 2017; Forrest et al., 2017; Hoxha and Jusselme, 2017; Linkosalmi et al., 2016). There is an excessive amount of different furniture products which all have different combinations of materials and product stages. The lack of knowledge on the subject, and the necessity of targeting areas for potential climate mitigation, is what motivated this project.

A project undertaken as part of the preparation for this thesis, calculated the carbon footprint of furniture in an office area of Norwegian University of Science and Technology (NTNU) together with the carbon contribution of the building. It was found that furniture was responsible for 16% of the $CO_2$-emissions in this building area in a 60-year perspective. In this assessment half of the furniture inventory was reused, furniture was set to have a lifetime of 15 years, and the furniture inventory was exchanged three times. In a scenario where all furniture was bought new, the total carbon impact from furniture would have been 20%. It was found that the most effective measures for reducing the carbon footprint of furniture in this area were to implement more reuse and prolong the usage time of the furniture products. Another effective approach was to target low-impact furniture for furnishing the office area. It was found that more information is needed on reuse, maintenance, repairs, and remanufacturing for further assessments (Lauvland, 2020).

Furniture is in this thesis referred to as movable items in a building which supports human activities as sitting, lying, eating, working or storage. It can be made of a variety of materials and designs (Postell, 2012). Furniture is both a tool and environment. It helps the user achieve a goal, whether it is entertainment, relaxation, education or work (Cornell, 2002). Carbon is in this project referred to as the emission intensity of greenhouse gases (GHG) in $CO_2$eq aggregated using global warming potential over 100 years (GWP100) (Krey et al., 2014). Any mention of emission refers to emissions of $CO_2$eq.

## 1.2 Objective and research questions

There is a need to further investigate the environmental impact of furniture and how this can be used in climate change mitigation. IPCC has declared buildings as a key for mitigation strategies. As furniture has a crucial role in buildings it is wanted to investigate the carbon footprint of furniture in a building perspective. The objective is defined as follows:

*What is the carbon footprint of furniture in non-residential buildings and what mitigation strategies could reduce the footprint?*

To provide answers to the objective the following research questions are asked:

1. What is the carbon footprint of furniture in selected non-residential buildings?
2. Which strategies are most effective to reduce the carbon footprint of furniture?
3. What are the biggest challenges to implementation of environmental analysis of furniture and mitigation strategies to furniture?

To answer the research questions, case studies of different non-residential buildings will be undertaken. Investigating several cases will give a better foundation to answer the question asked, and allows for comparison. The non-residential case projects investigated in this thesis are two upper secondary schools, two university buildings, and two offices at different locations in Norway. To gain perspective and knowledge on furniture, relevant theory will be laid out together with a literature study undertaken on the subject. Research question 1 will then be answered by detecting the furniture inventory of each case project and finding the carbon footprint of each furniture product. The total carbon footprint of furniture will be calculated and compared with the carbon footprint of the building to find the significance of furniture in the buildings. To answer research question 2, different mitigation strategies will be tested on the case projects to observe how it affects the carbon footprint of furniture. The mitigation strategies investigated will be increased reuse, prolonged usage time, increased refurbishment, and differences in material and design choice of furniture. Results from research questions 1 and 2 will be used together with findings from literature study and conversations with actors of the furniture industry and furniture managers to answer research question 3. A comparison of the case studies and a discussion of the findings will then follow to unravel the carbon footprint of furniture and what mitigation strategies should be chosen to ensure lower emissions from furniture and what challenges must be overcome to do so.

Chapter 2

# Theory

Furniture is an assembly industry which combines different raw materials into new products. Following it has a complex value chain and many processes. To unravel the complexity of furniture products, findings from literature review and relevant theory are presented in this chapter to give a perspective on furniture and environmental considerations.

## 2.1 Furniture and the value chain

The value chain of furniture has many stages, as seen in Figure 2.1. The first stage of raw material extraction and processing consists of processing materials like wood, oil for plastic, metals, bio-based materials, and minerals. After extraction, these materials are sent to further production of material pieces to be used in furniture. The pieces of different materials are then assembled before being packaged and stored. The finished products are then distributed to suppliers. In the use phase there might be processes of maintenance and repair before it reaches the end-of-life stage. In the last stage, the furniture is landfilled, incinerated, recycled, or reused (Cordella and Hidalgo, 2016). The most used materials in furniture are wood, plastic, and metals (Parikka-Alhola, 2008). Additionally, textiles are an important part of many furniture products. Thereby, the environmental scope is wide and has many sources of raw materials with different environmental consequences. As seen in Figure 2.1, the materials of furniture are extracted from different sources, which contributes to the complexity of furniture and further environmental analysis.

The furniture industry employs 1 million workers in Europe, mostly in small and medium-sized enterprises (SMEs), and is a net exporter and manufactures 28% of the furniture sold worldwide. 10.5 million tonnes of furniture is consumed every year, and this number is continually increasing. At the same time, 10 million tonnes of furniture is discarded every year, where most of it ends up in landfill or incineration. Some improvements have been made in the last years in Europe, with less ending up in landfills. This is a result of new and improved policies in the EU. However, fewer improvements are made for the

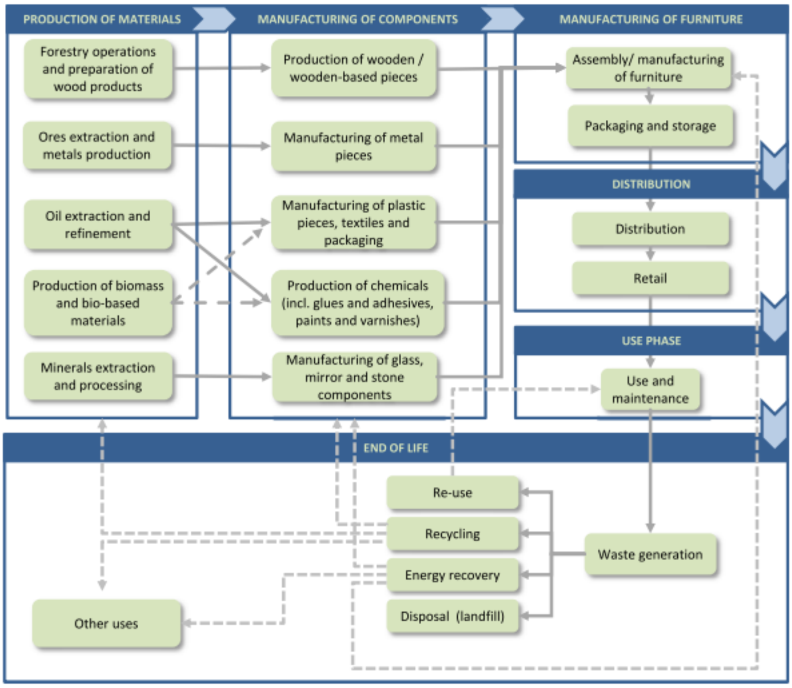


**Figure 2.1:** Value chain of furniture (Cordella and Hidalgo, 2016)

processes higher up in the waste hierarchy, as for reuse, remanufacturing, and recycling, which are the most beneficial towards reaching a circular economy. The waste hierarchy is described as, from the most preferable option to the least preferable option: avoid waste, reuse, remanufacturing, recycling of parts, material recycling, energy recycling, and landfilling. In the EU, only 2% of the furniture is remanufactured, and reuse is still mostly at a small scale with social goals, as charity and second-hand shops (Forrest et al., 2017).

In Europe, the building industry has been given strict requirements to reduce their GHG emissions over the next years. Furniture is not considered part of this, and the furniture industry is facing requirements from consumers, rather than national policies and regulations. Consumers are demanding environmentally friendly products, and manufacturers are trying to meet these demands (Zutshi et al., 2016). As the climate challenge is getting more and more attention, the pressure is increased on the companies in the furniture industry to provide their products with environmental information. For smaller businesses, it can be challenging to provide such information, but initiatives like Environmental Product Declaration (EPDs) could make this easier (Fet et al., 2009). The industry has a huge potential in becoming circular, and it is estimated that this would create 160 000 jobs and avoid 3.3-5.7 megatonnes of $CO_2$ emissions (Forrest et al., 2017). There is an increase in products being developed that are considering environmental burdens and gradually moving towards sustainability to mitigate climate change (Zhao et al., 2012). However, the industry is facing many challenges, both economic, regulatory, and environmental. To ensure competitiveness in a market with an increasing demand for environmentally friendly products, it is necessary to provide declarations and also avoid greenwashing (Babarenda Gamage et al., 2008).

Literature review has shown that the literature is split between buildings and furniture, and few studies include both. Information on environmental analysis of buildings is widespread, but they never include furniture. Hoxha and Jusselme (2017) found that furniture had a 10% contribution to the environmental impact of a building. This assessment also included electrical equipment, so if electrical equipment was excluded, the share of furniture contribution would be even higher. It is clear that actions need to be taken on the subject.

Furniture is a functional item often bought for the purpose of replacement. However, office furniture is often not only replaced because of functionality, but because of aesthetic and corporate branding purposes. Clients of furniture in offices may not want to enter into long-term agreements on office furniture because furniture might become obsolete in the future (Besch, 2005). This leads to furniture products in offices being replaced before reached lifetime (Parker et al., 2015). In the procurement of office furniture, there is often a contract and demands from the buyer to the distributor or supplier. Following, purchasers of office furniture have a big influence on sustainability in the furniture industry as they can set demands on environmental performance on the product (Parker et al., 2015).

## 2.2 Environmental improvement areas of furniture

As furniture has a vast and complex value chain it can be challenging to locate areas of improvement (Cordella and Hidalgo, 2016). Several environmental assessments of furniture have been analyzed to locate the most typical environmental ”hotspots” of furniture. Hotspots represent areas in the life cycle of a product with high emissions. To locate these areas, environmental assessments like LCAs are important tools and should be a part of the decision-making processes to achieve more environmentally friendly products (Hartini et al., 2019).

In Figure 2.2 LCA results of furniture products found in literature study are presented. The findings are mostly cradle-to-gate i.e. the emissions from raw material extraction to supply. There is one exception from Spitzley et al. (2006), where the results are cradle-to-grave.

It is found that furniture products have life cycle emissions in the range 6-220 kg $CO_2$eq, where most are between 10-80 kg $CO_2$eq. The highest emissions in the figure are from cradle-to-grave results, which describes the big difference between some of the products. The emissions might not seem substantial in themselves, but large volumes of these lead to greater emissions. Detailed investigation of these results could target which stages or materials of furniture have the highest contribution to carbon emissions.

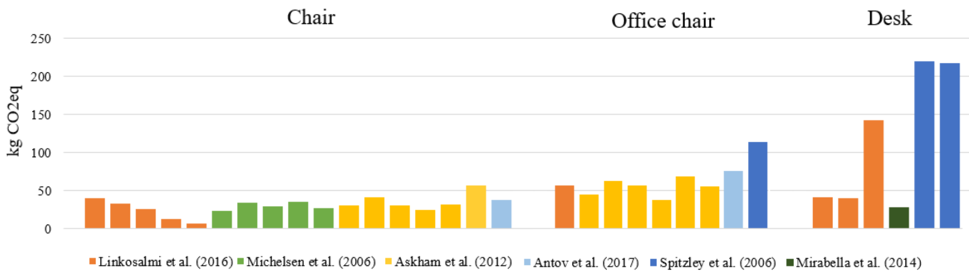


**Figure 2.2:** Cradle-to-gate LCA results from literature in kg $CO_2$eq per product. Spitzley et al. (2006) are cradle-to-grave.

The impact category assessed in this thesis is climate change and emissions in $CO_2$eq. In this chapter, other impact categories are included as well to gain perspective on the total environmental impact of furniture. The general finding from the investigated studies is that climate change is the most affected impact categories, but that different materials and finishing processes affect other impact categories where furniture production could be improved. Human toxicity and metal depletion are two other categories that are affected by furniture production due to the use of chemicals and metals (Hartini et al., 2019). Literature has provided many different answers to what areas should reduce impact. Findings from the most important materials and processes of furniture have been addressed below to cover the most important improvement potentials.

### 2.2.1 Life cycle stages

**Production and manufacturing**

A study of 82 LCAs found that the cradle-to-gate impacts are the largest, i.e. the supply of materials and manufacturing, with the supply of materials being the largest of the two (Cordella and Hidalgo, 2016). This is confirmed by the Norwegian Digitalisation Agency (DIFI) which found raw material extraction and further production to have 80-90% of the total environmental burden of a furniture product (Digitaliseringsdirektoratet, 2020). Several studies support that the supply of raw material has a significant effect on climate change (Babarenda Gamage et al., 2008; Cordella and Hidalgo, 2016; Iritani et al., 2015; Linkosalmi et al., 2016). All furniture assessed in this study are mostly produced on fossil-based energy, and a decrease in this energy and an increase in renewable energy could decrease impacts of the furniture (Askham et al., 2012). However, the impact varies from material to material, and within the different processes in the production and manufacturing stages. Some of these will be further explained in the sections below.

**Finishing processes**

A recurring hotspot in the life cycle of furniture is the finishing processes, which mainly consist of paint and thinner for coating. Coating and painting of furniture have been identified as processes which should reduce their emissions (Cordella and Hidalgo, 2016; Hartini et al., 2019; Iritani et al., 2015; Linkosalmi et al., 2016; Mirabella et al., 2014). There are many toxic emissions as well as high energy demand for this process and it thereby affects several impact categories. The toxic elements in glue and paint affect mainly impact categories like acidification. Glue and paint can be replaced with water-based options to ensure a more environmentally friendly product (Höglmeier et al., 2015). The high energy use of these processes is a contribution to climate change (Askham et al., 2012).

**Use phase**

Most studies found does a cradle-to-gate assessment when investigating the environmental contribution of furniture (Askham et al., 2012; González-García et al., 2011, 2012; Hartini et al., 2019; Iritani et al., 2015; Linkosalmi et al., 2016; Mirabella et al., 2014), and subsequently miss any emissions from use phase. There might be several reasons for this. Among them, that the emissions from the use phase and end-of-life is dependent on consumer behaviour and local waste management, and thereby emissions from these phases could be difficult to locate (Cordella and Hidalgo, 2016). Several studies leave out emissions from the use phase. This can be justified with the assumption that furniture products require no electricity nor water to function, and if a lifetime is set to e.g. ten years there is an assumption that no repairs are done (Babarenda Gamage et al., 2008). Other studies simply assume that there are no emissions in the use phase with no further explanation (Babarenda Gamage et al., 2008; Hoxha and Jusselme, 2017; Michelsen et al., 2006). The only inclusion found of use phase emissions is found in selected EPDs (The Norwegian EPD Foundation, 2020). It is suggested in the Product Category Rules (PCR) that emissions in the use phase should be included. This is said to be emissions from maintenance, repair, replacement or other relevant modules. It does not say in more detail how these emissions might be found (The Norwegian EPD Foundation, 2018). The need for maintenance of furniture can vary, and some might not need maintenance at all (Linkosalmi et al., 2016). How many actual perform maintenance on their furniture products might also be few. There is a need for more information on how the user of furniture can further reduce the environmental impact of the furniture product through information on maintenance, service, reuse, recycling, guidance on disassembly and waste handling (Fet et al., 2009; Forrest et al., 2017). A survey done in 2013 by Forbrukerrådet (the Norwegian Consumer Council) found that around one third got no information on precautions, use or maintenance when buying furniture products. Around 40% does not look up information on maintenance by own initiative on furniture bought (Forbrukerrådet, 2013). As there is little information and initiative in maintenance and repair of furniture, emissions from this phase might get missed, but there might be more of this in the future with an increased focus on long-lasting products, repairs and maintenance.

**End-of-life**

10 million tonnes of office furniture is discarded in the EU every year (Forrest et al., 2017). Several LCAs only assess cradle-to-gate and miss information on what happens after use. Often this approach is taken because of little information about the end-of-life process, or to simplify the assessment. Impacts from end-of-life depend on local waste management and could have large varieties (Cordella and Hidalgo, 2016). After use, fur-

niture could be landfilled, incinerated, recycled, remanufactured or reused. According to the waste hierarchy, the most desired method is reuse (Environment Protection Authority, 2017). The amount of furniture that goes to reuse is low, and often small-scale through commercial second-hand shops, social enterprise companies or charities. The demand for cheap furniture makes producers produce furniture of low-quality materials, like plastics, chipboard and medium-density fibreboard (MDF). This decreases the potential for reuse and often the products are not designed for disassembly, which also complicates reuse and refurbishment activities (Forrest et al., 2017). The best option for low impact after reuse is recycling. As furniture consists of different types of materials, furniture must be disassembled to be recycled or remanufactured. Today, only 10% of furniture is material recycled in Europe (Parker et al., 2015). And a high amount of recycled content in the furniture product leads to less environmental impact (Babarenda Gamage et al., 2008). Wood waste is found to be more sustainable than other material waste as it minimizes potential impacts because it contains less harmful substances which can potentially be emitted in the end-of-life phase (Iritani et al., 2015). Besides, it is biodegradable. In general, without looking at specific material, all discarded furniture is regarded as 50% biodegradable (Alexander and Smaje, 2008). Following, there are many furniture products which are made from materials that must be properly handled at end-of-life.

**Lifetime of furniture**

One of the most important actions to reduce the environmental impact from furniture for a user could be to choose long-lasting furniture (Digitaliseringsdirektoratet, 2020; Forrest et al., 2017; Lauvland, 2020). It can be challenging to estimate a correct lifetime of furniture, and the found results of the lifetime for furniture in literature search are presented in Table 2.1.

There are great variations in lifetimes of furniture products from different institutions. Some studies have accounted for how long a furniture product actually can last and some have accounted for a typical lifetime, which does not consider how long a furniture product is applicable (Gutowski et al., 2011). The results will also vary between different furniture products. Parker et al. (2015) explains that chairs tend to have a shorter lifetime than e.g. a desk. The lifetime of wood could be shorter than for other materials if not properly treated. Hence, the material choice should be thoroughly adapted to the intended use of the furniture product. Prolonged product lifetime could be strategic design characteristics (Cordella and Hidalgo, 2016). Another obstacle to this is how furniture must be adapted to follow the time that we live in. The learning environment is rapidly changing. User-centred design is becoming more popular, and there is a focus on functional need, flexibility, mobility and wire management (Cornell, 2002). The need for furniture to adapt to these changes might lead to reduced usage time of already bought products.

| Study or institution | Lifetime [years] | Explanation |
|---|---|---|
| ATD Home Inspection (2020) | 10-100 | Life expectancy of different household furniture |
| Besch (2005) | 12 | Customer analysis on office furniture |
| CPSC (2008) | 15-17 | Sales data on household furniture |
| EPA (2014) | 10-20 | Literature search |
| The Norwegian EPD Foundation (2018) | 15 | Typical service lifetimes |
| Hoxha and Jusselme (2017) | 10-40 | Literature search |
| Parikka-Alhola (2008) | 5-10 | Literature search |
| Parker et al. (2015) | 5-15 | Own estimates |
| Skullerud (2000) | 10-20 | Analysis of furniture containing plastic parts |
| Tudor et al. (2017) | 15 | Literature search |

**Table 2.1:** Lifetime of furniture presented by different institutions or studies

### 2.2.2 Materials

The main materials in furniture is metals, wood, plastics and textile, with wood having the biggest share (Parikka-Alhola, 2008). All of these materials contribute to emissions from furniture which will be further described. However, it is found little information on the environmental impact of furniture textiles, and it is therefore not included. Textiles have the smallest share of the mentioned materials and is not considered as the most urgent improvement area. For further investigations on the topic, textiles should be considered.

**Metals**

Metals are present in most furniture products, as it is often used to connect furniture parts, used as legs for tables or chairs or could be the main material. Several studies have found that there are large environmental impacts attached to metals in furniture (Babarenda Gamage et al., 2008; Hartini et al., 2019; Iritani et al., 2015; Mirabella et al., 2014). The total amount of metal in furniture products is often small, and the metal parts are often screws, nails, bolts and so on. Compared to other furniture parts of bigger volume and weight, the impact is not substantial. However, some furniture has large furniture part of metal. It was found that in the comparison of two chairs, a chair with aluminium base had a bigger environmental impact than the chair with glass-filled nylon base (Babarenda Gamage et al., 2008). Primary aluminium can have a high impact on climate change (Cordella and Hidalgo, 2016). Linkosalmi et al. (2016) found that metals had high contributions to GHG emissions, but that the emission-mass ratio is low. The importance of recycling metals is emphasized, and it is found that there are far fewer burdens attached to recycled aluminium. A benefit of metals using is that they often can be reused and recycled as long as it exists proper systems supporting these processes. As much as 83% of metals are recycled and there is potential for an increase. In addition to climate change contributions, metals have typical high impacts to impact categories metal depletion and human toxicity (Hartini et al., 2019; Iritani et al., 2015). This is caused by the use of heavy metals and chemicals in production. By recycling, the emissions from the production of these substances can be avoided, but treatment and end-of-life emission of these will still occur.

**Wood**

Wood is the most used material in furniture (Cordella and Hidalgo, 2016). The interest in procurement of sustainably produced wood-based goods has increased. Both consumers and retailers, especially in developed countries, are demanding products with positive social and environmental contributions (González-García et al., 2011). Wood is often used in domestic furniture, but less in office furniture. Non-domestic furniture, as office furniture, typically has a bigger relative weight of metals and plastics (Cordella and Hidalgo, 2016). In an assessment on replacing furniture material with wood material, office furniture had the biggest reduction potential and avoided emissions (Babarenda Gamage et al., 2008). Numerous LCAs emphasize the low environmental burden of wood products in comparison to other materials serving the same function. It is found that wood substitution in furniture products originally made of energy-intensive conventional materials could reduce the carbon footprint by 34% (Geng et al., 2019). However, wood produces several types of wood materials, and not all are of low impact. Several studies find that production of wooden panels has a substantial carbon impact (González-García et al., 2012; Hartini et al., 2019; Höglmeier et al., 2015; Mirabella et al., 2014). Furniture of mixed materials, like wooden panels, metals and plastics, have a generally higher environmental impact compared to wooden furniture. It is suggested that changes in manufacturing operations and that use of alternative wood furniture components are feasible improvements (Höglmeier et al., 2015).

Cordella and Hidalgo (2016) find in their literature search that wood is the best material from an environmental point of view. It is both renewable, and less energy-intensive than other materials. What is often not included in the LCAs is the biogenic $CO_2$ consumption during biomass growth in forest activities (González-García et al., 2012; Iritani et al., 2015). The most affected impact categories from wood production to furniture are climate change, human toxicity and metal depletion (Hartini et al., 2019).

**Plastics**

Plastic furniture products are typical for non-domestic furniture inventory (Cordella and Hidalgo, 2016). No literature found have been pointing out plastic as the main contributor to environmental impact, nor is it found to be the least harmful. It is found that in general, it has higher environmental impacts than wood, and less environmental impacts than metals. Because of the low weight of plastic as a material, it subsequently has some environmental gains. Plastic is an efficient material in production compared to some other materials. This leads to less energy use in production. The main impacts come from the use of oil. Plastic furniture production uses oil, a scarce resource, for both feedstock and energy use (Cordella and Hidalgo, 2016). However, there is a potential of decreasing carbon emissions from production by using recycled plastic in the furniture made of plastic

(The Norwegian EPD Foundation, 2020; Iritani et al., 2015; Skoe, 2020). Mirabella et al. (2014) and Hartini et al. (2019) target exclusion of plastics as a strategy for reduction of environmental impacts. However, concerns are raised to the unknown content of hazardous substances after use of plastic furniture, and this concern also applies to the use of recycled plastic in furniture (Donatello et al., 2020).

## 2.3 Carbon Footprint

A carbon footprint represents the direct and indirect carbon emissions of a product or activity (Krey et al., 2014). These emissions are represented in terms of a single unit which covers the intensity of several GHGs in $CO_2$eq. In addition to carbon dioxide, compounds of other GHGs like methane, nitrous oxide, chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) are included in the carbon footprint. The global warming or radiative forcing contribution from each of these GHGs are different, and their relative contribution is added in terms of equivalents to one unit of $CO_2$. Over time, the potency of the different GHGs included in the carbon footprint changes according to the gas behaviour and how long the gas lasts in the atmosphere (Bakshi, 2019). In this project, the carbon footprint will be considered with global warming potential in a 100-year perspective, also known as GWP100. The GWP100 is the most common perspective used for these types of calculations. Additionally, the GWP100 metric is useful as the environmental performance can be compared to EU and UN goals, as well as IPCC documentation, which are all described in GWP100 (Krey et al., 2014).

## 2.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodological framework and holistic approach which considers all life cycle activities of a product or process (Bakshi, 2019). It is developed to raise awareness of the importance of environmental protection and environmental impact related to products. LCA quantifies and characterize material flows related to the life cycle of a product or process, and further specify the related environmental burden of these flows (Graedel and Allenby, 2015). By doing so, the total environmental impact of a product can be assessed, improvement areas identified and comparison of environmental performance to other products and processes be undertaken. LCA helps understand the communication of industrial processes and the environment. Indifference to carbon footprint, LCA considers several environmental impacts in addition to the global warming potential the carbon footprint describes. These are impacts as ozone depletion, human toxicity, acidification, eutrophication, ecotoxicity etc. The carbon footprint of a product or activity can be read from LCA results (Bakshi, 2019).

LCA follows a standardized procedure. The result of this procedure is quantified environmental impacts sorted in impact categories and further interpretation of these. An important prerequisite for the assessment is the definition of functional unit and system boundaries. The functional unit is a description of the function of the assessed product and determines a reference for all calculations. System boundaries define which processes are included in the assessments, and which are left out. A product or process can be assessed cradle-to-gate, cradle-to-grave or cradle-to-cradle. By cradle-to-gate the life cycle impact until the point of a product is produced and ready to leave the factory gate is included, i.e. all resource extraction and further production impacts. With cradle-to-grave the impacts from the point of raw material extraction to end-of-life is included. Use phase and disposal are thereby included. By cradle-to-cradle, phases from resource extraction and to supply new identical product is included (Graedel and Allenby, 2015). When doing an LCA, it must also be considered whether to undertake a consequential or attributional LCA. A consequential LCA estimates how the environmental impacts are affected by the life cycle processes of the product or service and is based on marginal data and avoid allocation. While an attributional LCA estimates the share of environmental impact which comes from the product or service. It is based on average data and allocation by partitioning (Ekvall and Tillman, 1997).

## 2.5 Environmental Product Declarations (EPDs)

EPDs are environmental certification of products and services, and represent standardized, verified and life-cycle based information. Norway is world-leading in the production of EPDs on furniture and has about 200 EPDs of furniture products available (Skoe, 2020). There are no environmental requirements to get an EPD, only that a life cycle assessment is done and that there is a third-party verifier to it. EPDs are transparent environmental information based on LCA calculations, with standardized system boundaries and LCA approach. The EPDs uses attributional LCA. The EPDs allows comparison and same use of the different declarations. The standard procedure is set by Product Category Rules (PCRs) in order for the EPDs to be of high quality and be comparable. For furniture, The Norwegian EPD Foundation has produced PCRs which complies with ISO14044:2006, Environmental management - Life cycle assessment - Requirements and guidelines and ISO12045:2006, Environmental management - Type III environmental declarations - Principles and procedures. These must be followed in the production of an EPD. In the PCR, it is defined that all furniture has the functional unit ”Production of one product solution provided and maintained for 15 years”. Following, all furniture products in the EPDs are set to a 15 year lifetime. No reuse is considered, but EPD targets recyclable parts of the products and does calculation for recycled parts where the raw material in itself is not accounted for, but the energy and material use from the recycling process is included. EPDs can be assessed cradle-to-gate and cradle-to-grave (The Norwegian EPD Foundation, 2018).

The EPDs can be used to find the carbon footprint of furniture and presents their climate change impact results in GWP100. The average, as well as the highest and lowest values, of different furniture categories found in the Norwegian EPD database, is presented in Table 2.2.

As seen in the table there can be large differences between the least and most emission-

| Furniture product | No. of EPDs | Average [kg$CO_2$eq] | Low [kg$CO_2$eq] | High [kg$CO_2$eq] |
|---|---|---|---|---|
| Chair | 34 | 18.1 | 7.6 | 36.3 |
| Office chair | 29 | 68.1 | 36.2 | 125.7 |
| Armchair | 9 | 27.6 | 6.1 | 85.4 |
| Sofa 3-seater | 13 | 98.7 | 36.2 | 188.9 |
| Working desk | 7 | 64 | 44.5 | 106.6 |
| Cabinets and shelves | 18 | 52.7 | 22.8 | 76.0 |
| Tower cabinet | 2 | 67.3 | 63.1 | 71.4 |
| Coffee table (W340-600) | 4 | 11.9 | 8.7 | 61.9 |
| Meeting table (1200x700-1600x800) | 5 | 31.7 | 19.0 | 40.3 |
| Round meeting table (W800-1200) | 6 | 31.5 | 14.5 | 45.6 |
| Conference table | 5 | 195.5 | 59.6 | 309.8 |
| Table screen | 4 | 12.1 | 5.5 | 23.1 |

**Table 2.2:** Carbon footprint (cradle-to-gate) for different furniture types compiled from Norwegian EPDs (The Norwegian EPD Foundation, 2020)

intensive products within the same furniture category. In literature search it was found similar results. It was found that chairs had an average of 30.4 kg $CO_2$eq, office chairs 57.4 kg $CO_2$eq and desks 62.7 kg $CO_2$eq. The EPDs of Table 2.2 presents results with lower carbon footprint for chairs and desks, but literature has presented better results for office chairs.

## 2.6 Reuse and allocation

To make a decision on what has the least environmental impact one must consider what is the most appropriate approach to consider reuse and recycling. Literature studies has not provided one common method on how to include reused furniture in an environmental assessment. Overall, there is no consensus on one method which best allocates emissions from reuse in LCAs and other environmental analyses.

Literature serves several methods on how to include reuse and recycling in environmental assessments. Several studies mention allocation as a challenge in environmental assessment. As society is working towards becoming more circular, this practice should be incorporated. To include reuse in environmental assessments of furniture it must be decided how to allocate the emissions of furniture products. Allocation in environmental assessment is the principle of partitioning related flows of a product of process life cycle between the product system under study and other related product systems. ISO suggest to first and foremost avoid allocation. If allocation is necessary, partitioning of input- and output flows should reflect the primary physical relationships between the flows (International Organization for Standardization, 2006).

Another approach to include reuse in calculations is to calculate the avoided emissions. Babarenda Gamage et al. (2008) used this approach in their analysis of an aluminium chair made with recycled aluminium and emphasized that the next use of aluminium hindered the production of raw material again. Following, all production outputs are included. Reuse gives a net negative GWP100 as it is an avoided burden from the production of new material. Loopfront, a company which delivers an online platform for reuse of furniture, uses the same approach when they calculate emission savings from reuse (Loopfront, October 2020). An advancement of this approach is to reward the first use for the avoided waste, and the second use for the avoided production of raw materials. Any environmental impacts from collection, cleaning and separation are attributed to the second product. If the product has a third user, the second user gets no impacts. With this method, there is a risk of double counting (Klöpffer, 1996). A third method is to not include any of the life cycle impacts for the second use of a furniture product, but rather include all the processes necessary for the reuse like storage and transportation etc. By using this method the lifetime of the furniture product can be seen as a timeline, and the first user have no responsibility to what happens with the chair after it leaves the door of the first user. This method is undertaken by Alexander and Smaje (2008), Gutowski et al. (2011) and Skaar (2011). EPD Norge partly uses this approach on recycled materials when only emissions and energy consumption related to the recycling process are included. Thereby no processes related to the production of the original product is included (The Norwegian EPD Foundation, 2020).

An additional approach is to split all emissions of a product between the different uses as an equal share of burdens. E.g. if a product is used two times, an allocation of the environmental impacts are split 50/50 between the two times of usage. By this method, both the first time user and second time user is equally responsible for the production of the product and for what happens after use. With this allocation double counting is not an issue (Klöpffer, 1996).

The use consequential versus attributional LCA should also be considered. This is also known as avoided burden versus partitioning. A consequential approach to recycling could give a strong incentive for recycling aluminium after use, while the attributional approach show that recycling aluminium is nearly equivalent to landfilling aluminium, and thereby provides no incentive for recycling after use. This is because the product does not receive any credit for the recycled content ending up on the market later on. This shows the importance of careful considerations of the type of LCA used, and the consequences attached to using some of the methods (Babarenda Gamage et al., 2008). Lastly, the efficiency of reuse, recycling or remanufacturing must be considered. It is important that the goal is to create a product with as little environmental impact as possible, not to create a product that is 100% recycled (Klöpffer, 1996).

## 2.7 Eco-design

The decisions made in the design phase could be responsible for up to 70% of the final cost of the furniture product (Jeswiet and Hauschild, 2005). Eco-design is a potential tool for furniture to limit environmental impacts as it integrates environmental impacts with the varied design possibilities. Strategies to ensure minimal environmental impacts are increasingly adopted to design processes (Höglmeier et al., 2015). To enter the market of green products, knowledge must be raised in regards of the typical materials and resources used in an industry (González-García et al., 2012). Eco-design is also important in order to achieve environmental certification and gain environmental labels. The reason why there is little uptake of environmental labels on EU furniture is that the criteria for making them are too complex (Donatello et al., 2020).

Eco-design strategies for furniture should be addressed in the conceptual stage. Environmental impacts from both production and consumption can be controlled by applying eco-design. Finding the more sustainable option in production can be limited by technical complexity and heterogeneity of products, available research and impact categories used in assessment (Cordella and Hidalgo, 2016). Eco-design is complementary with LCA, and an important strategy in eco-design is to investigate LCAs to locate which areas need improvements and act accordingly. Eco-design strategies include a short supply chain and implementation of eco-design principles. Implementation of this involves a thorough assessment of aspects related to all stages in the supply chain (Höglmeier et al., 2015).

Eco-design could reduce the total environmental impact from furniture with 14%. The key issue in eco-design should be to choose the right resources and materials with little environmental impact (González-García et al., 2012; Linkosalmi et al., 2016). Wood is mentioned in many eco-design strategies. As wood is the main material in furniture and also has relatively low environmental impacts, it should be promoted. Using certified wood is a strategy used, but it is not possible to calculate the effect of this in LCA. For wood, it is found that effective measures are to reduce resources that are used, multifunctional design, substitute MDF with plywood, optimization of energy requirement, transport alternatives and create a protocol for disassembling wooden products. Using solid wood instead of wood-based panels might also reduce the complexity of the furniture value chain (Donatello et al., 2020). In addition, a multifunctional design could erase the need for another new product (González-García et al., 2011).

Another strategy to reduce the environmental impact of furniture production is remanufacturing. Remanufacturing of furniture keeps products and materials in the loop, and waste from furniture consumption is avoided. It leads to an extension of furniture product lifetime which in turn reduces environmental impact and economic costs of the product. One of the most common remanufacturing products is office furniture (Remanufacturing Industries Council, 2020). The $CO_2$ savings from remanufacturing of furniture in Europe is 131 000 tonnes annually. When remanufacturing the product is renewed by either exchanging parts, painting or other improvements before reusing. There are more processes related to this than to reuse. With this follows a challenge to how the emissions from remanufacturing should be allocated. Office furniture is often ideal for remanufacturing because whole volumes of furniture in an office are replaced and needs to be renewed (Parker et al., 2015). Besch (2005) had the same conclusion based on literature review, that the most valuable strategies for minimising environmental impacts is to design furniture that is suitable for material recycling, has a long usage time and thereby reducing the consumption.

Chapter 3

# Method

This chapter presents the case projects investigated, system boundaries, assumptions, and the chosen method of calculating the carbon footprint of the case projects. The method presented is used to answer research question 1 and 2, while conversation with managers and handlers of furniture is used to answer research question 3. The scope of the method includes data from furniture EPDs and added processes. The furniture inventory of the case projects includes both reuse and refurbishment of furniture products, and a method for inclusion of these processes is included. These results are combined with life cycle emission data from the buildings of the project. Strategies for mitigating the emissions of the furniture inventory of the case projects have been evaluated. It is found through literature search that the most efficient initiatives towards environmental friendly furniture are long usage time, ecological profiling of materials, environmentally sound packaging, recyclability and environmentally sound production processes (Parikka-Alhola, 2008). In Lauvland (2020) it was found that increased reuse and long usage times were efficient mitigation measures. To meet the objective of this project and resources available, the chosen mitigation strategies of investigation in this project are reuse, prolonged usage time, added maintenance processes and investigations on material use. The presented method is based on the method used in the previous project thesis, with adjustments in reuse calculations and added processes. The method can be adapted to new projects.

## 3.1 Case projects

For the investigation of carbon footprint in non-residential buildings, it is gathered information on six case projects. Among the case projects are two upper secondary schools, two university buildings and two offices. All are located in separate parts of Norway. Data on each have been individually gathered from persons involved in the different projects. Each case project is presented in this section, and a summary of technical data is presented in Table 3.1. The case projects vary in functionality, users, size, construction strategy and furnishing strategy which creates a foundation for informative comparisons and can further lead to a greater understanding of the final results. More details on what data was accessed and used for each case project can be found in Appendix A.1.

**Polarsirkelen**

Polarsirkelen is an upper secondary school consisting of several buildings in Mo i Rana in northern Norway. The school was built to gather all upper secondary schools in the county at the same premises. One of the largest buildings at the site, Fellesbygget, is investigated in this project. This building contains classic classrooms, as well as facilities for culinary teaching, canteen, and administrative- and teacher offices for 500 students and 130 staff members. 30% of the furniture inventory of Fellesbygget are reused products from previous premises, while the rest was bought new for the opening. The construction was completed in 2018 and has three floors, where two is furnished. Parking spaces and technical rooms are located at the ground floor (Nordland fylkeskommune, 2020; Stein Hamre Arkitektkontor, 2020).

**Figure 3.1:** Polarsirkelen upper secondary school (Stein Hamre Arkitektkontor, 2020)

**Heimdal**

Heimdal upper secondary school is located in Trondheim. The construction was finished in 2018, and the students moved from old premises in the neighbouring building. In the moving process, 4% of the furniture inventory at the new school was moved from the previous site. It is a multi-purpose building for cultural and sporting activities as well as educational facilities. It includes offices, lecture rooms, facilities for group study, a sports hall, a gym, a concert hall, music practice rooms and dancing practice rooms spread across four floors. It is a large building, and has a total area of 26 356 $m^2$. 1140 students attends and 200 staff members work at the school. It is constructed as a Zero Emission Building (ZEB) and the first upper secondary school ZEB project in Norway. The building produces enough energy to cover the energy demand for operation, in addition to compensating for part of the embodied emissions from material use in the building process. The energy comes from a 2000 $m^2$ solar panel facility, as well as geothermal and biogas energy production at the site (Trøndelag Fylkeskommune, 2019).

**Figure 3.2:** Heimdal upper secondary school (Rambøll, 2020)

**ILP UiT**
In 2020, a new building for the teacher students of the University of Tromsø (UiT) named ILP, was constructed. The building is accounted for 1900 part- and full-time students, and has offices for 176 staff members. The building has six floors containing class rooms, offices, study rooms for master students, a coffee shop, as well as technical and administrative facilities. In addition to classic lecture rooms and laboratories, ILP UiT has educational rooms for culinary, creative and musical courses. The construction project aims to reduce the GHG emissions of the building with 30% compared to reference buildings. To meet this aim, solar panels is installed on the roof as an alternative energy source. This is the biggest solar panel facility north of the Arctic circle, and produces 140 000 kWh yearly (The Artic University of Norway, 2020).

**Figure 3.3:** ILP-building at UiT (The Artic University of Norway, 2020)

**K2 HVL**
K2 building is a part of Kronstad campus at the Western Norway University of Applied science (HVL) in Bergen. The building is intended for students studying teaching, social work and kindergarten teaching. They moved from previous premises 2 km from the new

location and had ambitions for high reuse of furniture products from the old premises. As a result, 44% of the furniture inventory at K2 HVL is reused products. The new building consists of six floors of modern architecture with lecture rooms, several teaching labs and simulator rooms, study rooms, mini kitchens, a cafe and offices for staff. It is designed to be facilitated for digital learning, which is an area of increasing interest. The construction was completed during the spring of 2020 and claims be the most modern teaching building in Norway. K2 HVL is a low-emission building with 30% reduction in carbon emission compared to reference buildings. Solar panels are installed on the roof, in addition to the building being constructed for low heat loss and with energy-efficient technical solutions (Western Norway University of Applied science, 2020).

**Figure 3.4:** K2 building of Western University of Applied Science (Western Norway University of Applied science, 2020)

**Asker kommune**
Administrative employees of Asker kommune (Asker county) has recently changed premises to Lensmannslia 4, in the eastern part of Norway. There is office space for 140 employees, and facilities for courses and seminars at the premises. Asker kommune's centre for innovation and learning is also located here. It is a said to be a meeting place for innovation and teaching. The building, Lensmannslia 4, was completed in 2003 where businesses and companies can rent office space. Asker kommune rents 5000 $m^2$ over four floors in this building. The staff in charge of the relocation decided to reuse as much as possible of the furniture from the old premises to reduce emissions attached to the relocation process. If the furniture was damaged or outdated, refurbishment of the furniture products was undertaken. Following, the furniture inventory has reuse from old premises, refurbished items and reused furniture bought from others. This resulted in only 2% of the furniture being bought new for the change of premises. Of the reused furniture products, 27% are (Asker kommune, 2020).

**Figure 3.5:** Asker kommune Lensmannslia 4 (Asker kommune, 2020)

**ZEB Laboratory**

ZEB Laboratory is a pilot ZEB project located at campus Gløshaugen at NTNU, Trondheim. The building hosts employees from NTNU and SINTEF across four floors. The construction was completed October 2020, and is a full-scale office building and laboratory for ZEB research, with a possibility to be used for educational purposes. It contains several offices, meeting rooms, seminar rooms and laboratories, as well as a cafeteria. It is facilitated for 100 people in the offices and meeting rooms of the building. The laboratories are meant for research on the ZEB project. Elements of the building can be modified and replaced for purpose of the building being a living lab and experimental parameter. It has been furnished with all newly bought furniture, but with an ambition of choosing furniture of low environmental impact. (ZEB Laboratory, 2020).

**Figure 3.6:** ZEB Laboratory (LINK arkitektur/Veidekke, 2021)

Technical data of each case project used in the calculations is gathered in Table 3.1. The table displays large variations of size, users and share of reuse in the case projects. Unfurnished areas as parking spaces and sports halls will not be taken into account in calculations.

| **Case project** | **Building type** | **Area** | **Users (employees/ students)** | **No. of furniture products** | **Reuse share** |
|---|---|---|---|---|---|
| Polarsirkelen | School | 5920 $m^2$ | 130/500 | 2540 | 30% |
| Heimdal | School | 18 675 $m^2$ | 200/1140 | 5511 | 4% |
| ILP UiT | University | 11 000 $m^2$ | 176/1900 | 3102 | 15% |
| K2 HVL | University | 11 900 $m^2$ | 300/3000 | 4242 | 44% |
| Asker kommune | Office | 5000 $m^2$ | 140/0 | 1274 | 98% |
| ZEB Laboratory | Office | 1742 $m^2$ | 100/0 | 563 | 0% |

**Table 3.1:** Technical data of the case projects

## 3.2 System boundaries

The system boundaries represent what processes are included in the assessment. As furniture originally is not included in environmental analysis of buildings, EPD data of furniture have been added with LCA data of buildings. As the data used for furniture is based on EPD data, their system boundaries for furniture products have been thoroughly investigated and used as a base for the system boundaries for the furniture products of this project. Reuse, refurbishment and maintenance processes which are not included in the system boundaries of the EPD have been added and thus created new system boundaries. The system boundaries of this assessment can be seen in Figure 3.7. The green processes are from the EPDs, while the yellow represents added processes which give a full representation of the carbon footprint of furniture with reuse, refurbishment and maintenance processes. This creates a foundation to further investigate strategies for mitigation.

Items like clothing racks and waste bins has been left out of the analysis. This is due to a lack of information on volume of these products in the assessed buildings, as well as lack of environmental data of these items. It varied whether or not these items were included in the inventory list and floor plans of the case projects. As they were not included in all case projects it was decided not to include in the furniture inventory in neither of the projects to be able to do comparisons on a fair basis. It can further be discussed if these items are considered as furniture products. Additionally, in the cases where items in the floor plan have been unable to identify as a furniture product, as well as unable to verify by inventory list, the item is not taken into account.

As all case projects are located in Norway, the proposed method for executing environmental analysis on buildings for Norwegian standard NS3720 ”Method for greenhouse gas calculations of buildings” is used as a basis. The buildings of the case project follow this

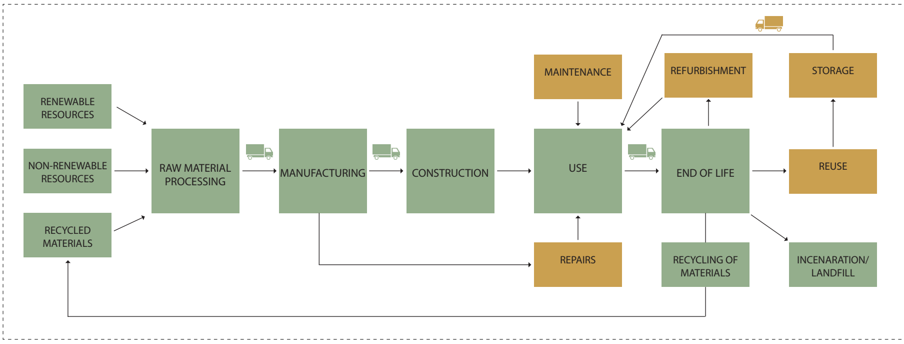


**Figure 3.7:** System boundaries of furniture products adapted and adjusted from The Norwegian EPD Foundation (The Norwegian EPD Foundation, 2020)

standard in their climate gas calculations. LCA is the proposed method for calculations, and requirements are set so that all buildings using this will be thoroughly investigated and comparable. In this standard, it is stated that what is to be included within the system boundaries must be classified according to NS3451:2009+A1:2019 ”Table of building elements”. Subsequently, what is not included in this list is not included in the building LCA. The only mention of furniture in NS 3451 is within ”fixed inventory”. Thereby, all fixed inventory as bathroom inventory, kitchen cabinets etc is estimated to be already included in the building emission calculations (Norsk Standard, 2018, 2019).

The chosen impact category in this project is climate change in kg $CO_2$eq. Climate change is one of the most pressing global issues today, and one of the most affected impact category of furniture production (Iritani et al., 2015). When more impact categories are included, reliable information seems to decrease and trade-offs seem to increase (Cordella and Hidalgo, 2016). This could complicate the already complicated issue. As it is found that the environmental information on furniture is limited and complex it is chosen to start with the pressing climate change. As the research area of the environmental impact of furniture increases, all impact categories should be given attention.

## 3.3 Assumptions

The analysis has been heavily dependent on assumptions, due to the gap in knowledge around environmental analysis of furniture and lack of wholesome information on furniture inventory in buildings. Conceptual assumptions which are important for the analysis method is included below. Further assumptions which are more individual for each furniture product or project are included in Appendix A.2.

- Lifetime of all buildings is set to 60 years based on NS3720 and ZEB standards.
- Lifetime of furniture is set to 15 years based on EPDs and literature search.
- Auditorium seats, bathroom inventory, kitchen cabinets and other fixed cabinets and wardrobes are not accounted for because they are assumed to be covered by building LCAs, according to NS3720.
- It is assumed that newly bought furniture products are used after end-of-life, i.e. the end-of-life process has not been included in the calculations of the carbon footprint. In the same manner, it is assumed that reused furniture is not used again an additional time, and end-of-life emissions are included for these furniture products.
- The whole furniture inventory is assumed to be exchanged at the same time every 15 years. The same share of reuse as presented in Table 3.1 is assumed for every exchange of furniture inventory.
- If the exact furniture product used in the building is not found among the EPDs, a best-fit based on the criteria or descriptive demands of the procurement have been used. The same is done when only the procurement demands, and not the exact product, is known. If there is no suitable fit or lack of product-specific information, an average of the furniture category has been used, presented in Table 2.2. Some chairs have been made with best-fit, and added emissions related to seat padding etc. found in the EPDs. By using a best-fit, one is less dependent on averages and gives an more realistic scenario that meets the furniture requirements.

## 3.4 Carbon footprint of furniture

The method for calculating the carbon footprint of furniture is based on the previous method developed in Lauvland (2020). Furniture intensity matrices and carbon intensity vectors is constructed and used to calculate the carbon footprint. The tool used for the calculation is Microsoft Excel. Baseline scenarios are created using the information from the case projects presented in Section 3.1. Further, the amount of reuse, refurbishment, maintenance and usage time is varied to investigate the effect of mitigation strategies.

The carbon intensity vector, $\mathbf{c}_{\text{furniture}}$, is of dimensions [furniture products x 1]. The elements of the vector represents the carbon footprint of one single furniture product, for all furniture products included in the respective building. The carbon values of $\mathbf{c}_{\text{furniture}}$ is taken directly from the EPDs or from the calculated average from Table 2.2. A furniture intensity matrix $\mathbf{F}$ is then created of dimensions [rooms x furniture]. The elements of $\mathbf{F}$ represents the number of different furniture products in each room or room category. Examples of $\mathbf{c}_{\text{furniture}}$ and $\mathbf{F}$ from the ZEB Laboratory can be seen in Appendix A.3. The rooms are categorized to compromise the matrices and ensure an easier investigation. The data in **F** is based on information from the floor plan and furniture inventory list of the building. When there have been inconsistencies in floor plans and inventory lists, the quality of the floor plan and the inventory list of the current building is considered, and an individual decision have been taken into which of the two data collections gives the most realistic answer to reality. $\mathbf{c}_{\text{furniture}}$ and **F** are then used to calculate the carbon intensity vector of furniture per room, $s_{\text{furniture}}$, and the total carbon footprint of furniture, $\text{CF}_{\text{furniture}}$, is found in Equation 3.1 and 3.2 respectively.

$$\mathbf{s}_{furniture} = \mathbf{F} \cdot \mathbf{c}_{furniture} \tag{3.1}$$

$$CF_{furniture} = \sum_{j=1}^{n} s_j \tag{3.2}$$

To find the total carbon emissions from furniture over the building lifetime, an exchange rate, *e*, is defined. It is calculated from lifetime of the building, $l_{\text{building}}$, and the lifetime of the furniture products, $l_{\text{furniture}}$, as seen in Equation 3.3. The total carbon footprint of furniture over a building's lifetime is then found by Equation 3.4.

$$e = \frac{l_{building}}{l_{furniture}} \tag{3.3}$$

$$CF_{furniture,total} = e \cdot CF_{furniture} \tag{3.4}$$

To find the significance of furniture on the building emissions, available information from environmental analyses on the respective buildings are used. The analyses are done according to NS3720 and shows the $CO_2$-equivalent emissions per square meter per year. They are all estimated to have a 60 year lifetime for the building. The different building emission intensities, *b*, in kg $CO_2$eq emission per square meter for each case project are presented in Table 3.2. When the emission intensity has not been available for a case project, average data on carbon emissions from Norwegian buildings is used as found by SINTEF. These investigations are done in compliance with NS3720 and have a reference lifetime of 60 years (Wiik et al., 2020). The calculations done of building emissions in Heimdal and ZEB Laboratory are not final and might deviate some from the actual emission. Heimdal and ZEB Laboratory are zero-emission buildings, and the building emissions are compensated for during the building's lifetime. ILP UiT and K2 HVL also have installed solar panels to compensate for emissions. However, the compensations are not calculated for in this assessment.

The total area of the building is represented in *A*. The total carbon emissions from the building, $\text{CF}_{\text{building}}$, is then found by Equation 3.5, and the total carbon footprint of both

| Case project | $b$[kg $CO_2$eq/m$^2$/yr] | Source |
|---|---|---|
| Polarsirkelen | 6.1 | School/university average (Wiik et al., 2020) |
| Heimdal | 10.7 | Design estimates (Schlanbusch et al., 2017) |
| ILP UiT | 14.6 | LCA calculations of building (Ekenstam, 2020) |
| K2 HVL | 12.1 | LCA calculations of building (Sweco, 2020) |
| Asker kommune | 5.0 | Office building average (Wiik et al., 2020) |
| ZEB Laboratory | 11.1 | LCA calculations of building (Veidekke, 2021) |

**Table 3.2:** Building emission intensities of the case projects

furniture and building in Equation 3.6.

$$CF_{building} = b \cdot A \cdot l_{building} \tag{3.5}$$

$$CF_{total} = CF_{furniture} + CF_{building} \tag{3.6}$$

There are two ZEB buildings in the project, Heimdal and ZEB Laboratory. Following, a method for finding how much energy must be produced at the project sites to compensate for furniture emissions as well as building emissions. An estimate of electricity production needed is calculated in Equation 3.7. In this calculation, the ZEB standard for specific $CO_2$ emission of electricity is used. This value is found to be 0.132 kg $CO_2$eq/kWh for a simulation towards 2050 in Europe, and is represented in **z** (Dokka, 2011).

$$E_{compensated} = \frac{CF_{furniture}}{z} \tag{3.7}$$

In Norway, the $CO_2$-equivalent emission from Norwegian electricity use is found to be 0.017 kg $CO_2$eq/kWh in 2019 (NVE, 2020). However, as a ZEB building would need to use the standards of ZEB in their calculations, the ZEB factor has been chosen for calculating the needed electricity compensation of furniture in the ZEB buildings. The ZEB factor is based on future projections and has a Northern-European perspective. For further calculations of emissions of electricity use, the Norwegian emission of 0.017 kg $CO_2$eq/kWh will be used as the case projects are all located in Norway, and the value is based on measurements in Norway.

## 3.5 Reuse

Five out of six case projects has reused furniture products in their furniture inventory and processes related to this should be included in the calculations. The allocation method chosen to include reuse in this project is to allocate the production emissions to first usage, and reuse processes and end-of-life emissions to the second usage. Several processes related to reuse has been identified and accounted for. The processes assumed to be included in the reuse process are: transportation, storage, repairs and end-of-life processes. It is assumed that all reused products are sent to waste handling after use and not used again ans therefore end-of-life emissions are included. The processes are gathered in the reuse matrix **R**, of dimensions [furniture products x reuse processes] with elements $r_{\text{ij}}$. An example of **R** and $\mathbf{c}_{\text{reuse}}$ is displayed in Appendix A.4. The **R** matrix is used to create a new carbon intensity vector, $\mathbf{c}_{\text{reuse}}$ with elements $c_{\text{i}}$. The carbon footprint of the reuse processes is found individually for each furniture product. Equation 3.8 describes how the carbon intensity vector, $\mathbf{c}_{\text{reuse}}$ is then found from **R**.

$$\mathbf{c}_{reuse} = \sum_{i=1}^{n} r_i j \tag{3.8}$$

To include which products are reused and not, the share of reuse $x_{\text{reuse}}$ and share of new furniture $x_{\text{new}}$ is found per furniture product. The share is then used to calculate for each furniture product of the carbon intensity vector $c_{\text{reuse}}$ and $c_{\text{new}}$ to create a a new carbon intensity vector $\mathbf{c}_{\text{furniture}}$ as in Equation 3.9. This is further used in calculations as in Equation 3.1. When calculating for reuse, all reused furniture products in the case projects have been located and individually given the correct carbon footprint when reused. But if information was missing on exact which furniture products was reused, given information on share of reuse in the furniture inventory of the case project was used. In both Polarsirkelen and Asker kommune the given shares of reuse of respectively 30% and 98% was used. In Asker kommune the 27% of refurbished furniture was also accounted for.

$$c_{furniture,i} = x_{new,i} \cdot c_{new,i} + x_{reuse,i} \cdot c_{reuse,i} \tag{3.9}$$

$$x_{new} + x_{reuse} = 1 \tag{3.10}$$

The transport, storage and repair processes of reuse have been given high, medium and low-efficiency variables as there is no available data on these processes from any of the projects to create exact calculations. It is therefore relied on varied estimations (see Appendix A.2). Calculation of each of the reuse processes is described below.

**Transport**

To calculate the carbon emissions of reuse, emissions from the transport of furniture have been investigated. An estimate of distances driven and volume of furniture carried per trip is done. The environmental data available for transport activity often presents the results in emissions per tonnes kilometre [tkm]. Hence, the emissions are dependent on the weight of the product. This is therefore found for each furniture product in the EPDs. The chosen transport activity is taken from Ecoinvent database with activity name *transport, freight, lorry 3.5-7.5 metric ton, EURO5, RER*. This activity describes transport within Europe, and the newest technology is assumed, therefore EURO5 is chosen. The activity includes data from the entire transport life cycle with impacts of vehicle and road from cradle including all upstream activities and direct emissions. The PCRs of Norwegian EPDs has defined that transport should include direct emissions, upstream emissions from fuel extraction etc. and life cycle emissions of vehicle and infrastructure. The transport chosen for the added processes in this thesis should thereby include the same. This activity has emissions of 0.51 kg $CO_2$eq per tkm for GWP100, represented in *t*. For this process high, medium and low-efficiency values are considered based on the capacity of the car. It is assumed that the car will not be loaded to maximum capacity, but with a high, medium and low efficiency value of 70%, 50% and 30% capacity, represented by *x*. If no other information is given, it is assumed that reused products require transport for altogether 50 km for driving to storage and final destination. The distance is represented in *v*. Some case projects had information that furniture is transported directly from old building to new building, and in that case, no storage is accounted for and informed driven distance is used.

$$CF_{transport} = \frac{1}{x} \cdot t \cdot v \cdot weight\ of\ furniture\ product \tag{3.11}$$

**Storage**
For several of the scenarios it is assumed that furniture is stored in a storage building between usages. A storage building will have emissions from the energy use of the building. To calculate the environmental impact of storage for reuse, typical values for energy use in storage buildings in Norway, *E*, is found. This method is inspired by previous studies on reuse by Skaar (2011). A literature search was undertaken to find the correct value for *E*. In Skaar's analysis from 2011, *E* was found to be 102 kWh/$m^2$/yr. SSB has found an analyses undertaken in 2011 that storage buildings use 151,7 kWh/$m^2$/yr (Abrahamsen and Bergh, 2011). While SINTEF found that storage and light industry buildings had a low, medium and high energy use values of 177, 223 and 244 kWh/$m^2$/yr respectively (Thyholt et al., 2003). Enova building statistics investigated 18 Norwegian storage halls and found that the average energy use was 116 kWh/$m^2$/yr (Enova, 2017). Several of the results found are older and included light industry in their analysis. In this assessment it is accounted for buildings where the only purpose is storage. Therefore, Enova's findings were used as a starting point. 116 kWh/$m^2$/yr is considered as a medium efficient value, and 100 kWh/$m^2$/yr and 150 kWh/$m^2$/yr are chosen for low and high-efficiency values based on the other findings.

It is assumed that furniture products in average take up 0.5 $m^2$, accounting for furniture that is stackable and not. This is represented in *o*. Further, the average for carbon emissions of electricity in Norway, found to be 0.017 kg $CO_2$eq/kWh in 2019, is used, represented in *h*. It is assumed that all furniture is stored for 6 months. The total contribution from storage is then found by Equation 3.12.

$$CF_{storage} = E \cdot h \cdot o \cdot years \tag{3.12}$$

**Repairs**
It is assumed that in a reuse process, some furniture must undergo repairs to be used again. For repair, there is made high, medium and low-efficiency shares of furniture product that require a fix that complies with 10% 20% or 30% of the emission of the furniture product. The repairs can be change of textile in a padded chair, change of screws, exchange of a sofa leg or cabinet door. This share is represented by *x* and the carbon emission of this process will be calculated as in Equation 3.13. It is estimated that not all furniture has to

undergo a repair process, and thereby this process is included only for 50% of the reused furniture products in each inventory.

$$CF_{repair} = x \cdot CF_{product} \tag{3.13}$$

**End-of-life**
End-of-life emissions have been included as part of the reuse matrix. These emissions are found individually for each product in the EPDs. Most EPDs provide information about emissions from these processes, perceiving they are cradle-to-grave assessments. If the furniture EPD only has cradle-to-gate results, estimates based on similar products or within the same brand is made to find a suitable end-of-life emission.

## 3.6 Maintenance and refurbishment

The same method is used for calculating the carbon footprint of both refurbishment and maintenance processes. In Figure 3.7, maintenance and refurbishment represent the same processes, but depending on if it is a part of reuse strategy or prolonged usage time strategy, it is placed differently in the life cycle. In Asker kommune, the method is used to account for the reused furniture products which were refurbished. For investigating the strategy of prolonged usage time, the method is to calculate the carbon contribution of increased maintenance. For maintenance and refurbishment processes, there is not added any variations with high, medium and low efficiency as done in the reuse process. This is due to a lack of resources and time to make these variations in this assessment. It is assumed that maintenance is performed once every 15 years to ensure a further usage time after reached lifetime.

A maintenance or refurbishment process often involves several processes. In this assessment, the processes and materials included are; change of upholstery, change of other parts, paint, change of screws as well as the energy demand for the processes. These processes have been individually considered per furniture product. They are gathered in a maintenance and refurbishment matrix, **M** as seen in Appendix A.3. The matrix is of dimensions [maintenance processes x furniture products] with elements $m_{\text{ij}}$. The rows of the matrix are then summarized to create a new carbon intensity vector $\mathbf{c}_{\text{maintenance}}$ as in Equation 3.14. Further, Equation 3.9 is used to calculate the total carbon contribution of the processes.

$$\mathbf{c}_{maintenance} = \sum_{i=1}^{n} m_i \tag{3.14}$$

Several EPDs include the carbon footprint of textile upholstery and armrest for chairs. These can be used to estimate the carbon footprint of exchange of these parts. There are two producers which include this information, Flokk and NCP. Table 3.3 presents the average of these two alternatives or the only alternative where only one of the producers included the carbon footprint of the furniture part. For the exchange of parts in cases of maintenance of refurbishment, an average of 10% of the furniture product is assumed to be exchanged. Thereby an carbon emission equivalent to 10% of the product is accounted for and found as in Equation 3.13

| Furniture part | kg $CO_2$eq/item |
|---|---|
| Seat upholstery | 4.25 |
| Full upholstery | 7.65 |
| Armrest | 5.80 |

**Table 3.3:** Carbon footprint of furniture parts in kg $CO_2$eq

Paint is included as a maintenance and refurbishment processes. This is accounted for wooden furniture or other furniture products which can be painted. To find the carbon footprint of paint, EPD of interior paint from The Norwegian EPD Foundation have been used. In this EPD the declared unit is 1 kg of paint and density is 1.36 g/cm$^3$. It is assumed that it goes 2 dl of paint for the painting of one furniture product, and the environmental contribution per product is estimated accordingly. It is found that 2 dl of paint entails 0.64 kg $CO_2$eq. The EPD only delivers cradle-to-gate results, so this is what is included in the analysis. Some furniture products might use wood stainer instead of paint, and the carbon footprint of this is assumed to be the same. Screws, nails and bolts are also assumed to be part of refurbishment processes. EPD Norway does not have any EPDs for these products in their database, so these emissions are found through a literature search. An LCA found of a steel nail showed that one nail causes 0.006 kg $CO_2$eq per nail. It is assumed that screws and bolts give a similar carbon footprint. Further, it is assumed that in average three nails, screws or bolts are exchanged in maintenance and refurbishment processes and that therefore each furniture product has a contribution of 0.018 kg $CO_2$eq for this process. This is a small amount, but considering the number of furniture products in the inventory of the non-residential buildings assessed, it should be accounted as part of the maintenance and refurbishment process. There will be some energy use attached to the repair processes. This will come from the use of electric tools for repairs, and perhaps storage and transportation of workers. Based on this it is assumed a gathered amount of energy use to be equivalent to 10 kWh of electricity for each furniture product. To find emission from the energy use, the same value for $h$ is used.

Chapter 4

# Results

In this chapter, the presented research questions are answered in respective sections with results from the case projects. The results give perspective to the carbon footprint of furniture in non-residential buildings and illustrate various opportunities for reducing the carbon footprint. Several challenges to reducing the carbon footprint of furniture have also been found.

## 4.1 Carbon footprint of furniture

This section presents baseline calculations of each case project to answer research question 1. This includes furniture used for 15 years in buildings with a lifetime of 60 years. The level of reuse in the buildings have been accounted for. Cradle-to-gate emissions are accounted for in new furniture products, while emissions from reuse processes and end-of-life are considered for the reused furniture products. It is considered that furniture is reused after 15 years if the original product is new, and discarded after use if it is a reused product. Three different scenarios for the reuse processes is included, with high, medium and low-efficiency values for the logistics required in the reuse processes. Additionally, carbon footprint of furniture if it were all bougth new is also included for each case project.

**Polarsirkelen**
Table 4.1 shows that furniture contributes with 12.6-13.1% of the total emissions of the building at Polarsirkelen upper secondary school, depending on the efficiency of the reuse. An all new scenario show a large share of building emissions of 15%. There was found few EPDs for the products used in this case project, which lead to a high reliance on averages of the different furniture categories. When this school was planned there was little requirements to environmental analysis of buildings, and this was not undertaken for Polarsirkelen. Thereby an average of reference school buildings have been used for building emissions.

| Reuse scenario | tonnes $CO_2$eq | Share of total building emissions |
|---|---|---|
| High efficiency reuse | 312.4 | 12.6% |
| Medium efficiency reuse | 319.2 | 12.8% |
| Low efficiency reuse | 327.4 | 13.1% |
| All new furniture | 384.9 | 15.1% |

**Table 4.1:** Carbon footprint of furniture at Polarsirkelen upper secondary school over 60 years with 30% reuse

**Heimdal**

Heimdal upper secondary school is a new school building where the students and furniture, was transferred from the old school building on the premises next to the new building. This lowers the carbon footprint of reuse as there are no storage or transport emissions in the process. However, reuse at this school is only 4%, so the total carbon footprint of the furniture inventory is not remarkably profited by low reuse emissions, as Table 4.2 illustrates. The difference between the reuse scenario with highest efficiency and all new furniture is only 0.2%. The emissions of furniture is around 6.3% of the total emissions from the building.

| Reuse scenario | tonnes $CO_2$eq | Share of total building emissions |
|---|---|---|
| High efficiency reuse | 807.7 | 6.3% |
| Medium efficiency reuse | 811.5 | 6.3% |
| Low efficiency reuse | 815.3 | 6.4% |
| All new furniture | 839.3 | 6.5% |

**Table 4.2:** Carbon footprint of furniture at Heimdal upper secondary school over 60 years with 4% reuse

Heimdal upper secondary school is a ZEB building which aims to compensate for part of material and construction emissions as well as operating emissions by producing their own renewable electricity at the site of the school. Furniture has not been in accounted as emissions of the buildings which shall be compensated for. It is therefore calculated how much more electricity the school has to produce if furniture is taken into account. It is found that the renewable energy sources on site would have to produce 104.0 MWh more electricity every year.

**ILP UiT**

In Table 4.3 it is seen that the ILP building at UiT have a share of around 5.0-5.2% the total emissions of the building depending on the efficiency of the reuse. ILP had the highest building emissions with 14.46 kg $CO_2$eq. This contributed to a low share of emissions from furniture. The reuse share of 15% in the furniture inventory, also contributes to a low share of emissions. There are small differences to the different reuse scenarios, but a significant improvement of more than 55 tonnes $CO_2$ emissions by having reuse rather than buying all new.

| Reuse scenario | tonnes $CO_2$eq | Share of total building emissions |
|---|---|---|
| High efficiency reuse | 462.0 | 5.0% |
| Medium efficiency reuse | 468.3 | 5.1% |
| Low efficiency reuse | 475.7 | 5.2% |
| All new furniture | 531.7 | 5.7% |

**Table 4.3:** Carbon footprint of furniture at ILP builing at UiT over 60 years with 15% reuse

**K2 HVL**

The K2 building of Western Norway University of Applied science in Bergen had high ambitions for their carbon footprint of furniture with high amount of reuse of 44%. The furniture was transported directly for two kilometre from the old building to the new, so there was no storage emissions and the transport emissions are low. This leads to furniture emissions only causing around 4.2% of the emissions of the building if considered medium reuse efficiency as seen in Table 4.4. By having this high amount of reuse the carbon, 220 tonnes $CO_2$eq emissions are saved if compared to the reuse scenario with medium reuse efficiency values.

| Reuse scenario | tonnes $CO_2$eq | Share of total building emissions |
|---|---|---|
| High efficiency reuse | 363.4 | 4.0% |
| Medium efficiency reuse | 379.6 | 4.2% |
| Low efficiency reuse | 401.7 | 4.4% |
| All new furniture | 599.5 | 6.5% |

**Table 4.4:** Carbon footprint of furniture at K2 building at HVL over 60 years with 44% reuse

**Asker kommune**

Asker kommune had an ambitious project to lower the carbon footprint of their furniture inventory with 98% reuse. Asker is the only case project which had refurbished furniture in their furnishing strategy and refurbishment processes have been included in the reuse scenarios. Table 4.5 shows that this amount of reuse and refurbishment have been very successful as this causes the furniture to have more than half the carbon emissions they would have if all were bought new if accounting for high or medium-efficiency reuse values.

| Reuse scenario | tonnes $CO_2$eq | Share of total building emissions |
|---|---|---|
| High efficiency reuse | 91.9 | 5.8% |
| Medium efficiency reuse | 104.4 | 6.5% |
| Low efficiency reuse | 119.2 | 7.4% |
| All new furniture | 214.9 | 12.5% |

**Table 4.5:** Carbon footprint of furniture at Asker kommune over 60 years with 71% reuse and 27% refurbishment

Asker kommune has based on previous investigations stated that more than 100 tonnes $CO_2$eq is saved by their furnishing strategy (Loopfront, 2020). By using the method described in this thesis, it is found that 29 tonnes $CO_2$eq emissions are saved by the first exchange. This is due to the fact that only avoided emissions from buying new have been calculated, and not the emissions attached to the processes of reused furniture.

**ZEB Laboratory**

Table 4.6 show that furniture has 6% emissions of the total building emissions. The ZEB Laboratory had no reuse in their furniture inventory, and therefore only results for all new furniture is presented. However, initiatives were taken to choose more environmentally friendly furniture. This is the only building in the project which has not transferred directly from other premises to a new location. Reused furniture are therefore less accessible than in the other cases which easily could transfer reused furniture from old premises. In the ZEB project, furniture is not accounted for in the compensation of emissions of the building. If furniture were to be included, it is found that an added amount of 9.5 MWh of electricity must be produced from the renewable energy sources at ZEB Laboratory every year.

| Reuse scenario | tonnes $CO_2$eq | Share of total building emissions |
|---|---|---|
| All new furniture | 74.4 | 6.0% |

**Table 4.6:** Carbon footprint of furniture at ZEB Laboratory over 60 years with no reuse

**Comparison**

In comparison of the case project, medium efficiency reuse values is considered for all case project except ZEB Laboratory which have no reuse. The carbon footprint of furniture and building of each case project is illustrated in Figure 4.1.

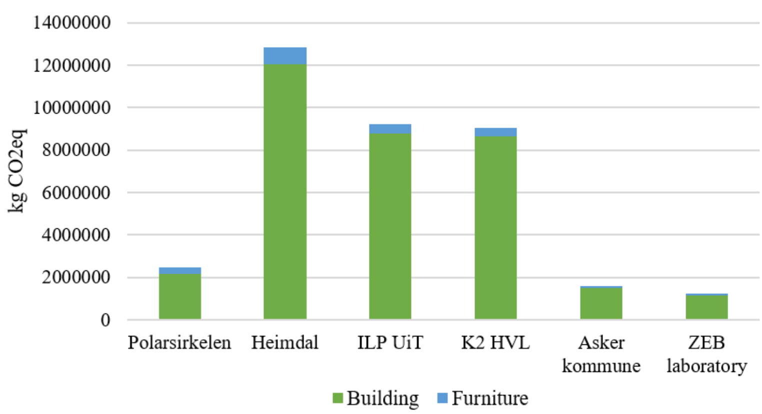


**Figure 4.1:** Building and furniture $CO_2$eq emissions from case projects with cradle-to-gate emissions from new furniture and medium efficiency values for emissions from reuse processes

The results for furniture's share of total building emissions varied between 4.2-12.8%. As seen in Figure 4.1 there is large differences in carbon emissions between the case projects due to their size and number of furniture products.

As all case projects had different building emission intensities, it effects the share of emissions from furniture in the buildings. Therefore, the share of furniture in all case projects is also found when all case project are calculated with a common building emission intensity. This is illustrated in Figure 4.2. The building emission value considered is 6.3 kg $CO_2eq/m^2/yr$ as found by SINTEF (Wiik et al., 2020). The value represents the average for non-residential buildings in Norway. The figure reveals that Polarsirkelen have little difference compared to the baseline results due to similar building emission intensity. The other case projects, except Asker, have higher shares of total building emissions when the new building emission intensity is used, and four case projects now have shares higher than 10% of total building emissions. K2 and Asker kommune which have high shares of reuse has the lowest share of the total building emissions.

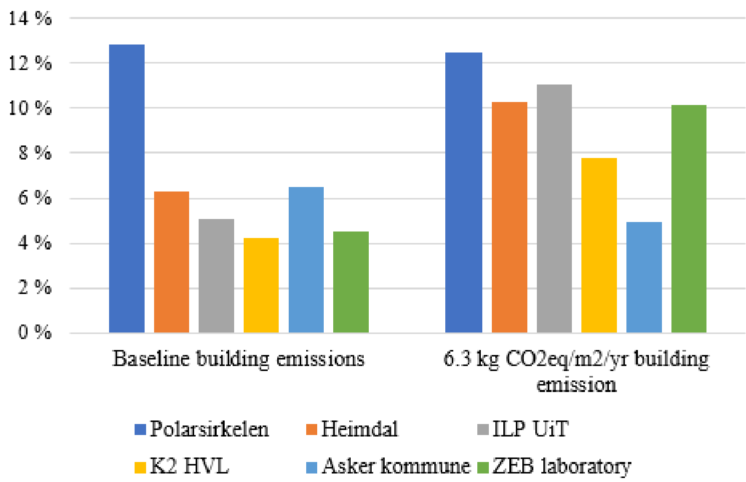


**Figure 4.2:** Results of furniture share to carbon emission in buildings when given the same building emissions with cradle-to-gate emissions from new furniture and medium efficiency values for emissions from reuse processes

To further compare the emissions from the furniture inventory of the case projects, common carbon emission intensity parameters are created. Seen in Table 4.7 are the carbon footprints of furniture per square meter, carbon footprints of furniture per product and carbon footprints of furniture per user in the respective case projects. These results can reveal the efficiency of furnishing in each building, as well as the efficiency of furniture choice. The different levels of reuse in each projects clearly affects the results. K2 HVL and Asker kommune which has the highest shares of reuse have the lowest emissions for both carbon footprint per square meter and carbon footprint per product. Heimdal, ILP UiT and ZEB Laboratory all have emissions over 10 kg $CO_2eq/m^2$, and over 30 kg $CO_2$/product. All cases projects except ZEB Laboratory had some share of reuse. This is also reflected in the results.

| Case project | kg$CO_2$eq per m$^2$ | kg$CO_2$eq per product | kg$CO_2$eq per user |
|---|---|---|---|
| Polarsirkelen | 13.5 | 31.4 | 126.7 |
| Heimdal | 10.9 | 36.8 | 151.4 |
| ILP UiT | 10.7 | 37.8 | 56.5 |
| K2 HVL | 8.0 | 22.4 | 28.8 |
| Asker kommune | 5.2 | 20.5 | 186.4 |
| ZEB Laboratory | 10.7 | 33.1 | 186.2 |

**Table 4.7:** Furniture emissions intensities from the different case projects with cradle-to-gate emissions from new furniture and medium efficiency values for emissions from reuse processes

The case projects are compared on furniture product level as well. All products are assumed bought new with cradle-to-gate emissions for this comparison to get an accurate illustration of the effect of each furniture category. In Figure 4.3 the furniture products of the case projects have been categorised, and percentage amount of each furniture category. Figure 4.4 illustrated the share of total carbon footprint for each furniture category. Some furniture products, as benches, table screens and floor screens, have been left out of this analysis. They are of small amount in all case projects, and not considered significant for the comparison.

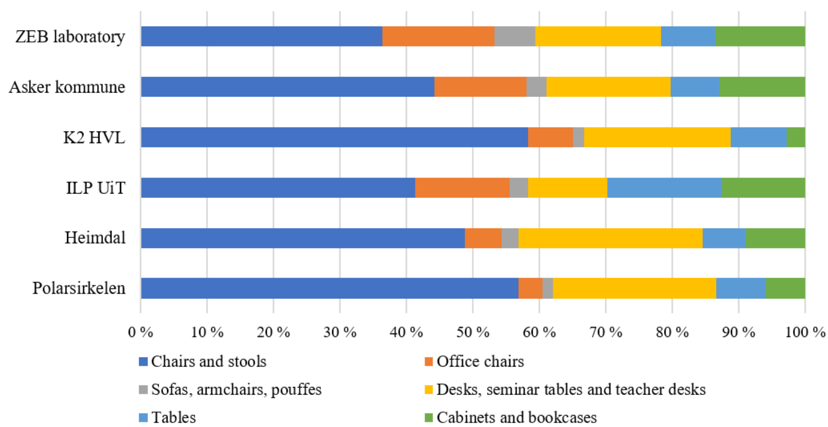


**Figure 4.3:** Share of furniture products for different furniture categories

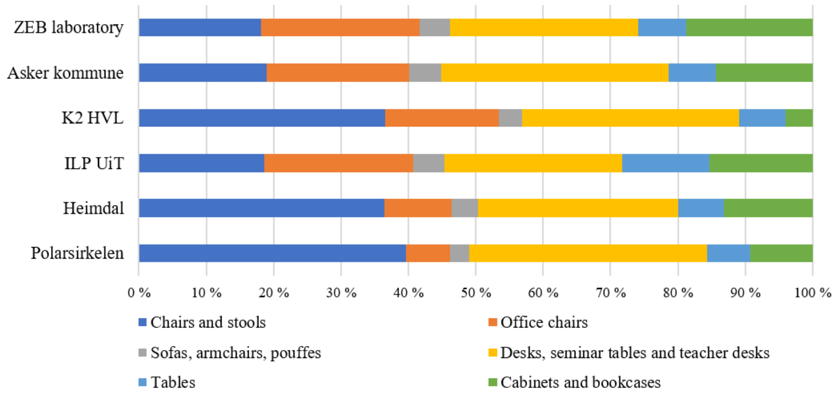


**Figure 4.4:** Share of cradle-to-gate emissions of different furniture categories

From Figure 4.3 it is clear that in all case products, chairs and stools have the biggest number of products of the furniture inventory with 36% or more in all case projects. Desks, seminar tales and teacher desk is another dominant furniture category. In Figure 4.4 it is revealed that even though chairs and stool have the highest amount of furniture products, they are not responsible for the highest share of emissions. Desk, seminar tables and teacher desks have a bigger amount of the emissions with share ranging between 26-35%.

## 4.2 Carbon mitigation strategies for furniture

In this section, research question 2 is answered. Different strategies for carbon mitigation are tested in all case projects to locate which are most effective for reducing the carbon footprint of furniture. The baseline calculations found in previous section are further used to create new scenarios with varieties in reuse, usage time, and refurbishment of the furniture products. Throughout this section, medium-efficiency values for the reuse processes are considered. No refurbishment is considered for Asker kommune in the strategies.

**Reuse**

To see the effect reuse has on the carbon footprint, the carbon footprint of the furniture inventory of all case projects have been calculated with different levels of reuse. It is chosen to investigate the reduction for a 50% reuse in the furniture inventory and for all reused furniture products. Figure 4.5 illustrates these results. The emissions displayed are from one exchange of furniture inventory. The illustration proves that efficient reuse processes could result in large reductions in the carbon footprint of furniture. In all case projects, the emissions are more than halved if all reused furniture products were to be chosen rather than all new.

In Figure 4.5 it is also seen that the 50% reuse scenario for K2 HVL has higher emissions than the baseline results, which accounts for 44% reuse. In the baseline calculations, the

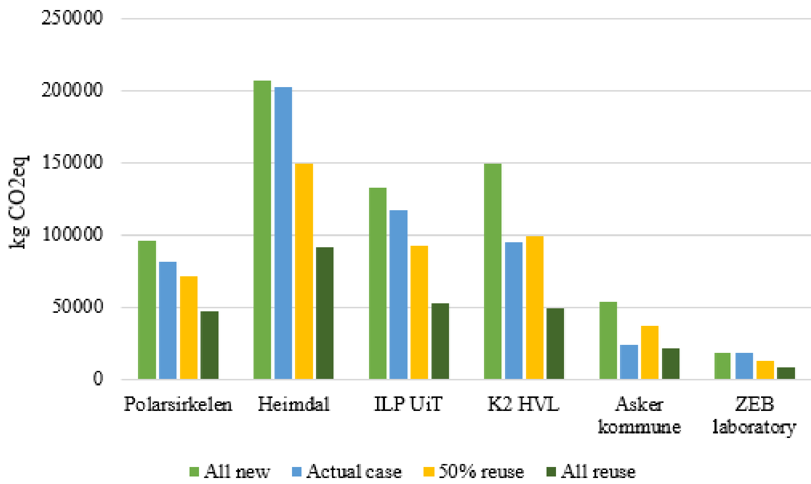


**Figure 4.5:** $CO_2$eq emissions of different reuse scenarios for the furniture inventory for all case projects with cradle-to-gate emissions from new furniture and medium efficiency values for emissions from reuse processes

share of reuse were investigated per furniture product. For the 50% reuse calculation, a general reuse of 50% for all furniture products was considered. Subsequently, the choice of which furniture products are reused could have a huge effect on the carbon footprint. In K2 HVL's case, it is clear that they have chosen wisely in which furniture products have been reused, as it contributed to a lower carbon footprint than if 50% of all furniture products were to be reused.

**Prolonged usage time and maintenance**

The given lifetime in all EPDs is 15 years. However, many furniture products could have a longer usage time than this. Figure 4.6 displays the reduction in carbon footprint following a longer lifetime for the furniture products in the building if they were bought new. In this analysis, all case projects are estimated to have all new furniture to properly see the effect of an extended usage time. All case projects halved their carbon footprint by extending the usage time to 30 years. This is an effective measure for reducing the carbon footprint of furniture. Extending even further leads to very low carbon footprints compared to the original results.

Figure 4.6 has included maintenance processes. To ensure a long lifetime, it is assumed that it is necessary with extra maintenance processes. The EPDs does not provide information beyond the functional unit of 15 years, and little use phase emissions are accounted for. If furniture is to be kept for longer than 15 years, it is considered that some maintenance is necessary for the furniture product with following emissions. The results of the maintenance processes have been defined and calculated and are presented in Table 4.8. It can be seen from the Table that the dimensions of the carbon footprint is small compared to the total carbon footprint seen in Figure 4.6.

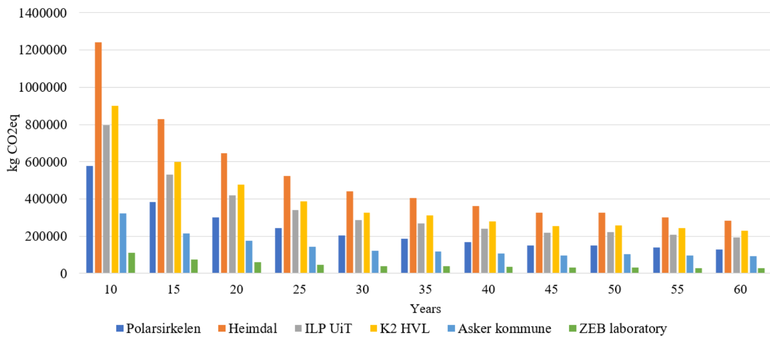


**Figure 4.6:** Cradle-to-gate $CO_2$eq emissions of furniture in all case projects with varying usage times of furniture and maintenance performed every 15 years

| **Case project** | **Maintenance emissions [kg $CO_2$eq]** |
|---|---|
| Polarsirkelen | 11 255.6 |
| Heimdal | 2 5594.6 |
| ILP UiT | 20 393.7 |
| K2 HVL | 26 630.2 |
| Asker kommune | 13 074.6 |
| ZEB Labratory | 3 161.9 |

**Table 4.8:** Carbon emissions of maintenance processes for each case project

Maintenance is assumed to be performed every 15 years. Following, if furniture is kept 30 years, maintenance is only performed once. This leads to low maintenance emissions for 30 year use, and more emissions for furniture that is kept longer. The reductions for a prolonged usage time is thereby smaller than if maintenance is not considered. The processes included for maintenance, are the same as included for refurbishment in Asker kommune. The processes attached to both are assumed to be same, but the carbon footprint of the processes can either be added to existing furniture inventory for the purpose of a longer usage time and upgrading, or as reuse for the purpose of styling and modernising reused furniture.

### Material and design choice

Because of the limited data on carbon footprint of furniture in a variety of materials, a mathematical modelling is not done for the carbon footprint of furniture in different materials. However, from literature and EPDs it is still possible to find some projections on how material choice could effect the carbon footprint of furniture.

In the literature study, several sources promoted wood as the material with least environmental impacts. This can be investigated verified with investigations of the wooden furniture in the EPDs as well. The furniture product with the most EPDs in the database is chairs. Chairs consisting of primarily wood and primarily plastic has been separated and analysed. From the Norwegian EPDs there was 16 plastic chairs and eight wood chairs available. Most of the chairs had seats and backs made of plastics or wood, and steel legs. The average for plastic chairs is found to be 18.31 kg $CO_2$eq while the average for wood chairs is 12.63 kg $CO_2$eq when considering cradle-to-gate emissions. The carbon footprint is included packaging for those who have included it. The wood chair has a lower carbon footprint even though the average weight of wood chairs, 6.54 kg, is heavier than the average of plastic chairs which is 5.22 kg. This is excluded the packaging. Plastic chairs have significantly less packaging with an average weight of 0.64 kg, compared to wood chairs that have an average weight of 1.82 kg on packaging.

The biogenic $CO_2$ consumption during biomass growth in forest activities is not included in EPDs. Including this could also affect the carbon footprint of wood chairs. For wood chairs, there were several products produced in Estonia. The plastic chairs were all produced in Norway or Sweden. The customer is estimated to be in Denmark or Norway for the LCA. In conclusion, even though the wood chairs are heavier, has more packaging and a longer travel distance, they still have a lower carbon footprint than the plastic chairs. This correlates with the findings in the literature study undertaken and strategies of eco-design.

Further investigation of one EPD, the S-1500 chair from NCP, reveals initiatives that have lead to a low carbon footprint from the product. In the production of this chair it has been used recycled plastic waste from Norwegian aquaculture farms, and the steel legs are partly recycled. This has resulted in the second lowest carbon footprint of all chairs in the EPD database, with cradle-to-gate results of 8.7 kg $CO_2$eq per chair. The only chair with a lower footprint is the Svea stacking chair from Helland. This chair is the only all wood chair among the Norwegian EPD database. The EPD informs that the wood does not have any potential for recycling. The same goes for the other wooden chairs from Helland, and also a wooden chair from the producer Fora Form. In S-1500 from NCP, all parts are recyclable. The lack of recyclable material could be a barrier to achieve circular economy and low carbon emission from avoided use of primary resources. However, if furniture is in solid wood and properly maintained, the furniture could last longer. Repair, remanufacturing and refurbishment could be processes which also keep wood furniture products in a loop.

**Strategies summarised**

The results of the strategies for each case project is presented in Table 4.9. The results if all furniture were to be bought new are also presented to give a proper evaluation of the effectiveness of the strategy. The results of usage time of 30 years has been included in the table as this is assumed to be a more likely scenario than having no exchange of furniture over 60 years. In the 30 year usage time scenario, all furniture is assumed to be bought new. The table display great reduction in results with implemented mitigation strategies. Compared to a furniture inventory of all new products, an all reused furniture inventory in average reduces the emission by 59%. Prolonging the lifetime to 30 years with maintenance reduces the carbon footprint by 46% in average.

| Case project | All new [$tCO_2eq$] | All new [%] | All reuse [$tCO_2eq$] | All reuse [%] | 30 year usage time w/maintenance [$tCO_2eq$] | 30 year usage time w/maintenance [%] |
|---|---|---|---|---|---|---|
| Polarsirkelen | 384.9 | 15.1% | 191.4 | 7.1% | 203.7 | 8.6% |
| Heimdal | 828.7 | 6.5% | 367.0 | 3.0% | 440.0 | 3.5% |
| ILP UiT | 531.9 | 5.7% | 213.6 | 2.4% | 286.4 | 3.2% |
| K2 HVL | 599.5 | 6.5% | 201.1 | 2.3% | 326.4 | 3.6% |
| Asker kommune | 214.9 | 12.5% | 87.7 | 5.5% | 120.5 | 7.4% |
| ZEB Laboratory | 74.4 | 6.1% | 34.1 | 2.9% | 40.4 | 3.4% |

**Table 4.9:** Emissions from furniture in tonnes $CO_2$eq and furniture share of total building emissions over 60 years of case projects with different mitigation strategies for furniture

A further way to investigate the effect of the mitigation strategies is to investigate the emissions of furniture per square meter per year as displayed in Table 4.10. The parameter kg $CO_2$eq/m$^2$/yr is a common parameter for buildings, and finding emissions from furniture in this unit could make it easier to add furniture emissions of the different strategies to building emissions for assessment. Using this unit also makes it easier to compare the environmental performance of the strategies without taking the building emissions into account. Table 4.10 display that reuse is the strategy which leads to least carbon emission per square meter per year. A 30 year usage time with maintenance also provides low emissions compared to a scenario where all furniture is bought new.

| Case project | All new [kg $CO_2$eq/m$^2$/yr] | All reuse [kg $CO_2$eq/m$^2$/yr] | 30 year usage time w/maintenance [kg $CO_2$eq/m$^2$/yr] |
|---|---|---|---|
| Polarsirkelen | 1.1 | 0.5 | 0.6 |
| Heimdal | 0.7 | 0.3 | 0.4 |
| ILP UiT | 0.9 | 0.4 | 0.5 |
| K2 HVL | 0.8 | 0.3 | 0.5 |
| Asker kommune | 0.7 | 0.3 | 0.4 |
| ZEB Laboratory | 0.7 | 0.3 | 0.4 |

**Table 4.10:** Results in kg $CO_2$eq/m$^2$/yr of case projects with different mitigation strategies

## 4.3 Challenges of furniture

To answer research question 3, several managers and handlers of furniture have been contacted to get a detailed view on the challenges the furniture industry and furniture management is facing. They have all confirmed that furniture is a rarely prioritised area in building design, planning, construction and operation. Literature study has also revealed several challenges to mitigation of environmental impact of furniture. A recurring event is that in most office spaces and business there is no responsible person or management for furniture, which makes initiatives towards reducing the carbon footprint of furniture more challenging (Asker kommune, October 2020; Eco Materials Collect, October 2020; Loopfront, October 2020; Lindbak, October 2020; Rom for flere, October 2020; Senab Eikeland, September 2020; Trøndelag fylkeskommune, October 2020).

Based on the conversations had it is clear that there is a wanted initiative to do something about furniture management and a need for knowledge on how to reduce the carbon footprint of furniture when furnishing offices and other non-residential buildings. In a conversation with Asker kommune and Trøndelag Fylkeskommune (TFK) it is confirmed that there is often no responsible person for furniture management in an office. Often it is the different divisions of a work place that is responsible for their own furniture, and they often have no information on how to treat and fix the furniture. There exist no database or common routines. Sometimes a janitor is responsible, and there can be variations to how dedicated a janitor or other is to fixing furniture rather than purchasing new when damages occur. Asker kommune also confirms that lack of information and knowledge about furniture and maintenance leads to well-functioning and easy repairable furniture being discarded. Loopfront, which handles reuse of furniture, emphasize that an issue with the furniture management is that there is no one responsible for a building's furniture inventory. In private buildings it is the ones who leases who are responsible for furniture, while in public buildings there is often no person in charge of furniture management. In Asker kommune and TFK's experience, if big changes and initiatives towards reuse and sustainability are to be taken there must be passionate employees taking initiative towards these changes. All these factor leads to functioning furniture being exchanged before reached lifetime, and mitigation options like reuse and refurbishment is out of reach.

Additionally, a challenge against sustainability occurs when offices are requesting offers from suppliers. There are often requirements attached to framework agreements to ensure fair competition, especially for communal projects. If no suppliers can supply reused or refurbished products, it can be difficult for the customer to make initiatives towards reducing their carbon footprint of furniture. In Asker kommune's case a social entrepreneur firm was used for the refurbishment, and the reuse was from their own offices, so there was no issue with competition and framework agreements. However, this is not common practice.

To deliver furniture to big institutions and offices, one is dependent on the supplier. The supplier distribute furniture in big quanta requested by the customer, and has a lot of influence on what furniture is available to the customer. In research and contributions to this project, some of the biggest suppliers in Norway has been contacted. All say that they are taking environmental precautions and that sustainability is an important area that they want to improve in their business. Senab Eikeland and Lindbak, two of the biggest suppliers of furniture in Norway, informs that they are both members of the common environmental organisations in Norway like Svanemerket, Grønt punkt and Miljøfyrtårnet and use EPD when possible (Lindbak, October 2020; Senab Eikeland, September 2020). Further, Lindbak says that only 30% of private corporations set environmental requirements to their framework agreements. Senab Eikeland confirms that the private sector show little interest. However, that 80% of the customers from public sector set environmental requirements for procurement of furniture. In another perspective, 50% of public actors has environmental concerns as award criteria in framework agreements, but only 10% of private actors set the same demand. A further challenge is that there is a lack of expertise in the field and the award criteria becomes unclear. Price is still the most important factor (Rom for flere, October 2020). Lindbak further says that they are not satisfied with available information on environmental footprint of their furniture products. Few producers has environmental information available. They say that they have sufficient information on about 1/8 of the furniture products they offer. Rom for flere says that the documentation available varies, with being really good for some products, like EPDs, to non existing environmental documentation. They also emphasize that it is the producers job to ensure green products while it is their job to communicate how their customers could make green choices.

The suppliers experience an increased amount of requests for reused furniture. However, delivering reused furniture products leads to additional and more complicated processes. The most efficient method is to directly reuse furniture. By direct reuse there is no need for added processes and materials for dismantling and refurbishment. Lindbak says that they yearn to have products which are not assembled by staples and glue. This makes dismantling and refurbishment easier. Following, if part of the furniture product is damaged or unfashionable, parts and textiles can easily be exchanged instead of throwing the product altogether. Both Lindbak and Senab Eikeland addresses the need for a platform for easier access to reused furniture. Senab Eikeland says that a challenge is to find a place for all the furniture a business wants to get rid of. Often it is difficult to find a new place for it or an intermediate storing facility and the furniture subsequently get destroyed. Rom for flere emphasize that the work for reuse has to start when the furniture is bought. In Rom for flere's experience, more control over the furniture bought and management of that furniture leads to more reuse.

In several conversations, standardization of office space is mentioned as an initiative to avoid discarding furniture before reached lifetime. If all offices had a standardized set of furniture, these furniture products avoid being damaged in moving processes, and furniture avoid getting have to exchanged and discarded because feelings of ownership to furniture products. A lack of requirements also leads to no one being in charge of furniture management in buildings and businesses. In many companies there a little to no systems for the furniture bought (Rom for flere, October 2020). More control over furniture inventory and management could increase the share of reuse and maintenance of the product. Another initiative presented by Lindbak is standardizing colors and materials to their furniture which camouflages dirt and filth. This will lead to the furniture remaining visually appealing for a longer period of time, and reduce the need to buying new furniture products. In Lindbaks experience there is a bigger focus on this from public actors, and there is increasing interest of this at bigger businesses as well.

Eco Materials Collect (EMC) is a Trondheim-based firm which handles disposal of furniture and other material. They confirm the lack of information on furniture and lack of proper management to ensure initiatives towards sustainability among furniture. They have experienced an increased interest in used furniture among offices and businesses the last couple of years. It is emphasized that this is a relatively new field, and furniture only recently has started to gain some of the attention it deserves. More businesses related to sustainable collection and disposal of furniture is necessary, and the end user are drivers of this change. They have several initiatives to reduce emissions from processes related to disposal of furniture. One measure taken is door-to-door transportation of materials in business relocation issues. This reduces emissions from unnecessary processes between uses of a product, like storage and transport to such facilities. EMC further cooperate with a factory which recycle wooden materials to chipboards. This practice avoids the material to first go through the local waste handling processes, and EMC is assured that the handled material is put to good use. An intermediate stay at a waste handling site will require more transport, storage and other processes, and the materials are easily polluted with other substances at these sites. An important prerequisite for successful recycling is pure material fractions, and this is often undervalued. Another matter EMC has implemented is assuring full containers and transportation units. EMC lastly point out that the biggest challenges is that no one has thought of the carbon footprint of furniture until recently. To do something about this, the mindset regarding furniture management must be changed. End users are important to make these changes along with passionate people in furniture management (Eco Materials Collect, October 2020).

Several managers of furniture have demanded a need for information and requirements from higher holds to take actions for decreasing the environmental burden of furniture. Lindbak says that platforms like Loopfront should be more available so that people can more easily procure and gather information on reused furniture. Also, Rom for flere mentions that a bigger focus on costs in the use phase combined with environmental records could be beneficial. There is too much focus on the initial cost today. As it is found that it is smart to procure long-lived furniture, it is a barrier that, especially for office chairs, these long-lived office chairs with environmental considerations in their design are often in the upper price range (Besch, 2005).

Chapter 5

# Discussion

This chapter will further evaluate and discuss the results found in the previous chapter. The discussion adds insight to the asked research questions, and study the cause of the varying results of the different case projects. The mitigation strategies are further reviewed and considered in light of findings from literature study and the challenges furniture management is facing. Lastly, an uncertainty analysis and discussion of the results is included.

## 5.1 Carbon footprint of furniture

Research question 1 was answered through obtaining results of the carbon footprint of furniture in the different case projects. These results show how significant emissions from furniture can be in a building perspective and how it varies with building type and furnishing strategy.

The carbon footprint of furniture in the case project revealed large carbon emissions that range from 74.4-811.5 tonnes $CO_2$eq for each building. Assuming that the results are representative for non-residential buildings, the contribution of carbon emissions from furniture in non-residential building is extensive. To face the pressing climate challenge, it is important that all substantial carbon emissions are acknowledged and mitigation strategies are implemented. Furniture has a contribution between 4.2-12.8% of the building carbon emissions in the case projects over 60 years, with an average of 6.8%. This is when accounting for reuse processes of medium efficiency. The results are in correlation with what was found in previous project thesis (Lauvland, 2020), and literature (Hoxha and Jusselme, 2017). This is a significant amount, and should be recognized as it demonstrated how furniture is an important part of building emissions in addition to the building functionality. It will be useful to consider furniture in carbon calculations of buildings as it can contribute to the carbon footprint of furniture to be acknowledged and for furniture to be a part of mitigation strategies of buildings. There exist many strategies for the building industry by both the EU and IPCC recognize, but no such strategies exist for furniture.

When analysing the furniture's share of emissions in buildings between the projects, it is important to consider the difference in estimated building emissions. As displayed in Table 3.2, there are large differences to the building emissions intensities. ILP UiT, K2 HVL, Heimdal and ZEB Laboratory have the largest building emission intensities. They are all considered to be low or zero-emission buildings. Low-energy performing and ZEB buildings often have high embodied emissions because of robust constructions to ensure low energy needs during the operational phase (Röck et al., 2020). K2 HVL had the highest building emissions, and this will lead to the share of furniture being lower, in addition to the high share of reuse at K2 HVL. The lowest building emissions intensities are Polarsirkelen and Asker kommune. These projects did not undertake environmental assessments of the buildings, and used reference buildings for calculations. The analysis of the reference buildings follow NS3720, but it is said that some emissions might be underreported in analysing after construction on existing buildings like this (Wiik et al., 2020). As a result, Polarsirkelen has the highest share of building emissions with 12.8 % when accounting for medium efficiency values for reuse. Asker kommune has a lower share of 6.5% due to their high amount of reuse.

To consider how the difference in building emission intensity affects the results on the share of building emissions, all case projects were given the same building emission intensity as seen in Figure 4.2. Polarsirkelen still has the largest share of furniture emissions in this figure. This is even though Polarsirkelen has a rather large amount of reuse with 30%. To understand the reason behind the large share of emissions from the furniture inventory of Polarsirkelen, other parameters should be investigated as well as the furnishing strategy of Polarsirkelen. In Figure 4.2, K2 HVL and Asker kommune which have a high share of reuse in their furniture inventory have low shares of total building emissions. All other case projects have a share of 10% or more of the total building emissions, which are significant results. This shows how the influence of furniture emissions on the total emissions of a building is widely dependent on the building emission intensity of the building.

Heimdal upper secondary school and ZEB Laboratory are both ZEB constructions. Following, the emissions from the construction and use of the building are compensated for during the usage time of the building. This is done by producing their own energy through solar panels or geothermal energy. In the results, it was estimated how much extra renewable energy needs to be produced at the site of the two projects. It showed that 104.0 MWh must be yearly produced at Heimdal, and 9.5 MWh at ZEB Laboratory. If furniture is to be accounted for in building emissions and part of a potential mitigation strategy for buildings, the emissions from these must also be accounted for in ZEB calculations. To produce these amounts of energy, an extension of the current energy source facilities of Heimdal and ZEB Laboratory might need to be installed.

To present a more nuanced comparison, the results in Table 4.7 was found. Aside from Polarsirkelen, it is seen that the ranking of the case projects is quite similar for carbon footprint per square meter and per product. K2 HVL and Asker kommune have a low carbon footprint for these values due to their high share of reuse in their furniture inventory. ILP UiT, which has a higher amount of reuse than ZEB Laboratory and Heimdal, has the highest results for kg $CO_2$ per furniture product, even though ZEB Laboratory has no reuse in the furniture inventory. This indicates that ILP UiT has chosen furniture of higher carbon footprint, and shows how greatly choice of low-emission furniture can affect the results as it has done for ZEB Laboratory. The table reveals that Polarsirkelen, which had the biggest share of emissions, proves more efficient when investigating emission per product. This inconsistency can be further explained by considering the number of furniture products per square meter. By further investigation, it is found that Polarsirkelen has 0.42 furniture products per square meter. All other case projects lie in the range of 0.26-0.35 furniture products per square meter. These results can also reveal if the building has unfurnished open space which results in high building emissions. The floor plans (see Appendix A.1) shows that Polarsirkelen has little open space. The floor plans of the other case projects show more open space, especially in Heimdal and K2 HVL. An increased amount of open space might reduce the amount of emissions from furniture per square meter, but will consequently increase the emissions of the building by constructing more open space which might not be put to efficient use. There is little furniture use in these areas, which are important for human activities in the buildings. Following, an efficient furnishing strategy might say more about the building emissions than the emissions from furniture. However, the ability to do so depends on the use of the building.

Some of the differences between the case projects are a result of the functionality of the building. This becomes obvious from the results of carbon footprint per user in Table 4.7. There are great varieties in the results, and clear differences between the type of buildings. Offices Asker kommune and ZEB Laboratory has the highest carbon footprint per user, while the university buildings ILP UiT and K2 HVL has the lowest carbon footprint per user. A university building like ILP UiT and K2 HVL has both full- and part-time students, and the flow of people is bigger, compared to an upper secondary school which will have the same users every day. An office will also have the same users every day, but likely take in more visitors. Offices in general also have more furniture products per user, as employees often have their own office space with office chair, desk and storage, in addition to shared meeting rooms and canteens. Asker kommune names their premises as a meeting place for innovation and teaching and is may expect to receive many visitors. ZEB Laboratory also takes outside visitors of students from NTNU. Thereby, these offices are in need of facilities to support this. A university building would not have a study space similar to an office space for all their students. Mostly, universities could not acquire a study space for all students in addition to auditoriums and group study rooms. And upper secondary schools have little study spaces for students outside the classrooms.

To find more detailed information about the carbon footprint of the furniture products in the case projects, Figures 4.3 and 4.4 was created. This illustrates the most dominant furniture categories and the most dominant carbon footprint of the categories. Chairs and stools are the most dominant furniture category in terms of the number of products but have a little carbon footprint per product. Office chairs do not have the biggest share of either number of products or carbon footprint, but it is seen that in all case projects, the share increases for the carbon footprint of this category. Hence, the necessity for office chairs should be considered. But this is dependent on the functionality of the building. In Polarsirkelen, chairs have the largest share in number of furniture products with 57%. Only 4% of the products are office chairs. This is a school, and it is clear that Polarsirkelen has only prioritised office chairs for the staff members and regular chairs for the students. This may have reduced the total carbon footprint. As a comparison, ZEB Laboratory, which is an office building, has 36% chairs and 17% office chairs. They could have benefited from exchanging some of the office chairs, as the carbon footprint share of their office chairs is the largest of all the case projects. Desks, seminar tables and teacher desks have a large share of the emissions in all case projects. The share of the carbon footprint is also large than the share in the number of products. Desks are often solid furniture which easily could be reused or refurbished. If they are made of solid wood, they could also last long. Initiatives of emission reduction could be targeted on furniture products which have large emissions.

From the results it is noticed some strategies implemented for the furnishing of the case projects that lead to low carbon footprints. Asker kommune had high ambitions for the carbon footprint of their furniture inventory. From the percentages of the share of emissions in the buildings, it might not seem like Asker kommune is performing greatly with their reuse- and refurbishment initiatives as they get similar results as many other case projects with furniture holding a 6.5% share of the building emissions. But when all case projects were given the same building emissions intensity in Figure 4.2, Asker had a share of 4.9%, while the other projects had shares between 7.8%-12.0%. This proves the efficiency of reuse and refurbishment for lowering the carbon footprint of furniture. ZEB Laboratory took initiatives to have low carbon footprint of their furniture. This gave results as ZEB Laboratory never has the highest results of the case project in any of the comparisons (see Figure4.2 and Table 4.7). The exception is for emission per user which is related to it being an office building. This is even though it is the only building with all bought new furniture. It should be further asked if the best strategy is to implement initiatives of buying new low-impact furniture or to focus on maintenance with long lifetime and reuse. In Table 4.10, ZEB Laboratory has one of the lowest carbon emissions when accounting for carbon emissions per square meter per year for all new furniture. However, this does not not measure with the low carbon emission of the all reuse strategy or longer usage times in the other categories. Yet, what strategy is easiest accomplished should also be considered. Due to the finding that information and services that facilitate reuse and maintenance are lacking, these processes might be complicated. At the same time, information about the environmental performance of furniture is also lacking but exists for some products. Therefore, it can be chosen to only furnish with these products through a regular procurement process. What strategy is most successful is further answered in the next section.

The projects analysed are all located in Norway, and the EPDs used are Norwegian. Following, the results might differ from other countries. Nordic countries are known to have high quality and design on their furniture and furniture consumption is extensive (Linkosalmi et al., 2016). 6% of Norwegian's expenses goes to furniture and household activities (Statistisk sentralbyrå, 2019). The desire Norwegians have for aesthetics and modern furniture, in addition to a high purchasing power, results in a large consumption and following environmental impacts. This reflects the furniture use in non-residential buildings as well. Norway has many ambitious projects with low and zero-emission buildings where initiatives are taken to reduce the carbon footprint of buildings (Wiik et al., 2020). The results found imply that furniture should be a part of this.

## 5.2 Carbon mitigation strategies of furniture

Table 4.9 illustrates how the strategies implemented on the case projects can be effectively used to reduce the carbon footprint of furniture in the respective case projects. There are considerable emissions that are saved through the presented mitigation strategies. In this section, research question 2 is further answered on with a discussion of the presented mitigation strategies.

**Reuse**
In literature and previous assessments, it is found that reuse is an effective measure to reduce the carbon footprint (Forrest et al., 2017; Loopfront, October 2020; Lauvland, 2020; Linkosalmi et al., 2016; Parker et al., 2015). The results found in this assessment confirms this, and there are considerably lower footprints with an increased share of reused furniture in all case projects as seen in Figure 4.5. An all reuse scenario lead to shares of under 3% for Heimdal, ILP UiT, K2 HVL and ZEB Laboratory. Using this strategy thereby effectively contributes to reducing the emissions of the building. ZEB Laboratory had initially no reuse in their furniture inventory. Having 50% reuse in the furniture inventory led to a reduction in emission of 27%, and for all reuse 54%. Thereby, in addition to choosing low-impact furniture, increased reuse could reduce the emissions of the furniture products of the ZEB Laboratory even further. For all case projects except Asker kommune, an all reuse scenario led to a 40% reduction or more compared to the baseline case. The most effective in addition to ZEB Laboratory was Heimdal and ILP UiT with a reduction of 55% and 54% respectively compared to buying all new. The results show that reuse is effective and more initiatives to include it should be promoted.

For the assessment of reuse in the baseline calculations, a variety of activities were included in the reuse process. This was important to illustrate the emissions that are related to reuse and to show that reuse is not a ”free pass” for emissions. Further, varieties were considered for the logistics of the reuse activities with high, medium and low-efficiency values. As seen in the results from the case projects, ensuring high-efficiency reuse values can be important for the results of the carbon footprint of furniture. Better planning of low storage and transport needs further lowers the footprint of furniture. These factors should be considered when choosing reuse to ensure a solution with as little carbon emissions as possible. Asker kommune had the greatest effect of different logistics of reuse. The difference in furniture emissions share in the total building emissions with high-efficiency values for reuse to low efficiency was 1.6%. Asker had the highest share of reuse, so changes in the logistics around reuse affects the results notably. K2 HVL also had a high share of reuse of 44%, but the driven distance between the old and the new building was only 2 km, and the furniture was transported directly with no storage. This resulted in reduced emissions from the reuse process, and small differences between the high and low-efficiency scenarios. For Asker information on distance driven and storage time was not available, and a general distance of 50 km was chosen and storage time of 6 months. These factors then contribute to higher emissions from reuse, and improving these would mitigate the emissions.

Figure 4.5 further reveals that for K2 HVL, the carbon footprint was lower for the baseline case with 44% reuse, than for the scenario of all furniture products having 50% reuse. This shows the significance of which furniture products are chosen for reuse. The contribution to the carbon footprint of different furniture products is revealed in Figure 4.4. Among furniture products which were reused at K2 HVL were working desks, sofas, conference chairs and office chairs. These are all furniture with a high carbon footprint compared to other furniture products used. Almost all the working desks, which have a carbon footprint of 96 kg $CO_2$eq per item, were reused. This is one of the highest carbon footprints of the furniture items, and is likely to have contributed to a large reduction compared to buying new. This shows how choosing the right products is an important factor for ensuring a low carbon footprint of furniture. By using information from EPDs, furniture with high carbon emissions can be targeted and used as a strategy to further ensure reuse.

For Asker, the reuse scenario was explored using reuse without refurbishment. The results show that reuse without refurbishment is more effective. This is to be expected as there are fewer processes involved. In the reuse scenarios, a share of the furniture has been estimated to undergo minor repairs, and some are not considered to undergo repairs. How realistic it is that such a large amount of furniture is reused without any modernisation or repairs is not certain. There is little information found about the environmental effect of refurbishment and maintenance in literature and how often it is undertaken. Furniture will get damage and tear from the reuse processes of exchanging premises, storage and transportation. It is assumed that most furniture will need some kind of tending during its lifetime, and refurbishment processes should therefore be considered.

For an increased amount of reuse to be possible, there are many factors which must be considered. As found through conversation with different businesses who buy big quanta of furniture for non-residential buildings, it is difficult to buy used furniture on framework agreements. The reuse in all case projects, except for Asker kommune, had been brought from the business or school's old premises to be used in the new. In other words, they did not have to go through a supplier to implement reuse in their furniture inventory. Asker kommune was the only case project which had bought reused products from outside sources to be used in their furniture inventory. This was an ambitious project which aimed to have mostly reused furniture, and the persons in charge took extra measures to ensure a high amount of reuse. For companies, it is often easier to set the requirements for their furniture products and have the supplier offer furniture meeting the demands. More suppliers should facilitate for offering used furniture as well as new products. However, a furniture producer's business opportunities are diminished by an increased amount of reuse. As the supplier is dependent on the producer, this matter can be conflicting.

In the allocation approach chosen for reuse, the production emissions are allocated to the first user, and the emissions for reuse processes as well as end-of-life emissions are allocated to the next user. The production process is accountable for about 70% of the total emissions of the furniture product, and thereby the first user is allocated the largest emissions. It should be asked who is responsible for the furniture product being used a second time and the following environmental benefit. The product would not have been reused if not the first user made a decision to send the product to a place where it can be reused rather than for disposal. Still, the second user gets credited by being allocated a smaller share of the total emissions of the furniture product. The next user is allocated no emissions from production, but as a user of furniture, the second user can be said to have a shared responsibility for the furniture product being made. This enlightens the missing information on how to properly allocate reused products between users and how to calculate the emissions. For furniture to be properly implemented in environmental analysis, allocation methods that best describes the total emissions and responsibility must be investigated and developed.

**Prolonged usage time**

The effect of a prolonged usage time to furniture leads to significant reductions in carbon footprint in all case projects. It is clear that the reductions are larger in the first years. After several years pass, the total benefits from a longer lifetime is reduced. This correlates with the number of exchanges. Keeping furniture for 10 years versus keeping it for 15 years is equivalent to exchanging the furniture inventory six times rather than four. The reduction in carbon footprint from a 10 year lifetime to a 15 year lifetime is thereby large and in e.g. Heimdals case a reduction of over 400 tonnes of $CO_2$eq. The maintenance emissions however are increased with a longer lifetime. Considering the dimensions of the maintenance processes displayed in Table 4.8 compared to the dimensions of Figure 4.6, the increased maintenance emissions do not diminish the positive effect of a longer lifetime. In terms of the total share of building emissions, the lifetime extension to 30 years proved most efficient in Polarsirkelen and Asker kommune which reduced their share from 15% to 8%, and 13% to 7% respectively. This is correlated to the low building emission intensity of these buildings. The rest of the case projects all have a reduction in share at around 3% for furniture with a lifetime of 30 years when all is bought new which is a low share compared to baseline results.

The results of this strategy imply that longer lifetime of furniture products with maintenance is more environmentally profitable than buying new. Nonetheless, it is seen that it has a cost. To ensure long-lived furniture, there will be a dependence on maintenance and repairs which will lead to increased use phase emissions. If mitigation strategies for furniture is to be implemented, it is important that all processes and emissions related to furniture are revealed. The literature study indicates that there are little emissions accounted for in the use phase of existing environmental analyses on furniture. When considering the short usage time of furniture today, the use phase emissions probably are low. However, if longer usage times are promoted, the following emissions of this should be acknowledged, as well as the emissions savings. A reason for the short usage time of furniture today is the poor consumer knowledge, and the desire for modern furniture products. Refurbishment and modernisation of existing furniture inventory might be another solution to this.

If furniture is to be a part of a circular economy with long lifetimes, there will likely be increased carbon emissions in use phase from maintenance and repairs. Some EPDs do include use phase emissions. Among these use-phase emissions, vacuum cleaning of textiles once a month is the only one found. In several EPDs, it is declared that the PCR does not provide detailed guidelines on what should be included in the use phase. The ”suggested” use phase emissions in the PCRs of the EPDs are; B1: Maintenance, B2: Repair, B3: Replacement, B4: Operational energy use. No further description is given. Most furniture does not run on energy, and energy use would not be relevant. The exception is electrically adjustable working desks, but this is not accounted for due to lack of information on this energy use. It is assumed that a lot of furniture products is exposed to maintenance, repair and replacement, and some energy use will follow these processes as included in this assessment. EPDs should address these use phase emissions, as well as the stated lifetime of furniture. To reduce carbon emissions we are reliant on consuming less, and the need for refurbishment and maintenance processes will increase.

To make maintenance and refurbishment more common, information and services attributed to the processes must be made more available. Furniture of good quality could last longer, and it should be questioned how furniture management, producers and users address this issue, in addition to EPDs approach on lifetime. However, the biggest challenge might not be the defined lifetime from producer or declaration, but the treatment of the furniture by the furniture user. As found in literature, many consumers do not get sufficient information on maintenance and precautions when buying furniture and do not look up this information at own initiative. Several researchers, managers and actors in the furniture industry emphasize the need for more information about these processes. The furniture industry is predominantly SMEs. This can constrain the furniture industry to implement more services like repairs and take-back due to lack of access to finance, expertise and infrastructure in these SMEs (Forrest et al., 2017).

For environmental benefits of furniture, the consumer is responsible to maintain furniture and avoid large consumption. At the same time, producers could facilitate decreased emissions from furniture by applying eco-design. Besch (2005) emphasize that important strategies for long usage time is design for durability, adaptability, compatibility and timeless design are important for office furniture. Making long-lasting furniture which is easily maintained, with spare parts easily available would make it easier. In addition, proper information on these processes should be accessible. This would decrease the emissions and make it easier to keep furniture in the loop.

**Material and design choice**

No calculations for the carbon footprint of furniture with a different choice of materials is undertaken in this study due to the lack of data for such an analysis. Still, some conclusions could be made to show how different choice of materials would affect the carbon footprint. The findings from the EPDs reveal that wooden chairs have less carbon impact than chairs of plastic and mixed materials. This is supported by the findings in the theory section, which reveals that wood is the material used in furniture with the least environmental effects. However, the wooden chairs and their packaging has a higher weight compared to plastic chairs, and improving this could lead to a lower carbon footprint. To use material choice as a mitigation strategy, the low carbon materials and areas of improvements in furniture production must be located. As previously found, finishing processes, and the production of some materials have bigger environmental consequences than others. More use of solid wood and less use of chemicals and painting will lead to lower environmental impacts from the furniture products. As for instance Figure 4.4 show, the right choice of furniture product can be important to lower the total carbon footprint of furniture.

It was found that the S-1500 chair from NCP had a low carbon footprint and all recyclable parts. However, the S-1500 chair is more expensive than chairs of similar design from the same producer (NCP, 2020). A further challenge is to make the environmentally friendly material choice more affordable. It was found that producers tend to use cheaper materials which are materials of poorer quality. This can limit the potential for the mitigation strategies presented and the use of environmentally friendly materials.

An evaluation of all mitigation strategies reveal that both lifetime extension and prolonged usage time are effective mitigation strategies for reducing the carbon footprint of furniture. It is seen from Tables 4.9 and 4.10 that all reuse provides better results than a 30 year usage time. In the all reuse calculation, production emissions are never accounted for. The allocation chosen for reuse processes only includes emissions from reuse processes and end-of-life processes. This leads to very low emissions for a reuse scenario. Material choice and eco-design of furniture as a strategy for furnishing of buildings must be further investigated, but it is clear that it can have an effect on the total carbon footprint of furniture. It was important in this project to emphasize that reusing, prolonging lifetime and refurbishment is not done without emissions, and one must be aware of the effect of these processes. By increasing awareness to these measures it is easier to make them more efficient and achieve even lower carbon footprints of furniture.

## 5.3 Challenges of furniture

When attempting to answer research question 3 it became obvious that several actors of the industry and furniture managers experience a lack of data and information about furniture, its environmental impact and furniture management. This was also a recurring challenge in the research for this project. This gap in knowledge affects both implementations of environmental analyses and mitigation strategies for furniture. A crucial element for overcoming these challenges is an increased information flow. Without this foundation of information, it is difficult to further undertake environmental analyses and create mitigation strategies. Subsequently, there must be improvements to furniture management in buildings in initiatives to use environmental analyses and mitigation strategies.

**Challenges to implementation of furniture in environmental analysis**

The first part of research question 3 on the challenges of implementing furniture in environmental analysis is discussed in this section. Conversations with suppliers revealed a missing availability to environmental information on the furniture they supply and a want for more information. To provide such information and environmental data for furniture, environmental analysis and evidence are needed. A producer is in this case responsible for transparent processes, and for creating EPDs. EPDs are the best available environmental documents on furniture products and are based on LCA. They can make it easier to further implement furniture in environmental analysis of the building, or for calculating the carbon footprint of furniture. For more EPDs or similar environmental information to be available, suppliers and other purchasers can set more requirements to their producers. At the same time, a supplier delivers based on the customer demand. The research revealed that many customers of suppliers did not set any environmental requirements for the procurement of furniture. Developers and tenders of non-residential buildings can be a part of the process by setting more environmental requirements.

There is a huge variety within furniture products. The Norwegian EPD Foundation has 200 EPDs on furniture available, and international registers have 90 EPDs available (The International EPD system, 2020). This does not cover the total range of furniture products that exist by far. The case projects were highly reliant on averages as the EPDs did not cover the products of the furniture inventories. The large volume and variety of products within that volume also complicate inclusion of furniture in environmental analysis. It is seen from Figure 2.2 and Table 2.2 that the carbon footprint of a furniture product vary greatly. It is not easy to claim a definite carbon footprint for furniture products as it will vary more greatly with bigger volumes of furniture.

In chapter 2.6, several methods for allocation was presented for the inclusion of reused furniture in environmental analysis. It exists a lot of literature on the implementation of recycling in environmental assessments, but there should be more for reuse. There are other processes involved in reuse operations, and the literature search showed that more investigations are needed on these processes as well. Without sufficient information and established methods for reuse of furniture, the motivation to do environmental analysis could decrease.

There are no requirements or policies regarding sustainable furniture use for public and private actors, i.e. there is no incentive to take actions for reducing the carbon footprint of furniture. From conversations it was revealed that if there are no incentives from the outside, there will be less initiative to do something about furniture management and to increase reuse and recycling of furniture. It is important to have policies and criteria for improving the environmental burden of furniture production and industry (Donatello et al., 2020). Locating how to improve the environmental burden is done through environmental analysis.

Lastly, furniture is not considered as a part of building inventory that must be taken into account in a building LCA. To make furniture a part of building environmental analyses like LCAs, more information and easier methods are needed. A more detailed method to find the carbon footprint of furniture within a building than what is undertaken in this thesis could be to do a full LCA of every furniture product within the building together with the building LCA. This is a highly time and resource-consuming process and was not possible within the time frame of this project. However, the presented method with matrices and average data on furniture manages to find the carbon footprint of furniture and locate hotspots. Findings from the assessment can be used to create strategies for reducing the carbon footprint of furniture. However, a combination of building and furniture in a gathered LCA would be highly beneficial. Other impact categories could be investigated in such an assessment as well. Because of the complexity of LCA and the need for extensive amounts of data to conduct the assessment, some argue that there is a need for a simpler approach (Zhao et al., 2012). This thesis presents such an approach. Another important initiative to make the environmental assessment of even higher quality is to produce more LCAs of furniture and add to LCA libraries for an easier implementation of furniture products in a LCAs of buildings. OneClick LCA is an LCA software which imports EPDs to do the LCA calculation. Thus it is possible to import the furniture EPDs to a building LCA and thereby create a building LCA including furniture. For this method, it is necessary that it exist EPDs of all furniture products of the inventory. The lack of furniture management and knowledge on furniture inventory among furniture managers will perhaps make it more difficult to undertake an environmental analysis on existing inventory. If it is a building of tenders, it is more difficult for a developer to take part in analysis and decisions regarding furniture on the premises.

To summarize, the most important findings of the challenges to environmental analysis is presented below.

- Lack of information on the environmental impact of furniture
- Huge varieties within furniture products and large volumes
- No standard for inclusion reuse and recycling of furniture products in environmental analysis
- Lack of environmental policies and requirements regarding furniture
- Furniture not included in standards for environmental analysis of buildings

**Challenges to mitigation strategies for furniture**

The second part of research question 3 regards challenges of the assessed mitigation strategies, and the limitations found are further discussed here.

The furniture suppliers informs that there are increasing requests for reused furniture. Nonetheless, it is more complicated than today's common practice of procuring furniture from the same producers and in turn offering those to the customer. It will require new practices and this can cause both supplier and customer to lose motivation for the initiative. Many of the suppliers have good intentions with e.g. wanting to avoid furniture attached with glue to ensure easier dismantling and increased reuse and refurbishment. This is an easier practice which suits the common practice with only some additional requirements. However, as long as the producers are not following this example, the supplier will not be able to offer it. The supplier must set demands, and the producer must make changes. In addition to being an obstacle to implementing environmental analysis of furniture, lack of environmental information on furniture leads to barriers for mitigation strategies as the customer or supplier does not know what to choose or recommend. As the suppliers experience a lack of environmental criteria on furniture from customers, it seems like many customers need more time to adapt to strategies and changes in furniture procurement. It is found that price is the most important factor for the customer, and thereby it is necessary to make the greener option more affordable.

In addition to environmental benefits, reuse and recycling has many benefits to society by providing cheaper products to people who cannot afford costly products. Because the benefits of recycling and reuse are difficult to quantify or implicit, it can be difficult to justify a case for funding by authorities or others to make these actions possible. In other words, it is necessary to provide better tools for measuring these benefits (Alexander and Smaje, 2008). EPDs are an enormous help toward ensuring valid environmental documentation needed to meet potential requirements. Providing EPDs of products is an important future challenge for suppliers (Linkosalmi et al., 2016). EPDs could simplify the process of providing environmental information on products for SMEs as new regulations require (Fet et al., 2009).

Keeping furniture for a longer period of time is shown to be an effective measure. However, lifetime extension strategies do not match with traditional business models (Besch, 2005). Maintenance and repair services provided by producers or retailers can seem counterproductive, as their main goal is to sell as much furniture as possible. However, many retailers and producers offer it for environmental benefits, which attracts customers. An example is Lindbak, which provide information on how maintenance and repair processes can be undertaken for their customers. In addition, they provide a service telephone and professional help that can assist the customer if the furniture needs upgrade and fixing. Lack of storage is another issue, and more efficient reuse processes could eliminate this need. Suppliers and producers are requesting a platform to make all the processes easier, available and more efficient.

To reduce the carbon footprint of furniture, the whole life cycle of a furniture product must be evaluated. Initiatives that make the processes of the life cycle more efficient will ultimately result in lower emissions from the furniture product. EMC has done so by avoiding intermediate and unnecessary processes as storage, transport and using local waste handling. This ensures a longer lifetime of the product with as few processes undertaken as possible. Environmental awareness of furniture is new. An increased interest from customers is positive, and the industry must follow. Another issue, presented by EMC, is to ensure proper recycling. There is a need for pure raw materials, and that the materials have not been contaminated in the recycling process.

For the customer and user of furniture, aesthetics is an important aspect (Postell, 2012). The aesthetics of a furniture product reflects the user of the product, and it exists countless designs to do so. A company that wants to appear attractive and to gain customers and interest, will want their furniture inventory to support that goal. Thereby, it can be questioned whether offices and other non-residential building are willing to maintain their furniture for 30 years or procure reused products, no matter the environmental benefits. Most companies exchange their furniture for aesthetic reasons, and not because they are worn out (Besch, 2005). 25% say they exchange furniture even though they are not worn out because they want new furniture. It is also found in this survey that newer generations are more inclined to buy new furniture (Forbrukerrådet, 2013). This is an important future challenge to the mitigation strategies and can be met by implementing more timeless designs and eco-design when developing furniture products. There is a need to change the furniture user's mindset around furniture and aesthetics, and furniture users should adapt to a circular future. Environmental thinking and considerations must be more attractive than only the appearance of the product. The biggest challenges is listed below.

- No common practice for furniture management and environmental considerations to furniture in non-residential buildings
- Lack of availability of reused furniture and practice for implementing reuse in furniture inventory for non-residential buildings
- Conflicts with traditional business models
- Lack of knowledge about efficient reuse, refurbishment and prolonged usage time processes
- Customers attention to aesthetics and following trends

Additional strategies that should be investigated as mitigation strategies for furniture are remanufacturing and leasing of furniture. Leasing can lead to furniture products having intensive use with multiple usages and over a long period of time. Leasing of office furniture is especially convenient due to the amount of furniture needed at the facilities. If the furniture producer still owns the furniture product, the producer gain incentive to facilitate a longer lifetime for the product (Besch, 2005). It is difficult to find data on the exact environmental effect of leasing furniture, but it is being tested as green initiatives in several pilot projects. The implementation of the service could however be challenging as the furniture industry being predominantly SMEs can constrain leasing due to lack of financial funds and infrastructure (Forrest et al., 2017).

Remanufacturing is another strategy that should be further investigated as an environmental strategy for furniture. Office furniture is suitable products for remanufacturing and can be embedded with supportive business models as leasing (Parker et al., 2015). The biggest obstacles to remanufacturing of furniture are volume and accessibility to products, customer recognition and legislation restrictions. The last years it has been observed that the trust in the quality of remanufactured products has increased on the customer side. This gives encouragement to further increase remanufacturing processes (Parker et al., 2015). Tax or environmental subsidies could further encourage more remanufacturing and leasing (Parker et al., 2015). Life-cycle costing is another tool which can be important to further understand the depth of this subject and create strategies for the furniture industry and consumption. In previous studies, furniture managers showed interest in knowing the cost of mitigation strategies for them to be feasible (Lauvland, 2020).

Together with the strategies presented, considerations should be made to how the future is going to change the furnishing of offices and schools. There is increased use of digital meetings and there is a need to provide facilities for this change. It was found in Lauvland (2020) that shared offices had lower emissions from furniture than private offices. This is assumed to apply for open space offices as well. With increased use of digital meetings, there might be a need for more private rooms. On the same note, there might be less need for several meeting rooms which may be constructed to welcome outside visitors for meetings. Carbon emissions from travel will also be saved. For schools and universities, there might be an increase in digital lectures, which could decrease the number of classrooms needed. Following, the difference in emissions from furniture in private offices, shared offices and open space offices should be further investigated, as well as the difference in emissions from furniture in classrooms, study rooms and private study spaces. All this should be done with considerations to the modern office and teaching facility in mind.

Finally, the adaptability of the strategies for furniture managers and furniture users must be considered, and strategies laid out for this implementation. Trends show that customers are beginning to be more aware, and demand greener solutions. When consumers set demands, the industry must follow. But it can take time. To speed up this process, an important element is that policies, restrictions and requirements are set from legislators for the furniture industry and furniture managers to gain an incentive to contribute to reducing emissions from furniture. This is an important starting point for future decreasing the carbon footprint of furniture.

## 5.4 Uncertainty analysis

An evaluation of the accuracy of the assessment undertaken is included in this section. In this assessment, LCA calculations of buildings based NS 3720 ”Method for greenhouse gas calculations of buildings” is combined with furniture EPDs from The Norwegian EPD Foundation. The building calculations based on NS 3720 and furniture EPDs are both based on attributional LCA, which is an important prerequisite. It is taken into account what products are included in NS 3720 through NS 3451 ”Table of building elements”. By that, it have been ensured that products included in the calculations of furniture has not already been accounted for in building calculations. The combination of these to find the carbon footprint of furniture is thereby considered valid. In addition to these sources of data, processes have been added for the reuse process and refurbishment and maintenance process. Some of the activities included in these processes, as end-of-life processes, repairs and paint, have been collected from EPDs of The Norwegian EPD Foundation. Transport and storage activities and the following amount and carbon impact of these have been collected from literature search. There should be further research to ensure that all furniture products and processes related to furniture can be found from the same sources and are undertaken by analysis of the same basis. Further, elements of the chosen method and input data used can be challenged, and results vary with different approaches taken. The biggest uncertainty and variations factors that are found for this assessment are listed below.

- Choice of allocation method
- Missing emissions in the carbon footprint of furniture products due to missing information and averages used
- Reuse and refurbishment processes solely based on estimates and assumptions
- Furniture products in the building not being accounted for due to missing information or inconsistencies between the inventory list and floor plans

There are several approaches which can be chosen to calculate the carbon footprint of furniture which all might lead to different results. In the assessment undertaken an approach for reuse where the first usage of the furniture product was given the production emissions was chosen, while second usage was given transport, storage, repair and end-of-life emissions. In the project thesis leading up to this assessment, a different approach was chosen. In this assessment, reused furniture was estimated to share all life cycle emissions 50/50 with the first lifetime, as explained in Section 2.6. To investigate variations in the results of this assessment, this approach is tested on the case projects and the results investigated. The results are displayed in Figure 5.1. ZEB Laboratory is not included in this analysis as there is no reuse in the furniture inventory.

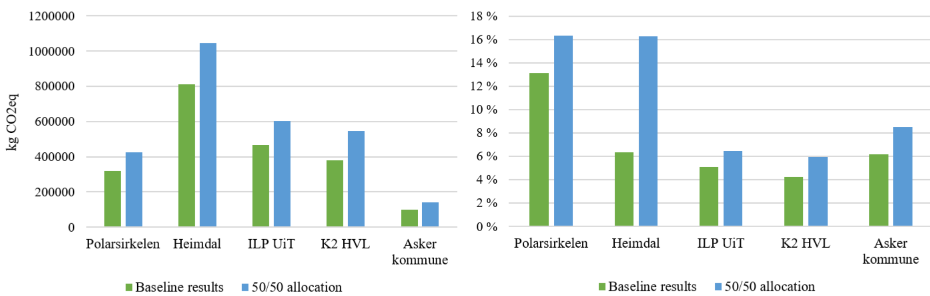


**Figure 5.1:** a) Carbon footprint of furniture and b) furniture share of total building emissions with different original method and 50/50 allocation

The illustrations show that the carbon footprint of furniture is increased in all case projects if the 50/50 allocation method is considered. This is due to the fact that reused furniture products now have a bigger carbon footprint, but also because the new furniture products are calculated with end-of-life emissions, as these emissions are not separated between the lifetimes. This is visible in e.g. Heimdal, which has an increase in the share of total building emissions by 10% even though the reuse share of the furniture inventory is only 4%. With this new method of allocation, Heimdal passes 1 million kg of $CO_2$eq emissions. By this method, no additional reuse processes are included, such as transportation, storage and refurbishment. By this, it seems reuse comes at a "cheaper price" if you account for the total emissions overall usage times. But in reality, processes related to reuse will have carbon emissions. Further, it can be asked who is responsible for the additional emissions, and where they should be allocated. This shows that the choice of allocation method and approach has great effects on the final carbon footprint of furniture. This is important to consider for further development of environmental analyses of furniture. As theory has shown, there is no consensus on one method to how reuse should be accounted for in LCA and environmental analysis.

When calculating reuse processes, there has been made estimates to transport, storage and repairs. None of these values has been possible to collect directly from the case projects, due to missing information. The exception is the driven distance of reused furniture in some of the case projects. Different estimates or collection of real-life results for each case project may therefore lead to variations in the original results for the carbon footprint of furniture. As the reuse calculations rely on more variables than the calculations for newly bought furniture, the results for reused furniture are of greater sensitivity than results from calculations of all new furniture.

It varied how detailed the information gathered from the case project was. This can further lead to inaccuracies in the results of case projects if missed information is replaced with averages of EPDs and estimations, in addition to faults in whether a product is reused or not. E.g. K2 HVL has detailed drawings on which pieces of furniture was reused, in addition to a detailed inventory list for the furniture products. This leads to a more detailed list of products and estimates for reuse. This is clear from the carbon intensity vector $\mathbf{c}_{\text{furniture}}$ which for K2 is of dimensions 37x1, while $\mathbf{c}_{\text{furniture}}$ for e.g. Polarsirkelen is 17x1 due to less detailed inventory list. Further, the total amount of furniture products counted was 15 561. With many elements comes a risk of some deviations in the numbers. There are also other uncertainties attached to the given information. Data gathered from Asker kommune informed of 1600 furniture products, but in the counting of the floor plan there was counted 1200 furniture products. There can be several reasons for this. Products can be missing from the floor plans, or the definition of furniture product can differ. In this assessment, clothing racks and waste bins have been excluded, and this can also be a cause of deviation in the number of furniture products. Additionally, there could be uncertainties to results due to inconsistencies in the inventory list and floor plan. This was the case in several projects. In some projects a detailed inventory list was non-existent, and furniture products were found by using pictures of the used products, which lead to an added uncertainty to the actual number of furniture products.

# Chapter 6

# Conclusion

The carbon footprint of furniture has been found in six different non-residential buildings, and the results show that furniture has a significant contribution to the carbon emissions of these buildings. This study has shown that furniture inventory in the buildings has an average contribution of 6.8% of the total building emissions if kept for 15 years with varying shares of reuse. This is when accounting for cradle-to-gate emissions for new furniture, and accounting for emissions from reuse processes and end-of-life for reused furniture. To ensure alignment with global targets of reduction of emissions from the building sector, furniture should be given more attention and be implemented in environmental analysis of buildings. Further, measures must be taken to reduce the carbon footprint of furniture products.

Reuse and long usage time of furniture have proved to be two efficient methods for mitigation of carbon footprint of furniture. Material choice and increased refurbishment can support these actions to ensure an even lower carbon footprint of furniture and these areas in knowledge needs more investigation. For these strategies to be implemented and long usage times ensured, an increase in information about the environmental impact of furniture and mitigation strategies must be further assessed and communicated. There is potential for reducing carbon emissions, but challenges must be overcome.

There is a need for change in every stage of a furniture lifetime. Producers must provide eco-efficiency to provide a responsible production, suppliers must provide sustainable furniture options to users, and facilitate for follow-up on maintenance and reuse. Developers must consider furniture in their projects and users must implement reused furniture products, apply maintenance and ensure long usage time for the furniture products. It is clear from this project that there is far too little attention brought to the environmental impact of furniture, mitigation strategies and its contribution to building emissions. The motivation for environmental assessments of furniture has been raised with every lack of data during this project.

# Bibliography

Abrahamsen, A.S., Bergh, M., 2011. Energibruk i bygninger for tjenesteytende. Technical Report. Statistisk Sentralbyrå.

Alexander, C., Smaje, C., 2008. Evaluating third sector reuse organisations in the UK: Case-studies and analysis of furniture reuse schemes. Resources, Conservation and Recycling 52, 719–730. doi:10.1016/j.resconrec.2007.09.005.

Antov, P., Vasileva Pancheva, T., 2017. Carbon Footprint of Furniture Products, in: Management and sustainable development 2017.

arkitektur og design AS, M., 2018. Høgskulen på Vestlandet - Møbleringsplan.

Asker kommune, 2020. Asker kommune sparer millioner på ombruk. URL: https://www.asker.kommune.no/klima-og-miljo/aktuelt-om-klima-og-miljo/ombruksprosjekt-i-asker-kommune/. (Accessed: 10.12.2020).

Asker kommune, October 2020. Conversation with Anja Østerli at Asker kommune.

Askham, C., Hanssen, O.J., Gade, A.L., Nereng, G., Aaser, C.P., Christensen, P., 2012. Strategy tool trial for office furniture. International Journal of Life Cycle Assessment 17, 666–677. doi:10.1007/s11367-012-0406-y.

ATD Home Inspection, 2020. Average life span of homes, appliances, and mechanicals. URL: https://www.atdhomeinspection.com/advice/average-product-life/. (Accessed: 18.09.2020).

Babarenda Gamage, G., Boyle, C., McLaren, S.J., McLaren, J., 2008. Life cycle assessment of commercial furniture: A case study of Formway LIFE chair. International Journal of Life Cycle Assessment 13, 401–411. doi:10.1007/s11367-008-0002-3.

Bakshi, B., 2019. Sustainable engineering principles and practice. Cambridge University Press.

Besch, K., 2005. Product-service systems for office furniture: Barriers and opportunities on the European market. Journal of Cleaner Production doi:10.1016/j.jclepro.2004.12.003.

Cordella, M., Hidalgo, C., 2016. Analysis of key environmental areas in the design and labelling of furniture products: Application of a screening approach based on a literature review of LCA studies. Sustainable Production and Consumption 8, 64–77. URL: http://dx.doi.org/10.1016/j.spc.2016.07.002, doi:10.1016/j.spc.2016.07.002.

Cornell, P., 2002. The impact of changes in teaching and learning on furniture and the learning environment. New Directions for Teaching and Learning 2002, 33–42. doi:10.1002/tl.77.

CPSC, 2008. 16 CFR Part 1634 Standard for the Flammability of Residential Upholstered Furniture; Proposed Rule. Federal Register 73, 1–52.

Digitaliseringsdirektoratet, 2020. Veiledning for grønne og sirkulære anskaffelser av møbler. URL: https://www.anskaffelser.no/sites/anskaffelser2/files/veiledning-gronne-sirkulare-anskaffelser-mobler.pdf. (Accessed: 25.08.2020).

Dokka, T.H., 2011. Proposal for CO2-factor for electricity and outline of a full ZEB-definition 4, 1–7.

Donatello, S., Cordella, M., Kaps, R., Kowalska, M., Wolf, O., 2020. Are the existing EU Ecolabel criteria for furniture products too complex? An analysis of complexity from a material and a supply chain perspective and suggestions for ways ahead. International Journal of Life Cycle Assessment 25, 868–882. doi:10.1007/s11367-019-01601-1.

Eco Materials Collect, October 2020. Conversation with Helge Gundersen at Eco Materials Collect.

Ekenstam, M., 2020. UiT, nybygg for lærerutdanning. Som bygget uten solceller - Klimagassutslipp, NS3720.

Ekvall, T., Tillman, A.M., 1997. Open-loop recycling: Criteria for allocation procedures. International Journal of Life Cycle Assessment 2, 155–162. doi:10.1007/BF02978810.

Enova, 2017. Enovas Byggstatistikk 2016. Technical Report.

Environment Protection Authority, 2017. The waste hierarchy. URL: https://www.epa.nsw.gov.au/your-environment/recycling-and-reuse/warr-strategy/the-waste-hierarchy. (Accessed: 26.10.2020).

EPA, 2014. Time Lag and Composition of Durable Goods URL: https://www.epa.gov/sites/production/files/2016-01/documents/msw_task8-1_timelagandcompositionofdurablegoods_508_fnl.pdf.

Esser, A., Dunne, A., Meeusen, T., Quaschning, S., Denis, W., 2019. Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU Final report. URL: https://ec.europa.eu/energy/sites/ener/files/documents/1.final_report.pdf.

Fet, A.M., Skaar, C., Michelsen, O., 2009. Product category rules and environmental product declarations as tools to promote sustainable products: Experiences from a case study of furniture production. Clean Technologies and Environmental Policy 11, 201–207. doi:10.1007/s10098-008-0163-6.

Forbrukerrådet, 2013. Undersøkelse om bruk og vedlikehold av sittemøbler .

Forrest, A., Hilton, M., Ballinger, A., Whittaker, D., 2017. Circular Economy Opportunities in the Furniture Sector. European Environmental Bureau (EEB) URL: file:///C:/Users/giuli/Desktop/Circular-Economy-in-the-Furniture-Sector.pdf.

Fremtiden i våre hender, 2011. Faktaark om forbruk. URL: https://www.framtiden.no/dokarkiv/faktaark/145-faktaark-forbruk/file.html. (Accessed: 21.09.2020).

Geng, A., Ning, Z., Zhang, H., Yang, H., 2019. Quantifying the climate change mitigation potential of China's furniture sector: Wood substitution benefits on emission reduction. Ecological Indicators doi:10.1016/j.ecolind.2019.04.036.

González-García, S., García Lozano, R., Moreira, M.T., Gabarrell, X., Rieradevall i Pons, J., Feijoo, G., Murphy, R.J., 2012. Eco-innovation of a wooden childhood furniture set: An example of environmental solutions in the wood sector. Science of the Total Environment 426, 318–326. URL: http://dx.doi.org/10.1016/j.scitotenv.2012.03.077, doi:10.1016/j.scitotenv.2012.03.077.

González-García, S., Silva, F.J., Moreira, M.T., Pascual, R.C., Lozano, R.G., Gabarrell, X., Pons, J.R.I., Feijoo, G., 2011. Combined application of LCA and eco-design for the sustainable production of wood boxes for wine bottles storage. International Journal of Life Cycle Assessment 16, 224–237. doi:10.1007/s11367-011-0261-2.

Graedel, T.E., Allenby, B.E., 2015. Industrial ecology and sustainable engineering. Pearson.

Gutowski, T.G., Sahni, S., Boustani, A., Graves, S.C., 2011. Remanufacturing and energy savings. Environmental Science and Technology 45, 4540–4547. doi:10.1021/es102598b.

Hartini, S., Wicaksono, P.A., Prastawa, H., Hadyan, A.F., Sriyanto, 2019. The Environmental Impact Assessment of Furniture Production Process Using the Life Cycle Assessment. IOP Conference Series: Materials Science and Engineering 598. doi:10.1088/1757-899X/598/1/012078.

Höglmeier, K., Steubing, B., Weber-Blaschke, G., Richter, K., 2015. LCA-based optimization of wood utilization under special consideration of a cascading use of wood. Journal of Environmental Management doi:10.1016/j.jenvman.2015.01.018.

Hoxha, E., Jusselme, T., 2017. On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings. Science of the Total Environment 596-597, 405–416. doi:10.1016/j.scitotenv.2017.03.107.

International Organization for Standardization, 2006. Iso14044:2006 environmental management - life cycle assessment - requirements and guidelines.

Iritani, D.R., Silva, D.A., Saavedra, Y.M., Grael, P.F., Ometto, A.R., 2015. Sustainable strategies analysis through Life Cycle Assessment: A case study in a furniture industry. Journal of Cleaner Production doi:10.1016/j.jclepro.2014.05.029.

Jeswiet, J., Hauschild, M., 2005. EcoDesign and future environmental impacts. Materials and Design 26, 629–634. doi:10.1016/j.matdes.2004.08.016.

Kharazipour, A., Kües, U., 2014. Recycling of Wood Composites and Solid Wood Products , 509–533.

Klöpffer, W., 1996. Allocation Rule for Open-Loop Recycling in Life Cycle Assessment - A Review. International Journal of Life Cycle Assessment 1, 27–31. doi:10.1007/BF02978629.

kommune, A., 2020. Asker kommune møbleringsplan.

Krey, V., Masera, O., Blanforde, G., Bruckner, T., Cooke, R., Fish-Vanden, K., Haberl, H., Hertwich, E., Kriegler, E., Müller, D., Paltsev, S., Price, L., Schlömer, S., Uerge-Vorsatz, D., Van Vuuren, D., Zwickel, T., 2014. Annex II: Metrics & Methodology. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change , 1281–1328URL: http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_annex-ii.pdf.

Lauvland, H., 2020. Carbon Footprint of Furniture. Project thesis. Department of Energy and process engineering. NTNU, Trondheim.

Lindbak, 2020. ZEB Laboratory.

Lindbak, October 2020. E-mail correspondence with Simon Morseth at Lindbak.

LINK arkitektur/Veidekke, 2021. ZEB Laboratory.

Linkosalmi, L., Husgafvel, R., Fomkin, A., Junnikkala, H., Witikkala, T., Kairi, M., Dahl, O., 2016. Main factors influencing greenhouse gas emissions of wood-based furniture industry in Finland. Journal of Cleaner Production 113, 596–605. URL: http://dx.doi.org/10.1016/j.jclepro.2015.11.091, doi:10.1016/j.jclepro.2015.11.091.

Loopfront, 2020. Kommune sparer millioner på ombruk. URL: https://blog.loopfront.com/no/blog/asker. (Accessed: 05.12.2020).

Loopfront, October 2020. Conversation with Katja Samara at Loopfront.

McCoubrie, A., Love, P.E., Iyer Raniga, U., 1999. Embodied energy analysis of fixtures, fittings and furniture in office buildings. Facilities 17, 403–410. doi:10.1108/02632779910291877.

Michelsen, O., Fet, A.M., Dahlsrud, A., 2006. Eco-efficiency in extended supply chains: A case study of furniture production. Journal of Environmental Management 79, 290–297. doi:10.1016/j.jenvman.2005.07.007.

Mirabella, N., Castellani, V., Sala, S., 2014. LCA for assessing environmental benefit of eco-design strategies and forest wood short supply chain: A furniture case study. International Journal of Life Cycle Assessment 19, 1536–1550. doi:10.1007/s11367-014-0757-7.

NCP, 2020. S-1500. URL: https://ncp.no/products/chairs/s-1500/. (Accessed: 05.01.2021).

Nordland fylkeskommune, 2020. Polarsirkelen videregående skole. URL: http://www.polarsirkelen.vgs.no/. (Accessed: 20.10.2020).

Norsk Standard, 2018. NS3720 Method for greenhouse gas calculations for buildings.

Norsk Standard, 2019. NS3451:2009+A1:2019 Table of building elements.

NVE, 2020. Strømforbruk i Norge har lavt klimagassutslipp. URL: https://www.nve.no/nytt-fra-nve/nyheter-energi/stromforbruk-i-norge-har-lavt-klimagassutslipp/. (Accessed: 17.11.2020).

Parikka-Alhola, K., 2008. Promoting environmentally sound furniture by green public procurement. Ecological Economics doi:10.1016/j.ecolecon.2008.05.004.

Parker, D., Riley, K., Robinson, S., Symington, H., Hollins, O., 2015. Remanufacturing Market Study. European Remanufacturing Network .

Postell, J., 2012. Furniture design. Jon Wiley and Sons, Inc.

Rambøll, 2020. Heimdal videregående skole. URL: https://no.ramboll.com/projects/rno/heimdal_vgs. (Accessed: 13.01.2021).

Remanufacturing Industries Council, 2020. What is remanufacturing? URL: http://www.remancouncil.org/educate/remanufacturing-information/what-is-remanufacturing. (Accessed: 05.10.2020).

Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Applied Energy doi:10.1016/j.apenergy.2019.114107.

Rom for flere, October 2020. E-mail correspondence with terje kristiansen at rom for flere.

Schlanbusch, R.D., Fufa, S.M., Andresen, I., Wigenstad, T., Mjønes, T., 2017. ZEB pilot Heimdal high school and sports hall. Design phase report. Technical Report. SINTEF Academic Press.

Senab Eikeland, September 2020. E-mail correspondence with Katrine Reppe-Øverlie at Senab Eikeland.

Skaar, C., 2011. Gjenbruk av kontormøbler og interiør i Trondheim.

Skoe, K., 2020. Stol - eller fårikål. møbel og interiør URL: https://mobeloginterior.no/aktuelt/stol-eller-farikal/. (Accessed: 02.10.2020).

Skullerud, O., 2000. Avfallsregnskap for Norge: metoder og resultater for våtorganisk avfall. Statistisk sentralbyrå .

Spitzley, D.V., Dietz, B.a., Keoleian, G.a., 2006. Life-Cycle Assessment of Office Furniture Products Life-Cycle Assessment of Office Furniture Products , 77.

Statistisk sentralbyrå, 2019. Dette bruker nordmenn penger på. URL: https://www.ssb.no/nasjonalregnskap-og-konjunkturer/artikler-og-publikasjoner/dette-bruker-nordmenn-penger-pa. (Accessed: 21.09.2020).

Statsbygg, 2020. ILP Møbleringsplan.

Stein Hamre Arkitektkontor, 2020. Samlokalisering av Polarsirkelen vgs. URL: https://shaas.no/prosjekter/samlokalisering-av-polarsirkelen-vgs/. (Accessed: 10.12.2020).

Stein Hamre Arkitektkontor AS, 2019. Fellesbygg Mjølan - Sameplan m/møbler.

Sweco, 2020. Notat - Samlet CO2 reduksjon for høgskule på Vestlandet.

Sør-Trøndelag Fylkeskommune, 2017. Heimdal videregående skole flerbrukshall.

The Artic University of Norway, 2020. Om ILP-nybygget – studiested Tromsø. URL: https://uit.no/prosjekter/prosjekt?p_document_id=675899. (Accessed: 29.10.2020).

The International EPD system, 2020. Furniture and other goods. URL: https://www.environdec.com/EPD-Search/?search_type=advanced&query=&country=&category=9492&certEpd=false&deregEpd=false&sectorEPD=false&ecoPlatformEPD=false&en15804EPD=false,note={(Accessed:11.01.2021)}.

The Norwegian EPD Foundation, 2018. Product Category Rules: PCR – Part B for Furniture , 1–23.

The Norwegian EPD Foundation, 2020. Møbler. URL: https://www.epd-norge.no/mobler/category328.html. (Accessed: 29.09.2020).

Thyholt, M., Dokka, T.H., Dagestad, B., Thyholt, M., Wigenstad, T., Blakstad, S.H., 2003. Nye forskriftskrav til bygningers energibehov. SINTEF rapport. Technical Report.

Trøndelag Fylkeskommune, 2019. Heimdal skole - Skolen uten klimautslipp. URL: https://www.trondelagfylke.no/politikk/politisk-organisering/fylkesordforer/nyheter/skolen-med-null-klimautslipp/. (Accessed: 02.11.2020).

Trøndelag fylkeskommune, October 2020. Conversation with Lillian Strand at Trøndelag fylkeskommune.

Tudor, C.R.P.H., Werner, F., Umwelt, W., 2017. Ecoinvent 3.7.1 dataset documentation: furniture production, wooden. , 3–7.

Ürge-Vorsatz, D., Lucon, O., Zain Ahmed, A., Akbari, H., Bertoldi, P., Cabeza, L.F., Eyre, N., Gadgil, A., D Harvey, L.D., Jiang, Y., Liphoto, E., Mirasgedis, S., Murakami, S., Parikh, J., Pyke, C., Vilariño, M.V., 2014. Buildings. In: Mitigation. Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. , 671–738.

Veidekke, 2021. ZEB Laboratory - Internal communication.

Western Norway University of Applied science, 2020. HVL har fått nøklene til nybygget K2. URL: https://www.hvl.no/aktuelt/hvl-har-fatt-noklene-til-k2/. (Accessed: 06.11.2020).

Wiik, M.K., Selvig, E., Fuglseth, M., Resch, E., Lausselet, C., Andresen, I., Hahn, U., 2020. Klimagasskrav til materialbruk i bygninger. Technical Report 24. ZEN Research Centre. URL: https://fmezen.no/wp-content/uploads/2020/05/ZEN-Report-no-24_Klimagasskrav-til-materialbruk-i-bygninger.pdf.

ZEB Laboratory, 2020. ZEB Laboratory. URL: https://zeblab.no/. (Accessed: 14.12.2020).

Zhao, R., Neighbour, G., Deutz, P., McGuire, M., 2012. Materials selection for cleaner production: An environmental evaluation approach. Materials and Design doi:10.1016/j.matdes.2012.01.014.

Zutshi, A., Creed, A., Holmes, M., Brain, J., 2016. Reflections of environmental management implementation in furniture. International Journal of Retail and Distribution Management 44, 840–859. doi:10.1108/IJRDM-10-2015-0154.

Appendix A

# Appendix

## A.1 Case projects

This section gives more detailed information on what data was available for each case, as well as floor plans. One floor of each case project is included to illustrate the furnishing and size of the buildings assessed. The information given varied greatly, and the level of detail and accuracy to reality has therefore varied between the projects. Some has relied more on assumptions, while other had the information enough to avoid some assumptions. Some of the information given is confidential and has therefore not been shared in detail.

**Polarsirkelen upper secondary school**
The used information of this project was:

- Floor plan of second and third floor (the furnished area of the building)
- Furniture inventory requirements for supplier
- Information that 30% of furniture is reused
- Further details of the building shared by people involved in the project, as well as the homepage of the project

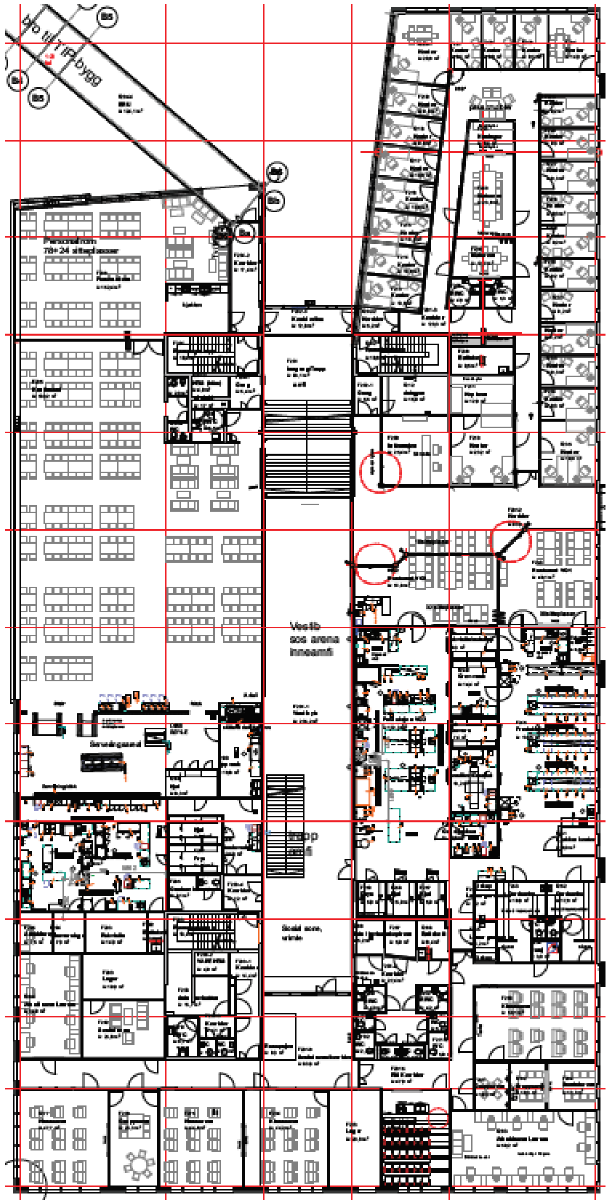


**Figure A.1:** Floor plan of second floor at Fellesbygget, Polarsirkelen upper secondary school (Stein Hamre Arkitektkontor AS, 2019)

**Heimdal upper secondary school**
The used information of this project was:

- Floor plan of whole building
- General list of furniture inventory used in communal buildings in Trøndelag Fylkeskommune
- List of reused furniture products
- LCA calculations of the building
- Further details of the building shared by people involved in the project, as well as the homepage of the project

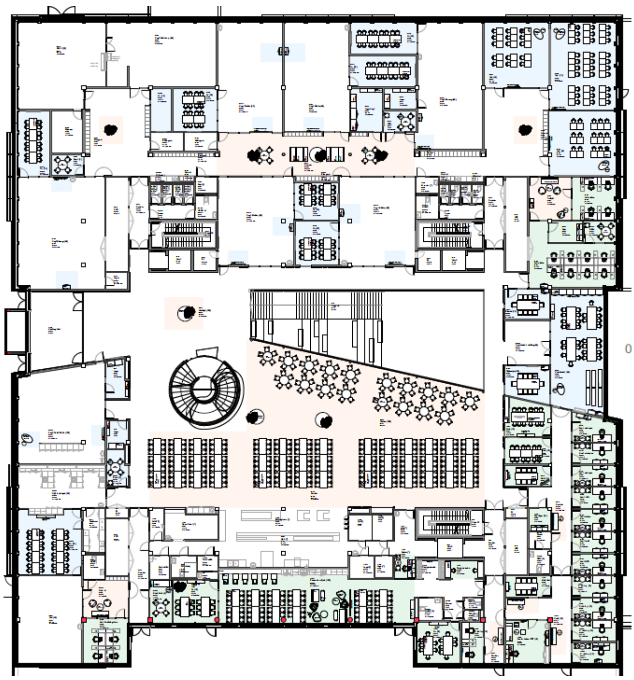

**Figure A.2:** Floor plan of third floor at Heimdal upper secondary school (Sør-Trøndelag Fylkeskommune, 2017)

**ILP UiT**
The used information of this project was:

- Floor plan of whole building
- Furniture inventory list
- Detailed description of custom furnishing for some educational rooms
- List of reused furniture products
- LCA calculations of the building
- Further details of the building shared by people involved in the project, as well as the homepage of the project


**Figure A.3:** Part of floor plan of second floor at ILP-building, University of Tromsø (Statsbygg, 2020)

**K2 HVL**
The used information of this project was:

- Floor plan of whole building with color coded reused and new furniture
- List of reused furniture products
- List of new furniture products
- LCA calculations of the building
- Further details of the building shared by people involved in the project, as well as the homepage of the project

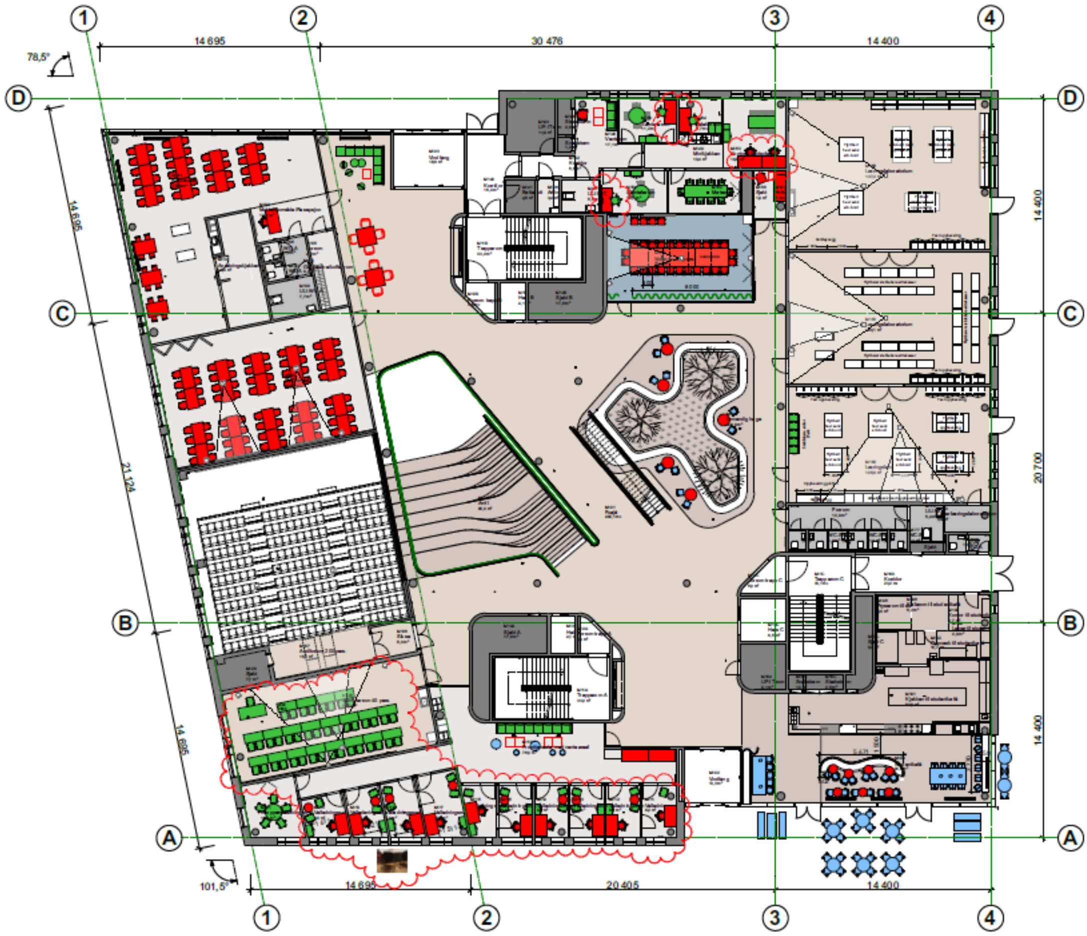


**Figure A.4:** Floor plan of ground floor of K2 building at Western Norway University of Applied Science (arkitektur og design AS, 2018)

**Asker kommune**
The used information of this project was:

- Floor plan of whole building with color coded reused and new furniture
- Pictures of furniture products used in two floors
- Statistics over share of reused, refurbished and new furniture
- Further details of the building shared by people involved in the project, as well as the homepage of the project


**Figure A.5:** Floorplan of the 3rd floor at Asker kommune (kommune, 2020)

## ZEB Laboratory

The used information of this project was:

- Floor plan of whole building
- Pictures of all furniture products used
- Information that no furniture was reused
- LCA calculations of the building
- Further details of the building shared by people involved in the project, as well as the homepage of the project

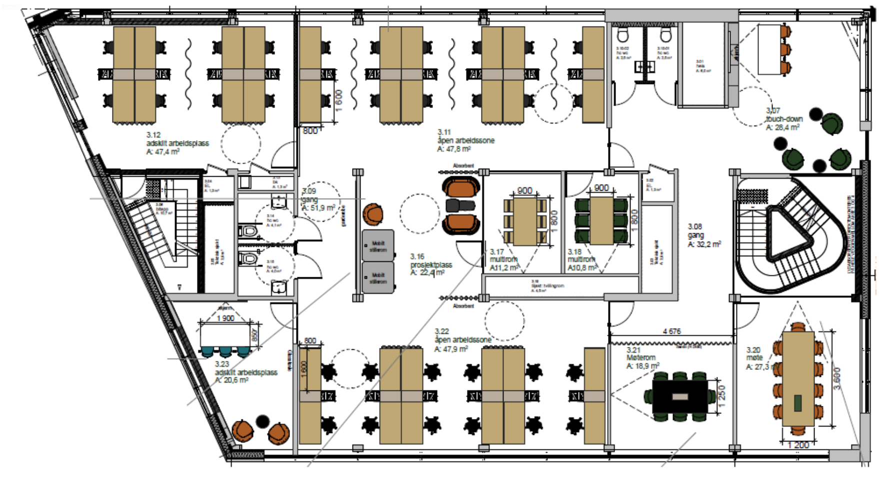

**Figure A.6:** Floorplan of the 3rd floor at ZEB Laboratory (Lindbak, 2020)

## A.2 Assumptions

- Where items in floor plan have been unable to identify as a furniture product, and unable to verify by inventory list, the item is not taken into account.
- Large unfurnished area as parking facilities and sports halls has not been included in the building area.
- Unidentifiable furniture products in technical rooms as copy room etc not included, in addition to waste sorting facilities
- Only 50% of furniture products needs some kind of repair when a furniture inventory is undergoing a reuse process
- Where no end-of-life emissions were available from the EPD (e.g. where only cradle-to-gate emissions are included), an estimate based on similar furniture or furniture of the same brand is made.
- The refurbishment activities done on each individual furniture is all based on assumptions because of lack of information on which processes are actually undertaken.
- Wardrobe cabinets in metal material have all been accounted for with the average of cabinets from EPDs. The EPDs only have cabinets of wood, but as they fulfil the same purpose they have been accounted for with this average.
- Teacher desk in front of classrooms is assumed to be similar to desks as there are no EPDs for these desks in the Norwegian EPD database
- For cabinets, when using average data, almost all sizes and types have been calculated using an average of all sizes. For cabinets available EPD data have shown little consistency between, size, type and $CO_2$ emission.
- The average data found for sofas are of three seat sofas. When sofas are larger or smaller than this, the total sofa seats have been counted and the number of sofas has been estimated to the nearest number that can be divided by three.
- All desks are estimated to be of size 160x80, if not corner desk, or student study desk. This was the most common size, so it is decided to be representative.
- When sometimes the weight was not able to find, e.g had the carbon footprint w/o armrest, the difference between another chair with and without armrest was found and used in another chair.
- When conference table has not been suitable, several meeting tables have been used.
- The latest technology is assumed for the transportation, and EURO5 is used.
- All furniture products are assumed to occupy in average 0.5 $m^2$ in a storage building.
- All furniture products are assumed to be stored an average of six months (0.5 years).
- The energy required to refurbish a furniture product is 10 kWh.
- For refurbishment and maintenance processes, change of upholstery are assumed for padded chairs and armchairs, but not sofas and pouffes.
- The assumed efficiency values for high/medium/low svenarios for the different reuse processes are presented in Table A.1.

| Process | High efficiency | Medium efficiency | Low efficiency |
|---|---|---|---|
| Transport capacity | 70% | 50% | 30% |
| Storage energy use | 100 kWh | 116 kWh | 150 kWh |
| Exchange of parts | 10% | 20% | 30% |

**Table A.1:** The assumed high, medium and low efficiency reuse variables for reuse processes

## A.3 Matrices and vectors for calculations

An example of the matrices and vectors used to calculate the carbon footprint of furniture is included in this section. The matrices and vectors displayed are taken from the ZEB laboratory calculations.

**Carbon intensity vector**

| Furniture | Best fit | kg CO2/item |
|---|---|---|
| Chair | Average | 18,08 |
| Chair | Fora Form CITY original | 9,1 |
| Plastic chair w/steel legs | NCP Public M | 17,2 |
| Conference chair | Fora form Clint VIP high back | 74,3 |
| Stool | Fora form Knekk | 3,34 |
| Office chair | Flokk HÅG Capisco 8106 | 47,8 |
| Office chair | Flokk HÅG Futu Mesh | 54,5 |
| Office chair | Flokk RH support 4501 | 39,3 |
| Saddle chair | Back app office chair | 53,8 |
| Armchair | Average | 27,56 |
| Pouffe | Average | 20,6 |
| Working desk | Average | 64 |
| Narrow table | Fora form Clip 450x1200 | 22,8 |
| Meeting table | Average | 31,72 |
| Meeting table | Svenheim Factor Lite 1800x900 | 43 |
| Meeting table | Fora Form Knekk | 72,7 |
| Meeting table Ø1200 | Average | 31,52 |
| Conference table 3600x1200 | Svenheim Factor 3600x1200 | 119 |
| Coffee table | Average | 11,9 |
| Coffee table | Fora Form Root | 10,7 |
| Cabinet | Average | 52,7 |
| Cabinet 3A4 w/doors | Aarsland Flexi cabinet F331 | 42,3 |
| Tower cabinet | Average | 67,3 |
| Table screen | Svenheim Vesta Acoustic | 12,08 |
| Floor screen | Svenheim Vesta Acoustiv floor scr | 50,4 |

**Figure A.7:** Carbon intensity vector with values in kg $CO_2$eq of ZEB laboratory

## Furniture intensity matrix

| Floor | Room | Chair | Chair | Plastic chai | Conference | Stool | Office chair | Office chair | Office chair | Saddle chai | Armchair | Pouffe | Working de |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st floor | Eating room | 24 | 48 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 7 | 0 | 0 |
| 2nd floor | Shared office | 0 | 0 | 0 | 0 | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 14 |
| | Research room | 0 | 0 | 0 | 0 | 0 | 0 | 22 | 0 | 0 | 0 | 0 | 22 |
| | Multiroom | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Meeting room | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Social zone | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 3 | 0 | 0 |
| 3rd floor | Open working area | 0 | 0 | 0 | 0 | 0 | 12 | 20 | 0 | 0 | 0 | 0 | 32 |
| | Closed working area | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 2 | 0 | 0 |
| | Project area | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 0 | 0 |
| | Multiroom | 6 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Meeting room | 8 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Social zone | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 3 | 0 | 0 |
| 4th floor | Lecture room | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Knowledge center | 0 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Social zone | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Figure A.8:** Furniture intensity matrix which displays number of furniture products in the different rooms of ZEB laboratory (1)

| Narrow tabl | Meeting tab | Meeting tab | Meeting tab | Meeting tab | Conference | Coffee table | Coffee table | Cabinet | Cabinet 3A4 | Tower cabin | Table scree | Floor screen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 8 | 0 | 0 | 6 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 14 | 0 | 28 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 22 | 0 | 19 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 2 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 28 | 5 |
| 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 |
| 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure A.9:** Furniture intensity matrix which displays number of furniture products in the different rooms of ZEB laboratory (2)

## Reuse matrix and vector

| Furniture product | Transport | Storage | Repair | End-of-life | Total |
|---|---|---|---|---|---|
| Chair average | 0,218 | 0,425 | 0,904 | 5,75 | 7,297 |
| Fora Form CITY original | 0,190 | 0,425 | 0,455 | 2,9 | 3,970 |
| NCP Public M | 0,185 | 0,425 | 0,86 | 5,4 | 6,870 |
| Fora form Clint VIP high back | 0,490 | 0,425 | 3,715 | 11,2 | 15,830 |
| Fora form Knekk | 0,182 | 0,425 | 0,167 | 3,8 | 4,574 |
| Flokk HÅG Capisco 8106 | 0,440 | 0,425 | 2,39 | 16,8 | 20,055 |
| Flokk HÅG Futu Mesh | 0,588 | 0,425 | 2,725 | 18,6 | 22,338 |
| Flokk RH support 4501 | 0,389 | 0,425 | 1,965 | 8,1 | 10,879 |
| Back app office chair | 0,349 | 0,425 | 2,69 | 16,8 | 20,264 |
| Armchair average | 0,615 | 0,425 | 1,378 | 11,11 | 13,528 |
| Pouffe average | 0,226 | 0,425 | 1,03 | 7,65 | 9,331 |
| Working desk average | 1,419 | 0,425 | 3,2 | 9,09 | 14,134 |
| Fora form Clip 450x1200 | 0,421 | 0,425 | 1,14 | 4,6 | 6,586 |
| Meeting table average | 0,926 | 0,425 | 1,586 | 7,18 | 10,117 |
| Svenheim Factor Lite 1800x90 | 1,335 | 0,425 | 2,15 | 16,5 | 20,410 |
| Fora Form Knekk | 1,188 | 0,425 | 3,635 | 7,3 | 12,548 |
| Meeting table Ø1200 | 1,052 | 0,425 | 1,576 | 9,1 | 12,153 |
| Svenheim Factor 3600x1200 | 3,760 | 0,425 | 5,95 | 39,1 | 49,235 |
| Coffee table average | 0,300 | 0,425 | 0,595 | 3,27 | 4,590 |
| Fora Form Root | 0,214 | 0,425 | 0,535 | 1,9 | 3,074 |
| Cabinet average | 2,049 | 0,425 | 2,635 | 21,9 | 27,009 |
| Aarsland Flexi cabinet F331 | 1,874 | 0,425 | 2,115 | 24,3 | 28,714 |
| Tower cabinet average | 2,946 | 0,425 | 3,365 | 35 | 41,736 |
| Svenheim Vesta Acoustic | 0,483 | 0,425 | 0,604 | 5,1 | 6,612 |
| Svenheim Vesta Acoustiv floor | 0,596 | 0,425 | 2,52 | 18,9 | 22,441 |

**Figure A.10:** Reuse intensity matrix and final reuse carbon intensity vector with high efficiency values in kg $CO_2$eq of ZEB laboratory

### Maintenance matrix and vector

| Best fit | Textile | Parts | Screws | Paint | Energy | Total |
|---|---|---|---|---|---|---|
| Chair average | 4,25 | 1,808 | 0,018 | 0 | 0,17 | 6,246 |
| CITY original | 0 | 0,91 | 0,018 | 0,64 | 0,17 | 1,738 |
| NCP Public M | 0 | 1,72 | 0,018 | 0 | 0,17 | 1,908 |
| Fora form Clint VIP high back | 7,65 | 7,43 | 0,018 | 0 | 0,17 | 15,268 |
| Fora form Knekk | 0 | 0,334 | 0,018 | 0,64 | 0,17 | 1,162 |
| HÅG Capisco 8106 | 7,65 | 4,78 | 0,018 | 0 | 0,17 | 12,618 |
| HÅG Futu Mesh | 7,65 | 5,45 | 0,018 | 0 | 0,17 | 13,288 |
| Flokk RH support 4501 | 7,65 | 3,93 | 0,018 | 0 | 0,17 | 11,768 |
| Back app office chair | 4,25 | 5,38 | 0,018 | 0 | 0,17 | 9,818 |
| Armchair average | 7,65 | 2,756 | 0,018 | 0 | 0,17 | 10,594 |
| Pouffe average | 0 | 2,06 | 0,018 | 0 | 0,17 | 2,248 |
| Working desk average | 0 | 6,4 | 0,018 | 0 | 0,17 | 6,588 |
| Fora form Clip 450x1200 | 0 | 2,28 | 0,018 | 0 | 0,17 | 2,468 |
| Meeting table average | 0 | 3,172 | 0,018 | 0,64 | 0,17 | 4 |
| Svenheim Factor Lite 1800x900 | 0 | 4,3 | 0,018 | 0,64 | 0,17 | 5,128 |
| Fora Form Knekk | 0 | 7,27 | 0,018 | 0 | 0,17 | 7,458 |
| Meeting table Ø1200 average | 0 | 3,152 | 0,018 | 0 | 0,17 | 3,34 |
| Svenheim Factor 3600x1200 | 0 | 11,9 | 0,018 | 0 | 0,17 | 12,088 |
| Coffee table average | 0 | 1,19 | 0,018 | 0,64 | 0,17 | 2,018 |
| Fora Form Root | 0 | 1,07 | 0,018 | 0,64 | 0,17 | 1,898 |
| Cabinet average | 0 | 5,27 | 0,018 | 0,64 | 0,17 | 6,098 |
| Aarsland Flexi cabinet F331 | 0 | 4,23 | 0,018 | 0,64 | 0,17 | 5,058 |
| Tower cabinet average | 0 | 6,73 | 0,018 | 0,64 | 0,17 | 7,558 |
| Svenheim Vesta Acoustic | 0 | 1,208 | 0,018 | 0 | 0,17 | 1,396 |
| Svenheim Vesta Acoustiv floor sc | 0 | 5,04 | 0,018 | 0 | 0,17 | 5,228 |

**Figure A.11:** Maintenance intensity matrix and final maintenance carbon intensity vector with values in kg $CO_2$eq of ZEB laboratory

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