Circular economy in the Swedish building sector

Investigating options for old windows

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

According to several studies, a circular economy in the construction industry is necessary to reduce the environmental impacts, waste and extraction of raw materials as well as meeting the environmental sustainability goals. While some building materials have been implemented in further circular methods of waste management, windows have not. Most window replacements during renovation end up as waste, even though they have the potential for reuse, all while sand is becoming a limited resource, which is the most important material for glass production. Window replacements usually occur because the windows are old and are contributing to high energy demand of buildings, including unsatisfactory thermal comfort. This problem has two different solutions, reuse and recycling, which are further investigated in this study.

There is not much information on economic benefits, opportunities, and ways to improve the potential outcomes. This also applies for procurement, warranty, responsibility, storage, and building regulations, where further information and possible solutions are investigated partly through a case study. This study attempts to answer what happens with windows today, what is the economic and environmental outcome of reusing/recycling windows, what limitations and possibilities are present today, and which window management alternative is most suitable for the case study in regard to environmental impact and profitability. The case study in this degree project consists of a building complex in Lund, Sweden, which is planned on being demolished and later rebuilt. As part of a research project within the programme Spara & Bevara, funded by the Swedish Energy Agency, with attempts to encourage against the demolishing of the buildings through reuse of materials, this study focuses on the possibility of reusing the current windows.

This study is executed by first gathering information through a site visit, interviews, and reports. This results in five different cases/possibilities being investigated, to determine the best option for this study. Later, energy simulations are made through Rhino 3D and Grasshopper, where the results are used for LCC and LCA. Lastly, an LCSA analysis, where LCC and LCA are weighted differently, determines the most suitable case for the case study.

Some of the conclusions for this study prove that it is more favourable to refurbish the windows rather than recycle them, and that not all types of reuse procedures are necessarily most environmentally friendly. Although, a circular economy contributes to new job opportunities, waste reduction and interesting architecture. Some of the biggest limitations for reuse or recycling is the immature/undeveloped business market, transport, and storage.

Terms and definitions

Building product	A construction element that is intended to be permanently included in a building.
Circular flows	Resources are included in a circular system: "Reuse, Repair, Recycle", reducing waste and extraction of raw material.
Reuse/Circularity	The product/material is used again, without changes in design or materials.
Recycling	The product is destroyed, and the materials are used to make new products.
Global Warming Potential (GWP)	Represents the heat absorbed by greenhouse gases and is thus trapped in the atmosphere, which in turn increases land and ocean temperature. Unit: *kg CO_2 eq.*
Acidification Potential (AP)	Represents the range of air pollutants that can transform into acids, which in turn affects the biotic environment through contamination of soil and waterways. Unit: *molc H+ eq.*
Eutrophication Potential (EP)	Represents the over-fertilisation or excesses of nutrients in aquatic and terrestrial environments. Unit freshwater: *kg P eq.* Unit terrestrial: *molc N eq.*
Ozone Layer Depletion Potential (ODP)	Represents the damage to the ozone which affects the warming of the earth surface, higher levels of UV radiation and impacts to ecosystems and human health. Unit: *kg CFC-11 eq.*
Photochemical Oxidant Formation Potential (POCP)	Also called "Photochemical smog". Represents the ground level ozone that is created by emissions of nitrogen oxide and volatile organic compounds in combination with sunlight. Ozone in the troposphere 56de6can be toxic for humans if in high concentrations. Unit: *kg NMVOC eq.*
Abiotic Depletion Potential (ADP)	Represents the use of non-renewable sources, i.e., fossil fuels, minerals and metals. Unit: *kg Sb eq.*
Endpoint	Endpoint indicators are defined by the areas of protection (natural environment, human health, and natural resources) at the end of a cause-effect chain.
Midpoint	Midpoint indicators define impact categories prior to the endpoints.
PCB	Polychlorinated biphenyls - the highly toxic substance that was common in sealing compounds of insulating glass units between 1956 and 1973.
CCbuild	Centre for circular building. A platform for businesses in the industry to meet and collaborate in regard to reuse and circular flows during construction, demolition and management.

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1. Introduction

This degree project is carried out within the field *Energy-efficient and Environmental Buildings* at Lund University, during the spring semester of 2021. The degree project comprises 30 credits per student and is part of an existing research project with a case study. The case study aims to investigate the possibilities of recycling or reusing building materials of a building complex in Lund, Sweden. This investigation intends to provide fundamental knowledge of circular economy and calculations of windows for future decision-making of the building complex by Lund municipality.

The introductory chapter will highlight the background and problem description of the subject, as well as the objective of the degree project and the chosen method to execute the investigation. Thus, the concerning areas of the report will be described in detail.

1.1. Background

The world is facing threats of climate change and environmental degradation, forcing humankind to take action and re-evaluate priorities and way of life (European Commission, n.d.). These actions have first been concretised as goals and categorised, and then gathered under one general syllabus – sustainability.

Sustainability, or sometimes mentioned as sustainable development, is most commonly described as quoted: “Sustainable development is development that meets the need of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987, p. 41). Further, the concept is parted into social, economic, and ecological aspects, where all three should be considered in synergy for the best outcome for humans and nature (Brundtland, 1987). This initiative later evolved, and resulted in the Paris Agreement and Agenda 2030, with 17 Sustainable Development Goals (SDGs) and 169 targets to be adopted and undertaken, in an attempt to be reached by the year 2030 (iisd.org, n.d.).

Following the SDGs, every country has evaluated its ability to reach the goals and targets, leading to measures counting welfare and greenhouse gas emissions (GHG emissions) among others. The latter being an emerging topic within the construction industry. The construction industry is expected to generate 2.2 billion tons of waste by the year 2025 (Transparency Market Research, 2021) and was responsible for 39 % of GHG emissions generated by the building processes and energy consumption, in 2017 (World Green Building Council, 2019). In these past decades, the industry has mainly focused on reducing energy use during a building’s operational phase through environmental certifications schemes such as BREEAM, LEED, and the Swedish Miljöbyggnad, but have neglected to put as much focus on the embodied energy (World Green Building Council, 2019). In order to build sustainable cities, it will be a necessity to discuss and implement circular flows within architecture and construction to reduce the embodied energy as well.

Circular economy is an efficient method to reduce the extraction of scarce resources, i.e., embodied energy, by reusing already processed products and materials, as well as reducing landfill waste (Regeringskansliet, 2021a). The extraction of materials has tripled over the past 50 years, accelerating over the last two decades, and now accounts for approximately 50 %

of the total GHG emissions including the processing of the natural resources (United Nations Environment Programme, 2019). The statistics are representing the global outlook for all industries. A circular economy could, therefore, be an essential element in the transition to sustainable societies according to the International Resource Panel (2019).

Circularity can also be described based on a biological and technical cycle of materials and products, see Figure 1.1.1. Each material or product should be assessed using a Cradle-to-Cradle lifecycle approach, rather than the inculcated Cradle-to-Grave approach. The means of the concept coincides well with several SDGs, such as 11: Sustainable Cities and Communities, 12: Responsible Consumption and Production, 13: Climate Action, etc. (General Assembly of the United Nations, 2018).

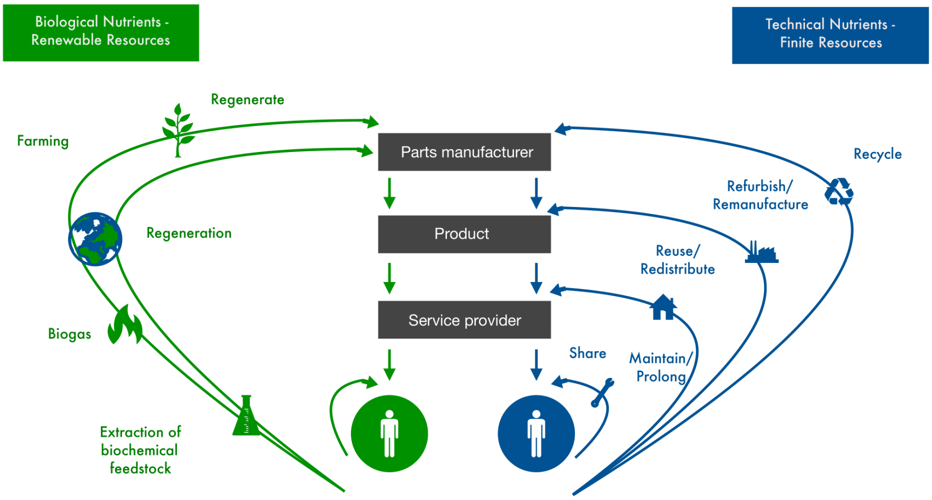

Figure 1.1.1. Circular economy system diagram.

One of the issues which delays the transition to a circular economy is economic feasibilities. The mentality within the construction industry is “to do what has always been done” while building cheap and not wasting time on disassembling elements etc. (IVL, 2021). The approach is commonly known as “Time is Money” and is limiting the ecological aspect of sustainability. Meanwhile, in other industries such as finance, sustainability is gaining importance and topics such as ‘Environmental, Social and Governance’ (ESG) and ‘Green Bonds’ are trending (Piasta et al., 2021). Questions regarding ESG include GHG emissions and supply chain management (Burenstam.se, 2017) which should be beneficial for circularity, but these topics mainly focus on financing new construction and environmental certifications rather than enhancing a necessary development of the market (UN Environment and International Energy Agency, 2017). ESG and Green Bonds are also not as regulated as they should be to achieve their full potential (Piasta et al., 2021; UN Environment and International Energy Agency, 2017).

Also, not many regulations regarding circular economy have been implemented at an EU level as of today, leaving room for innovative and free concept interpretations. The EU has presented a new Circular Economy Action Plan as part of the European Green Deal, an agenda for sustainable growth (European Commission, n.d.). The new action plan aims at reducing pressure on natural resources and creating sustainable growth and jobs, by including and targeting all phases of a product's lifecycle. This should be achieved by focusing on sectors that use the most resources and have a high potential for including circularity, such as the construction industry (European Commission, n.d.). Regardless, a few European countries have implemented circularity and are thereby reducing the embodied energy. Nordic countries such as Denmark are advocating circularity on a larger scale and are doing so efficiently in both economic and ecological aspects, as well as getting recognition for it worldwide. Sweden, on the other hand, follows the 2030 Agenda, intending to be climate-neutral by 2045 and will incorporate a mandatory climate declaration for new buildings by 2022 (Boverket, 2021a). Simultaneously, action plans for reducing waste and re-circulating existing building material are in progress.

In 2018, the Swedish construction industry accounted for 21 % of the total GHG emissions (including imported emissions) and 35 % of the total amount of waste in the country (Boverket, 2021a). The active transition towards a circular economy is in the first phases in Sweden, recently introducing 100 new measures for circular readjustments in the society, online marketplaces for used building elements and materials, implementing mandatory climate declarations, and discussing the possibilities of product passports etc. The mentioned measures are discussed and implemented on a governmental level. There are also local directives from counties and municipalities providing guidelines to encourage and support sustainable cities.

Lund is one of the municipalities in Sweden that is leading in the progress for sustainable cities. By developing a report for the city's ecologically sustainable development and entering innovation programmes for climate action, Lund is working actively to reduce its environmental impact (Lunds kommun, n.d.). Despite the efforts of educating about and increasing circular flows within the construction industry, clear guidelines of how to handle e.g. windows as resourceful waste in the technical material cycle have not been provided. This has resulted in an increasing issue in the transition to a circular economy in the municipality.

1.2. Problem description

While some building materials, such as bricks or roof tiles, have been implemented further in circular methods of waste management, windows have not. Most window replacements during renovation end up as waste, and not many windows are being reused or recycled. Replacing windows this way is inefficient since the materials have the potential for reuse (Souviron and Khan, 2020). Even during the manufacturing of glass, waste is inevitable, and since glass is considered an inert material that can be recycled endlessly, the potential for recycling is high (Souviron and Khan, 2020). Today, about 45 % of all flat glass is sent to recycling (Almasi et al., 2018).

Window replacements usually occur because the windows are old and are contributing to high energy demand of buildings, including unsatisfactory thermal comfort (Hantverkarhuset, 2020). Replacing windows leads to more material extraction than not exchanging them, which potentially has a higher environmental impact. Another problem is that sand is a limited resource, which is the most important material for glass production (Widing, 2020).

A problem is that there is not much information on the subject of reuse and recycling of windows in Sweden, meaning that there are not many professionals with this area of expertise, which in turn leads to a lack of information on the economic benefits, opportunities, and ways to improve the potential methods. The same theory applies to procurement, warranty, and responsibility when a window or a material is being reused. All these factors can be a matter of interpretation, which goes back to the fundamental question – when and where can you request recycling as part of a project and how is it approved?

It is assumed that most companies would rather choose economic profit than make a choice based on environmental impact when having to choose. The most common way to manage glass as waste is by disposal (Souviron and Khan, 2020). Although, managing residues as waste limits resources, meaning that if someone chooses this process, a completely new window must be manufactured to replace the old, unlike the competing alternatives. Sometimes the requirement for better windows exceeds the capacity of renovation, e.g., achieving certain technical requirements. Therefore, there must be economic profitability that is larger when reusing or recycling windows to further encourage circular flows of products.

A solution to implementing circular glass waste management includes both upcycling and downcycling. By downcycling glass, other products of lower quality or functionality, such as glass wool, can be manufactured (Souviron and Khan, 2020), while the opposite is defined for upcycling. The question is whether there is a way to guarantee the quality of upcycled glass or reused windows. The term “product passport” is a new topic being addressed on a governmental level and will during the year 2021 be further investigated by governmental agencies (Naturvårdsverket, 2020a). A product passport would solve the issue of lack of information about the existing building products and materials, by implementing a way of documentation to follow the entire value chain (Naturvårdsverket, 2020a). This would provide easily accessible and transparent data which would enhance decision-making and favour a circular economy. The product passports would include information about life expectancy, environmental impact, manufacturers data, and resource management (e.g., for recycling or reuse) (Naturvårdsverket, 2020a). Even though this might be a step towards enhancing a circular market, the issues regarding information availability, warranty, responsibility, and quality when reusing products are still unsolved.

Since reuse of building products is not common praxis yet, several other difficulties and issues need to be solved. These difficulties include storage, Swedish building regulations, knowledge gaps, government procurement etc. Questions regarding the Swedish building regulations arise from the need for clarification of concepts, especially concepts revolving around new production, renovation, circularity, and relevancy (IVL, 2021). The Swedish building regulations are also regulating what criteria certain components of the building envelope must fulfil to be approved. These national regulations are considered stricter in Sweden compared to, e.g., Denmark and are requiring verification of the technical information of reused products. Comparing the technical requirements for windows in Sweden and Denmark, the Swedish regulations present values for the heat transfer coefficient (*U*-value) while the Danish regulations has a limit on the energy demand for windows (Bolig- og Planstyrelsen, 2021; Boverket, 2020a). Since fulfilling and verifying the *U*-value of reused windows is difficult, it in turn complicates and arguably discourages reuse of building envelope components in the Swedish building sector. When studying the governmental or public procurement of new building projects, economic factors play a critical role. The tenders for the procurement are considered by price, cost, or cost in relation to quality, neither including circular economy as a standard in the process (Upphandlingsmyndigheten, n.d.). This usually benefits tenders with cheaper solutions/design which falls in line with the conservative mentality in the industry – “to do what has always been done”.

This degree project focuses on a building complex in Lund, Sweden, which is located near the hospital. Five residential buildings are planned to be demolished in order to later be re-built on the same property. The brick buildings, with a concrete structure and 2-pane standard dimension windows with flat glass and wood frame, were erected around 1950 and were assigned as housing for employees of the county council (Lunds Byggnadsnämnd, 1981). They are today considered in need of renovation or demolition in order to use the land for other purposes and later construct new, energy-efficient buildings on the same plot. As part of a research project within the programme Spara & Bevara, funded by the Swedish Energy Agency, this report focuses on analysing the options of reuse, recycling, or disposal of the existing windows. The options will be investigated by environmental impact and cost. The results will be conducted through energy simulations, LCA and LCC calculations.

Lund municipality has an active approach towards developing the city in a sustainable direction. With participation in Klimatkontrakt 2030, an agreement between cities, authorities, and Viable Cities, the city will work to reduce its GHG emissions and encourage innovation for a sustainable built environment (Viable Cities, n.d.). Innovation should provide new and effective ways of cooperation within the municipality and together with the society, engaging citizens in the action for climate neutrality. The board of Viable Cities provides support for the processes of adapting rules and policies, and facilitates long-term and systematic innovation work (Viable Cities, n.d.). In order to evaluate and reflect upon Lund’s contributions, the municipality has produced a report that states its priorities in environmental work and focuses on the ecological dimension of sustainable development, while taking the social and economic aspects into account (Lunds kommun, 2017). The report, LundaEko II, is one of the municipality’s most important governing documents for politicians and officials in the work for sustainability. It is based on the national environmental goals but modified after the municipality’s eight priority areas for its environmental work:

- Engage more people
- Sustainable consumption
- Reduced chemical load
- Reduced climate impact
- Climate adaption
- Sustainable urban development
- Biodiversity and ecosystem services
- Fresh water and fresh air

The municipal board carries the responsibility for LundaEko II and has taken upon themself to annually coordinate the follow-up of control and action documents for the environmental indicators (Lunds kommun, 2017). With this extensive initiative, the question for the management of building products and waste resources has risen. Windows as resourceful waste would be in line with the municipality's vision for a sustainable city, yet today, old windows are not considered as a resource. This degree project will therefore also investigate the possibilities and current issues with reusing or recycling already existing windows for new buildings.

1.3. Objective and research questions

This degree project aims to investigate the possibilities of circular building methods and answer questions regarding the end-of-life stage for windows. The objective is to study the building sector's progress of transitioning to a sustainable future and derive knowledge to build a foundation of possible outcomes for the replaced windows in the buildings in Lund, Sweden. This will be based on environmental impacts, energy use, and economic profitability. The purpose of gathering this information is to make it easier to choose a sustainable and economic way to deal with replacements of windows in a building, in order to utilise as many available resources as possible.

The research questions to answer will be:

- What happens with used windows today (i.e., how does the process of transport, recycling, and other alternatives look?)?
- What is the outcome of reusing or recycling windows, considering the environmental impact, waste reduction, costs and/or energy performance?
- What are the limitations and possibilities of reusing or recycling old windows in Sweden?
- Which window management alternative, considering the case study, is the most suitable regarding to environmental impact and profitability?

1.4. Delimitations

This report circulates the concept of sustainability, with a focus on the environment and economy. The concept of circular economy will be studied only for the building sector and will be limited to investigating the technical cycle of materials, particularly windows. Lifecycle costing (LCC), lifecycle assessment (LCA), and energy use will be assessed and calculated to yield results for the buildings in Lund. Changes and updates in laws, directives or regulations and reports that became available after May 2021 was not considered.

The executed interviews within this study will be limited to gathering information on the general processes of different ways to deal with circular economy and windows today. The same limitations will be applied for possible solutions, as new solutions are always invented, and this study will focus on a few but realistic outcomes.

The case study will be limited to the buildings in Lund, meaning that the calculated results may not be generalised for the whole building sector, but the methods and the study of circular economy may be.

Similarly, the simulations and calculations are limited to one of the five buildings, see Figure 1.4.1. The results are though applicable to all buildings, since they are built similarly, and will be presented as per m^2 window. The calculations for LCA only focus on the production stage and end-of-life stage for windows and do not investigate results from different databases.

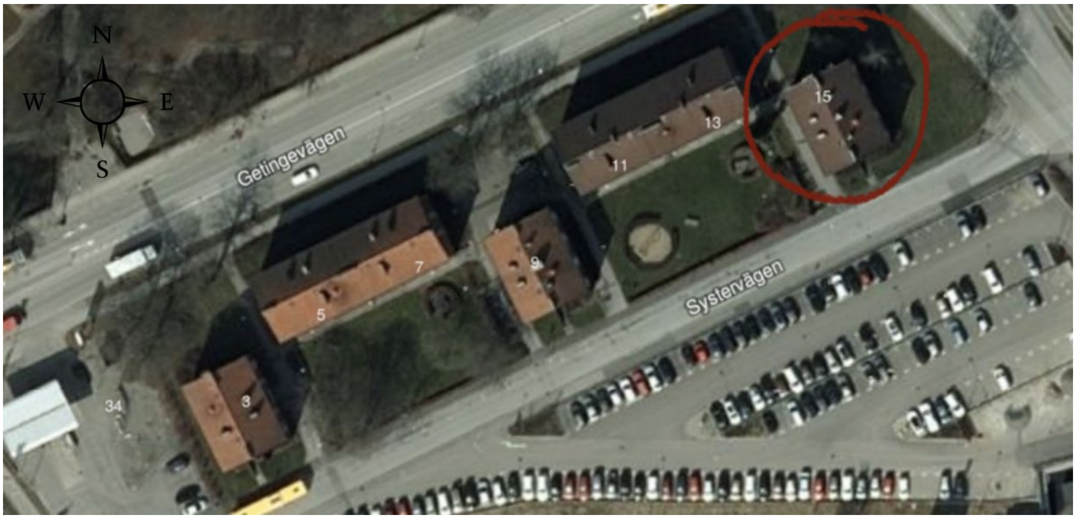

Figure 1.4.1. Building 5 chosen to be simulated and calculated.

1.5. Disposition

This report begins with an introduction to describe the subject, the background and the problem, the research questions, the aims, and the goals. The introduction is followed by the method, which will describe the outline of this research, followed by the theoretical framework and the empirical study which will underline a thorough study of the subject and interviews, respectively. Lastly, the results and analysis will be presented, combining the theory with calculations and simulations, and then discussed in order to draw conclusions.

1.6. Contributions

While both authors were engaged in all parts of this study, they also worked together with the interviews, finding relevant information and literature, and setting up the calculations for LCC. Amra Lukac focused on the literature review, LCA and report, including correcting and finalising the content. Tarik Ljajic focused on energy simulations, LCSA, finalising the LCC, and report. Both authors analysed the results and made a conclusion based on the results.

2. Theoretical framework

This chapter explains some important information in detail for further understanding of the subject.

2.1. Sustainable directives on global, national and local levels

There are 17 universal Sustainable Development Goals (SDGs) that are laying a foundation for environmental work on both regional and local level. The SDGs revolve around all three aspects of sustainability and aims to protect the planet, end poverty and increase prosperity (iisd.org, n.d.). The 17 goals are divided into 169 targets and the overall goal is to reach them by 2030, which is why they can be referred to as the 2030 Agenda as well. Sweden has adapted these and interpreted them into 16 environmental goals as well as a generational goal (sverigesmiljomal.se, n.d.). The Swedish Environmental Objectives are thus focusing on the ecological factors of sustainability – recovering the ecosystems, conserving biodiversity, enabling efficient energy use etc. These goals include:

- Reduced climate impact
- Clean air
- Natural acidification only
- A non-toxic environment
- A protective ozone layer
- Zero eutrophication
- A safe radiation environment
- Flourishing lakes and streams
- Good-quality groundwater
- A balanced marine environment, flourishing coastal areas and archipelagos
- Thriving wetlands
- Sustainable forests
- A varied agricultural landscape
- A magnificent mountain landscape
- A good built environment
- A rich diversity of plants and animal life

These goals should also be applied in the construction industry and have further inspired local regulations and requirements. The construction industry shares a large portion of the emissions and is therefore essential to regulate and control. Municipalities apply the goals differently and to different extents. Lund municipality includes an extensive programme with directives (LundaEko II) that is based on the Swedish Environmental Objectives. Furthermore, the Swedish environmental laws are regulated by "Miljöbalken" (Eng. :"Environmental Code") and include, e.g., how to manage waste and implement a sustainable development (Riksdagsförvaltningen, 2020).

In Sweden, windows are included in and verified to several standards both on European and national level. In order to sell windows within the EU, they should be verified to the harmonised standard SS-EN 14351-1, have a declaration of performance and be CE-marked (Boverket, 2019). Some other standards that include windows are:

- SS-EN 16034; Pedestrian doorsets, industrial, commercial, garage doors and openable windows – Product standard, performance characteristics – Fire resisting and/or smoke control characteristics
- SS-EN 17213; Windows and doors - Environmental Product Declarations - Product category rules for windows and pedestrian doorsets

2.2. Circular economy in the construction industry

Circular economy is about relinquishing the linear method of product treatment and adopting a circular flow instead, where environmental and economic resources can be saved (Ellen MacArthur Foundation, 2015). By increasing resource efficiency, energy use for extracting raw material is reduced and therefore climate impact is reduced as well (Kanters, 2018). Circular economy is based on this principle and previous studies have indicated that circular economy is favourable from both environmental and economic perspectives (Ellen MacArthur Foundation, 2015). Previous studies also indicate that circularity is seldom used within the construction industry (Kanters, 2018) and that innovation is slow (Leising et al., 2018).

The principles should be implemented throughout the whole lifecycle of a building or building product. It is therefore important to plan for flexibility and reuse or recycle in the initial phases of construction. Products need to be designed and constructed to last longer and allow renovation given that 80 % of a product's environmental impact is determined at this stage (European Commission, 2010). By extending a product's lifespan through repair and re-manufacturing, resources are used more efficiently, energy is saved and environmental impacts are reduced (Allwood et al., 2011). Studies have shown that between 30 % and 90 % of resources can be saved when repairing an existing product compared to manufacturing a new one. Allwood et al (2011) conclude that the lifespan of products is constantly abbreviated and that they are replaced prior to reaching the end of the lifespan. This is due to new products being cheaper than repairing or renovating existing products. Although, new products can be both more resource-efficient and energy-efficient due to technical developments, which in some cases might result in early replacements being more beneficial from a climate impact point of view. In a linear business model, products often lose value after consumption and therefore go to waste, while in a circular business model, the value is remaining in the system (Nußholz, 2017).

Reusing a product can be done through direct replacement or non-destructive recycling (Allwood et al., 2011). By direct replacement, the entire product is moved from one area of use to another without changing its structure. Non-destructive recycling refers to changes in a product's shape without adding or removing parts of the product. Although, this is a method under development (Allwood et al., 2011). If the building must be planned according to what materials are available on the market, using reused products in a construction project makes the project more complex, which increases the cost for design. Reused products might also need to be certified or tested in order to ensure that they maintain high standards, which is an additional costing (Allwood et al., 2011). By adapting to a circular business model, new job opportunities and relationships between companies arise (Nußholz et al., 2020) which may be valued more than the additional costs. It may also provide competitive advantages on the market given the social trend of sustainability, which in turn could result in solutions and innovations in the future that provide economic profitability.

Buildings should be planned to easily adapt for different businesses to meet the market needs without having to be demolished. When buildings are designed so that products can be reused, waste is also reduced. This is also one of the main goals of a circular economy (Sparandara et al., 2019). Building products should be easy to dismantle and still be intact, which in turn also reduces releases of toxic particles that can occur during demolition. This is not the reality today. Older buildings usually contain hazardous substances which hinder circularity and favours demolition and waste (Sparandara et al., 2019).

The most common demolition method today is hard demolition. This is the most effective method based on labour and time consumption, but it damages valuable building materials that could be reused (Sparandara et al., 2019). Additionally, large amounts of emissions and waste are generated by this method, which indicates the importance of planning construction for future dismantling and reuse. Another important factor is whether information on existing products and materials is accessible, in order to properly dismantle a building (Sparandara et al., 2019). Inventories are therefore a significant part of transitioning the building industry to a circular economy.

All phases of a building's lifecycle require processes for energy and resources. It is therefore important to establish the possibilities of waste management and reuse or recycle when possible. The EU has provided a waste hierarchy of how to handle waste from construction among other industries (EU, 2008):

- Prevention
- Preparation for reuse
- Material recycling
- Other recycling, e.g., energy recovery
- Disposal

When the hierarchy is applied, there should be economic policies and other measures to provide an incentive for the application as well as to promote the alternatives that provide the best results for the environment (EU, 2008). Additionally, Sweden has recently undertaken 100 new measures for circular readjustments that includes waste management. Resources should be used efficiently by reuse or recycle in order to increase lifespan and economic value, and reduce extraction of raw material and disposal (Regeringskansliet, 2021b). This transition aims at meeting the environmental and climate goals as well as several SDGs, and would in turn strengthen the competitiveness of Swedish companies while reducing the pressure on ecosystems.

Two common terms in the Swedish construction industry are "Byggvarudeklarationer" (Eng.: "Construction Product Declarations") and "Byggproduktförordningen" (Eng.: "Construction Products Regulation"). Construction product declarations are a system for disseminating environmental information about building products and is based on voluntary commitment in the Swedish building sector (Jarnehammar et al., 2016). The construction products regulation is mandatory in order to sell building products and include the requirements for CE-marking the products if a certain type of standard is followed (Boverket, 2021b). Both subjects are affected by a circular economy.

2.3. Lifecycle Assessment

According to the standard ISO 14040:2006, Life Cycle Assessment (LCA) can be defined as follows:

"LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)" (ISO 14040, 2006)

It addresses any effect on the environment due to actions and lifestyle behaviour and is dependent on the source of emission and location. The method is also subcategorised in four phases for easier assessment and continuity for every project delivering an LCA analysis (ISO 14040, 2006). These four phases include goal and scope definition, inventory analysis (LCI), impact assessment, and interpretation.

The goal and scope phase defines within what boundaries the LCA should be conducted. It is recognised that defining the goal and scope of a study in different ways lead to different system models (Salazar, 2007). It is important to clearly state the purpose of the LCA in this phase. The functional unit should also be determined in this stage and serves as a starting point that relates the analysed product to an overall product system (Baumann and Tillman, 2004). The functional unit should define and quantify the product by relevance. In this phase, the system boundaries should also be set, and relevant assumptions made. The system boundaries determine the geographical location (also divided into global, regional or local levels) and what lifecycle stages should be included in the analysis. Lifecycle stages are either defined by the steps of a product's lifecycle or by an EN-standard. The steps of a product's lifecycle are:

- Cradle-to-Grave: Starts with raw material and ends with waste treatment
- Cradle-to-Gate: Starts with raw material and ends with produced product
- Gate-to-Grave: Starts after the product's production and ends with waste treatment
- Cradle-to-Cradle: Starts with raw material and ends with the material being reused

The EN 15804 and EN 15978 standards define the lifecycle stages as presented in Table 2.3.1.

Table 2.3.1. Definitions of the lifecycle stages.

A: Production stage	A1	Raw material extraction
	A2	Transport
	A3	Manufacturing
A: Construction stage	A4	Transport
	A5	Construction and installation process
B: Use stage	B1	Use
	B2	Maintenance
	B3	Replacement
	B4	Repair
	B5	Refurbishment
	B6	Operational energy use
	B7	Operational water use
C: End of life stage	C1	Deconstruction/demolition
	C2	Transport
	C3	Waste process
	C4	Disposal
D: Benefits and loads beyond the system boundary	D	Reuse – recover / Recycling – potential

When proceeding with the LCI the base is first set in the goal and scope. Needed data is then collected according to the set specifications and can be derived from site-specific data, generic data and/or assumptions and estimations. If some desired data is not available or processes are different than anticipated, then the goal and scope definition may be reconsidered and adapted to the available information (ISO 14040, 2006). Depending on the used database, available data differs which in turn affects the results. This is the reason for transparency in LCA. The flows of material and energy are then connected into one product system and allocation is determined. Allocation is defined in the ISO-standard as "partitioning the input and/or output flows of a process to the product system under study", and can generally be divided into physical, economic or casual allocation. Physical allocation refers to the amount, e.g., weight, area or volume, while economic allocation refers to the economic value of the different products. Casual allocation is divided by the own defined factor.

The results from the LCI are then assessed by midpoint assessment or endpoint assessment (Meijer, 2014). An endpoint method refers to the environmental impact at the end of a cause-effect chain which includes ecosystems, human health and resource depletion. A midpoint method looks at the impacts earlier on the cause-effect chain, before reaching the endpoint, which includes categories such as Global Warming Potential (GWP), Eutrophication Potential (EP), Acidification Potential (AP), Abiotic Depletion Potential (ADP) etc. Choosing the appropriate impact categories depends on the target of the study and available recommendations and data. After the results are assessed by the chosen method, they are interpreted and re-calculated or complemented if needed.

Results can also be normalised and weighted to further understand and simplify the impacts. With the normalisation step, all values are multiplied with either external or internal normalisation factors to obtain dimensionless units. External normalisation refers to factors that are independent of the study that also represent an overall inventory of a reference (e.g., global normalisation by a whole country or an average citizen) (Huppes and van Oers, 2011).

Internal normalisation refers to an internal reference system within the study, e.g., division by sum or maximum value etc. Even though normalisation is not considered a scientific but rather a political strategy, it can provide insights into the relative importance of different impacts in the categories. The normalised values can then be weighted by factors representing the overall importance on the environment. Although, impact values do not always have to be normalised in order to weigh them by importance.

2.4. Lifecycle Cost

It is important to make an investment calculation in order to know if an investment is economically feasible or not. To show the total costs of a building material through its lifetime, an LCC calculation should be made (Upphandlingsmyndigheten, 2021). To show the different profits between the different cases, calculations are made where profit and loss are combined. Profits are made from the energy use reduction by renovating through the different cases, and losses are made from the costs needed to conduct the work and buy the materials. A simple equation to show the calculations made for this study can be represented as shown below,

NPV = - Investment cost (one time) + energy reduction,

Where NPV stands for *Net Present Value* and represents the future value transformed into current value. The investment cost is negative since it is a loss, and the energy reduction is positive since it is a profit. The method of calculating NPV's is common for several industries including finance.

LCC's are important to use as it considers different parameters such as interest rate, price growth, and lifetime. The interest rate can be divided into real interest rate and nominal interest rate, where the difference between these two is that the inflation is taken into account in the latter option. The same theory applies for the price growth, which in this case is the yearly price growth of energy which is hard to predict. The lifetime of the product is considered in the calculations, which can be used to calculate the NPV for a specific year. It can also be used to find the year where the NPV is above zero, which shows that the investment is profitable and is called break-even time.

2.5. LCSA

LCSA, which stands for Life Cycle Sustainability Assessment, is a method of combining the results of both LCC and LCA (and social impacts if relevant) of one study and analyse the impacts of them. This is done through internally weighting the results together, where the impacts become a percentage of the total impact. Later the impacts are combined where a "weight" is put on both LCC and LCA in a form of a percentage, where a higher percentage means that a higher value is put on either LCC or LCA.

This is done to see the economic and environmental impact at the same time because it is of interest for companies and/or people to see what option is the best, depending on if the economy or environmental impact will be the larger factor to consider in a project.

3. Method

This chapter describes the methods chosen to carry through the study. To obtain relevant information, different methods were assumed suitable to retrieve necessary data.

3.1. Implementation

A simple SWOT-analysis was conducted to investigate what strengths, weaknesses, opportunities and threats may occur when recycling or reusing existing windows. With this analysis, the challenges and research questions were identified which provided the basic knowledge to further immerse into. The SWOT-analysis is presented in Table 3.1.1.

Table 3.1.1. SWOT-analysis of managing windows.

STRENGTHS:	**WEAKNESSES:**
- Better for the environment *- Saving resources* *- Less waste*	*- Costly* *- Guarantee and responsibility for product* *- Lack of knowledge and methodology*
OPPORTUNITIES:	**THREATS:**
- Circular economy is on the rise *- New market* *- New job opportunities*	*- Economic issues* *- Building regulations*

Through the analysis it was evident that the strengths were mostly benefits for the environment, meaning that with circular flows there would be savings for both waste and resources. The weaknesses included knowledge gaps for how such a process would proceed, which in turn would affect the economic aspects. Since there are no standards on how to treat old windows and reuse the materials, it is obvious that such a process would both be time-consuming and costly. Also, when reusing materials, the question of responsibility for the products arose. On the other hand, there has been an increasing trend on circular economy within the industry which brings opportunities to the table. There will be a new market for reused products with low competition and a possible first-mover advantage. This would in turn create new job opportunities. The possible threats of these opportunities would include economic hurdles given that new material and disposal are assumed fairly cheap and building regulations that are not adapted to enhance circularity.

The research questions were then stated and guided the implementation of the report.

In order to answer the questions, different approaches needed to be implemented. In general, a qualitative approach was used to retrieve data and information since this is a relatively new subject. According to Patel and Davidsson (2011), qualitative data is also called “soft data” which describes the data collected from verbal analysis methods of textual material and data from qualitative interviews. The latter being the chosen method for this degree project. The interviews were unstructured with open-ended questions, but with a limited number of companies that only deal with recycling, circularity, and/or windows. The same approach was applied for the literature review, where the purpose was to gather an extensive amount of information within the subject.

Later, a quantitative approach was used to gather and analyse the results of the case study. Quantitative data is data that uses numerical information (Eriksson and Wiedersheim-Paul, 2011). Various calculations for energy use, LCC, and LCA were conducted in order to find a preeminent solution. The results will be presented as statistics and will therefore be analysed in that way, in order to present the best choice in economic values and numbers in environmental impact.

3.2. Data retrieval

Data is collected through different sources and can be divided into the following:

- Site visit with a thermal imaging camera
- Literature review
- Empirical research
- Simulations and calculations
- Costs

3.2.1. Site visit with a thermal imaging camera

A site visit was conducted in the neighbourhood where the buildings are located in order to take thermal images of the existing windows. Images were taken of every type of window to find how much heat leaks out of the windows, see Appendix A. Besides the thermal imaging, a quick physical inspection of the windows was made to see what conditions they were in and what factors to include in the calculations.

The windows were mostly in good shape, except for a few windows in the hallway that had some cracks. The windows are 2-pane windows with a wooden frame. Based on the thermal images, the windows did not transfer as much heat from the apartment to the outside environment as expected for an old building. That is because windows installed during the ’50s are mostly of high quality and should therefore rather be refurbished than recycled based upon interviews and reports (Antell and Lisinski, 2003). The wooden frames need renovation since the white colour is being peeled off, other than that no other problems were detected.

3.2.2. Literature review

The purpose of the literature review was to research the chosen subject in order to answer the stated questions and gain proper knowledge to carry out the calculations and simulations for this degree project. A thorough review of research papers, articles, and books was carried out using different databases such as Scopus, ScienceDirect and Google Scholar. The knowledge and data gained from these sources were used to explain the present situation, the possibilities, and the issues that are associated with this subject. The literature review, combined with interviews and events, would provide enough input data and information to make it possible to conduct simulations and calculations, as well as assign realistic cases of reuse/recycling of windows for the project.

3.2.3. Empirical research

Interviews and events were conducted and attended for the same purpose as the literature review, as well as for confirming information provided by the research papers and articles. The interviewees and the contacted companies were carefully selected by their experience and knowledge within the subject, which would benefit the research project in Lund. The events were attended for the same reason, where more companies were gathered at one place at the same time, giving valuable information in this line of work. Due to the current Covid-19 pandemic, most events were held online and were easily accessible, making this type of data collection easier.

By conducting unstructured interviews with non-standardised questions, there was room to answer the questions freely (Patel and Davidson, 2011). Qualitative interviews are characterised by simple questions providing complex and high content answers, according to Trost (2010). The gained content from the interviews answers the research questions and provide a solid foundation to proceed with the simulations and calculations for the case study.

3.2.4. Simulations and calculations

The energy use of the building was simulated to distinguish the differences between the studied cases, which in turn would affect the LCC as the energy use was different from case to case. The simulations were run in Grasshopper in Rhino 3D, through Ladybug and Honeybee, where the climate data was set to Lund, Sweden, see Figure 3.2.1. The building was divided into different zones: hallway, basement, bathroom, room, and attic. Materials and characteristics were added to the building geometry, and HVAC settings were put for all zones. The building was simulated with Honeybee_Export to OpenStudio and the results were given monthly. The building chosen was the last building to the East of the neighbourhood, where dimensions, floor plan, materials, and characteristics of the building were taken from a file with information about all the buildings in the neighbourhood, see Appendix B. No sun protection or thermal bridges were calculated due to lack of provided information.

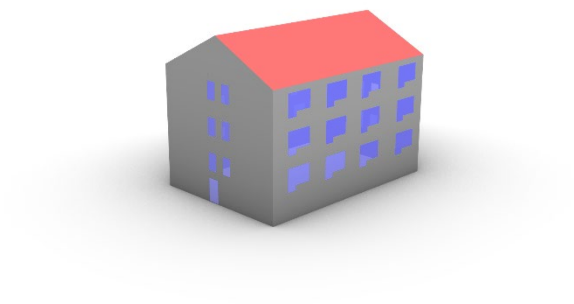

Figure 3.2.1. The apartment-building modelled in Rhino 3D and Grasshopper.

Further, the LCA for the different cases was conducted using the software OpenLCA with the European impact assessment method ILCD Midpoint using data from the year 2011. This software is developed for fast and reliable calculation of models for LCA and provides in-depth analysis of impact categories (openlca.org, n.d.). The impact assessment method is complying with ISO 14040 and ISO 14044, and is based on the midpoint method with values from 2010 (Acero et al., 2015; JRC, 2012). The cases were analysed for different building information life cycle stages, covering the production stage extracting raw material and the recycling/reuse stage, which is within the capacity of the software. The results provided by this software were assumed acceptable and correct for the cases in this report.

3.2.5. Costs

In order to calculate the LCC, energy prices and prices for different workloads and materials were needed. Prices for materials were found through websites selling products, and prices for the work and time needed to conduct the job were found through Wikells Sektionsfakta, containing information about prices in the building industry and time needed to finish the installations. The LCC was then obtained by equations calculating the Net Present Value (NPV) for the different cases.

3.3. Workflow

The method, including extracted and assumed values for implementation, is presented in the following subchapters.

3.3.1. Literature review

Prior to describing the subject and its shortcomings in Chapter 1.1 and 1.2, a literature review of previous research provided the knowledge needed to formulate the problem description and the research questions for this report. Since this report is part of an existing research project, the issues of circular economy and windows have already been stated meaning that it was not a priority to investigate proposed further studies from previous research.

3.3.2. Empirical research

The literature review, along with information on the businesses of the interviewees, did also contribute to formulating the interview questions. The majority of the interviews were held online or by phone, a few interviewees preferred answering questions by e-mail. The meetings were recorded and transcribed, and then sent back to the interviewed persons for approval of the gained content. All interviewees were offered anonymity in the report and are therefore presented by a hyphen in the table below when choosing to remain anonymous. Table 3.3.1 presents a compilation of the performed interviews.

Table 3.3.1. Compilation of interviewees.

Business/Institution	Name	Role
Lund municipality	Elin Dalaryd	Environmental strategist
Swede Glass United	-	-
JM AB	-	-
NorDan	Fredrik Jonsson	Team Leader
Kaminsky Arkitektur	Karl Warrol	Architect
IVL Svenska Miljöinstitutet - *Event*	-	-
Research Institutes of Sweden (RISE)	Anders Widing	Project Leader
Lunds Kommuns Fastighets AB (LKF)	-	-
Malmö Återbyggdepå	-	-
Avfall Sverige	-	-

3.3.3. Simulations and calculations

With the knowledge gained from the literature review and the interviews, simulations of energy use and calculations of LCA and LCC could be conducted. The energy simulations were performed for the entire building while the LCA and LCC were evaluated per m^2 window. Although, the results from the energy simulations were only considered in the calculations of the LCC by assessing the saved energy. For the LCA, the impact from energy use during the use stage was not considered relevant for this report nor is it a requirement by Boverket. The energy source for the building complex is a district heating network. It should also be mentioned that the demanded energy for the buildings was provided by renewable sources according to Kraftringen, and thus considered sustainable. The cases for calculating the LCC are presented in Table 3.3.2. The cases for calculating the LCA are presented in Table 3.3.3, where Case 4 from the LCA has been included in Cases 3.1 through 3.3 in the LCC.

Table 3.3.2. Cases calculated for the LCC.

Case	Remove	Add	Other
1	Interior windowpane	New energy pane	
2	Interior windowpane	New insulating glazing unit	
3.1	Window	New window	Glazed partition walls
3.2	Window	New window	Swede Glass United
3.3	Window	New window	

Table 3.3.3. Cases calculated for the LCA.

Cases	
1	Renovating window with energy glass
2	Renovating window with glass cassette
3.1	Reusing the glass for partition walls + new window
3.2	Recycling window + new window
3.3	New window
4	Waste treatment of existing windows

3.3.3.1. LCC and energy simulations

The energy use was simulated for three cases for a whole building. All three cases were then compared to The Swedish National Board of Housing, Building and Planning's (BBR) maximum reference value for primary energy of apartment buildings, to see if the window improvements alone are fulfilling the criteria. The requirement in the latest version of BBR is set to 75 kWh/m^2 heated floor area (Boverket, 2020a). When calculating the LCC, the same energy demand was used for Cases 3.1, 3.2, and 3.3, since they all have new windows installed in the building. The area of the windows for the whole building was 79.5 m^2, which excludes the windows in the hallway as they are not included in this study. For Case 1, the interior windowpane was substituted for a new energy pane which reduced the *U*-value to 1.8 W/m^{2}K (interglas.se, n.d.) and the old windowpane was sent to waste. In Case 2, a similar approach was made where the interior windowpane was substituted by a new insulating double glazing unit filled with argon gas, reducing the *U*-value of all the windows to 1.3 W/m^{2}K (Grundels Fönstersystem, n.d.) and the old windowpane was also sent to waste.

In Cases 3.1 through 3.3, the old windows in the apartments were substituted by new energy-efficient windows with a *U*-value of 0.9 W/m^{2}K.

- Case 3.1 uses the old windowpanes and new frames to build partition walls in the apartments and sends the window frames to waste.
- Case 3.2 sends the old windowpanes to recycling and the window frames to waste.
- Case 3.3 sends the whole window to waste.

The five different cases were chosen based on the interviews and reports. The first two cases are seen as the two most applicable renovation methods to most windows in Sweden that are in decent quality, even if no access to the windows from the inside was provided to see if this can be done. The last three cases are seen as different outcomes of the old windows when choosing to replace them, which can be further developed if wanted, and applies to most buildings.

The in-data for the HVAC in the energy script is presented in Table 3.3.4. Some input values were taken from sources that have simulated this building before, but due to all information not being available, some in-data had to be assumed to reasonable values for an older apartment building. The window-to-wall ratio was calculated to 13.2 %.

Table 3.3.4. In-data for energy simulation.

	Heat Set Point/(°C)	Ventilation Type	Air Leakage/(l/s)	Airflow per person/(l/s)
Apartment	20	CAV	0.5	7
Basement	15	CAV	0.5	7
Attic	5	CAV	0.5	7
Hallway	15	CAV	0.5	
Bathroom	20	CAV	0.5	
	Airflow per m²/(l/s)	**Equipment Load/(W/m²)**	**Lighting Density/(W/m²)**	**Number of People/(ppl/m²)**
Apartment	0.35	4	5	0.06
Basement	0.35	4	5	0.02
Attic	0.35	4	5	0.02
Hallway	0.35	2	6	
Bathroom		4	4	

The *U*-values were calculated based on the construction drawings, see Appendix C. The windows *U*-value were assumed based on common *U*-values for 2-pane windows from the '50s, which was motivated by the thermal images of the windows of the building, see Table 3.3.5. These values were also added to the energy script, more precisely to the modelled building in Rhino 3D, where walls, roof, ground, attic floor, and windows were automatically separated in Grasshopper and were given the material characteristics which include U-value, thermal conductivity, and thickness.

Table 3.3.5. U-values for the building.

Building product	*U*-value/(W/m²K)
Walls	0.89
Roof	1.19
Ground	0.23
Attic floor	2.38
$\text{Windows}_{\text{hallway}}$	3.00
$\text{Windows}_{\text{apartment}}$	2.80

Statistics for supplied energy through a district heating system of the neighbourhood arrived during the ending stages of the study, which included all five buildings and not separately. This gave a reference value to compare the simulated results to, see Appendix D. To compare the simulated results with the measured energy, the results had to be assumed to be the same for all five buildings per m^2 heated floor area. The approximate area of the buildings (five heated floors including stairwell per building) is 8 000 m^2. Dividing the total energy use from the statistics with area yielded a result of approximately 127 kWh/m^2.

Since some information was not available, time values for specific actions were assumed in order to proceed with the calculations, see Appendix E. The assumptions were based on websites that explain how to conduct the renovation (leifarvidsson.se, n.d.). The price of sending the windowpanes for recycling to Swede Glass United was also assumed to be similar to regular waste management in Lund, but just a bit more expensive since its facilities are not as large as the waste management. The assumption was necessary since no price information was shared by Swede Glass United. Furthermore, as the prices were calculated per m^2 window, so was the energy use when calculating the LCC as it was divided on the total area of the windows in the apartments. VAT of 25 % was added to the work costs and so was a cost surcharge of 272 % based on references from Wikells Sektionsfakta. Further information of what is included in the surcharge was not obtained but is assumed to be payroll taxes etc. The material costs are presented in Table 3.3.6 and work hours with costs are presented in Table 3.3.7.

Table 3.3.6. Material costs per m^2 used for LCC calculations.

Material	Price/(SEK/m^2)
Energy glass	600
Insulating unit	900
New window	4 700
Oil, colour, putty	244
Window frame	1 000
Waste windowpane	10
Waste window frame	10
Waste window	19
Recycling	15

Table 3.3.7. Working time needed for a job and price per m^2 used for LCC calculations.

Material	Work	Unit	SEK/h	h/m^2	SEK/m^2
Energy glass	Remove old windowpane	*h*	218	0.2	202.74
	Add new energy glass	*h*	218	0.2	202.74
	Scrape, oil, paint	*h*	218	0.6	608.22
	Total				**1 013.7**
Insulating unit	Remove old windowpane	*h*	218	0.2	202.74
	Add new insulating unit	*h*	218	0.4	405.48
	Scrape, oil, paint	*h*	218	0.6	608.22
	Total				**1 216.44**
Partition wall	Remove old window	*h*	218	0.6	608.22
	Carefully remove old windowpane	*h*	218	0.4	405.48
	Install panes in frames	*h*	218	0.5	506.85
	Install new windows	*h*	218	4.6	4663.02
	Total				**6 183.57**
New window	Remove old window	*h*	218	0.6	608.22
	Install new window	*h*	218	4.6	4663.02
	Total				**5 271.24**

LCC can be calculated in different ways, meaning through different equations depending on what is calculated. In this study, only a geometric gradient equation was used because of the price growth of energy, see Equation 3.3.1, as well as one-time costs which such as costs for the materials and work conducted. The geometric gradient equation results in the present value of a value in *N* years, depending on the real interest *i* and the real price growth *g*. In this case the interest rate was determined by Sveriges Kommuner och Regioner (SKR) (Stjernborg, 2020) and the price growth was determined by Energieffektiviseringsföretagen (EEF) (eef.se, n.d.). A lifetime value of *N* = 30 years was chosen, the reason being that the renovated windows should have a lifetime value of at least 30 more years, according to an interview with RISE. It should be noted that a new window has a longer lifetime than 30 years but was still limited to this value to simplify the calculation. Since energy prices are not stable and vary with time, the price was assumed to be 1 SEK/kWh for both district heating and electricity. The input values for the equations are specified in Table 3.3.8.

$$P = A_1 \left[\frac{1-(1+g)^N (1+i)^{-N}}{(i-g)}\right] \quad \text{(Equation 3.3.1.)}$$

Table 3.3.8. Input values for the equations.

Parameters	Values
Real interest	1.50 %
Lifetime	30 years
Real energy price growth	2.50 %
Energy price	1 SEK/kWh

3.3.3.2. LCA

The goal and scope of the LCA-study was to investigate the environmental impact of managing the windows in the existing buildings, by assigning different process scenarios for evaluation. Not all life cycle stages were included in the study. The functional unit for the LCA is one window of 1.0 m^2, including a wooden frame, that enables daylight into the apartment. The selected impact categories that were analysed were based on recommendations from ISO 14042, which states to include categories for which international consensus was reached (Stranddorf et al., 2005). Therefore, the selected environmental impact categories for this study include:

- Global Warming Potential (GWP)
- Ozone Layer Depletion Potential (ODP)
- Photochemical Oxidant Formation Potential (POCP)
- Acidification Potential (AP)
- Eutrophication Potential – Freshwater (EP – Freshwater)
- Eutrophication Potential – Terrestrial (EP – Terrestrial)
- Abiotic Depletion Potential (ADP)

Some assumptions needed to be included in the study since not all information could be provided for the windows. Given the level of detail needed for the investigation, it was concluded that these assumptions were accepted for this report. The analysed lifecycle stages and inputs, and assumptions are presented in Table 3.3.9 and Table 3.3.10.

Table 3.3.9. Analysed lifecycle stages for each case.

Case 1	**Case 2**	**Case 3.1**
Lifecycle stages	**Lifecycle stages**	**Lifecycle stages**
A1-A3 + A4	A1-A3 + A4	A1-A3 + A4
C1-C4	C1-C4	C1-C4
Input	**Input**	**Input**
New energy glass	New energy glass	New wood frames – pine
Paint	Argon	Paint
Transport	Spacer frame – steel	Transport
Recycle old pane	Paint	Recycle old wood frames
	Transport	
	Recycle old pane	

Case 3.2	**Case 3.3**	**Case 4**
Lifecycle stages	**Lifecycle stages**	**Lifecycle stages**
C1-C4	A1-A3 + A4	C1-C4
Input	**Input**	**Input**
Recycle glass	Glass	Demolition waste
Recycle wood frame	Energy glass	Landfill glass
Transport	Argon	Landfill wood frame
	Wood frame – pine	Paint waste
	Transport	Transport

Table 3.3.10. Assumptions for modelling the cases.

Assumptions	
Density glass	2 500 kg/m^3
Density pine wood	500 kg/m^3
Density steel	7 900 kg/m^3
Density paint	1 200 kg/m^3
Density argon	1.449 kg/m^3
Thickness glass	6 mm
Thickness frame	105 mm
Air/Gas gap	14 mm
Area windows	0.8 m^2
Area frame	0.2 m^2
Transport - small lorry	40 km

The results were based on physical allocation and were then normalised according to EU-27 values from 2010. Later, the normalised results from the calculations were weighted by the recommended "equal weighting"-method by applying the same weight to all impact categories (JRC, 2016). Three more weighting methods were applied to give a range of results. These three methods are based on weighting the impact categories by importance, see Table 3.3.11.

Table 3.3.11. Factors for different weighting systems.

		Weighting Factors			
Impact category	**Reference unit**	**Equal**	**EPA**	**BEES**	**NOGEPA**
GWP	kg CO_2 eq.	**6.67 %**	**16 %**	**29 %**	**32 %**
ODP	kg CFC-11 eq.	**6.67 %**	**5 %**	**2 %**	**5 %**
POCP	kg NMVOC eq.	**6.67 %**	**6 %**	**4 %**	**8 %**
AP	molc H+ eq.	**6.67 %**	**5 %**	**3 %**	**6 %**
EP - Freshwater	kg P eq.	**6.67 %**	**5 %**	**6 %**	**13 %**
EP - Terrestrial	molc N eq.	**6.67 %**	**5 %**	**6 %**	**13 %**
ADP	kg Sb eq.	**6.67 %**	**5 %**	**10 %**	**-**

3.4. Credibility and reliability

Literature reviews require high credibility. Credibility is a noun that can be described by the concepts of validity and reliability. According to Patel and Davidsson (2011), validity means to investigate what is intended to investigate and reliability intends to describe the quality or degree of the credibility. Literature reviews also require source criticism, which is covered and described by four criteria (Uggla Waldenström, 2017):

- Authenticity: Is the source what it claims to be? Is it the original source or a copy? Is it authentic or fake?
- Time/Date: When was the source established? Is the information up to date? Are any new occurrences affecting the subject of the source?
- Dependency: Is the source independent or is it related to or based on other sources?
- Tendency: Are the sources based on valuations or interests of the sender? What is being presented?

By following the four criteria when checking facts, it is assumed that the references supporting statements should be valid and reliable. Scientific papers and investigations, governmental/institutional reports and websites, and interviews are the main sources in this report. By confirming and correlating these sources with each other, the reliability is increased. In order to increase the validity of the interviews, information of the businesses was retrieved and analysed beforehand, to be able to ask relevant interview questions. All interviews were recorded meaning that the answers could be checked and confirmed several times.

Given that this report is objective on the subject, the authors have not included their own opinions as facts. Own interpretations and opinions of the results have only been included in Chapter 7 (Discussion) and Chapter 8 (Conclusions).

4. Empirical research results

This chapter presents the empirical data from the interviews and events. A total of nine interviews and two events were held or attended. The collected information provides theoretical input for further studies as well as answers the stated questions in this report. Each interview focuses on different aspects of the subject, depending on the work experience of the company. The information gathered from the events gives a solid foundation of the current regulations and industry statistics in Sweden.

4.1. Municipality of Lund

Elin Dalaryd is an environmental strategist at Lund municipality and has expertise in how the municipality is implementing environmental work in their organisation. She shares details of LundaEko II, saying that the programme involves everyone within the municipality. The report sets goals for managing resources and reducing energy use and environmental impact. LundaEko II also expands into more specific programmes such as the energy plan which regulates the goals for energy use and release of emissions in the construction industry. The department for service management at the municipality has decided to follow and apply the criteria from the certification system Miljöbyggnad for new construction, without certifying the buildings through Sweden Green Building Council. Since the municipality does not sell their buildings, it is deemed unnecessary to include external certification, which is why they follow the protocol but do not pay for getting the certificate. Dalaryd further explains that they have also provided design instructions that include environmental requirements beyond the certification criteria, and that they have the possibility to require certain demands for tender procurements. They review and update their documents and guidelines annually, and have worked with development projects where they have investigated how inventories in demolition can become more efficient and how they can implement reuse in their projects.

The goals in LundaEko II are concretised to requirements for the tenants and the department must make sure that these requirements are easy to meet. Although, they are not always following up on the goals since they do not have statistics to compare measures with, and therefore are not setting requirements, but rather recommendations, for all aspects. This issue will be revised in the future and since The Swedish National Board of Housing, Building and Planning (BBR) is implementing climate declarations, it is assumed it will be easier to get the needed statistics in order to set specific requirements.

When asked if they work with reuse in their organisation, Dalaryd answers that they have not worked with it on larger scales or in structured ways, nor have they requested a certain amount of reused materials to be included for new constructions. For this past year, they have begun looking into how to implement a circular economy in their work and are trying to find ways to apply the method in projects. She mentions that she was part of an investigatory project that deconstructed a building and sold reused products in order to see if there was a market for circular economy and what the response was. The knowledge and experience drawn from this project were implemented in two more inventories, where they tried out tools for registering and providing information of materials. This experience has also given the knowledge to be able to formulate some requirements for contractors to follow. Unfortunately, the projects have also given them insights into how immature the market is for this method since the businesses are not developed to handle existing materials in other ways than by demolition and waste generation. Warehousing is a difficult issue to solve since the municipality only has smaller storages and would therefore need to rent space, which in turn is expensive if the stored products are not requested on the market. This means that the economic profitability did not include a circular economy at the time. The question regarding getting a larger storage unit is something they are discussing at the department this year.

The economic system in their projects is also not completely compatible with a circular economy-approach since last-minute changes in a project might be hard to implement in the budget. A product in a building has an economic value, when the product is considered waste and is sent for disposal, the product is economically transcribed. If this product is instead re-directed to a new building, the value of the product needs to be assigned. All components/products in a building have also a depreciation period meaning that the cost for the component/product is distributed a little every year. When re-assigning a product that is already transcribed and has a certain lifespan, the issues of how to handle its value is essential to solve. Given that the value will set the base for rent for the tenants, it is also important to know the quality of the product or component, according to Dalaryd. She continues stating that old and bad-quality windows might be better to use for partition walls or atriums. When handling material within the municipality, the material belongs to the municipality which facilitates the process.

Further discussing projects and circular methods, Dalaryd explains that they have not received any offers including reused materials but that they have not requested it either. When presenting projects for public procurement, it would be possible to include requests for certain materials to be reused or to set regulation for carbon footprints which would force tenders to apply circular methods in their calculations. She further explains that the possibility to include circularity as a criterion for discussion and work with collaboration contracts could be another way to implement it in their projects. This way it will not be known what material will be reused but will be discovered with the contractor throughout the project.

She claims that there are some difficulties with reusing windows in the building envelope again unless they are renovated in some way, which is costly and difficult and limits the potential for reusing them. It is easier to reuse the windows in the interior, such as for atriums. Regulations for documentation and the amount of information that needs to be available for certain materials or products would need to be compromised when including reused products. Yet, it is still important to know whether there are any hazardous substances in the products to be able to approve them for any kind of reuse. Dalaryd also explains that given that they are following the criteria from Miljöbyggnad, the requirements for windows to achieve a certain standard could be too high for it to be possible or economically beneficial to renovate old windows for new construction. Therefore, it is important to properly state the requirements and concretise what reused materials should be used and where they should be placed, so that the presumption for the tenders is the same. A company that specialises in renovating windows would also need to develop a method to verify and document that the reused windows meet the given standards, which is a separate issue that needs to be addressed.

Changing the windows usually occurs with larger building renovations according to Dalaryd. When everything else is being renovated, they tend to change their windows from 2-pane to 3-pane windows at the same time. The demolition company deconstructs the products since the new legislation for sorting waste has been enforced. She states that they have not had any projects with demolition included since the new legislation was put in force, but that this does enable for a circularity plan to be created.

She also speculates that new material is cheaper than reusing existing material which might be the reason why circularity has not been implemented in the Swedish building industry to a greater extent. Other countries such as Denmark and the Netherlands might have policies and an adjusted economy that allows for a circular economy to be a more common choice of method. Yet, she is optimistic that circularity will play a bigger role in Sweden as soon as methods for handling materials becomes more efficient. Many building types have lower standards to achieve and might therefore be more suitable for using reused products in construction today.

4.2. Swede Glass United

Swede Glass United is a company that specialises in recycling glass, including flat glass (swedeglassunited.com, n.d.). They receive flat glass from all over Sweden which includes around 20 000 tonnes of glass per year. The glass is separated according to provided guidelines and most of it is collected from municipalities, industries and other large corporates in the industry. One criterion is that the glass must be as clean as possible which prohibits glass with PCB (a hazardous substance mostly used in windows between 1969 and 1973) to be received. Other than that, tempered, laminated and coloured glass are accepted. The glass that is collected in Sweden is exported by lorry and boat to their parent company, Reiling, in Germany where it is sorted by precise technology once again, and then sent to the glass industry where it is melted and manufactured into new products. The company is only responsible for delivering clean and sorted glass to the glass industry and ensuring that other residues are sorted and sold to relevant recycling centres. The glass industry is then responsible for further processes and distributing their products in their respective countries. This also means that the exported glass is not directly imported back to Sweden, but rather indirectly through construction and production trade.

Reiling has two facilities in Poland, thirteen in Germany and two in Denmark, and covers the Swedish market through Swede Glass United. The processing centre in Denmark is located near a canal which enables shorter distances for shipping the glass from Sweden and excludes part of the lorry transport. The company is proactively working to reduce the environmental impacts by re-evaluating its business and transportation methods.

The cleaning and sorting process is described by certain stages. The glass is firstly crushed to a specific size that facilitates the process and then sent through a stage of different lighting and magnets that remove the metals. Thereafter, it is processed by another set of lighting and compressed air. The temperature is regulated throughout the process to extort the different fractions of pollution, and the crushed glass is lastly washed to remove the last unwanted materials. This procedure takes less than a day. Before delivering the cleaned and sorted glass to the glass industry in Germany, it is stored in certain compartments. Most of the removed materials are sent to their respective recycling centres and manufactured into new products. Approximately 2 % of the removed material goes to incineration each year. This process applies to all glass types and qualities they receive.

Glass can be recycled many times without compromising on quality. Recycling glass requires less energy than producing new glass, which reduces the environmental impact and saves resources. Glass is also not harmful to the environment which is why digging down windows has been a solution to handling the waste. Statistics for this solution are hidden and the process is unnecessary since raw material must be extracted from the soil again to produce new glass. Companies that own land and provide the service of landfill can benefit economically by taking in old windows and bury them underground, according to Swede Glass United. Given that this procedure is not forbidden or punishable, businesses revolving around waste management are allowed and can be cheaper than recycling.

Swede Glass United cooperates with Naturvårdsverket (Eng: Environmental Protection Agency) and Länsstyrelsen (Eng: County Administrative Board) and follows the guidelines provided by the agencies. The parent company has laboratories where the glass is tested regularly to provide good quality of the process and ensure no harmful substances are being released. The collected glass received by the company is charged by glass type and quality, but the aim is to constantly compete with prices for landfill disposals.

4.3. JM

JM AB is one of the leading property developers in Sweden, Norway, and Finland. The company has a long-term goal to include sustainability work in all operations and is therefore actively incorporating UN’s initiative for a sustainable built environment (jm.se, n.d.). When asked about their experience of window replacement and/or reuse of windows, they reply that their work usually revolves around replacing entire, new windows due to wrong window types being purchased or replacing damaged parts, such as glass panes or aluminium details. They experience that it has been more common to replace details and parts rather than entire windows during construction, although both these actions are usually uncommon. Their warranty department rarely does replacements of older windows. They also reply that they do not have experience in reusing existing windows. No comments were received on window replacement during building renovation for reduced energy demand. Statistics of how many windows are replaced annually were not retrieved.

If the existing windows are in good shape, then it is common that Malmö Återbyggdepå gets them after deconstruction in order to re-sell them. With good organisation on the construction site, the handover of building products is a smooth process. There are also several procedures that require careful work of handling windows according to JM. One critical criterion is that the entire replacement should occur on the same day to minimise the risk for interior damage due to weather. When further asked about deconstruction/demolition of windows and the cost for the procedure, JM answers that this depends on the type of work needed and during what building phase the replacement occurs. Are carpenters already available on the construction site, then there is no need to hire workers for this. Depending on the building design, there might be a need for scaffolding as well. Also, depending on the façade and interior surfaces, the replacement involves different types of work, e.g., if the windowsill is already mounted and requires disassembling or the façade panels need to be removed. JM sums up the answer by saying it is a difficult question to answer given that the later the replacement occurs, the more time and money is required.

4.4. NorDan

NorDan is a manufacturing company in Sweden, specialised in windows and doors (nordan.se, n.d.). The opportunities for circular material flows during renovation were investigated in a pilot project in Helsingborg, Sweden, called Brf Eddan. NorDan cooperated with NCC for this project, investigating how existing windows could be part of the circular process during renovation. Fredrik Jonsson is team leader for environmental certification at NorDan, with in-depth insights of the pilot project in Helsingborg.

With new regulations for waste management, each material must be separated and sorted before being disposed of. Glass is one of the materials that have the highest amount of emissions released into the air during manufacturing, and is usually recycled into new glass products rather than new flat glass, according to Fredrik. Glass does also have high reuse/recycling potential, which is not common for all materials, but it can be hard to guarantee the quality. He further explains that this encouraged them to investigate how to increase the amount of glass being recycled by minimising the amount of material going for energy recovery and to landfill. Today, the most common procedure for recycling includes burning certain materials. This project has provided useful knowledge and has proven that it is possible to increase the efficiency of waste management.

Jonsson discusses the economic issues, specifically that it might be more feasible to dispose of the material. He says that materials do not have a high value given that they contribute to higher costs during a renovation process. The industry needs to re-structure, mature and put a higher value on materials by producing products with intentions to reuse or recycle. Today, only recycling companies make money on this process. Jonsson says that there is an increased interest for circularity and that the industry is trying to evolve in that direction, but that this approach often results in increased prices as well. The additional costs of managing and verifying or testing materials are often expenses the customer is not willing to pay extra for. Other issues include lack of information or data on how products have been manufactured and what materials are included. This is not true for new construction since products today are registered via “Byggvarudeklarationen”.

The customer will require certain criteria, such as transmission, to be met for their building and with a reused window, these criteria are not guaranteed to be met. Jonsson says that there are certain technical parameters for existing windows that cannot be verified today due to lack of data which raises the question of warranty and responsibility. This also means that the *U*-values can be estimated to be worse than they might be in reality, but Fredrik believes that there are existing methods that can investigate the issue, though it might be a difficult approach for on-site investigation. The lack of product data and information is a large issue according to Fredrik since this halt the progress of circular flows. The more information is presented when manufacturing a product, the more information is available when that product is replaced or recycled/reused. Therefore, Fredrik believes that recycling is easier than reuse since there is no guarantee that old products can meet today’s industry requirements, but the possibility does exist. When different materials of a product have different life spans, then the argument for circular methods increases given that only part of the product could be replaced and the other part reused. He further discusses that NorDan wants to be able to upgrade old windows to current quality and standard, but they have not developed that procedure yet.

When asked about warranty and responsibility for reused materials, Fredrik replies that it is the certified entrepreneur who executes the process that is responsible for ensuring the right criteria is met. He also states that this is why windows are especially difficult since the demands for windows are high given that they are part of the building envelope.

An inventory is an important part of exploring the potential of reuse or recycle of windows. The windows construction is established, and technical functions and data are either discovered or assumed depending on the year for manufacturing. Thereafter, the deconstruction is executed semi-manually, with equipment, which is more time-consuming and therefore costly. The industry is reluctant to pay more for deconstruction for future reuse/recycle when raw material is cheaper, according to Jonsson. He then further explains that when doing an LCA for reused materials it is important to exclude stage A1 since the raw materials have already been extracted once so the new life stage starts from A2 and counts forward. Other new materials needed to produce a product are then calculated from A1 if the product is only partly made of reused material. He also shares that there are figures on how big the environmental savings are per kilogram of recycled glass, depending on how much energy is saved during the manufacturing process. Recycled glass requires less temperature to melt and therefore requires less energy for the process. The glass of a product stands for 60 % to 70 % of the entire product's climate impact, therefore recycling is a good option for waste management. Fredrik mentions that even though the economic benefits do not match the environmental benefits for recycling, the industry is a large holdback.

4.5. Kaminsky Arkitektur

Kaminsky Arkitektur is an award-winning architectural firm based in Sweden. They are known for incorporating sustainability with their design and have been acting as consultants for reuse and circular economy (kaminsky.se, n.d.). Karl Warrol is an architect at the firm and has also experience as a consultant for circularity for a hospital project in Stockholm, Sweden. Given the project's distinction from a workflow including only new products and construction, it was important to establish how an inventory for a building with ambitions to reuse materials is different from that of an ordinary inventory. Warrol explains that for this specific project, the difficulties have been that many components in the building are mislocated after tenant adaptation and given the size of this project, this becomes an issue. He further answers that since this building was built in the 1970s, not many materials are considered to have cultural or historical importance and many toxins are built into the construction which is troublesome. Before executing this inventory, a lot of information was retrieved by the circular economy guides provided by CCbuild and by reading in on inspirational projects from Denmark and the Netherlands. During the inventory, the initial work included getting a comprehensive image of what materials and products have the potential to be reused and then document them in a “Materialhanteringsplan” (Eng.: “Material Handling Plan”). This document is then the foundation for the decision-making process together with the architects, the builders, and the customers. In this material handling plan, each product or material is being assessed and graded from 1 to 5 by its climate impact savings, logistical solutions, economic savings, and environmental savings, as well as described by its current function and potential future function. Thereafter, decisions of what to keep in place, what to reuse, recycle or upcycle, what to give away for re-selling, and what to treat as waste are being made.

Products that are common, such as lockers, sinks, and toilets, are usually reused. Other materials, like bricks, are also possible to reuse depending on what year they are from according to Warrol. If the brick is from before the 1960s then the mortar is usually soft and the brick is, therefore, easier to separate, while it otherwise might be possible to extract approximately 60 % of it. This is a fairly expensive process but might benefit future renovations by storing the same brick type and use it when needed. Concrete is harder to reuse and is usually downcycled to fillings for roads.

The material handling plan has also impacted the design of the new hospital by adapting the new floorplans to the existing floorplan in order to reduce the need for deconstruction and by downcycling the current building products and materials to give them a new function. Later in the project, a deeper investigation on the environmental and economic savings will be executed.

When asked about how they have handled the windows in their project, Warrol answers that it was discovered that there was PCB in the windows and that the decision to try to recycle the glass was made. The glass could be recycled into new glass products, glass wool, or as a filling in foundations. One manufacturing company that also handles recycling is Saint-Gobain, another option could be to sell the material to Latvia since they have a large industry within recycling glass, according to Karl. In this particular case, it is Skanska that is responsible for this process in the project. An additional cost to the removal of the windows is the sanitation of the brick around the window construction because of the PCB.

When further questioned about the goals and requirements for this project, set by the customer, Warrol answers that the ambitions were set high and that it was discussed to set a limit of tonnes of CO_2 emissions released into the air. The aim was also to certify the building according to LEED criteria.

Warrol explains that an economic budget can limit circularity as well. Considering that it is still an uncommon and non-standardised method in construction projects, it is not fully established yet how to calculate the benefits. The quality of the products also has an important role in the budget. If the product requires renovation, then the complexity of the renovation determines the economic strain on the budget. The industry has also not been adapted to the new concept of circular economy, which means that the cost for some procedures (like re-locating products within the building) is not properly established. All of this determines the feasibility of the project. Smaller companies have the ability to restructure their business to enhance circularity easier than bigger companies.

Karl believes that the linear ways of industrial structures and standards are hindering the evolving of a circular economy. He thinks that innovation is one of the answers to this issue. There is a movement for implementing circular flows in middle-sized companies which will hopefully spread further. There is an increasing demand for circularity and manufacturing companies have started to meet this demand, but the process is slower for the construction companies providing labour. Another issue is the warranty. It can be common that products go to waste only because the warranty has expired, and no one wants to be responsible for reusing the product. He continues explaining that given that there are no guidelines for circularity within projects, it has given their company the possibility to create guidelines or a type of standard on how to design and build for future reuse.

He believes in an increase in job opportunities which will further benefit a circular economy within the construction industry. He also believes that circularity will be more economically beneficial in the future, especially when reuse centres develop and start storing larger quantities of building products.

4.6. IVL Svenska Miljöinstitutet

IVL Svenska Miljöinstitutet is an independent research institute with focus on the environment and sustainability (ivl.se, n.d.). The work includes applied research and evidence-based consulting assignments that contribute to meeting both the global sustainable development goals and the Swedish environmental goals. During two events in March 2021, IVL shared important information about Swedish regulations and circular economy, including facts and statistics of the current situation.

The construction and property sector was responsible for 21 % of Sweden’s GHG emissions in 2018 (Boverket, 2021a). Construction has a high potential for changing the influence on the environment given the new legal requirements. Construction also generates 35 % of Sweden’s total waste and 22 % of all hazardous waste (when excluding waste from mining), according to statistics from 2018. This is an increase from previous years. Approximately 52 % of the waste is recycled. By circulating or recycling material, the number of emissions and waste reduces.

A circular building can be defined by a lifecycle-based approach where the useful time of the building is optimised, the final life stage is integrated into the design and new ownership models enable materials to be stored temporarily in buildings. This would mean that a building could work as a material bank (Leising et al., 2018). But to fully describe circularity in a single overall index is difficult. The principles for circular construction are included in the EU’s waste hierarchy.

There are several challenges with circularity in the Swedish construction industry. These include knowledge and experience, and the market, which in turn raises questions of quality and warranty, and time and resources (Gerhardsson et al., 2020). The challenges are to some part regulated by habits and attitudes. It is common to not change approaches and methods since they have worked in the past. It limits the potential for improvement. Yet, the possibilities are many. The solution may include more material inventories, displaying visible effects and resources, cooperation, sharing experience, and knowledge, new work methods and/or policies, and legal requirements.

New legal requirements regarding control plans, material inventories, sorting material at construction sites, and ways to report hazardous waste were implemented on the 1st of August 2020. Previous to the new regulations, it was mandatory to present an inventory of the demolition material in regard to potentially hazardous waste and how all types of waste should be handled. After the new regulations, it is mandatory to map out what demolition material can be reused, recycled, or should be treated as hazardous waste, including how the material will be handled for reuse or recycle (Boverket, 2020b; Naturvårdsverket, 2020b). Hazardous waste needs to be reported through a waste register and the new regulations state that the remaining waste should be sorted into the following groups:

- Wood
- Mineral (concrete, clinker, ceramics etc.)
- Metal
- Glass
- Plastic
- Gypsum

The developer is in charge of selecting adequate building products for a construction project that fulfils the set requirements. There are several systems to help to choose adequate products such as CE-marking, type-approval and/or manufacturing control, product certification by an accredited body, and manufacturing and production control by an accredited body. Although this is targeted for new products and means that old or reused products do not require the assessment of performance to be described or documented, they just need to be considered adequate. For example, CE-marking is referred to the manufacturing process of a product and is therefore not compatible with assessing a circular method. This in turn means that a review of the "Byggproduktförordningen" (Eng.: "Construction Products Regulation") (CPR) is a must in order to adapt to a circular economy.

When discussing quality and warranty, topics regarding industry practice and attitudes arise. These subjects are not regulated as much by law nor are there any regulations on how to assure the quality of materials and products. The General Conditions of Contract for the construction industry (AB 04, ABT 06, etc.) are applied in projects but they do not concern reused materials which means that it is voluntary to take on responsibility for reused products. This is considered an issue. Possible solutions could be letting the product supplier and/or contractor take the risk, letting the customer abstain from warranty requirements with the condition that the contractor takes on responsibility in exchange for lower demands, or enter into partnerships and provide written agreements for circularity. Another issue that arises when upcycling a product for reuse is defining the product, meaning whether the product is considered new or renovated which in turn lifts uncertainties of relevant requirements.

By setting requirements for procurement, it is possible to include or require a circular economy. It provides the possibility to set environmental requirements throughout a product's entire lifecycle, verify for achieving requirements, refer to environmental management systems in order to provide evidence for sufficient technical capacity to fulfil contracts, include LCC's in procurement processes, and depart from the principle of minimum price by awarding the contract to tenders that can present the most economically advantageous tender. Today, information and guidelines for reuse and recycling are lacking since the subjects are rarely mentioned in central guidance systems for procurement in Sweden. There is an international standard for sustainable procurement, ISO 20400, that could be adopted in Swedish systems. A work model for how to direct a project for a circular economy would include increased incitement, a work process that includes circularity (by taking advantage of prerequisites and plan for timelines and budget around circularity), and enabling future circularity. Options that are mentioned include renting products to ensure sustainable products are used and avoid paying for maintenance and manage waste, longer use of products, purchasing products with long life expectancy and/or easy assembly to enable for future reuse etc. This in turn shows that an analysis of the demand is becoming increasingly important for transitioning to sustainable procurements.

Several challenges with reuse are mentioned:

- Risks of including hazardous substances
- High energy use during operational phase compared to new alternatives
- Poor/uncertain standard for acoustics
- Limited ability for disassembly to maintain function
- Limited possibility to transport product from the site
- Limited possibility to store
- Low demand on the market
- Lacking information about the products
- Poor conditions and lacking possibilities to recondition the products

4.7. RISE

Research Institutes of Sweden (RISE) is a research institute that through international collaboration with industry, academia, and the public sector, contributes to a sustainable society (ri.se, n.d.). Anders Widing, project leader at RISE, offers expertise in the recycling of glass and gave valuable insight for this report. He claims that many windows are being replaced due to aesthetical reasons and flat glass is deposited, rather than recycled, to a greater extent. The possibility to recycle glass in Sweden is limited. Swede Glass United is a company specialised in recycling flat glass that has collection centres in Sweden, but the material is being transported long distances to the recycling facility and then from there to the glass industry. An option would be to restore and renovate existing windows by applying coatings to the glass, this would improve *U*-values and the performance of these windows could be compared to new ones. Unfortunately, this method has not been developed today. Damaged or scratched glass could theoretically also be repaired, like repair of car glass, but the glass would most likely be weaker than new.

Some issues with older windows with lower *U*-values due to gas filling is leakage. When the gas filling is leaking the *U*-value changes and worsens. This issue is one of the reasons window replacements occur. Would improvements for better performance of connected windows be needed, then the preference is to replace the interior windowpane with low-e glass rather than adding another pane to the window. Low-e glass would also be a better option compared to insulating glass since the required thickness for construction of low-e glass is smaller and not all window systems have a frame that can hold thicker glass solutions. In his opinion, windows of the quality in this study of a building that was made in the 1950s should be able to have a remaining lifetime of 30 to 50 years if maintained correctly.

Widing further discussed the possibilities for reuse of windows, stating that a building product can be tested for certain criteria and then approved or dismissed by RISE. Having a reused/upcycled window approved by RISE would mean that the method for execution would be approved, which in turn allows for reuse of the procedure. The cost for testing and approving a window by RISE is around 20 000 SEK, however, they might request to test windows from different weather orientations before approving the method for a project.

4.8. LKF

Lunds Kommuns Fastighets AB (LKF) is a non-profit company owned by the municipality with the main task to offer Lund residents quality housing at a reasonable cost (lkf.se, n.d.). LKF promotes sustainability through its work with properties by collaboration with several initiatives and organisations such as Viable Cities and Future By Lund. When asked about the management of window replacement, LKF answers that they have had experience of mainly replacing old, damaged windows. They mean it has been common to manage windows with damaged frames and sometimes also due to poor thermal insulation and sound insulation. The final decision of replacement often occurs due to maintenance neglect, complaints from residents, or many repair measures. It is the maintenance manager or deputy property managers that decide if the windows will be replaced. Waste management is then planned and handled by the contractors for increased energy recovery and recycling (when possible and applicable). When discussing the possibilities for renovation of windows for reduced energy demand LKF answers that windows with wooden frames from the 1970s and 1980s are often in such poor conditions that renovation is not an option. They further argue that it is often difficult to lower *U*-values of old windows without adding clumsy extra windowpanes, which is another reason to replace rather than renovate.

No statistics of how many windows are replaced annually were retrieved.

4.9. Malmö Återbyggdepå

Malmö Återbyggdepå is an architectural salvage store that takes in used building products for free and re-sell them for both renovation projects and new construction (malmoabd.se, n.d.). It is run by Sysav and Malmö City Service Administration. They state that they do not receive many windows since most are treated as waste, and the windows that are delivered in collaboration by construction and demolition companies (such as JM and Peab) are sometimes brand new. These are then stored until re-sold. They also confirm that their windows are rarely sold to new construction projects, but rather to private persons with intentions to build greenhouses and conservatories or for renovation opportunities. Given the performance criteria (i.e., sound, transmittance, and thermal requirements) for windows for new building construction, the decision often ends on purchasing a new product. This is despite the fact that the windows they receive are inspected and in good shape before retrieval. While at the salvage store, they check the products visually and physically for rot or damage but do not renovate if needed. When asked about waste management, they answer that they report every kilogram of waste to the environmental protection association and provide samples of various materials for inspection.

Malmö Återbyggdepå further explains their business expressing that they do not provide any warranty for the collected products. The customer ensures an inspection is performed and documented. Furthermore, they do not approve of receiving windows with PCBs, hence they are deposited for a cost between 10 000 SEK and 12 000 SEK.

They further state that they have had previous experience of exporting old windows to Poland, but that the price for purchasing new windows in the country has dropped significantly and is now cheaper than importing existing windows from Sweden. The quality of the new windows is usually poorer, yet they do not consider that to be an issue.

4.10. Avfall Sverige

Avfall Sverige is the municipalities' industry organisation for waste management and advocacy work is being conducted both nationally and within the EU (avfallsverige.se, n.d.). Their work is based on the waste hierarchy: prevent waste, work to ensure increased reuse, and that waste is recycled and managed in the best way. Avfall Sverige initiates referring to Naturvårdsverket's guidelines for how to manage waste sorting given the new regulations being implemented on 1st of August 2020. The new sorting regulations include glass and wood management, describing how the materials should be kept separated to easily prepare for reuse or recycling. Given the new regulations, they are assuming that an increasing trend for reuse or recycling of materials should be evident soon.

Avfall Sverige's experience is that windows should not be damaged to the extent that renovation is not possible, in order to reuse the product. They also point out that the customer buying the old windows might have further requirements that need to be met. Furthermore, they state that as long as it is complicated to purchase used products, and both easier and cheaper to buy new, many will continue to buy new products. There are also uncertainties regarding old, used windows and whether there is a risk for PCB in the construction. If that risk does exist for certain windows, then they are usually deposited since reuse is not recommended. An explanation for this could be the lack of information or knowledge of how to identify windows with hazardous substances such as PCB or lead. This might reduce the amount of glass or windows that go to waste. Avfall Sverige is currently working on a project together with IVL, on how to increase knowledge and share information on the reusability of construction and demolition waste in order to increase the number of recycled products. Their goal is to do so by providing a form of "Waste lexicon" or "Material atlas". The project is planned to be completed by the end of the year.

They do not believe there are statistics on how many windows go to landfills as waste, and they state that some windows also go to material recycling centres. The cost for depositing waste varies from facility to facility given that they can be municipal or private facilities. Municipal facilities accept all waste or some waste from households and in Lund municipality, waste is managed by Sysav, a corporation owned by 14 municipalities in Skåne. Glass that does not go to recycling can also be crushed and used as a drainage layer for landfill. The drainage layer streamlines drainage and reduces the water load on the waterproofing membrane of the landfill.

Avfall Sverige assumes that glass that goes to landfill as waste has low environmental impact due to the fact that glass is an inert material and does not react into other substances once deposited. Unlike organic waste that forms methane gas when landfilled, and is therefore prohibited to deposit in Sweden. However, the environmental impact can be reduced by material reuse, i.e., preventing waste, or recycling. Avfall Sverige also shares a table from their report ”2019:19 Klimatpåverkan från olika avfallsfraktioner” (Eng.: ”2019:19 Climate impact from different waste fractions”) with the amount of emissions released for recycling flat glass, see Table 4.10.1.

Table 4.10.1. Release of kg CO2e per kg waste of recycled flat glass.

Fractions	Prevention		Recycling/treatment	
	kg CO_2e per kg waste	Equal to km per kg (car, fuel)	kg CO_2e per kg waste	Equal to km per kg (car, fuel)
Flat glass	-1.2	-10	-0.2	-1

5. Results from simulations and calculations

In this chapter, the results from the energy simulations, the LCC, and the LCA are presented. Each case is presented according to the relevant category.

5.1. Energy simulations

The energy use simulated for the building is presented in Table 5.1.1. The results are shown for the whole building and per m^2 heated floor area of the building. There are three different energy renovations that are used, as presented in Table 5.1.1. In the table, the new *U*-values of the windows is presented, including the energy reduction compared to the existing building case. The simulated energy use of the existing building has less than a 10 % difference from the measured energy use supplied through a district heating system, which is 127 kWh/m^2.

Table 5.1.1. Energy use simulated for the building.

Existing building	**Energy use/ (kWh/m²)**	**Energy use/ (kWh)**	***U*-value window/ (W/m²K)**	
	136.4	141 092	2.8	
Add energy glass (Case 1)	**Energy use/ (kWh/m²)**	**Energy use/ (kWh)**	***U*-value window/ (W/m²K)**	**Energy reduction/ (%)**
	121.4	125 572	1.8	11
Add insulating unit	**Energy use/ (kWh/m²)**	**Energy use/ (kWh)**	***U*-value window/ (W/m²K)**	**Energy reduction/ (%)**
(Case 2)	118.7	122 750	1.3	13
New windows	**Energy use/ (kWh/m²)**	**Energy use/ (kWh)**	***U*-value window/ (W/m²K)**	**Energy reduction/ (%)**
(Case 3.1, 3.2, 3.3)	115.9	119 928	0.9	15

5.2. LCC

The calculated cases for LCC are again presented in Table 5.2.1, and the input values for the calculations are presented in Table 5.2.2.

Table 5.2.1. Cases calculated for the LCC.

Case	Remove	Add	Other
1	Interior windowpane	New energy pane	
2	Interior windowpane	New insulating glazing unit	
3.1	Window	New window	Glazed partition walls
3.2	Window	New window	Swede Glass United
3.3	Window	New window	

Table 5.2.2. Input values for the equations.

Parameters	Values
Real interest	1.50 %
Lifetime	30 years
Real energy price growth	2.50 %
Energy price	1 SEK/kWh

Results of the calculations are presented in Figure 5.2.1. The results are shown as NPV per m^2 window after 30 years, where the negative values present the losses and positive values the profits. The results from the energy simulations were used, where the energy and cost per year savings are shown in Table 5.2.3. The results show that after the estimated lifetime of a renovated window, 30 years, the most profitable option is to substitute the interior windowpane with a double-glazed insulating unit, followed by substituting the interior windowpane with an energy pane. Figure 5.3.2 shows the break-even point for every option, meaning at what year the investment becomes profitable. Case 1 and 2 becomes profitable after ten years, Case 3.1 after 38 years, and the rest of the cases after 33 years.

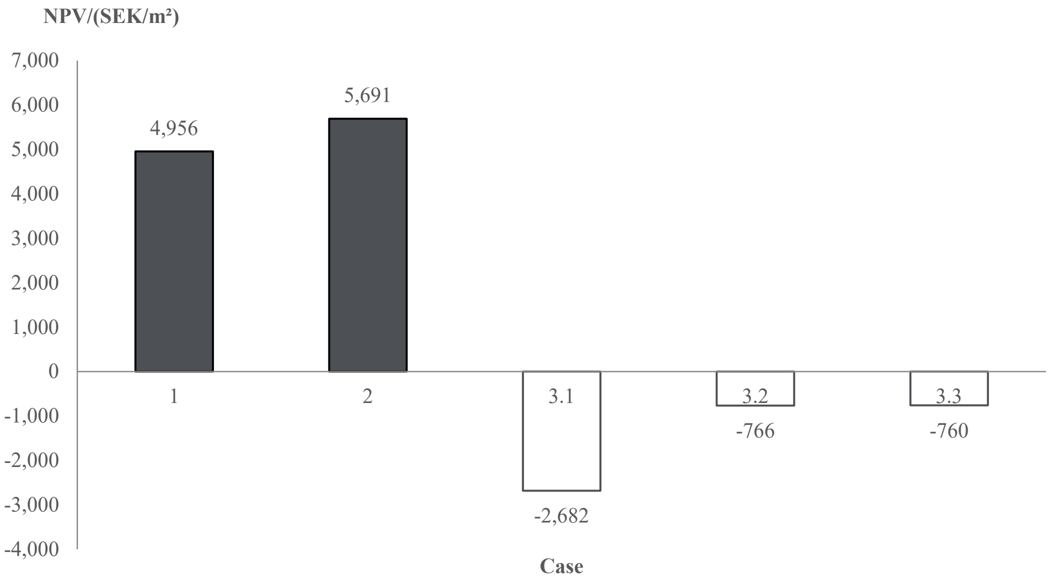

Figure 5.2.1. NPV for the calculated cases.

Table 5.2.3. Energy savings and cost savings based on energy simulations.

Cases	Energy savings/(kWh)	Savings/(SEK/y)
1	15 520	15 520
2	18 341	18 341
3.1 - 3.3	21 163	21 163

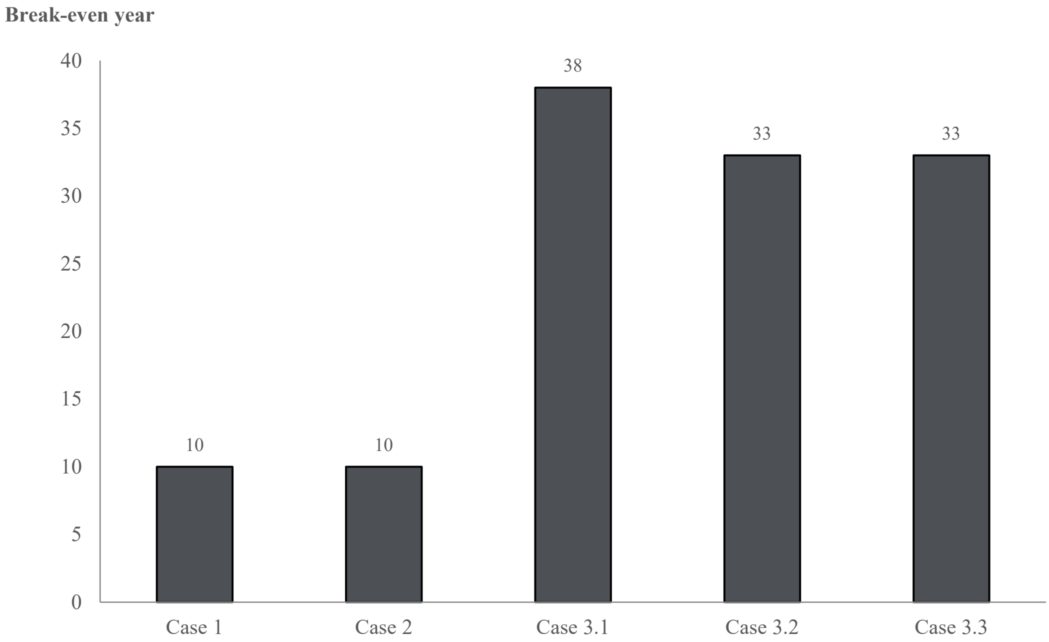

Figure 5.3.2. Break-even point for every case.

5.3. LCA

The calculated cases for LCA are again presented in Table 5.3.1.

Table 5.3.1. Cases calculated for the LCA.

Cases	
1	Renovating window with energy glass
2	Renovating window with glass cassette
3.1	Reusing the glass for partition walls + new window
3.2	Recycling window + new window
3.3	New window
4	Waste treatment of existing windows

The results from the calculations are presented for the different weighting panels, see Figure 5.3.1, Figure 5.3.2, Figure 5.3.3, and Figure 5.3.4. The results are presented as a single score for environmental impact for each case, meaning that positive values have a negative impact on the environment and vice versa. Manufacturing new windows have the highest impact on the environment while reusing or renovating the windows has the lowest impact. Both Case 3.1 and 4 also have negative scores, indicating a positive impact on the environment.

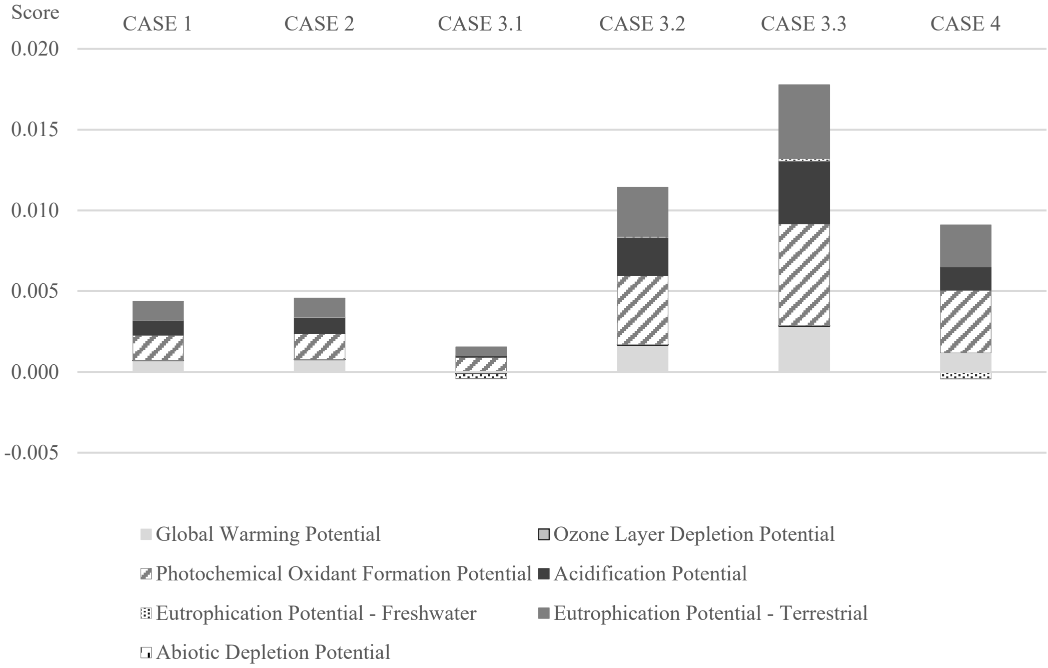

Figure 5.3.1. LCA with equal weighting factors.

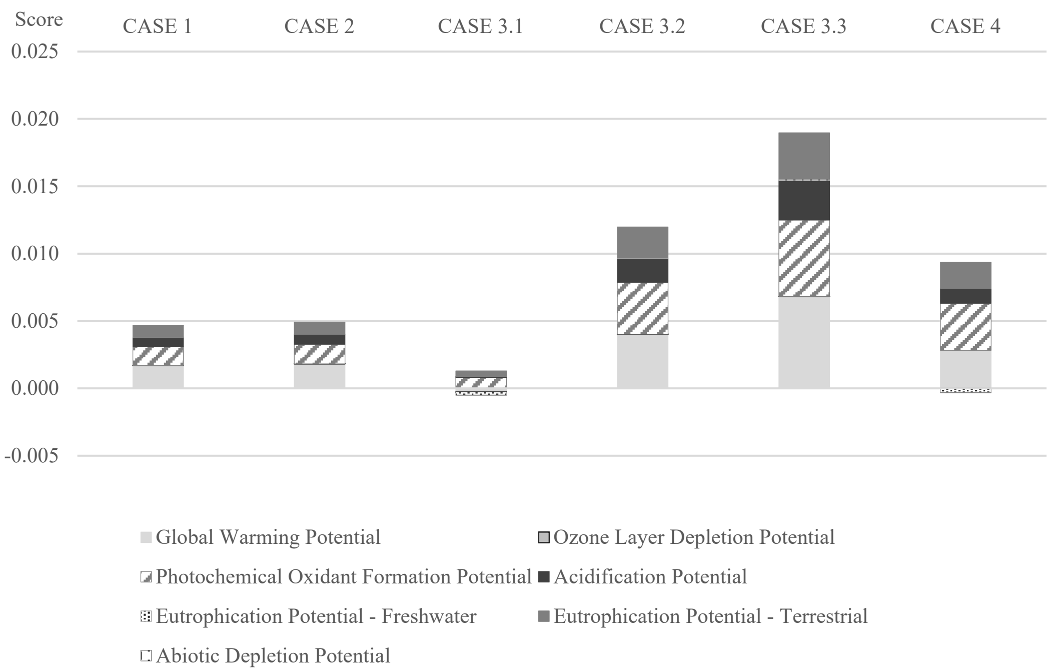

Figure 5.3.2. LCA with EPA Science Advisory Board weighting factors.

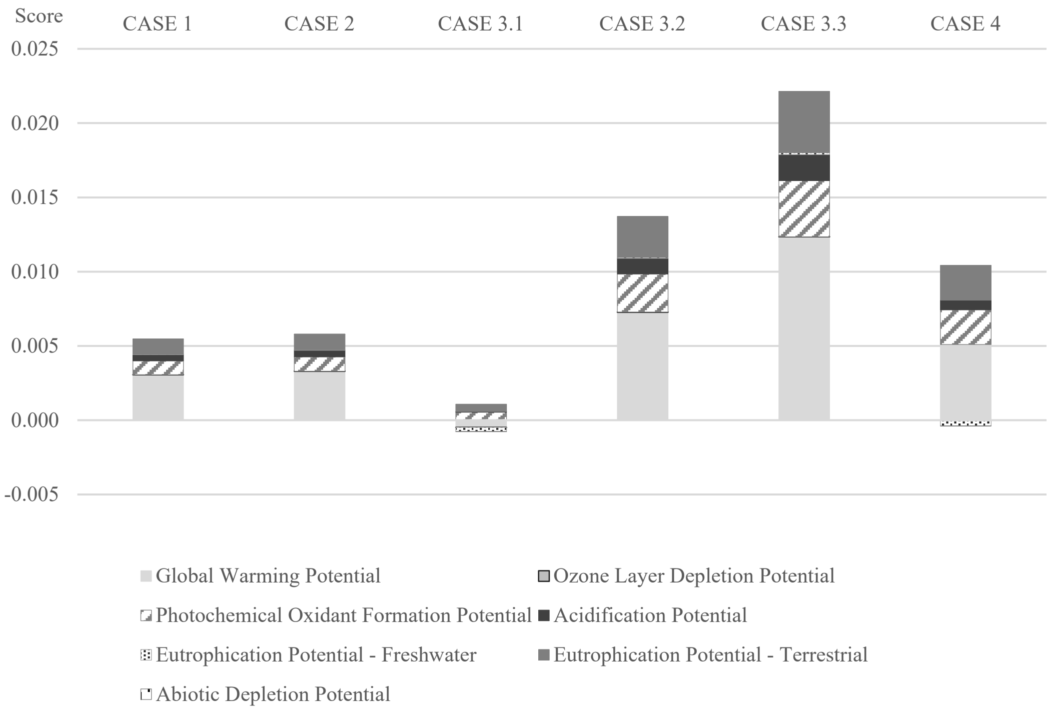

Figure 5.3.3. LCA with BEES Stakeholder Panel weighting factors.

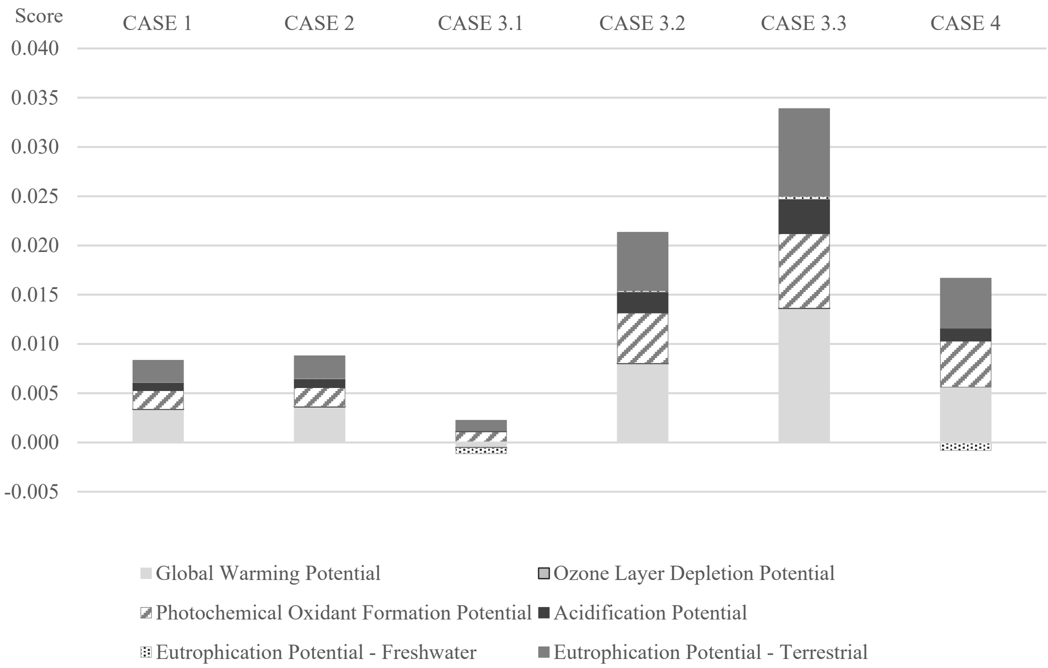

Figure 5.3.4. LCA with NOGEPA weighting factors.

The results are further presented in tables in the appendices, see Appendix F.

6. Analysis

An analysis of the results is presented by the subject in the following subchapters.

6.1. Energy simulations

The energy use of the building was simulated based on information gathered from different sources, and some values were assumed because of lack of information. The assumed values were the characteristics of the windows, operating time, schedule, number of people, equipment load, and lighting density, which were based on one person living in the apartment.

The simulated results yielded a similar result to the measured values provided by the research team. With an acceptable margin of error of 10 % for simulating energy usage, the simulated results fall inside the 10% range.

None of the improved cases fulfil the criteria of BBR, which is that the energy use should be less than 75 kWh/m^2. If the goal of renovating the building is to get a lower value than the criteria, more options for refurbishment have to be investigated and applied to this study. BBR also sets a maximum *U*-value for windows of 1.2 W/m^{2}K which is not fulfilled for the renovated windows, but could be possible to deviate from if the exception is because of reduced climate impact due to reuse of products. Given that the existing windows are in good shape, based on the analysis of the images from the thermal imaging camera, it could be considered beneficial to argue for renovation rather than demolition of the building product.

6.2. LCC

The LCC calculations mostly depend on input values, hence the interest rate and price growth should be carefully considered. In this case, choosing the right interest rate and price growth for energy is difficult since there are different values which vary a lot. The interest rate for this study was chosen through the SKR which provides a general interest to follow every year. The same issue is seen for the price growth of energy since no one knows how the energy price will develop through the years, neither has the price development been steady the last years. A value between 2 % and 3 % was recommended by EEF to use.

Higher development in energy price will yield a higher cost saving after many years since the energy saved over a prolonged period results in higher costs being avoided. A lower price development will instead result in lower cost savings for the opposite reason. An increment in interest rate will result in higher economic losses as it follows the general principle of paying borrowed money, and lower interest rates yield higher profits since less money should be paid back. Different price growth rates, 4 %, 6 %, 8 %, and 10 %, were calculated to see the different break-even points depending on the development of energy cost, see Figure 6.2.1, Figure 6.2.2, Figure 6.2.3, and Figure 6.2.4 respectively. It can be seen that an increment in price development will result in all renovation options being profitable earlier than if the energy prices follow the predictions of today. Cases 3.1, 3.2, and 3.3 are impacted more by the energy price increment, resulting in a higher difference in the break-even point, which is due to the higher energy saving of those options.

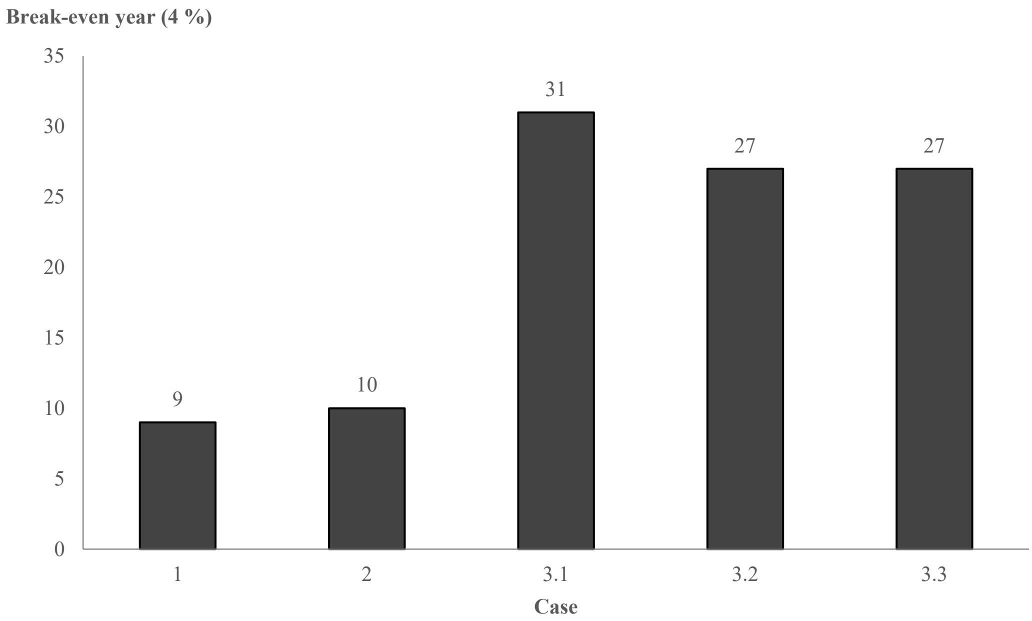

Figure 6.2.1. Break-even point with an energy price growth of 4 %.

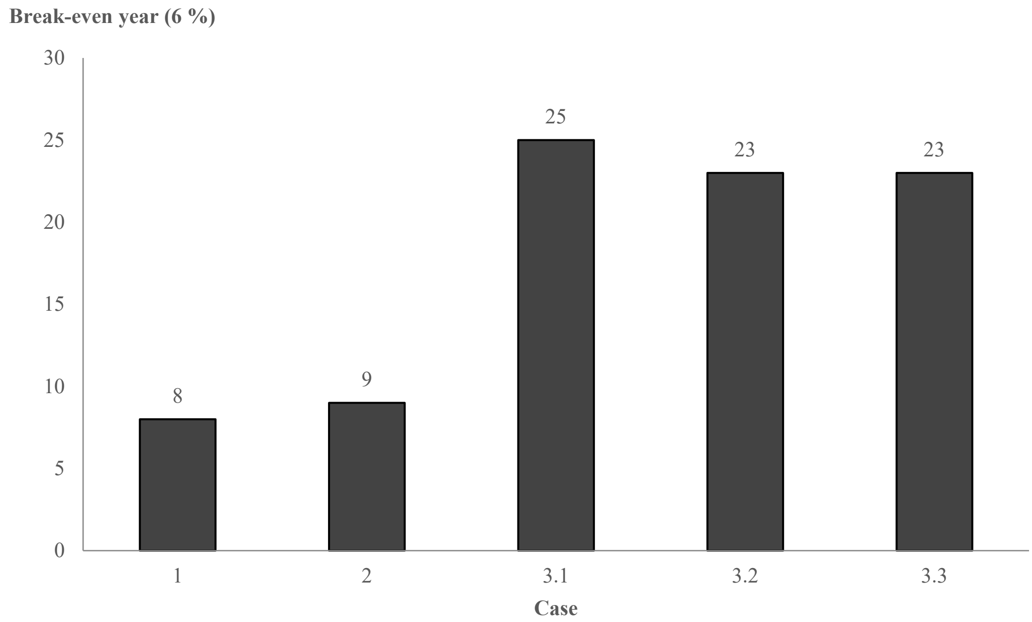

Figure 6.2.2. Break-even point with an energy price growth of 6 %.

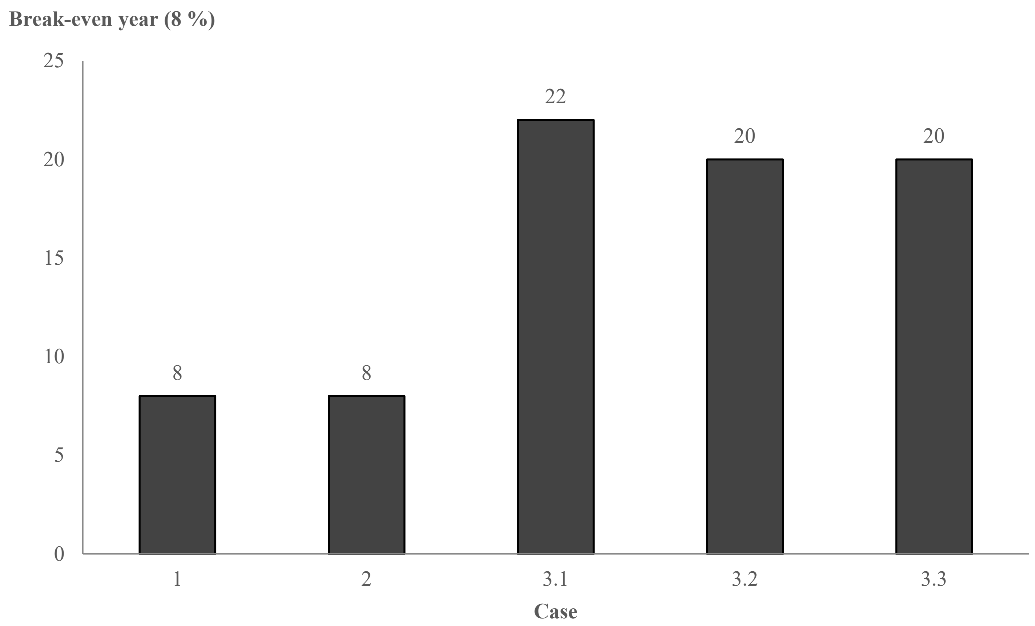

Figure 6.2.3. Break-even point with an energy price growth of 8 %.

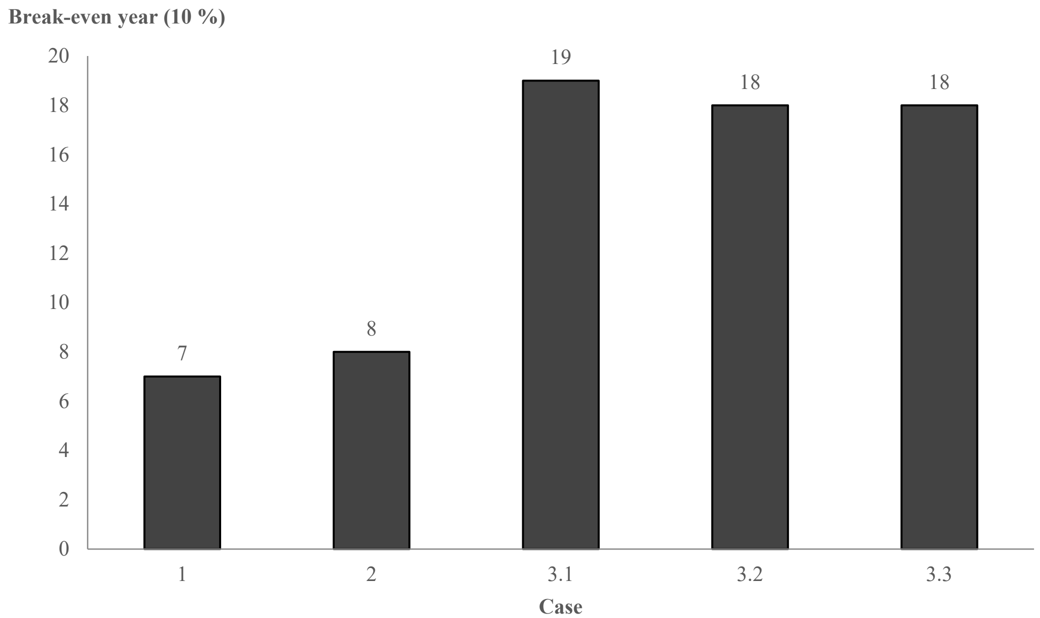

Figure 6.2.4. Break-even point with an energy price growth of 10 %.

In this study, altering the interest rate or the price growth would alter the results. Though, since all cases depend on the same parameters in the calculation, a change in the values mentioned above would not result in a different outcome. Cases 1 and 2 would still be assumed the most profitable of all options presented in this study.

6.3. LCA

Studying the results from the LCA calculations for the different cases coincides with the findings from empirical research. Reusing glass is better for the environment than manufacturing a new window which indicates that glass is a climate intense material to produce. Large differences are shown in GWP when studying the different weighting systems. However, if an LCA were to be conducted for the entire building then creating interior partition walls, only for the purpose of assigning the glass for reuse within the project, would include unnecessary emissions.

Manufacturing a new wooden frame has a lower environmental impact than glass, see Figure 6.3.1. This indicates that glass is the main source of emissions by material. Comparing this to the results of manufacturing a new window in this study, provides evidence that transport is another source with a large impact on the environment.

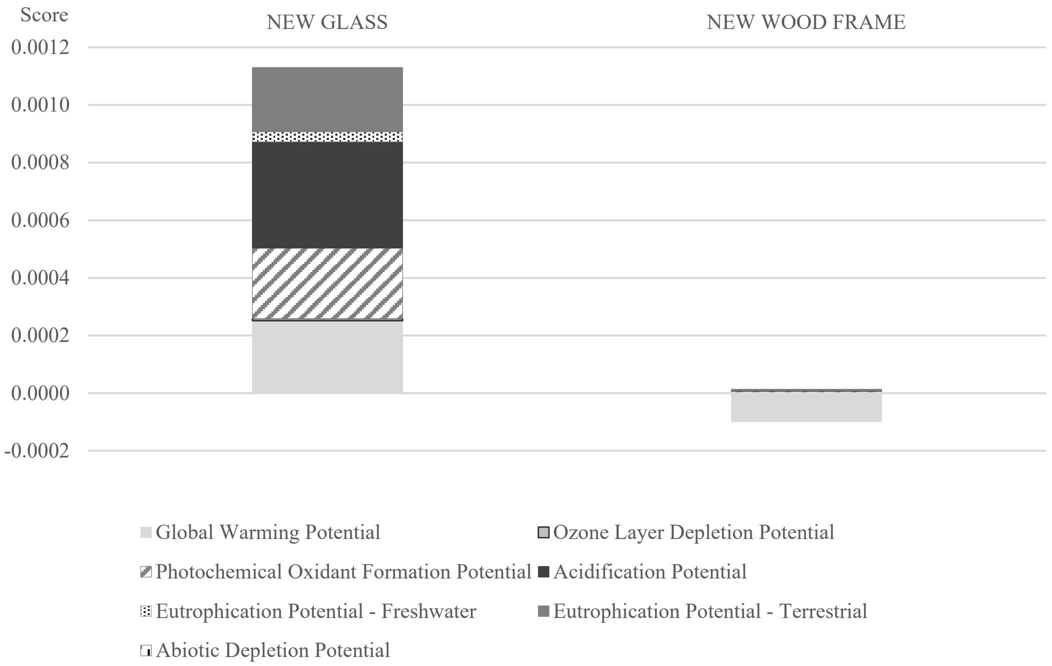

Figure 6.3.1. Impacts of producing the main materials for a 1.0 m² window, based on equal weighting factors.

Using already processed glass is better for the environment, a fact derived from the empirical research. An in-depth study for this case study would be required to confirm the statement, given that recycled glass requires less energy to be re-produced. Studies have shown that approximately 2 MWh/(ton of glass) is required to produce flat glass, and 300 kg CO_2/ton is emitted when melting raw material (Widing, 2020). No new gases are emitted when melting recycled glass and energy use for the process is 30 % less compared to melting raw material. Additionally, 1 ton of recycled glass becomes 1 ton of new glass (Widing, 2020).

When analysing the current results for recycling and excluding the transport, the process has a positive impact on the environment which is stated in several studies (Miliute-Plepiene et al., 2019), see Figure 6.3.2. This is a finding that could strengthen the argument that processed glass is better for the environment compared to producing new glass, which would also enhance circular methods of waste treatment. But it also means, again, that transport has a large impact on the environment and that the option for transporting materials to and from a construction site should be evaluated. With the extensive infrastructure in Sweden and to neighbouring countries, the methods could be improved which would improve the effect on the environment.

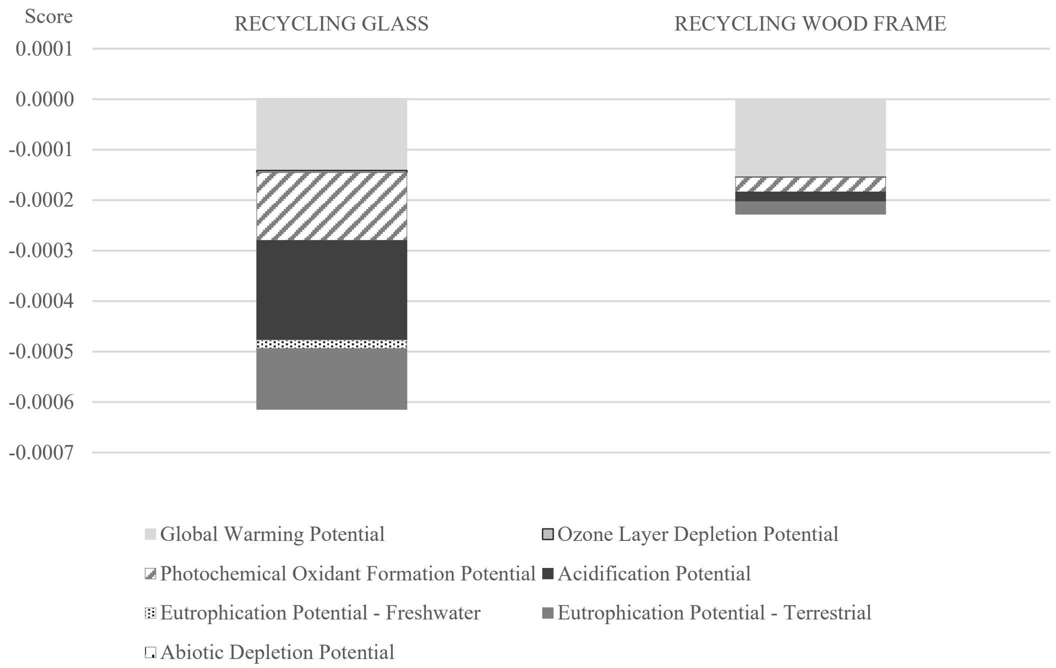

Figure 6.3.2. Saved impacts for recycling the main materials of 1.0 m² window, excluding transport based on equal weighting factors.

Recycling an entire window is a more energy-intense method compared to landfills, which in turn has a higher impact on the environment. Comparing these two methods in this study results in 25 % fewer emissions when treating windows as waste. When studying the results, in this report, for producing new windows compared to circular methods, it is evident that circular methods have higher savings. For Case 1, renovating with energy glass, and Case 2, renovating with glass cassette, it is possible to obtain environmental savings up to 75 % and 74 % respectively. Reuse of glass has even higher savings, up to 95 %.

Given the level of detailing of modelling the cases, the results could be different, with a higher or lower impact on the environment. Although, since the level of detailing was applied similarly to all cases, the relationship between them would not change. Using different databases or impact assessment methods also gives a difference in results and proves that consistency is key. The input data in databases are from different years which affects the outcomes and when normalising using the compatible normalisation factors, it becomes questionable whether the results from different databases are comparable. Since there is not only one "right" way to present an LCA it is also questionable whether an analysis of different databases would contribute to any relevant findings. An LCA is also geographically dependent, meaning that analysing input values in a database from a continent to a specific country will most definitely result in differences without indicating what input values are wrong. Since there is a geographical dependency, it is also important to understand the geographical location from the input, meaning that the relevant location should be addressed for the target of interest. E.g., it is not accurate to use a database specific for America to investigate the environmental impacts in Europe.

The results from the weighting systems provide comparable results, although, it is unclear from what geographical location some of the factors derive (Huppes and van Oers, 2011). NOGEPA refers to the Dutch system while EPA and BEES might be referring to the American system, which is unclear, which is why the factors are given different importance. Would the latter two be referring to a system outside of Europe, then they should be addressed with caution in this study. This is due to the impacts having different importance in different locations. All three weighting systems, besides equal weighting, prioritise the impact categories relatively similarly and give high importance to the GWP. Therefore, the graphs show a range of results but the relationship between them is similar and does not indicate what method is more correct to use for this study.

6.4. LCSA

An analysis of both LCC and LCA was made in form of an LCSA for a lifetime of 30 years, where the cases combined are given weight in form of a percentage. They are weighted in three different weight scales, where the first option is to give equal weight to both LCC and LCA. The second option is to give LCC 70 % of the total weight where LCA gets 30 %, and the third option is conversely 30 % for LCC and 70 % for LCA where LCA has a higher impact on the result. The impacts are weighted together with the four different LCA weighting methods Equal, EPA Science Advisory Board, BEES Stakeholder Panel, and NOGEPA as shown in Figure 6.4.1, Figure 6.4.2, Figure 6.4.3, and Figure 6.4.4 respectively. The result of each case is presented as the result of the total LCSA for all cases.

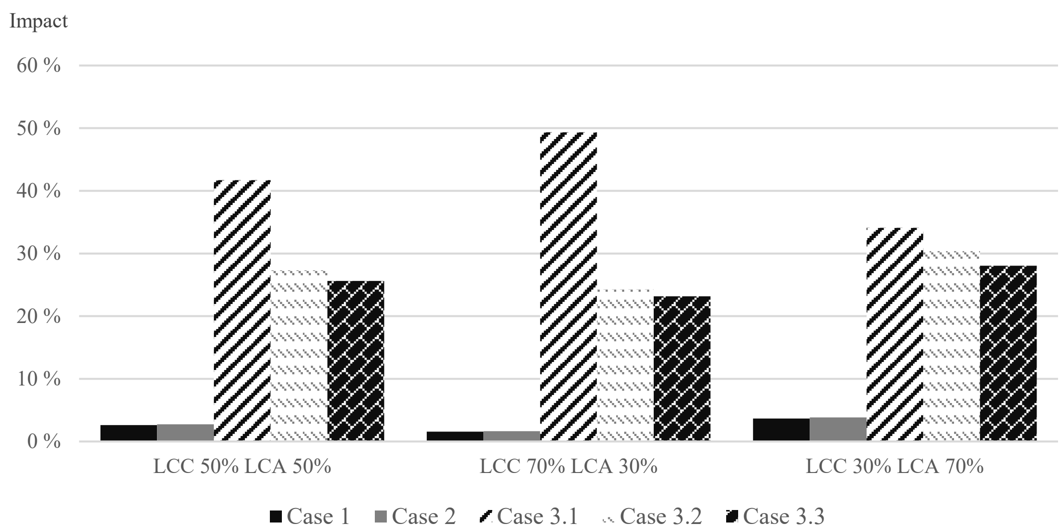

Figure 6.4.1. LCSA through the Equal method.

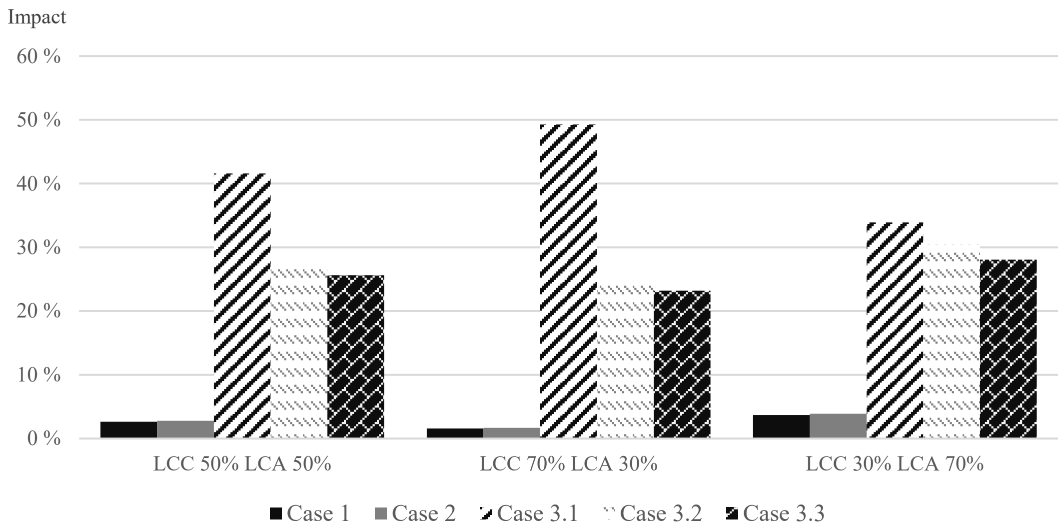

Figure 6.4.2. LCSA through the EPA method.

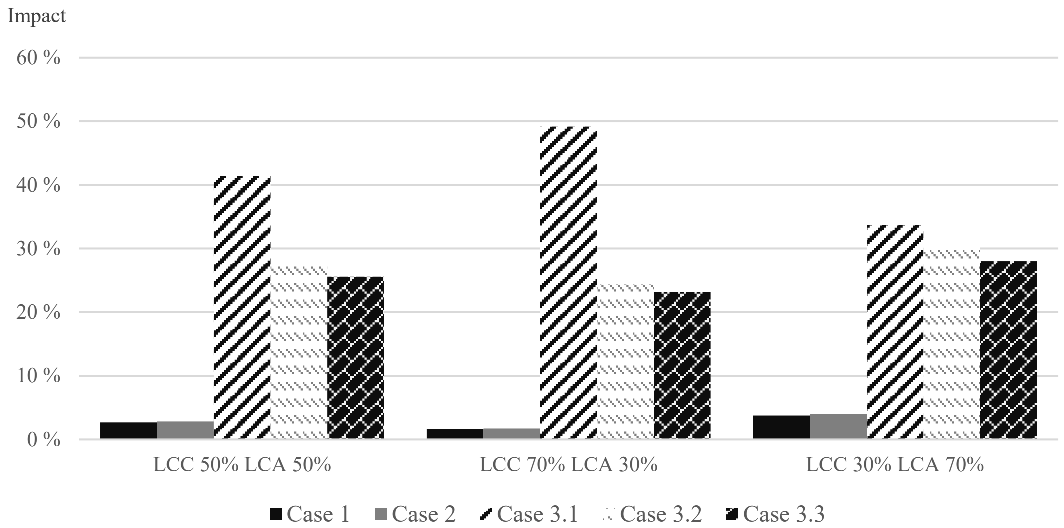

Figure 6.4.3. LCSA through the BEES method.

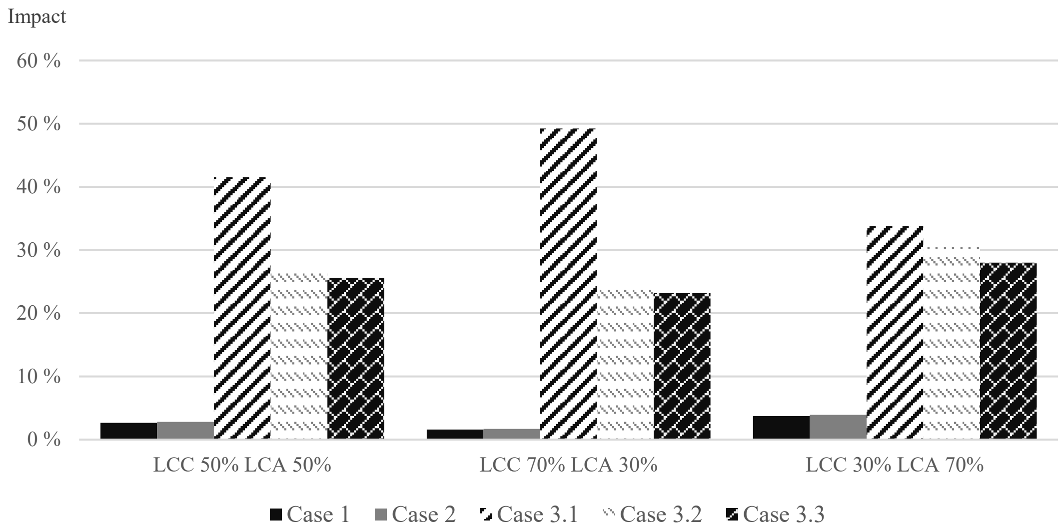

Figure 6.4.4. LCSA through the NOGEPA method.

There are no larger differences between the four weighting factors and the results show the same impact depending on the weight of LCC and LCA. What is deduced from these results is that Case 1 and Case 2, replacing the interior windowpane with an energy glass and insulating unit respectively, have the least impact on both environment and economy. This is due to that this renovation method requires the least materials compared to the other options, and the price of the renovations is low due to the shorter time needed to install the units and lower cost of materials since fewer materials are needed. What is excluded from this study is the cost for testing and documenting the window renovations at RISE (an additional cost of approximately 20 000 SEK per tested window) if this action is considered needed.

Furthermore, the least feasible case is to exchange all the windows for new ones and use the old windowpanes to install interior walls in the building, Case 3.1. This is mostly due to cost, as can be seen when LCC has the superior weight of 70 %, and almost similar impact as Cases 3.2 and 3.3 when LCA has the superior weight. This is due to new windows and new wooden frames being bought, as well as more working hours than any other case. The environmental impact is lower than for Case 3.2 and 3.3, but due to the high costs, this option is still least favourable even if a higher weight of 70 % is applied to LCA.

The last two cases, 3.2 and 3.3, have similar results no matter the weight on either LCC or LCA. This is due to that Case 3.2, exchanging all windows for new ones and recycling the old windowpanes, is both a little bit more expensive and has a little bit more environmental impact than Case 3.3, where similarly the windows are exchanged to new ones and the old windows are sent to the local waste disposal.

An investigation was made to see how the LCSA impacts develop over time, starting with year 5, then year 10, and lastly year 20, see Figure 6.4.5, Figure 6.4.6, and Figure 6.4.7 respectively. This was done to see how the LCSA values will differ from the results above when Case 1 and Case 2 have no economic benefit. It was calculated with the EPA weighting values since all weighting factors yielded similar results.

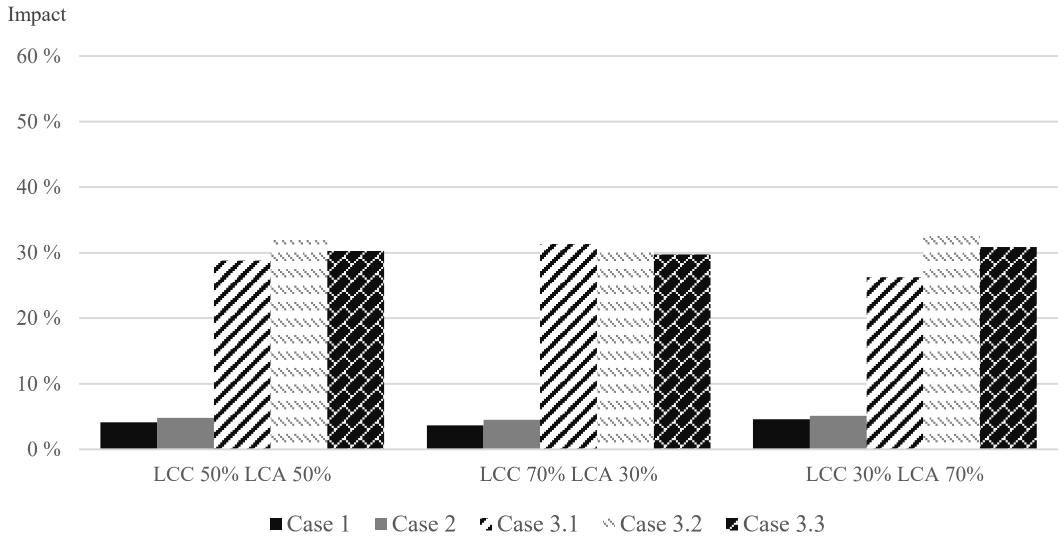

Figure 6.4.5. LCSA after 5 years.

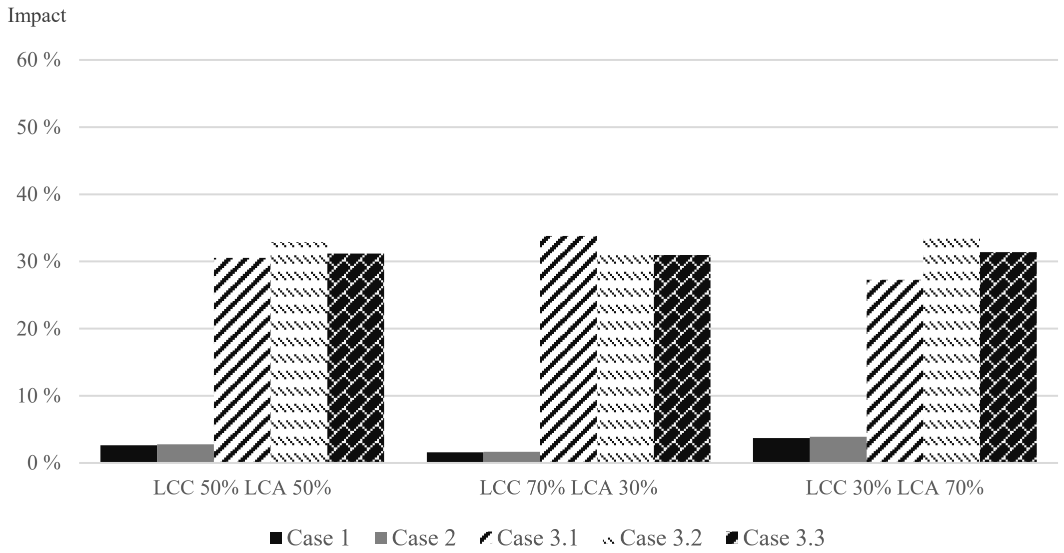

Figure 6.4.6. LCSA after 10 years.

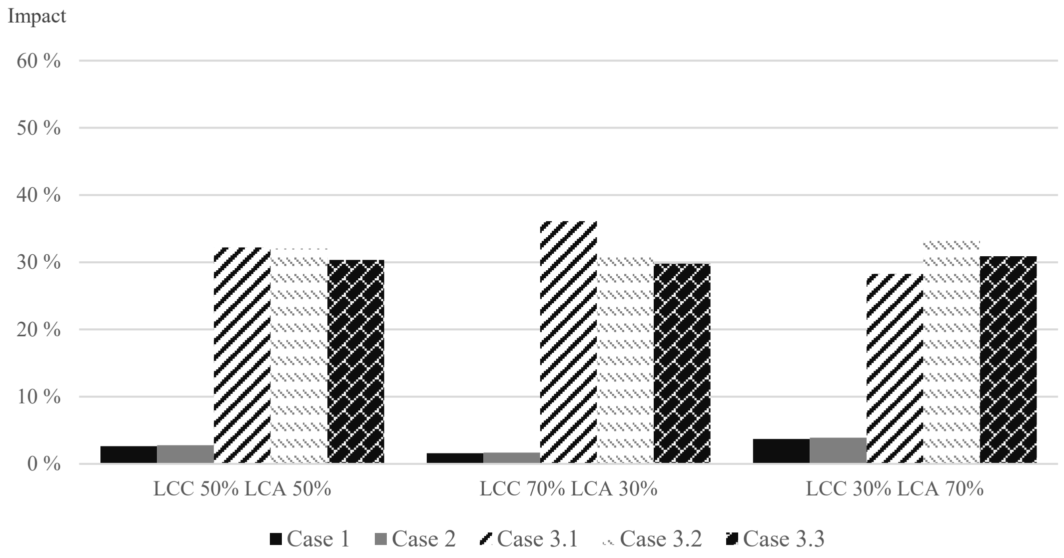

Figure 6.4.7. LCSA after 20 years.

When varying the span of years, no big difference can be detected for Case 1 and Case 2, except that the impacts are a bit higher but not significantly. Case 3.1 is the one that is more remarkable at this point since it seems to be more feasible to opt for that option in the first years instead of Case 3.2 and 3.3. This is due to that it still has a lower environmental impact and the economic difference in percentage between Cases 3.1, 3.2, and 3.3 is less than in the future which indicates the LCC having a less important role.

6.5. Empirical research

The previous subchapters of the analysis discuss the profitability and environmental impacts of the different options to deal with the windows in this study. This subchapter focuses on combining the results with the opinions of people in the building industry.

One term that is emphasised in some interviews is warranty. Not many people want to guarantee that the renovated window will fulfil the building requirements, nor the requirements set by the developer/customer. As proven in this study, renovating a window can reduce the *U*-value depending on how it is renovated. This can however not be guaranteed, nor can requirements for transmittance, sound, fire safety, etc. be guaranteed to be met. Another parameter to be considered is what BBR defines as renovation and reconstruction and to follow the respective requirements. This alone could affect the possibilities of how to deal with the windows.

PCB and leakage are other constants to be considered. Before performing any renovation, a careful inventory should be executed in order to be acquainted with the possibilities of renovations and recycling. Windows containing PCB limits the possibilities, where renovations and recycling usually is not an option but waste management for a higher price is. PCB is usually found in windows installed in the ’60s and ’70s, meaning that it most likely is not found in the windows in this study. Gas leakage is also a reason for changing windows as it worsens the *U*-value, where no other information is obtained in this study arguing for the possibility to renovate these types of windows.

If window renovation is not possible, but the glass does not contain any harmful substances like PCB, glass can be recycled into other products as it can be recycled many times. Usually, this glass is not recycled into a new flat glass which can be used for windows, making it harder to calculate the environmental benefits when it cannot be reused in the same project. It is believed that recycling is preferred to reuse because there is no guarantee that old products can meet today's industry requirements. Another option, which was not calculated, is the export of used windows to other countries, such as Poland, and the reason being that it is cheaper to buy new windows in those countries than to buy existing ones from Sweden.

Generally, the interviews lay a good foundation to further build on. Many of the interviewees agree on circular economy being essential to a sustainable building sector, but that the Swedish building market is not yet fully developed for the transition. This study mainly presents the issues, but a further investigation of the mentioned issues would be necessary to determine options for proper solution.

7. Discussion

The discussion of the results and a discussion of the implementations in this study is divided into the following subchapters.

7.1. Discussion of the results

The reuse of products is a mindful and sustainable way of dealing with used products and can tell stories by simply using them again. The method of upcycling products has given a name to companies implementing circularity, resulting in people being inspired and motivated to use used products. Reusing products and materials avoids the extraction of raw materials and manufacturing new products, and evidently by the interviews and cases in this study, this could reduce the environmental impact. This itself sounds like a natural work method for a business to profit off even more in a field. However, this has shown not yet to be fully applicable in the Swedish industry. The transition to a circular economy requires reform in the structure of the industry and regulations are needed for it to be profitable. A thriving circular economy would require collaboration between different industries. When it comes to windows, a lot of flat glass is going to waste and less than half is being recycled, meaning there is a substantial potential for circular flows in this field.

This study has shown though that before switching to a circular method of managing windows, there are other problems to solve first. The first problem is in what way should one reuse or recycle the product. For reusing the windows, only two methods have been investigated in this study, meaning there are other solutions that can be carried out after careful consideration. A real solution would be to exchange all windows in the buildings for new ones, while the existing windows are repaired and put into use in another building. With the right timing of deconstruction and new construction, this might be a brilliant option as the used windows could be reused into satisfactory products, while the current buildings install new windows to avoid storage issues. In this study, larger repairs/renovation might not be needed because of the good quality of the existing windows, but for buildings conducted between the ’60s and ’80s, this method should work better rather than exchanging windows with a linear business mindset.

This of course leads to other problems which were discussed during the interviews. The first problem is the question of responsibility. New windows installed must fulfil criteria from the Swedish BBR which includes energy use, *U*-values, transmittance, sound, etc. The person renovating the windows need to guarantee that these criteria will be fulfilled for a certain lifespan. The renovation itself requires considerably more manhours for repairing the windows, adding a cost which not many are willing to pay for, especially in a linear market which is used to cheap costs for products going to waste at their end-of-lifespan. Warehouses are needed to store building products that are not going to be used for some time, which allows for a new business market in the industry. In some cases, before a building is about to be reconstructed or demolished, an inventory is held and building products can be taken for further use in other buildings. This also requires a warehouse to store the products. It is evident that there are still many challenges to overcome, and several solutions must be provided by governmental authorities. Yet, it has been proven by neighbouring countries that circularity is possible to implement and still fulfil building requirements on European level, would the national regulations allow for more flexible, alternative solutions.

It seems to be more favourable to recycle products such as windows rather than reusing them as it is cheaper to direct materials/products for recycling. Also, it is cheaper to buy new windows. An issue with recycling is that there are few options in Sweden, and most often it does not contribute to a closed loop by allowing the material to stay within the country. This means that this is an issue that should be solved parallel to implementing reuse of products. Three ways of recycling flat glass in Sweden were discovered, whereas two of these were investigated further. There is an option to recycle them at the waste company, Saint-Gobain which uses glass in their insulation materials for the brand Isover, and at Swede Glass United which sends their products to Germany. Sending it to Saint-Gobain results mainly in insulation products, which can be calculated through LCA if a whole building is being rebuilt where old windowpanes can come back as insulation material. Sending it to Swede Glass United ends up in Germany, where the products do not come back to Sweden directly and makes it therefore harder to calculate further benefits of recycling within the country or for a specific project.

Uncertainties can also demotivate the reuse of windows, such as the economic value of the product. A value to the reused product has to be assigned as the value of products sets the economic foundation for rent and tenants, which is based on the quality of the product. The quality must be set and guaranteed by someone that is certified within the area. Although, it is important to know and consider that windows user-value is not reduced throughout the years, like other products or e.g., cars. When upcycling or renovating a material that is again used in the same building, uncertainties regarding what the project should be labelled as arise. This might change the outlook of the project completely as different criteria might need to be met depending on what type of project it is.

Solutions integrating a circular economy in the Swedish building sector can generally be to industrialise circular flows and let companies change their company culture. This is of course easier said than done, and any change, especially for big companies, has big consequences and is time-consuming. Given by the empirical research, it is also assumed easier for smaller companies to switch to this type of business than it is for bigger companies since smaller businesses can adapt and change more than larger companies. The empirical research indicates that changes are slow but that the increase of climate awareness and sustainability is fuelling the industry, even though circularity is not a new idea or innovation.

Reuse has to become cheaper than disposal or recycling for it to be successful, and it does not happen until the market adapts. Several more warehouses are needed to minimise the cost of storage, planning for reuse has to become a new normal so that old but usable building products can be delivered, and products have to be designed for deconstruction. This is most likely not happening without the initiative of the government, legislations, and criteria from organisations. Although, it is going in the right direction since Boverket will demand climate declaration by standardised values by January 2022, which is aimed at enhancing circularity. This is something that external criteria companies might want to accomplish, such as Miljöbyggnad, LEED and BREEAM, but since the criteria for these certification systems do not revolve around a circular economy, adding criteria for restriction of environmental impact in order to yield high scores, could be something to motivate reuse. This would also motivate and include other industries, such as finance, to finance circular flows.

Other solutions were discussed such as that the municipality, or the procurement organisations, set requirements on the use of used products. When companies leave a tender for a building project, requirements can be set on the use of old windows in some sense. This might yield a problem, as there must be available products which can be used in the project. When that problem is solved, projects must be adapted to the use of old products, meaning that old windows might need to be used as interior partition walls or atriums, if only new windows can be installed in the façade. With "Byggvarudeklarationer" (Eng.: "Construction Product Declarations") as a common acceptance for "Byggproduktförordningen" (Eng.: "Construction Products Regulation") for reused products, they could be promoted and encouraged while current regulations are under revision. Another solution could be a platform that is used, as the marketplace developed by CCbuild, where old but usable building products can be bought. There also has to be more information about old products in order for one to buy them and judge their quality. This requires a lot of work but if a circular economy is adapted by companies, this will be a necessity. Another solution that would make recycling profitable earlier is to have higher energy prices than what would be predicted, this is also easier said than done as it is based on politics and other factors, and a separate investigation on this theme is needed in order to make any conclusions.

Some thoughts that could be a solution to further enhance a circular economy include waste management and education. Material suppliers should be encouraged to manage their own materials/products after consumption, which would reduce waste and extraction of materials, and potentially reduce costs for the business. In order to be able to plan for future deconstruction and reuse, architects, engineers and carpenters must learn about it already during university studies. This way, knowledge is increased, and the current knowledge gap can be bridged. Finally, sustainability and circularity must be assessed and measured in absolute numbers and not relative numbers. For example, renting products in order to avoid maintenance and waste residues, as mentioned in Chapter 4.6, does not mean that maintenance or waste does not occur, but that the responsibility is put elsewhere. Therefore, solutions to a sustainable future must not be limited to own business frameworks but seen from a global perspective.

How this knowledge is applied to this study is that the renovation options, Case 1 and Case 2, is just one part of the work. A practical study on methods and tests must be conducted in order to get more definite results. The results show a very distinct difference between the repair options, Case 1 and Case 2, and the other options, Case 3.1, 3.2, and 3.3, where the repair is both more economically profitable and environmentally less impactful than the other options. This of course can differ from reality depending on many things, firstly the interest rate and energy price growth. It is difficult to find the values needed, which is common for every company and person conducting this work and changing the values can yield different results. Other parameters that could yield a different result are the prices for materials and working hours needed to conduct a specific task, most of the working hours for conducting the renovations were assumed based on experience, research, and information on Wikells Sektionsfakta. The prices of materials could vary also depending on where one buys it from and if there is some discount based on how many units are bought. The work itself could also be considered as a ROT work, meaning repairment, reconstruction, and extension in Swedish.

For this, there is a special discount called ROT-avdrag where one can as most get 50 000 SEK in return. There can also be other materials and work that has not been included in the calculations due to lack of information.

The building is planned on being reconstructed, meaning that a new floorplan is considered. No information on the planned design of the building was attained, but having the architecture in mind and calculating for the whole building would most likely yield different results. An example is if a common room is planned with partition walls, calculating the environmental impact and the cost difference between a completely new partition wall and the wall made from the old windowpanes as in Case 3.1, improved results could most likely be attained. In this study, a partition wall is only simulated by the purpose to reuse the old windowpanes and thus the impact would be higher for a calculation of the entire building. It is important to have the whole picture in mind when calculating the impacts in order to calculate all profitability and have higher possibilities to attain a circular loop of building materials.

7.2. Discussion of the implementation

The methods for conducting this report were considered appropriate for this study. The extensive literature review was necessary to outline the available knowledge, challenges and possibilities to proceed with investigating alternatives for the case study. The literature review was also important for providing background information in order to formulate interview questions.

By interviewing selected companies, part of the building industry’s attitude towards a circular economy was identified, and with this, several further challenges uncovered. Although, it would have been desirable to conduct more interviews, especially with material suppliers, window renovators and demolition companies, to further cover the market and attitudes for circularity.

Other approaches for interviewing companies could have been chosen, but free and non-standardised interviews seemed like a natural choice for the desired outcome. Standardised interviews or surveys could be another method to yield empirical results, which would benefit the analysis chapter. By having standardised questions for all interviews would mean having results that are easier to analyse and compare between each other, but would also limit the study. Given that the interviewees have different backgrounds and expertise/niches, a wider spread of the industry is covered. The interviews also mainly provide knowledge in the aspect of construction and businesses rather than customers and tenants that rent the constructed buildings.

The method for conducting the simulations and calculations is considered sufficient for initial decision-making and an overlook of the alternatives. Would a certain approach/case be of interest to execute for the building complex, a deeper study with specific inputs would be required. This is due to that the presented study in this report contains many assumptions and estimations, and is rather to be interpreted as indications than definitive calculations.

8. Conclusions

The extensive research on the challenges and problem description indicates a large amount of information on the subject. Even throughout the empirical research, the widespread of niches and knowledge lies evident that circular economy and recycling has not been defined and limited in the Swedish dictionary for the construction industry. In this study, it can be concluded that:

- The most common way to manage old windows in Sweden is by treating them as waste for landfills. The second option is recycling since it is considered an easier method than reuse.
- The market for recycling flat glass in Sweden needs to be developed with several facilities within the country. As does the market for reuse of products, particularly windows.
- Material/product transport is another challenge to take upon to further reduce the environmental impacts within the construction industry.
- Reusing windows reduces waste residues but does not necessarily result in the lowest amount of released emission compared to other options. Nor is it the cheapest option or the most energy-efficient.
- Recycling and disposal of windows (glass and wood) has a positive impact on the environment if the transport is not considered.
- The biggest limitation for reusing or recycling windows is the immature/undeveloped business market, along with responsibility and warranty issues since no standards or regulations are enhancing a circular economy.
- The possibilities and benefits that arise with reusing or recycling windows are new job opportunities, interesting architecture and reduced environmental impact and waste.
- The best alternatives for managing windows of the building complex in Lund is either Case 1 (replacing one windowpane with an energy glass) or Case 2 (replacing one windowpane with an insulating cassette) if these alternatives are further proven to be practically executed efficiently.
- The chosen method has provided sufficient results to be used as a basis for the initial decision-making of the building complex in Lund.

It should further be stated that these conclusions are not generally applicable for the whole construction industry but limited to the case study. This is due to that the characteristics of the buildings have been included in the simulations and calculations. Although, the method used in this study could be generally applicable for the initial decision-making of construction projects in the industry.

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LUND UNIVERSITY

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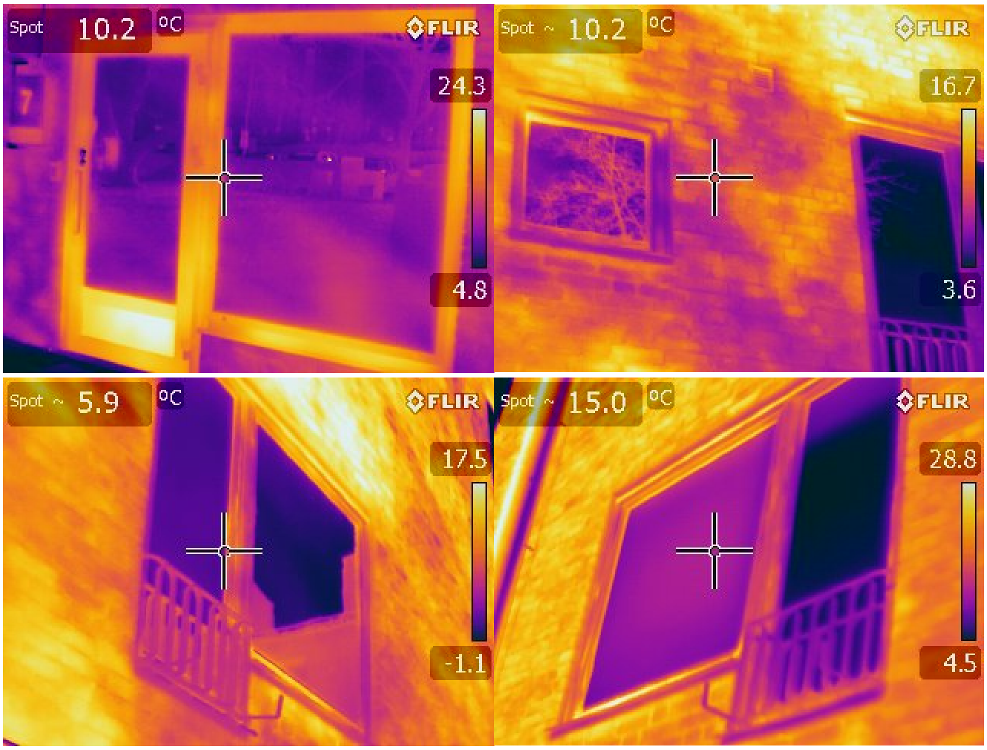
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services

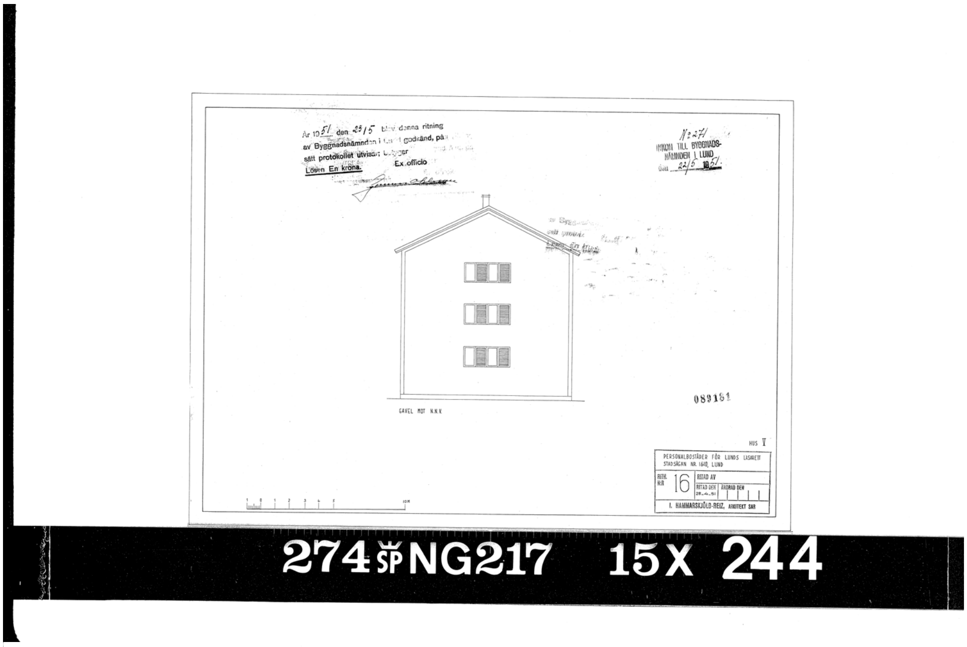
Appendix A

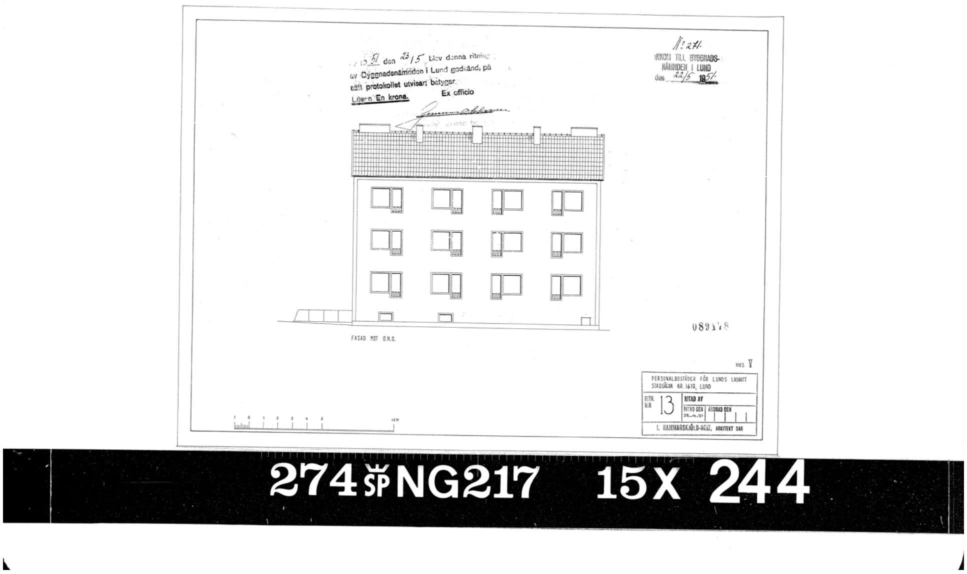
A few of the pictures from the thermal imaging camera. The snapshots are taken of the buildings included in this study.

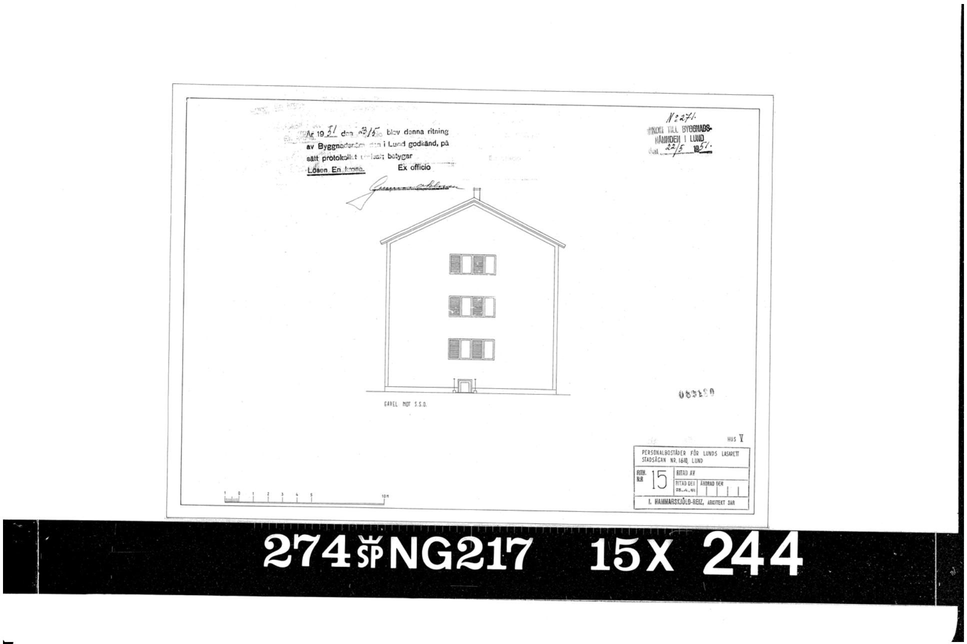


Appendix B

Provided drawings of the buildings, including façades, floorplans and construction details.



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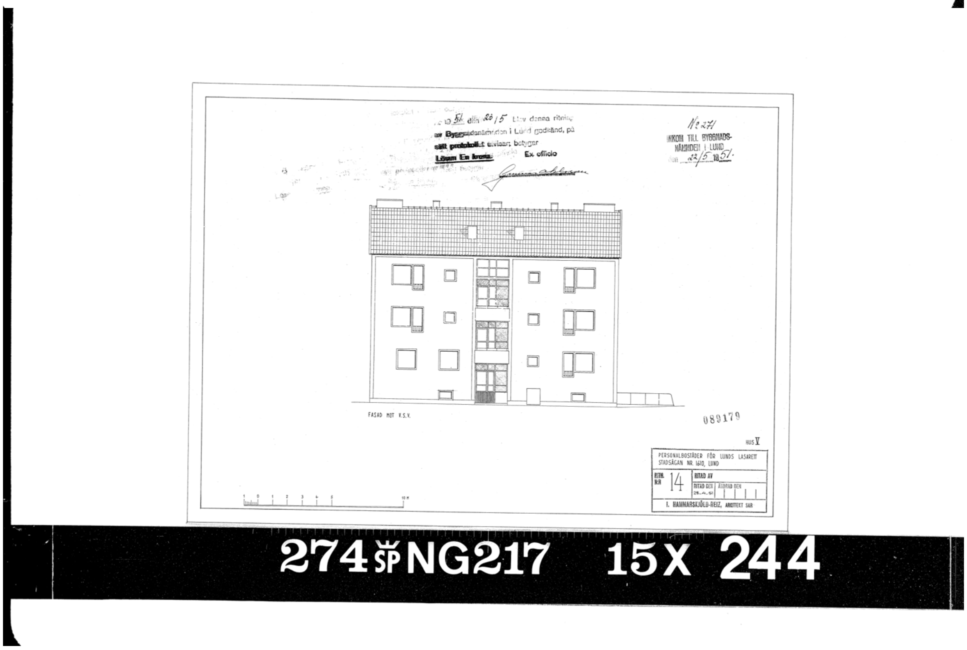
274 SP NG217 15X 244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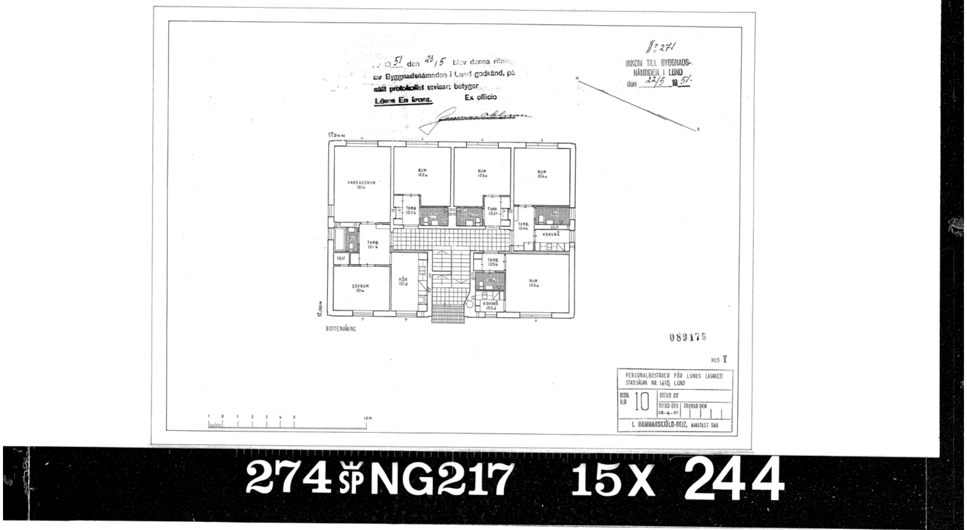
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INKOM TILL BYGGNADS-
NÄMNDEN I LUND
BOTTENVÅNING
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PERSONALBOSTÄDER FÖR LUNDS LASARETT
I. HAMMARSKJÖLD-REIZ, ARKITEKT SAR
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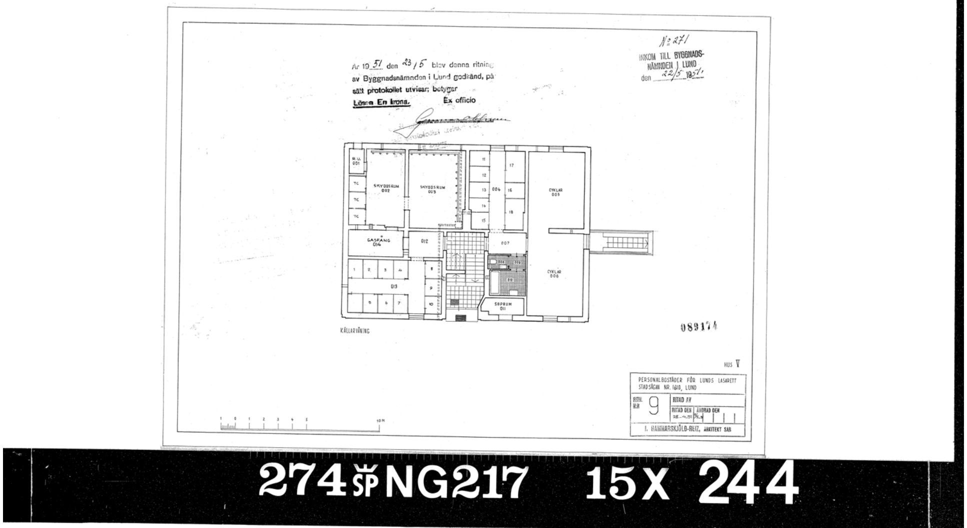
av Byggnadsnämnden i Lund godkänd, på
sätt protokollet utvisar; betyger
Lösen En krona.
Ex officio
INKOM TILL BYGGNADS-
NÄMNDEN I LUND
KÄLLARVÅNING
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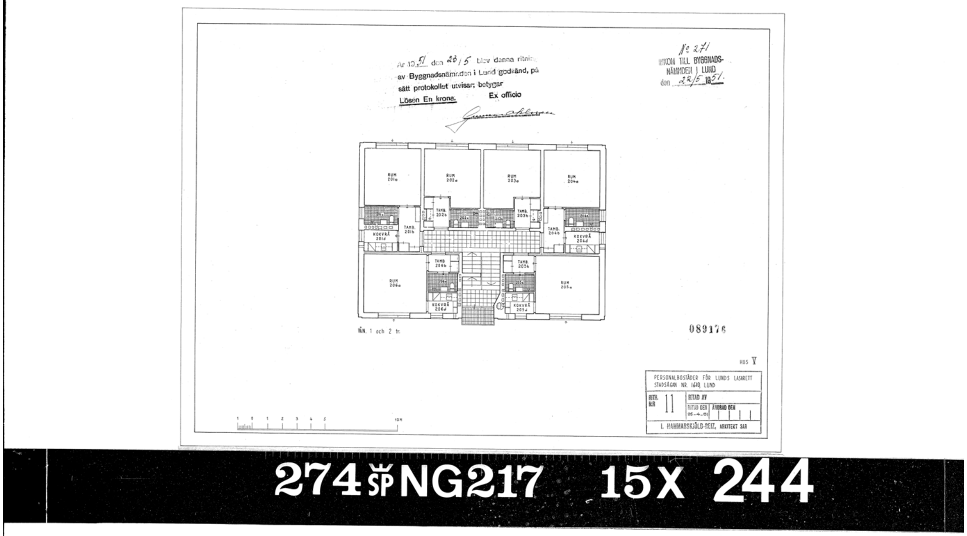
PERSONALBOSTÄDER FÖR LUNDS LASARETT
I. HAMMARSKJÖLD-REIZ, ARKITEKT SAR
274 SP NG217 15X 244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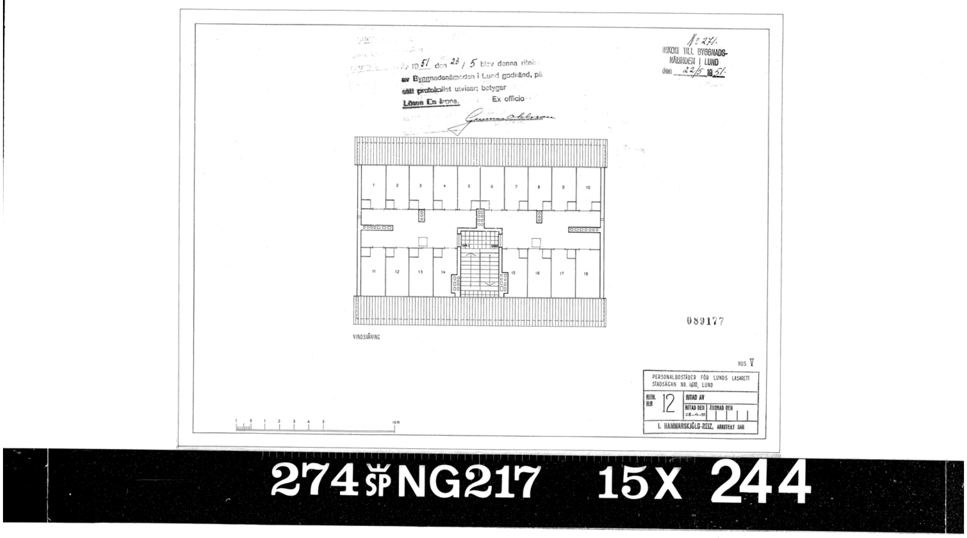
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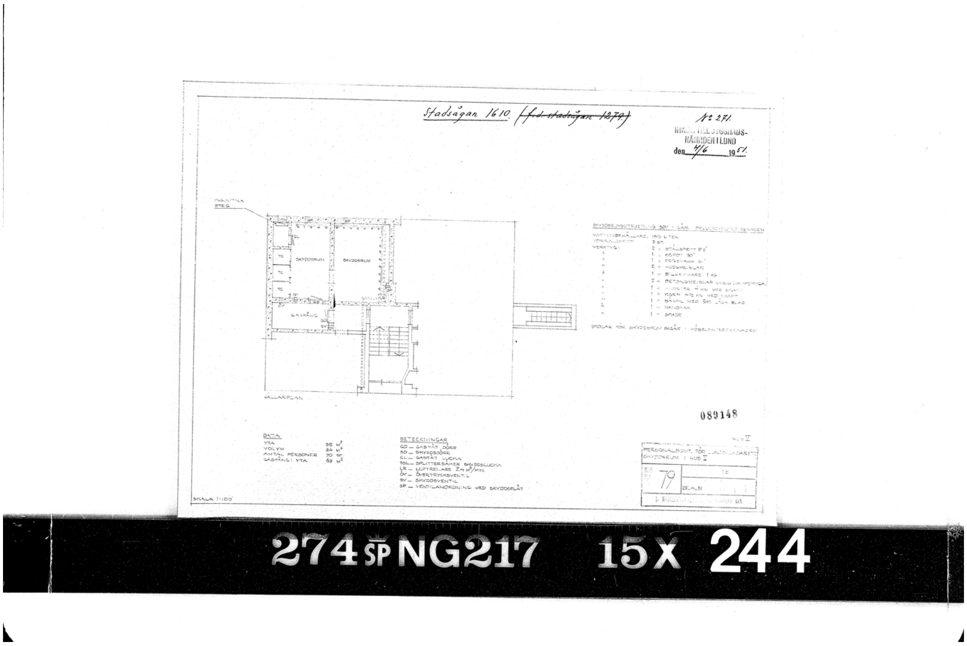

Stadsågan 1610. (f.d. stadsägan 1279.)
№ 271.
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den 4/6 1951.
KÄLLARPLAN
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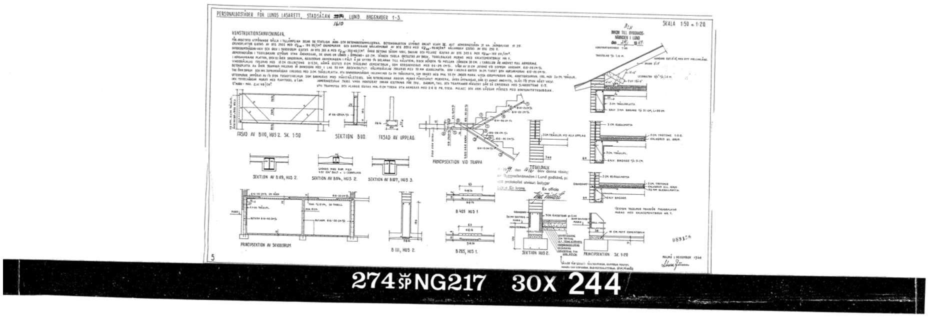
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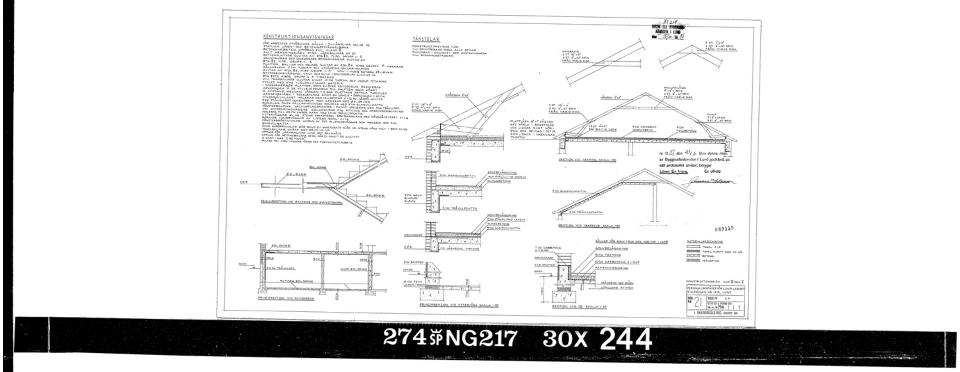
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Appendix C

Input values for calculating the *U*-values for the energy simulations. Both Rsi and Rse were included in the calculations.

Walls	Material	d (mm)	λ (W/mK)	R (m²K/W)	U-value (W/m²K)
	Facade block	120	0,6	0,2	
	Glass wool	30	0,04	0,75	
	Multi-hole brick	120	0,7	0,17	
					0,89

Roof	Material	d (mm)	λ (W/mK)	R (m²K/W)	U-value (W/m²K)
	Concrete	150	1,7	0,088	
	Glass wool	30	0,04	0,75	
					1,19

Ground	Material	d (mm)	λ (W/mK)	R (m²K/W)	U-value (W/m²K)
	Tretong	50	0,15	0,333	
	Areated concrete	100	0,4	0,25	
	Glass wool	150	0,04	3,75	
	Concrete	100	1,7	0,06	
					0,23

Attif floor	Material	d (mm)	λ (W/mK)	R (m²K/W)	U-value (W/m²K)
	Cement mortar	50	1	0,05	
	Cellular concrete	90	0,3	0,3	
	Concrete	120	1,7	0,07	
					2,38

The sources of the lambda-values are presented below:

facade block	https://www.energihandbok.se/konstanter/varmeledningsformaga-och-u-varden-for-olika-material
glass wool	https://www.energihandbok.se/konstanter/varmeledningsformaga-och-u-varden-for-olika-material
multi-hole brick	https://slunik.slu.se/kursfiler/TN0258/30276.1011/Tabellbilaga_U-ber.pdf
concrete	https://www.energihandbok.se/konstanter/varmeledningsformaga-och-u-varden-for-olika-material
tretong	https://betong.se/2017/01/06/2307/
aerated concrete	konstruktionsdetaljer appendix B
cement mortar	https://www.energihandbok.se/konstanter/varmeledningsformaga-och-u-varden-for-olika-material
cellular concrete	konstruktionsdetaljer appendix B

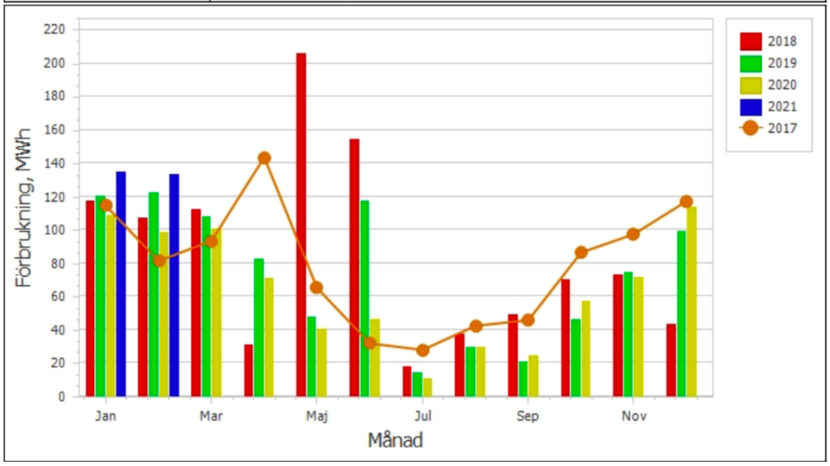
Appendix D

Provided statistics for the energy use of the neighbourhood, including space heating and common electricity.

Regionfastigheter

RS leverantörsmätare Fjärrvärme

Media	Mediabenämning
5600	**Fjv (Klimatkorrigerad)**
Förv.objekt	Förvaltningsobjektsbenämning
8101 mfl	**Skånes Universitetssjukhus, Lund**



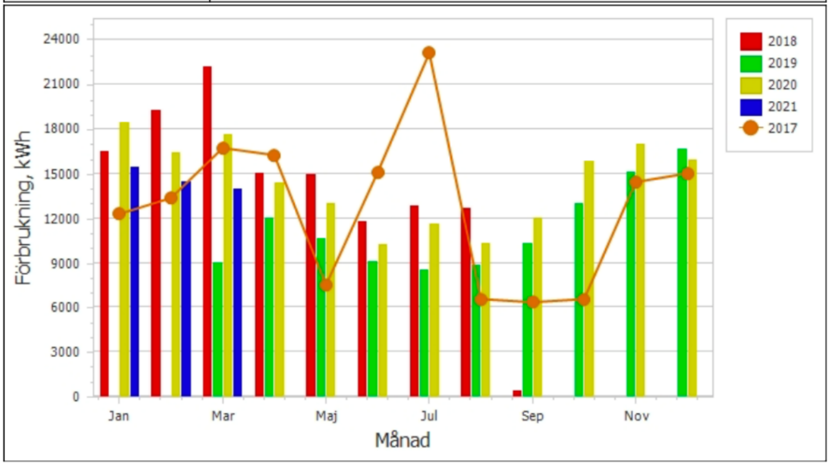
Förbr. klimatkorrigerat

Månad	Ref. år (2017)	2021	2020	2019	2018
Jan	114,60	135,19	109,01	120,47	117,93
Feb	81,37	133,82	98,93	122,91	107,45
Mar	93,40	0,00	101,19	108,56	112,74
Apr	143,56		71,25	82,81	31,46
Maj	65,13		40,80	48,16	206,22
Jun	31,80		46,50	117,49	155,22
Jul	27,90		10,66	14,33	18,00
Aug	42,36		29,76	30,00	37,82
Sep	45,75		24,41	20,82	49,37
Okt	86,38		57,76	46,69	70,65
Nov	97,40		72,01	74,74	73,73
Dec	117,25		114,03	99,93	43,51
Totalt:	946,90	269,00	776,32	886,92	1 024,11

Regionfastigheter

RS leverantörsmätare El

Media	Mediabenämning
6300	**El**
Förv.objekt	Förvaltningsobjektsbenämning
8101 mfl	**Skånes Universitetssjukhus, Lund**



Förbrukning

Månad	Ref. år (2017)	2021	2020	2019	2018
Jan	12 278,96	15 450,56	18 497,87	0,02	16 537,29
Feb	13 361,89	14 502,24	16 497,83	0,02	19 310,35
Mar	16 723,21	14 000,69	17 677,17	9 075,73	22 210,31
Apr	16 243,00		14 433,07	12 090,68	15 101,36
Maj	7 501,00		13 026,13	10 653,35	14 996,00
Jun	15 091,13		10 240,03	9 153,05	11 829,68
Jul	23 112,58		11 688,97	8 522,02	12 836,59
Aug	6 547,20		10 359,93	8 909,95	12 723,46
Sep	6 336,00		12 090,78	10 361,83	411,19
Okt	6 547,20		15 923,98	13 077,97	0,00
Nov	14 430,49		17 008,09	15 166,98	0,00
Dec	15 009,73		15 979,35	16 665,15	
Totalt:	153 182,40	43 953,49	173 423,20	113 676,75	125 956,23

Appendix E

Input and assumptions for calculating the LCC.

Material	SEK/m²		Source
Energypane	**590**		glasnet.nu
Energypane	**641**		interglas.se
Insulating unit	**990**		glasgiganten.se
Insulating unit	**570**		interglas.se
Insulating unit	**890**		glasnet.nu
New window	**4700**		fonster24sju.se
New window	**4750**		doorly.se
Window oil	**54**	0.2L/m²	bygghemma.se
Window colour (base)	**50**	0.25L/m²	bauhaus.se
Window colour	**30**	0.1L/m²	byggmax.se
Window putty	**110**	0.3L/m²	bauhaus.se
Windowpane 4mm (waste)	**10**	950 SEK/ton	sysav.se
Windowframe (waste)	**1**	450 SEK/ton	sysav.se
Window (waste)	**19**	950 SEK/ton	sysav.se
Swede Glass United	**15**		Assumption
Windowframes	**1000**	780 SEK/m²	byggmax.se

material	work	unit	SEK/h	h/m²	SEK/m²	source
energy pane	remove old window pane	h	218	0,2	202,74	assumption
	add new energy pane	h	218	0,2	202,74	assumption
	scrape, oil, paint	h	218	0,6	608,22	assumption
	total				**1013,7**	
insulating unit	remove old window pane	h	218	0,2	202,74	assumption
	add new insulating unit	h	218	0,4	405,48	assumption
	scrape, oil, paint	h	218	0,6	608,22	assumption
	total				**1216,44**	
glazed wall	remove old window	h	218	0,6	608,22	Sektionsfakta
	remove old window pane carefully	h	218	0,4	405,48	assumption
	install panes in frames	h	218	0,5	506,85	assumption
	install new windows	h	218	4,6	4663,02	Sektionsfakta
	total				**6183,57**	
new window	remove old window	h	218	0,6	608,22	Sektionsfakta
	install new window	h	218	4,6	4663,02	Sektionsfakta
	total				**5271,24**	

Appendix F

LCA results (normalised and weighted) in tables.

EQUAL						
Impact category	**CASE 1**	**CASE 2**	**CASE 3.1**	**CASE 3.2**	**CASE 3.3**	**CASE 4**
Global Warming Potential	0.000703369	0.000757179	-0.000111643	0.001672815	0.002837470	0.001172311
Ozone Layer Depletion Potential	0.000004065	0.000004826	-0.000009730	0.000006691	0.000021780	-0.000013560
Photochemical Oxidant Formation Potential	0.001566280	0.001616131	0.000905668	0.004273162	0.006303438	0.003892018
Acidification Potential	0.000927912	0.000989982	0.00009500	0.002363192	0.003892179	0.00143763
Eutrophication Potential - Freshwater	0.000031070	0.000035505	-0.000301955	0.000063029	0.000144056	-0.000415385
Eutrophication Potential - Terrestrial	0.001124389	0.001157677	0.000552293	0.003040423	0.004570107	0.002608404
Abiotic Depletion Potential	0.000000477	0.000000486	-0.000000020	0.000000937	0.000000048	-0.000000029

EPA Science Advisory Board						
Impact category	**CASE 1**	**CASE 2**	**CASE 3.1**	**CASE 3.2**	**CASE 3.3**	**CASE 4**
Global Warming Potential	0.001688001	0.001817139	-0.000267929	0.004014556	0.006809587	0.002813405
Ozone Layer Depletion Potential	0.000003048	0.000003619	-0.000007297	0.000005018	0.000016334	-0.000010169
Photochemical Oxidant Formation Potential	0.001409582	0.001454445	0.000815060	0.003845653	0.00567281	0.003502641
Acidification Potential	0.000695899	0.000742449	0.000071249	0.001772305	0.002918988	0.001078169
Eutrophication Potential - Freshwater	0.000023302	0.000026628	-0.000226455	0.000047270	0.000108037	-0.000311523
Eutrophication Potential - Terrestrial	0.000843250	0.000868215	0.000414199	0.002280203	0.003427409	0.001956205
Abiotic Depletion Potential	0.000000358	0.000000365	-0.000000015	0.000000703	0.000000036	-0.000000022

BEES Stakeholder Panel						
Impact category	**CASE 1**	**CASE 2**	**CASE 3.1**	**CASE 3.2**	**CASE 3.3**	**CASE 4**
Global Warming Potential	0.003059502	0.003293565	-0.000485622	0.007276382	0.012342377	0.005099297
Ozone Layer Depletion Potential	0.000001219	0.000001448	-0.000002919	0.000002007	0.000006534	-0.000004068
Photochemical Oxidant Formation Potential	0.000939721	0.000969630	0.000543374	0.002563769	0.003781874	0.002335094
Acidification Potential	0.000417540	0.000445470	0.000042749	0.001063383	0.001751393	0.000646901
Eutrophication Potential - Freshwater	0.000027962	0.000031953	-0.000271746	0.000056723	0.000129644	-0.000373828
Eutrophication Potential - Terrestrial	0.001011900	0.001041857	0.000497038	0.002736244	0.004112891	0.002347446
Abiotic Depletion Potential	0.000000716	0.000000729	-0.000000030	0.000001406	0.000000072	-0.000000044

NOGEPA						
Impact category	**CASE 1**	**CASE 2**	**CASE 3.1**	**CASE 3.2**	**CASE 3.3**	**CASE 4**
Global Warming Potential	0.003376002	0.003634279	-0.000535858	0.008029111	0.013619175	0.005626811
Ozone Layer Depletion Potential	0.000003048	0.000003619	-0.000007297	0.000005018	0.000016334	-0.000010169
Photochemical Oxidant Formation Potential	0.001879442	0.001939260	0.001086747	0.005127538	0.007563747	0.004670188
Acidification Potential	0.000835079	0.000890939	8.54985E-05	0.002126766	0.003502786	0.001293802
Eutrophication Potential - Freshwater	0.000060584	0.000069232	-0.000588782	0.000122901	0.000280896	-0.00080996
Eutrophication Potential - Terrestrial	0.002192450	0.002257358	0.001076917	0.005928528	0.008911263	0.005086133