Turning Up the Efficiency: The Office Building Retrofit Challenge

Alex Camango, Viktor Karlsson

Both authors have together contributed to the entire study. Real Estate Science
Department of Technology and Society
Faculty of Engineering
Lund University
Lund, Sweden

Authors

Alex Camango: Master of Science in Engineering, Surveying and Land Management, Faculty of Engineering, Lund University
Viktor Karlsson: Master of Science in Engineering, Surveying and Land Management, Faculty of Engineering, Lund University

Supervisor

Rebecka Lundgren, PhD Student, Real Estate Science, Faculty of Engineering, Lund University

Examiner

Riikka Kyrö, Senior Lecturer, Real Estate Science, Faculty of Engineering, Lund University,

Opponents

Emma Rosén: Master of Science in Engineering, Surveying and Land Management, Faculty of Engineering, Lund University
Emma Westin: Master of Science in Engineering, Surveying and Land Management, Faculty of Engineering, Lund University

Acknowledgements

Several people have helped us with minor and major hick-ups, to whom we would like to extend our gratitude. Thanks to our supervisor Rebecka Lundgren, who has helped and guided us and done so quickly and tirelessly. Thanks to Edvin Ottosson and Emil Palmenäs for answering questions about the program IDA ICE. Thanks to Emil Lönn for help in interpreting poorly quality drawings. Thanks to Björn and Rickard Karlsson for help understanding reasonable measures from a property owner's perspective. Thanks to Jenny Wahl and Tobias Kvist at Wihlborgs for encouraging us to carry out this work and helping us with some technical questions.

Faculty of Engineering, Lund University
Lund, May 2023

Viktor Karlsson

Alex Camango

Abstract

This study is a single case study of a building situated in Malmö, Sweden, examining various retrofit measures and their potential impact on the building's energy performance. A pre-study was carried out to gain knowledge on applicable retrofitting measures from existing literature. Subsequently, the case study consisted of three major phases. In the first phase, building information was collected to understand possible areas of improvement. In the second phase, a model was created to perform energy simulations to examine the efficiency of various retrofit combinations. Finally, in the third phase, the economic feasibility of the different options was evaluated. The data collection process involved a combination of existing blueprints, assumptions based on template data, a site visit, and information provided by the owner. Investment costs were collected from various sources, and energy prices were gathered from area specific yearly futures sources. The study results provide insights into retrofitting strategies for buildings with poor energy performance, where retrofitting measures to the HVAC system significantly impacted energy consumption and the energy saving rate. One optimal retrofit combination of measures was identified based on a trade-off between economic feasibility and potential energy savings. The study concludes that retrofitting existing buildings can lead to substantial energy savings. It is also concluded that adding additional insulation to the external walls and roof beyond a certain point resulted in marginal increases in energy savings. Concurrently, it was found that there is a limit towards which the energy consumption converged as the investment cost increased, magnifying the arguments for finding an optimal solution concerning energy savings and cost.

Keywords – Energy Efficiency, Retrofit, Retrofitting Measures, BEETs, NPV, SPP, Insulation, HVAC, Windows, IDA ICE

Sammanfattning

Denna studie är en fallstudie av en byggnad belägen i Malmö, Sverige, som undersöker olika energieffektiva åtgärder och deras potentiella påverkan på byggnadens energikonsumtion. En förstudie genomfördes för att inhämta kunskap om tillämpliga energieffektiva åtgärder från befintlig forskning. Därefter genomfördes fallstudien i tre huvudsakliga faser. I den första fasen samlades byggnadsinformation in för att förstå möjliga förbättringsområden. I den andra fasen skapades en modell för att utföra energisimuleringar och undersöka effektiviteten hos olika kombinationer av åtgärder. Slutligen, i den tredje fasen, utvärderades de olika alternativens ekonomiska genomförbarhet. Datainsamlingen involverade en kombination av befintliga ritningar, antaganden baserade på data från schabloner, ett platsbesök och information genom mail med ägaren. Investeringkostnader samlades in från olika källor och energipriser baserades på terminspriser. Resultaten från studien ger insikter om energieffektiva strategier för byggnader med dålig energiprestanda, där åtgärder som rör HVAC-systemet hade en betydande påverkan på energiförbrukningen och energibesparingsgraden. En optimal kombination av åtgärder identifierades baserat på en avvägning mellan ekonomisk genomförbarhet och potentiella energibesparingar. Studiens slutsats är att energieffektivisering av befintliga byggnader kan leda till betydande energibesparingar. Det konstaterades också att ytterligare isolering av ytterväggar och tak utöver en viss punkt resulterade i marginella ökningar av energibesparingar. Samtidigt visade det sig att det finns en gräns där energiförbrukningen konvergerar när investeringskostnaden ökar, vilket betonar behovet av att hitta en optimal lösning med avseende på energibesparingar och kostnad.

Nyckelord – Energieffektivitet, Renoveringsåtgärder, BEETs, NPV, SPP, Isolering, HVAC, Fönster, IDA ICE

Contents

List of Figures

List of Tables

1 Introduction

As the world's largest energy consumer, buildings account for 38 % of both total energy consumption and CO_2 emissions (United Nations Environment Programme, 2021). In Sweden, the corresponding figures are 34 and 21 %, respectively, where a vast majority of consumed energy is used for heating (Boverket, 2023b,c). The Paris Agreement commits us to prevent global temperature rises greater than 2 ° C, to take actions to prevent a rise greater than 1.5 ° C (United Nations Framework Convention on Climate Change, 2015). On an EU level, the target is to reduce greenhouse gas emissions by a minimum of 55 % by 2030 compared to 1990 and to be climate-neutral by 2050 (European Commission, 2021), while in Sweden, the goal is to reduce emissions by 50 % by 2030, compared to 2005 (Boverket, 2019).

New and existing buildings are often labeled with certifications, demonstrating that they reach today's required standards (Boverket, 2021; Sweden Green building Council, n.d.a). Over time, it has been presented that the minimum performance standards have become more strict, demanding better-performing buildings. Although there have been noticeable accelerations in more sustainable technologies invested in buildings, the energy demand in buildings rose by almost 17 % from 2010 to 2021, where the increase still outpaces the energy efficiency in buildings (IEA, 2022). Furthermore, the International Energy Agency (IEA) has assessed the building sector to not be on track to eliminate emissions by 2050. The situation is dire, and there is an evident need for change (IEA, 2022).

The effects of adopting sustainability measures in buildings have been examined extensively in recent years, both on a broader level and single measures in detail (e.g., Ho et al. (2021); Wan et al. (2022); Nutkiewicz et al. (2021); Shadram et al. (2020); Gustafsson et al. (2017); Aslani et al. (2019)). However, the focus has tended to be on new construction and recycling of building materials as opposed to existing buildings (Cruz Rios et al., 2021). Retrofitting of existing structures refers to the process of improving or upgrading these. This involves reducing heat loss and changing elements to newer techniques, reducing the building's energy needs. It is of importance as it is in most cases more sustainable to refurbish and reuse existing buildings than to demolish and construct new ones (Conejos et al., 2015; Baker et al., 2021), and it is predicted that 50% of the building stock that will exist in 2050 will have been built before 1975 (IEA, 2013; BPIE, 2011). Though most studies suggest that retrofits help reduce energy consumption in buildings, there is no consensus on whether it is economically feasible or justified (Boverket, 2019). This study will therefore examine the effects of adopting sustainability measures on existing office buildings in the real estate industry. This is done with the aim for buildings to be in line with the EU taxonomy, which was developed to facilitate and enforce investments to be more sustainable and reach the goals of 2030. This applies to the energy performance of newly constructed and existing buildings in the real estate industry.

1.1 EU-taxonomy

The EU taxonomy is a system classifying activities in sustainability to help businesses, legislators, and investors define actions that can be justified by how environmentally sustainable they are. The taxonomy was developed to form a plan of action for sustainable finance to reach sustainable development goals and covers a comprehensive range of actions (European Parliament and the Council of the European Union, 2020).

Sustainability reporting is mandatory for Swedish companies with more than one of: more than 250 employees, disclosed total assets of more than 175 mSEK, and net sales of more than 350 mSEK, in the previous two years (Annual Accounts Act (1995:1554)) (Årsredovisningslagen).

According to the Swedish Finanical Supervisory Authority (2022) (Finansinspektionen), more strict requirements on sustainability reporting will begin in 2023.

Regarding the real estate sector, the taxonomy applies to three categories in limiting climate impact: new constructions, renovations or reconstruction of existing buildings, and acquisition of existing buildings. To be classified as a sustainable investment, changes in existing buildings should yield 30 % lower energy performance. According to the Swedish classification system, acquired assets should have an energy classification of grade A or have an energy performance equal to the top 15 % of buildings in Sweden. This applies to buildings erected before the 31st of December 2020 (Sweden Green building Council, n.d.b). The top 15 % have a primary energy of 80 kWh/m^2 (Fastighetsägarna, 2022).

In order to push the green transition and to be aligned with the EU's goal of reducing greenhouse emissions by 55 % by 2030 (European Commission, 2021), some countries have implemented mandatory requirements for the energy performance of their existing building stock called Minimum Energy Performance Standards (MEPS). Companies that do not comply with the standards are penalized. However, these requirements and penalties differ from country to country. In France, the requirements imply that buildings with an energy grade of G or worse are prohibited from being let by 2028. In the United Kingdom, lease contracts are prohibited from being renewed if the building has an energy grade worse than grade E. In the Netherlands, office buildings with an energy class worse than C are prohibited from being let as of 2023, emphasizing the importance of proactively making buildings sustainable. To this date, there are no MEPS regulations implemented in Sweden (Fastighetsägarna, 2021).

1.2 Obstacles and the Landlord Tenants' Dilemma

In the pursuit of sustainable buildings, there are many obstacles that hamper the work. One is the landlord tenants' dilemma, a situation occurring from a misalignment of interests between the parties. The dilemma impedes sustainability work at large, and one explained reason is split incentives (Ástmarsson et al., 2013). The two common terms cold rent and warm rent are widely known when drafting leasing contracts. In warm rent agreements, electricity is included in the rent. It does not give the tenant any economic incentives to reduce energy consumption and solely gives the landlord argument to perform actions for energy efficiency. In Sweden, cold rent agreements are common for office buildings, where energy is not included, and the tenant pays for energy used, giving incentives for restrained use (Boverket, 2022). Investments in energy efficiency would yield less consumed energy and lower energy costs. The landlord would not be compensated for the investment if it would not lead to a higher rent, which erodes the landlord's motives. Another explanation for the dilemma is the lack of information sharing between stakeholders (Berardi, 2013).

However, as buildings' energy performance requirements increase, there are growing incentives for performing energy-saving actions. A comprehensive investigation was conducted by CBRE, where regression analysis was used on more than 44,000 leasing contracts throughout Europe, which showed a rental premium of 5.5 % for certified buildings (Marina, 2022).

1.3 Energy Consumption in Swedish Office Buildings

Energy performance certificates are used to compare the energy consumption of buildings. The performance certificate describes variables such as heated area, heating, cooling, and hot tap water consumption, as well as energy performance in relation to new buildings and more. There are seven classes from A to G, where A has a low energy consumption and G a high. Energy performance is expressed in unit kilowatt hour per square meter and year, shortened to kWh/m^2 (Boverket, 2023d). The energy class is dependent on the primary energy, which is not the same as the energy consumption of a building. This will be presented further in section 3.7. It is worth mentioning that different countries in the EU have different requirements for the same classes; for example, yearly consumption of 450 kWh/m^2 in France corresponds to grade G, while in Sweden, the same grade requires 176 kWh/m^2 (Fastighetsägarna, 2021).

An extensive report conducted by Boverket (2019) showed that as much as two-thirds of multi-dwellings and commercial premises in Sweden have an energy class of grade E, F, or G, i.e., the three worst classifications. A large part of these was constructed between 1940 and 1980. There is great potential in working with existing buildings with a large maintenance backlog, whereas a mere 15 to 25 % of buildings erected before 1981 were estimated to be renovated before 2020. Furthermore, the report presents that one of Sweden's road map milestones is to decrease the energy consumption per sqm and reduce the share of buildings with energy classes E-G.

Heated space for commercial buildings in Sweden was estimated at around 176 million square meters by 2016 and had an average energy performance of 186 kWh/m^2. Offices, hotels, and schools are examples of the type of users for commercial premises, where the most energy is consumed by offices erected between 1960 and 1989, which have an energy classification of E-G (Boverket, 2019). See figure 1.1 for the distribution of energy consumption per grade for commercial premises.

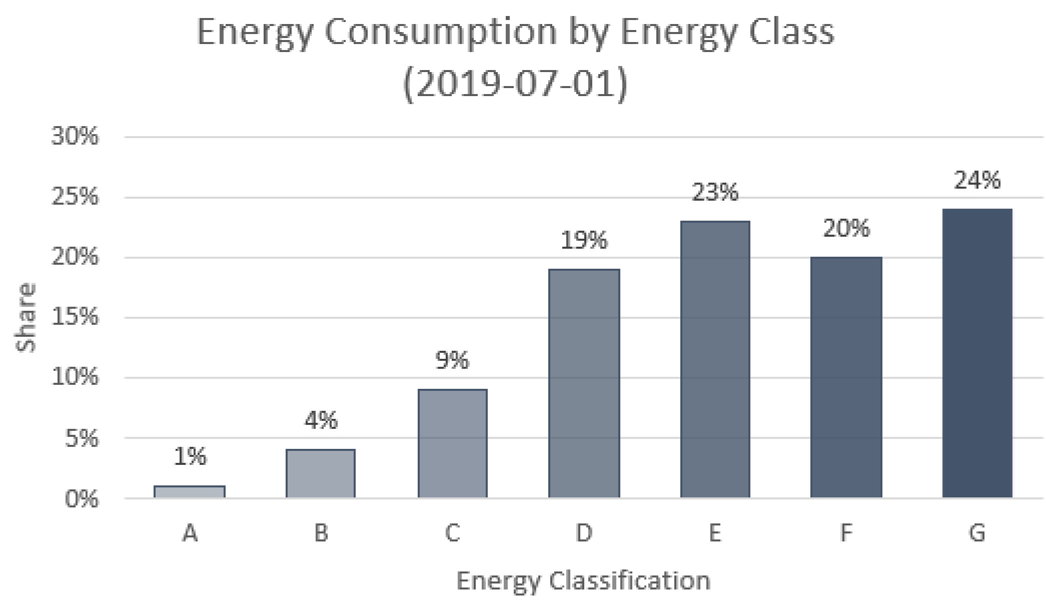


Figure 1.1: Percentage of total energy consumption by grade (Boverket, 2019).

Figure 1.1 shows the share of energy consumption per grade for commercial buildings. The graph is translated from Swedish and formatted to fit this study. It was retrieved from Boverket (2019), which conducted the report in collaboration with the Swedish Energy Agency (Energimyndigheten). The data of the energy consumption for commercial buildings which gathered the data from the register of energy declarations from Boverket (the National Board of Housing).

The building's energy class is determined by its compliance with the requirements for new buildings, its heating source, and the building's geographical location. Buildings located in the northern part of Sweden are permitted to have higher energy consumption levels than those in the south. The energy classes derives from the requirements of energy consumption's of newly constructed buildings, and are defined as follows: A requires energy consumption that is equal to or less than 50 %, B requires consumption between 50 % and 75 %, C requires consumption between 75 % and 100 %, D requires consumption between 100 % and 135 %, E requires consumption between 135 % and 180 %, F requires consumption between 180 % and 235 %, and G requires consumption greater than 235 % (Boverket, 2023a). The requirement for constructing new commercial premises is 70 kWh/m^2 and year (Boverket, 2022).

1.4 Aim, Research Questions, and Limitations

1.4.1 Scope

This study aims to find cost-effective retrofit actions that can reduce energy consumption in an existing office building. It intends to find an optimal solution that can inspire and help professionals make buildings more energy efficient. This is examined through a case study applied to an existing office building in Malmö and will be examined to an extent that is possible from the limited resources in terms of a study semester, information about the building, and software programs that can be used. The adopted retrofits will be measures that have been adopted in previous studies but combined for an office building with poor energy consumption in Malmö.

The research questions are as follows:

- Can the energy consumption of poorly performing office buildings be improved using combinations of actions, and how effective are these in energy savings?
- What or which combinations are optimal in terms of energy savings when considering the economic cost perspective?

1.4.2 Limitations

Due to limited resources of time and information, there will have to be limitations to the study. The study will only look at changing or adding building components and not examine what parts do not need an upgrade, i.e., the retrofit measures will be added to the entire building. The study will not evaluate the building from a life cycle perspective nor look into the embodied emissions from the used materials. Emissions from the operational phase are another subject commonly examined in studies, but this study will not be included. In short, the study will adopt retrofit measures of building parts to compare the current energy consumption with the potential.

1.5 Nomenclature

BEET	Building Energy Efficiency Technologies
BMS	Building Management System
HVAC	Heating Ventilation and Air Conditioning
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
PIR	Polyisocyanurate
NPV	Net Present Value
SPP	Simple Payback Period
PUR	Rigid Polyurethane
Energy class	A classification of a buildings energy performance
Energy Consumption	The total energy consumed by the building, expressed in kWh/m^2
Primary Energy	A metric used to describe a building's energy performance in relation to other buildings

2 Retrofitting measures

In this section, studies with different retrofitting measures are presented. First, in a general overview, then at an in-depth look at retrofits in different building elements that can be implemented in office buildings.

2.1 Studies on national and international level

Significant savings in environmental impact can be achieved by adopting energy refurbishments, instead of constructing new buildings, as the construction phase accounts for a large part of the embodied emissions (Moncaster et al., 2019). The Swedish Government tasked the National Board of Housing, Building, and Planning (Boverket) and the Swedish Energy Agency (Energimyndigheten) to develop a national strategy for energy-efficient renovations. The report produced reference scenarios to showcase how the current market situation and existing policies impact energy use between 2016 and 2050. The results showed that the current renovation pace would only lead to a 10 % decrease in energy consumption for office buildings. However, it was also underlined that enormous energy-saving potentials are not realized at every renovation. By applying the strategy, it was estimated that 30 % of the buildings could have a 50 % reduction in consumed energy (Boverket, 2019).

The subject has also been investigated internationally, where the IEA found a critical need to change existing buildings in OECD countries. Two ways of making buildings more energy-efficient are deep renovations or retrofits of building elements. While deep energy renovations can significantly improve a building's energy performance, they are extensive, time-consuming, and expensive operations (IEA, 2013). Several studies on energy efficiency have found that retrofit measures are a cost-effective way of improving existing buildings' energy performance by changing obsolete technical elements. Retrofits are commonly performed during the dilapidation period when there is a change of tenant or when the interior or exterior of a building has deteriorated, and there is a substantial need for renovation. However, building renovations do not necessarily lead to automatic energy savings (Wan et al., 2022; Shadram et al., 2020; Javid et al., 2019).

2.2 Studies on single and combined retrofits

Measures for retrofitting are often called building energy-efficient technologies (BEETs). Common BEETs are improvements to the building envelope, including windows and walls, lighting and lighting system upgrades, heating, ventilation, and air conditioning (HVAC) system upgrades, as well as installing building management systems (BMS) (Santamouris and Dascalaki, 2002; IEA, 2013; Ma et al., 2012).

Different kinds of single retrofit measures have been studied extensively. Aslani et al. (2019) used a hype cycle diagram to analyze different building envelope technologies for reduced energy consumption. Belany et al. (2021) examined lighting systems as possible retrofits, where the original lighting system was compared with two modern ones. One of the two was movement based, and another used daylight sensors. Li et al. (2020) investigated the effects on energy efficiency by implementing real-time data that measured CO_2 concentration and indoor temperature as a proxy for a retrofitted HVAC system. Furthermore, combining several types of retrofits has been shown to affect final energy savings in buildings significantly. Nutkiewicz et al. (2021) conducted a case study of 29 closely situated buildings in Sacramento, California in the US. The authors found an optimization algorithm to maximize electricity savings when selecting retrofit measures. Boyano et al. (2013) used the simulation program EnergyPlus in a case study on a European representative office building. They examined the effects of improvements in the insulation of the windows and external walls, lightning system controls, and the orientation of the building. They highlighted that European office buildings could benefit from lightning controls and that the orientation of the building played an important role. They also concluded that the lack of knowledge is one of the main barriers to energy efficiency.

Shadram et al. (2020) studied the trade-offs in life cycle energy of different retrofit measures on a 1980s multi-family residential building in a subarctic climate zone in Sweden. The trade-offs between the embodied and operational energy of the building were studied for various Swedish building standards through multi-objective optimization. Changes were made to the HVAC system and the building envelope. The results indicated that the multi-objective optimization approach is applicable when identifying optimal retrofit solutions. In this case, it resulted in energy savings equal to 18 years of operational use.

Office buildings have been examined in different parts of the world. Gustafsson et al. (2017) used an energy simulation program to study office buildings in three different climate zones in Europe, the Nordics, the Continental, and the Mediterranean. The retrofits used were windows, insulation in both roof and wall, measures to the HVAC system, and added solar photovoltaics. They used different levels of BEET standards, which were simulated for a period of 30 years and resulted in reductions of non-renewable energy by 43 - 89 %. Wan et al. (2022) examined potential energy savings gained from retrofit measure combinations in a typical Beijing office building. The combinations were weighted against the life cycle cost to create a framework for professionals to facilitate decision-making in this area. The measures performed included changes in the building envelope, walls and windows, HVAC, and lighting. The optimal solution reduced energy usage for the entire building by 13 % and had a payback period of 7 - 8 years.

According to Swedish Ministry of Infrastructure (2010) (Infrastrukturdepartementet), there is no consensus on which energy-efficient technical measures are profitable to implement during a renovation. The profitability of implementing energy-efficient technical measures during renovations is subjective, as each building has its characteristics, and each company has distinct conditions and return requirements that dictate which investments are considered profitable or not.

Many technologies are available for retrofitting buildings today, and they can contribute to significant savings in energy consumption. Still, they might not be easily adopted because of their complexity (Dipasquale et al., 2019).

2.3 Building envelope

A building's envelope is the outer shell that protects against the outdoor climate and includes the exterior walls, foundation, roofs, windows, and doors. Thermal conductivity explains a material's ability to conduct heat and is expressed in the unit W/mK. Heat loss in transports through a building element is determined by the difference in indoor and outdoor temperature and the heat transfer coefficient, or U-value, expressed in W/m^2K. The lower the U-value, the better the element's insulation capability, i.e., there is less heat loss. Thermal bridges are areas in a building's structure with a higher U-value and where more heat is transferred than in the surrounding areas. Thermal bridges are created in areas where there is a change in materials, or there is a penetration in the insulation material. These should be avoided to minimize heat loss (Strandberg and Lavén, 2018). To minimize heat loss through the outer shell, the U-value, for newly constructed houses, should for roof and exterior wall be less than 0.12 and 0.15, respectively (EKRS, n.d.b).

2.3.1 Exterior walls and roof

Many studies have examined the type of material and insulation thickness in walls and roofs. Lee et al. (2019) added 100 mm insulation of glass wool material to the existing wall consisting of 150 mm reinforced concrete and 50 mm EPS insulation, which, together with new windows, led to a predicted reduced demand of 40 % for heating. Guo et al. (2022) conducted a study in China using the EnergyPlus software, where they studied the effects of reducing heat loss by examining how added insulation and changed windows could affect energy consumption. Their results were in line with Aste, Angelotti, and Buzzetti Aste et al. (2009), who found that adding insulation positively reduces energy consumed for heating and cooling.

A master's thesis by Höglund (2016) used IDA ICE to examine building elements from a life cycle cost (LCC) perspective and presented that the most cost-effective wall insulation thickness is in the interval 150 - 250 mm Höglund (2016). In the study conducted by Gustafsson et al. (2017), different levels of insulation thickness, 24 and 130 mm, were used for the Expanded polystyrene (EPS) material. Shadram et al. (2020) considered both traditional and high-performing insulation materials, such as EPS, mineral wool, cellulose, polyisocyanurate (PIR), and vacuum-insulated panels (VIP). Traditional insulation materials require thick building walls to achieve lower operational energy use. However, it may not be feasible from either an architectural point of view or a space point of view.

In a study conducted in Turkey, the optimal insulation thickness in wall insulation for reduced heat loss was examined through a life-cycle cost analysis for a period of 20 years, taking the cost of energy into account. The author found that there is an interval for optimal insulation varying between 54 - 192 mm in the exterior wall, depending on the used insulation material. The optimal thickness depends heavily on the thermal conductivity of the material (Ozel, 2012).

Moreover, Rodrigues and Freire (2014) investigated added insulation to roofs, where they simulated and measured 27 different retrofit scenarios. The scenarios were based on three types of insulation materials: Rock wool, Extruded polystyrene (XPS), and Polyurethane foam (PUR), and three different thicknesses of 40, 80, and 120 mm. They concluded there is a threshold for insulation thickness in the interval of 40 - 80 mm, in which additional thickness in the insulation of 40 mm to 120 mm did not result in further significant reductions in operational energy.

Into the bargain, Wan et al. (2022) arrived at another interesting conclusion. They looked at combinations of retrofit measures where different insulation materials were used. These were Extracellular Polysaccharide board (EPS), Rigid Polyurethane (PUR), and Extruded Polystyrene board (XPS), where the wall thickness was 0.59 m in all scenarios. From the simulations of combined technologies, the authors concluded that the different insulation materials used are not easily distinguishable but that the crucial factor is the implementation of additional insulation.

2.3.2 Windows

Windows are essential for transmitting natural light and might be an area of great potential in heat loss. There are different kinds of windows; the most common are windows with 1, 2, or 3 panes. Windows with three panes consist of three glass layers in the window arch. Between the panes, air or argon gas commonly works as insulation (Strandberg and Lavén, 2018). The several layers contribute to heat insulation. Window techniques have continuously developed, and those produced today have much greater quality than windows 40 - 50 years ago. There are glasses created to reduce cold air infiltration, reducing the need for compensating with additional heating. Increasing demands on building energy performance have made 3-pane windows more common (EKRS, n.d.a).

In the study conducted by Lee et al. (2019), changes in walls, roofs, and doors resulted in a 38 % reduction in energy from the heat demand. The U-value of the new windows was 1.6 W/m^{2}K. Double-glazed windows were replaced with triple Low-E (emissivity) glasses, and the U-value significantly changed from 4.439 to 1.226. The building in their simulation had a window-to-wall ratio of 30 %. Valdiserri and Biserni (2016) conducted a study on a building in northern Italy and found that changing to low-E windows did not result in a positive net present value (NPV), and hence was not economically motivated. The authors discussed a few reasons for the outcome: the building was situated in a warm climate, the window-to-wall ratio was relatively small at 14 %, and the glasses were double-glazed already before the retrofit.

A study by Poirazis et al. (2008) examined buildings' energy usage with different window-to-wall ratios. The ratios they looked at were 30 %, 60 %, and 100 %. They found important variables to be the building orientation, landscape or cell office, window-to-wall ratio, and if shading devices exist. Buildings with a larger ratio of windows as a single skin are likely to have a greater energy consumption than those with smaller ratios. Some other reasons that are assumed to be crucial for energy performance are the shape of the building, the location, the orientation, and how large the occupancy rate is. The main conclusion is that buildings with high levels of glazing should be designed carefully to achieve low energy consumption and good thermal comfort Poirazis et al. (2008).

2.4 Lightning systems

Lighting systems are also a part of the building that can yield great savings in consumed energy. Boyano et al. (2013) conducted a case study using the simulation tool EnergyPlus, of a building chosen to be representative of office buildings in Europe. Their findings suggest that by installing lighting controls, European offices could benefit from their energy consumption and energy costs. The study also highlighted that the orientation of a building has a meaningful role in its energy demand. In their conclusion, they acknowledge that one of the main barriers to energy efficiency is a lack of knowledge in understanding what affects energy usage.

Dubois and Blomsterberg (2011) conducted a literature review of energy-efficient measures in lighting systems, primarily in Northern Europe. They presented how the change to T5 from T12 lamps could yield a saving of 40 % in office buildings. Though, T5 and older lamps will be phased out and cease to exist on the market in the second half of 2023. This is due to an EU Restriction of Hazardous Substances Directive (RoHS) to remove lamps containing mercury that is not as energy efficient as required by today's standards (Energimyndigheten, 2022). However, Dubois and Blomsterberg (2011) suggested other strategies for enhanced energy savings, such as using more energy-efficient luminaries, ambient lighting, switches responding to occupancy rate, daylight dimming, and harvesting the daylight. Furthermore, Dubois and Blomsterberg (2011) mentions that human factors and behavior play a vital role in the consumed energy.

According to Energilyftet, a website by the Swedish Energy Agency to raise competence and help professionals in their work towards low-energy buildings, it might not always be economically motivated to change from T5 lamps to LED, as LED lamps are the most expensive on the market (Energilyftet, n.d.).

2.5 Heating, Ventilation, and Air Conditioning

The purpose of the heating, ventilation, and air conditioning (HVAC) system is to maintain good indoor air quality and thermal comfort (Borodinecs et al., 2022). The HVAC system accounts for a large amount of the building's total energy consumption, Boyano et al. (2013) found that the HVAC system accounts for 50 % of the total energy consumption for the average European office. Che et al. (2019) reduced the energy consumption by 50 % and maintained a comfortable indoor climate by installing a BMS system with a two-stage particle filtration system that dehumidifies the outdoor air. The results indicate that applying retrofit measures to the HVAC system can significantly affect a building's final energy consumption.

Abdul Hamid et al. (2020) investigated the effects on energy use and environmental quality by simulating two different non-invasive ventilation retrofits on the HVAC system for two heritage office buildings located in Sweden. The study showed that installing a mechanical ventilation system with heat recovery in the chimney pots could reduce CO_2 concentrations and total energy consumption by 47 %. They also found that installing dampers to reduce the air conditioning and refrigeration during the after-hours could reduce energy use by up to 12 %. Moreover, heat recovery was also studied by Wang et al. (2016) in a Swedish multi-family building by evaluating the influences of two types of low-temperature heating systems combined with a ventilation retrofit. The ventilation heat recovery jointed low-temperature system could save up to 55 % of the final energy. Heat recovery was also examined in a case study by Akgüç and Zerrin Yılmaz (2022), where they investigated the impact of advanced retrofit measures applied to the HVAC system of a high-rise residential building aimed at achieving a cost-optimum energy efficiency level for similar buildings in Turkey. The study concluded that combining a decentralized heat recovery ventilator with a demand-controlled ventilation scheme would decrease the energy consumption of high-rise residential buildings by 39 %.

Li et al. (2020) found that the tenant is a factor that largely contributes to the final energy consumption for manual HVAC systems, as users easily forget to adjust the system according to the buildings' varying occupancy rates. For irregularly used offices, the authors suggest that controlled HVAC systems that use real-time data to consider the CO_2 and temperature are preferable choices. A system that automatically adjusts the ventilation can yield significant energy savings compared to a system with a constant airflow according to a schedule that is turned on or off manually.

The possibilities of introducing modern HVAC systems are sometimes limited. This may apply for buildings that are of high cultural value (Abdul Hamid et al., 2020), or for buildings that are limited from an architectural or space point of view (Shadram et al., 2020; Boverket, 2019). When there are limitations in installing modern HVAC systems, airflow control is of great importance. Reducing the airflow is an easy and effective way of achieving considerable energy savings. This is especially important for building zones with varying occupation rates, for example, meeting rooms (Goodfellow and Wang, 2021). This was also confirmed by Akgüç and Zerrin Yılmaz (2022), which concluded that constant airflows result in considerable energy consumption.

2.6 Economic Frameworks in Existing Studies

The cost of retrofit measures depends on the building's location, size, intervention, the local market and labor cost, etc. (Lee et al., 2019). While deep renovations have been shown to impact buildings' energy performance greatly, it is often an expensive option. Previously mentioned studies have shown retrofits to reduce energy consumption and be cheaper to perform (e.g., Wan et al. (2022); Shadram et al. (2020)).

Different types of economic analyses have been used in the literature. Shadram et al. (2020) looked at the trade-off between reduced operational energy use and embodied (life cycle) energy. Wan et al. (2022) used a combination of net present value (NPV) and payback period to determine the profitability of retrofits. They looked at life cycle costs and life cycle energy savings. Guo et al. (2022) also used NPV and payback period to determine whether insulation is economically viable. Belany et al. (2021) combined energy efficiency and life cycle cost to analyze the total cost of ownership of renovation packages. These consisted of investment, replacement, maintenance, and total energy consumption costs. Gustafsson et al. (2017) also used an NPV and life cycle analysis to examine economically feasible retrofits by examining the environmental impact.

Ho et al. (2021) conducted a systematic literature review to find key performance indicators for evaluating different retrofits economically. One part of their study examined the accuracy of different economic analyses performed in literature, 17 in total, where a focus group was used to rate these. Time-wise, professionals can't adopt all of the economic indicators. These are total investment cost per area (¤/sqm), net present value, and the simple payback period in years. All of these were used by Wan et al. (2022).

3 Research Design

This section declares the methodology used to examine the research topic. It will also include a description of the case study, the building and its location, the adopted retrofit measures, and the economic analysis used.

3.1 Research Approach

The approach used for this study has abductive reasoning. The study uses findings of retrofit measures from other studies to see how they can affect the energy performance in the examined building. Our findings will be used from the energy simulations to draw generalized conclusions about whether these measures help. Technical documentation about the building is limited, and to be able to simulate the energy consumption, assumptions about the components will be made from template data, which is found in abductive reasoning (Säfsten and Gustavsson, 2020).

3.2 Case Study

The study will be a single case study, looking at a building in Malmö, south of Sweden. Case studies are commonly used when examining energy performance and have been adopted for different building types and locations worldwide (e.g., Shadram et al. (2020); Nutkiewicz et al. (2021); Boyano et al. (2013)). A case study is suitable when one wants to investigate a real-life case in-depth, where one could gain valuable information about the case (Yin, 2018). It would allow for examination of the energy performance of a real-life existing building with poor performance and present how, and if possible retrofit combinations could lead to better performance. This is particularly relevant when retrofitting buildings as the EU taxonomy will demand a 30 % increase in energy efficiency for buildings to be considered sustainable (Sweden Green building Council, n.d.b), as stated in section 1.1.

The study uses a specific case to examine the possible options of retrofit measures and their results. Although every building has specific characteristics (Ma et al., 2012), one can generalize from specific cases but should carefully deem the specific case as the only possible option. However, the generalization of a case study is still interesting as it contributes to the accumulation of knowledge gathering and the research in the field (Flyvbjerg, 2006).

A pre-study was conducted to find retrofitting measures previously performed and understand how they could be applicable in this scenario. The case study consists of three phases. In the first phase following the pre-study, information about the building was gathered to understand why the building had a high energy consumption and highlight improvement areas. Due to the absence of building data, template data has been used to make assumptions where site-specific data was missing. In the second phase, energy simulations were executed to examine the efficiency of various combinations of retrofit measures on the building's final energy consumption. Finally, in the third phase, the costs associated with each retrofit combination were evaluated to determine its economic feasibility. During this phase, an in-depth analysis was carried out to identify an optimal retrofit solution based on both economic feasibility and potential energy savings. An overview of the workflow is presented in figure 3.1.

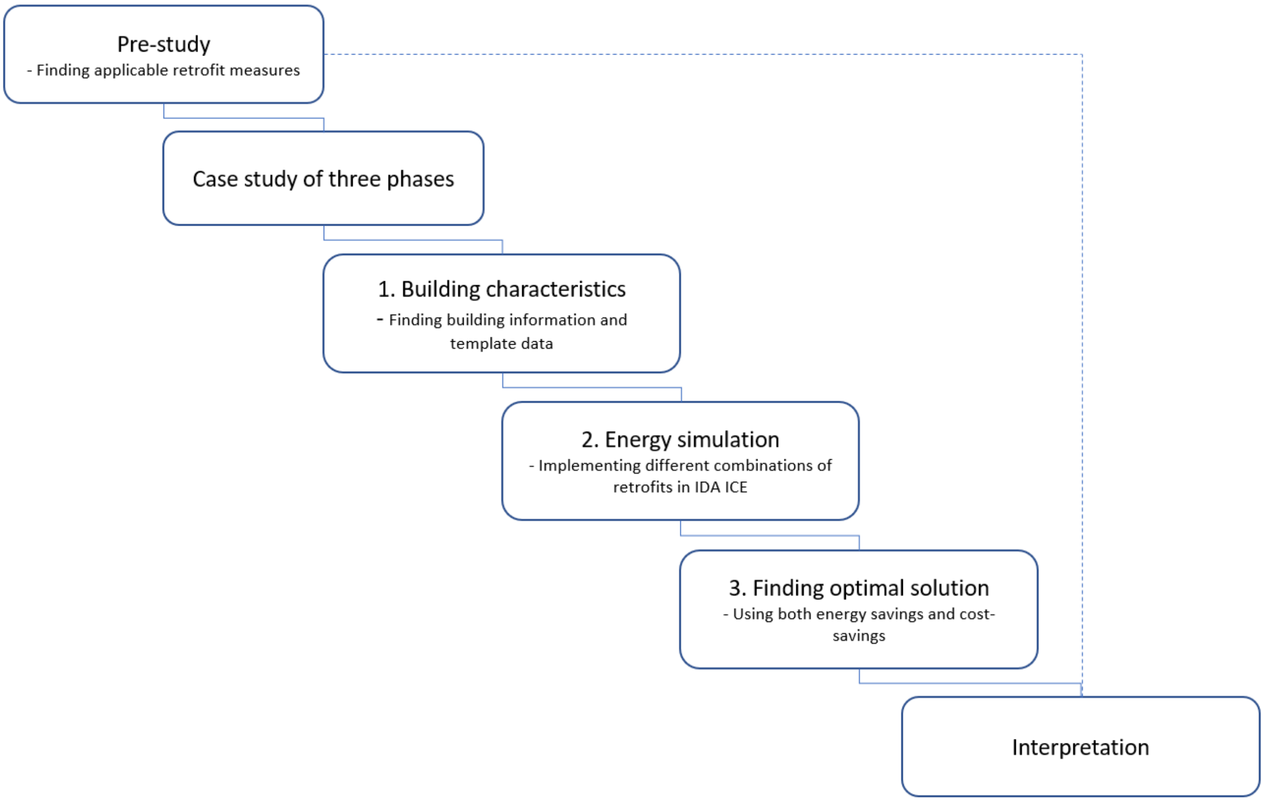


Figure 3.1: The main steps used in this study.

This type of workflow was adopted by Ma et al. (2012), where they in the first phase looked at available resources and mapped problems about the operation of the building. The second phase was an audit phase, where the authors tried to understand energy usage and waste. They also presented non or low-cost actions to reduce energy consumption. In their third phase, they identified possible retrofit options using energy models and economic analysis. In the fourth phase, they implemented and commissioned the chosen retrofit methods, and in the fifth and final phase, they measured and verified the chosen methods. Similarly, Wan et al. (2022) simulates the energy before and after adopted retrofit measures, to examine the change in energy consumption. The workflow of this study is based on the study of Ma et al. (2012), but where it has been adjusted with regard to limited resources in time and availability to the building examined.

When conducting a study, two important areas are validity and reliability to ensure the research quality (Yin, 2018). To ensure (construct) validity, the program used for the energy simulations is well-known and accurate, and the retrofit measures adopted have been used in many previous studies, and have been shown as effective in reducing energy consumption in buildings, see section 2. The employed input data selections in the energy simulation tool can be found in the appendix to ensure reliability. See tables A0.1, A0.4, and A0.5. Moreover, when technical description has not existed, template data were used from a well-known and easily accessible source with industry-standard, from Sveby and an encyclopedia from Repab.

3.3 Data collection

Data employed in this study draw on a combination of existing blueprints, assumptions based on template data, a site visit, and further information provided by the owner verbally or via email. Blueprints were retrieved from the Malmö city archive, as the owner only possessed floor plan blueprints. The building blueprints are limited as no physical copies exist, and only scanned files are available for use. Additionally, the available construction files are incomplete, and a significant proportion of the scanned files are of poor quality and lacking numbering, which impedes navigation through the files. Consequently, the model utilized for the energy simulations must rely on a series of assumptions derived from a combination of existing blueprints that can be interpreted, template values, inquiries directed toward the building's owners, and information obtained from published literature on comparable structures. Despite these challenges, the resulting model represents the best approximation of the building's design and performance characteristics and was developed with careful consideration of the limitations imposed by the available data.

The investment costs of each retrofit action will be collected from the encyclopedia of construction costs Repab (2017), as well as from market retailers such as Bauhaus, Nordiska Fönster, and Menta Fösnter, as they are companies with market prices for the used materials. For each combination, the costs will be summarized, to later be divided by the total heated area of the building.

Energy prices were gathered from Nasdaq OMX Nordic for futures. Historical prices are obtained from Nord Pool Group, which is the leading power market in Europe and that shows day-ahead as well as intraday prices. This is used as it is an easily accessible source.

3.4 Building Characteristics

The property name is Malmö Ritaren 1, and was selected as a convenience sample. The property is closely situated to where this study was written, and the owner, Wihlborgs, was able to help with a floor plan and a few technical questions. Additionally, the building has the characteristics of buildings with high energy consumption, such as the description in section 1.3 Office Market in Sweden. It was constructed in 1967 with an energy class F, and primary energy performance of approximately 250 kWh/m^2 (according to its energy declaration performed in 2019), and due to the energy consumption is expected to have a high maintenance backlog. It is therefore a highly suitable object for this study.

The building is comprised of two distinct sections, which are referred to as Building Part 1 and 2. Part 1 has a rectangular shape with its longer sides oriented north-south. Part 2 was added subsequently in early 1980, connecting to the western side of the southern-facing facade, creating an L-shaped configuration when viewed from above. The building's first section features windows positioned to face in a northerly direction, as illustrated in figure 3.2 below. Correspondingly, the southern-facing facade of the building is similarly outfitted with windows of the same type. Likewise, the second section of the building incorporates windows oriented towards the western side, as depicted in figure 3.3. The opposite facade, which faces east, is also equipped with windows of the same style. A summary of the overall building characteristics is presented in table A0.1, the building's components are further explained in tables A0.1, 3.2, and 3.3.

Table 3.1: Overall building characteristics for the entire building.

Room height	3 m	Number of occupants[2]	1 person / 20 m^2	
Type of use	Office cells	Working hours[2]	08 - 17 weekdays	
Heated area[1]	3,213			
Windows[1]	Window no.	Placement	Thermal conductivity, $\lambda(W/mK)$	Size (width x height cm)
Glass brick	W1	BP1, facing north and south	2.9	70 x 50
Double pane	W2[3]	BP1, facing north and south	2.9	70 x 140
Double pane	W3	BP1, facing west and east	2.9	60 x 280
Double pane	W4	BP2, facing west and east	2.9	40 x 120
Double pane	W5	BP2, towards west and east	2.9	100 x 120
HVAC				
Constant air volume flow (CAV)[4]	1.5 - 2 l/s,m^2			
Mechanical FTX system	Always running			
Heat recovery rate	60 %			
Lightning	W/m^2	Distribution of light sources		
LED	10	80%		
Older, T8[5]	18	20%		

[1]The office space (LOA) is about 80 % of this, around 2,700 m^2. All space is assumed to be heated, and the larger value is used in the analysis when computing the NPV.
[2]Assumption origins from "Brukarindata kontor" Sveby (2013).
[3]No blueprints exist, construction assumptions are based on a similar structure described by Dellgar and Wänglund (1995).
[4]No blueprints exist, construction assumed to be the same as Building Part 1.
[5]There is no information regarding what type of windows, the U-value has been assumed from EKRS (n.d.a).

Table 3.2: Building Part 1 Properties.

Building element	**Thickness (mm)**	**Thermal conductivity (W/mK)**	**U-value (W/m^2K)**
Exterior walls			**0.299**
½ Brick wall	120	0.6	
Air gap	30		
Insulation, Rockwool	100	0.037	
Concrete	150	1.7	
Roof			**0.232**
Flat roof insulation, Rockwool	30	0.037	
Insulation, Rockwool	120	0.037	
Concrete	220	1.7	

Table 3.3: Building Part 2 Properties.

Building element	**Thickness (mm)**	**Thermal conductivity (W/mK)**	U-value (W/m^2K)
Exterior walls			**0.176**
Concrete	80	1.7	
Wall insulation, Rockwool	200	0.037	
Concrete	90	1.7	
Aluminum	15	218	
Roof			**0.131**
Aluminium	5	218	
Wood	23	0.14	
Air gap	20		
Insulation, Rockwool	2x100	0.037	
Flat roof insulation, Rockwool	60	0.037	
Concrete	200	1.7	

Furthermore, the building is relatively highly glazed with a window-to-wall ratio of 27 %. There are no construction documents about what type of windows are used in the building, and neither are there any planning application that indicates that the windows have ever been changed. Therefore, U-values for windows have been assumed to be 2.9, as typical for buildings constructed in the same period (EKRS, n.d.a). In figure 3.2 and 3.3 drawings of the building are presented, together with the different types of windows.

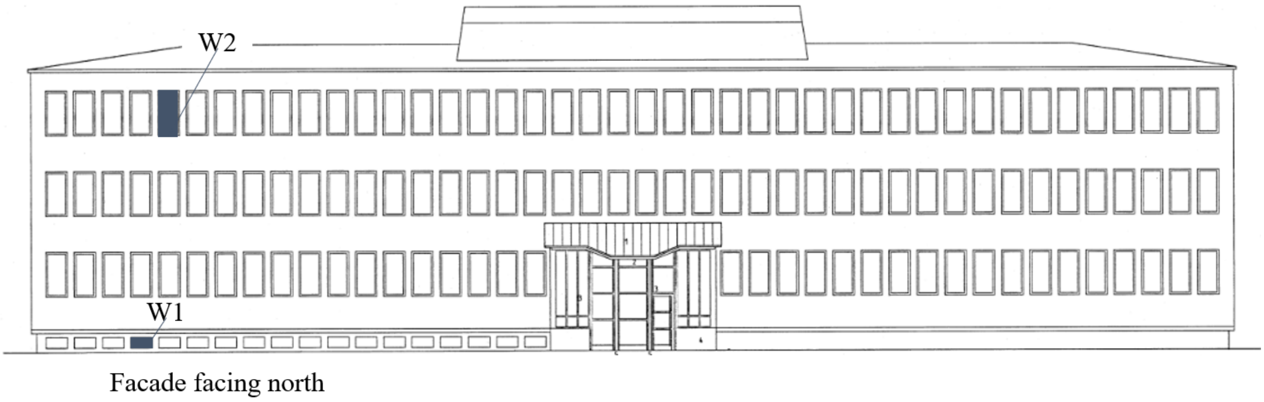


Figure 3.2: Window type W1 and W2, presented on Building Part 1, facing north.

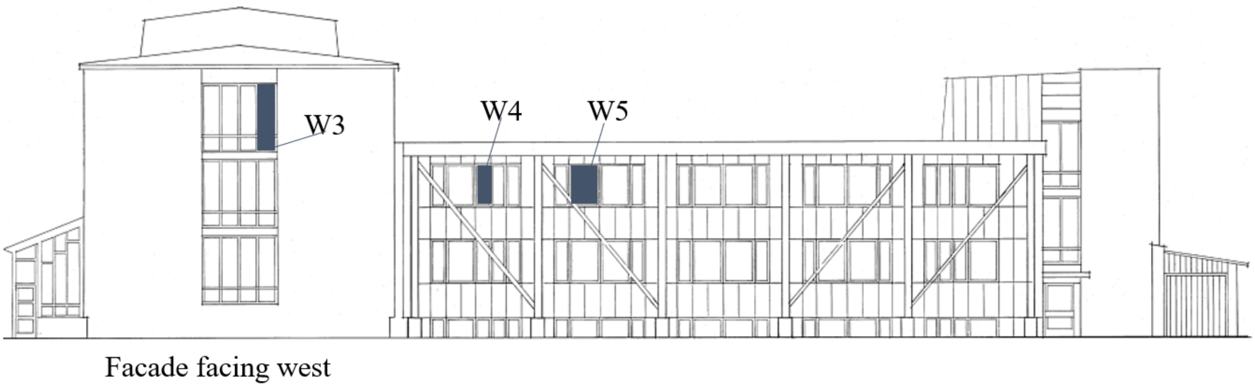


Figure 3.3: Window types W3, W4, W5 and W2, presented on west facing facade of Building Part 1 and 2.

3.5 Combinations of Retrofitting Measures

The quality of elements in building structures deteriorates over time, and correspondingly the preservation of heat does too (Wan et al., 2022). Additionally, older buildings are worse than newer at conserving heat (IEA, 2013), and adopting retrofits aims to enhance the conservation. When buildings are refurbished, the entire potential in energy savings is seldom utilized, and buildings would in general benefit from several retrofit measures (Boverket, 2019). This study will consider nine retrofitting measures relating to insulation, windows, and HVAC.

Retrofit measures were selected based on the findings of the literature review, availability on the market, and with respect to what is feasible from an architectural point of view. As around 35 % of heat loss origins through the exterior walls for various air leaks (El Saied et al., 2022), three retrofitting technologies will be used. The maximal thickness for additional insulation in the exterior wall was limited to 100 mm. As a result, there will be different combinations with different U-values, both above and below the desired limit stated by EKRS (n.d.b), i.e., a U-value of 0.15, and 0.12 in the wall and roof, respectively. Adding insulation to the exterior wall on the outer side would change the facade's appearance. Changes in buildings often require building permits (Planning and Building Act (2010:900)). The permits for changing the facade are assumed to be more time-consuming and costly than for changes to the HVAC system. Because of this, additional insulation will be added to the inner part of the exterior walls to avoid changes to the facade. Although adding insulation on the inner side can cause problems with water vapor condensation (Wan et al., 2022), all additional insulation will be added on this side. Moreover, there will be two options for adding insulation to the roof, where they will be added to the existing insulation. According to the structural drawings, there is an outdoor climate between the roof shell and the insulation and enough space for adding an additional 100 mm of insulation. A graphical representation of the retrofitting measures for both building parts is presented in table 3.4.

Windows in office buildings often have a significant share of the wall, and for the building used in this study, the window-to-wall ratio is 27 %. Poirazis et al. (2008) found this ratio to considerably impact heat loss. In practice, the U-value of 2-pane windows increases when the temperature drops and the wind increases, whereas the change in U-value is marginal for 3-pane windows. This makes them useful for cold and windy climates, such as the Nordics (Strandberg and Lavén, 2018). Two window options will be used, one with three-pane windows with a U-value of 0.9 and the other with double-pane windows with a U-value of 1.1.

Older buildings often have inefficient HVAC systems that run too long and too high or low load. Corresponding for up to 50 % of consumed energy, there is a huge energy efficiency potential (Boyano et al., 2013). From inquiries to the building owner used in this study, it was revealed that the current ventilation had a supply airflow of 2 - 2.5 l/s,m^2, whereas it according to Sveby (2013), can be reduced to 1.5. This study will adopt two options with changes to the HVAC system. The first option applies changes to the current constant air volume system (CAV) by scheduling it according to an occupancy scheme. Furthermore, the airflow is reduced to 1.5 l/s,m^2, and the heat conversion rate increases from 60 to 85 %. For the second option, the CAV system is replaced by a variable air volume system (VAV) with temperature and CO_2 sensors. This is coupled with the same occupancy schedule as option one and changes to the air volume through the controller set points.

The owner has already replaced 80 % of the lamps with LED, and it is assumed that changing the remaining 20 % would not likely be motivated from an energy or cost savings perspective. Hence, no lightning measures will be incorporated into the combinations. Prior to conducting the simulations, each possible combination, excluding the lightning system, was performed to see if it would decrease in the building's final energy consumption, which was the case. In further simulations, only combinations of simulations will be performed to answer the research questions. Furthermore, each retrofit measure will be applied to the entire building, e.g., all of the building's windows will be replaced, or additional insulation of 50 mm will be added to all the exterior walls. However, additional insulation to the roof is only possible in Building Part 1. Adding roof insulation in Building Part 2 would require reconstruction of the roof, which is assumed to have a low likelihood of being cost-efficient with respect to possible energy savings.

From what is stated above, a total of nine retrofit measures have been selected, forming a total of 24 combinations that will be applied (3*2*2*2). These measures are performed through a simulation program, later presented in section 3.6. Each measure is presented in the table 3.4 and each simulation runs for a time frame of 4 - 8 hours.

Table 3.4: Retrofitting measures in both building parts.

Element	Cl[1]	No.	Energy-Saving Technology	Thermal conductivity λ, (W/mK)	U-value (W/m²K)	Thickness (mm)	Cost (SEK/m²)	Deterioration period years[3]
Exterior wall	A	A1	EPS	0.037	0.213	50	58	100
		A2	EPS	0.037	0.165	100	111	100
		A3	PIR	0.022	0.127	100	484	100
Roof	B	B1	EPS	0.037	0.177	50	58	100
		B2	EPS	0.037	0.143	100	111	100
Windows	C	C1	Double pane		1.100		1,839,542 (total)	40
		C2	Three pane		0.900		3,458.092 (total)	40
HVAC	D	D1	Heat recovery of 85 %	Schedule: Heat & fan operator running 07-17, only on weekdays			748,562 (total)	20
		D2	VAV (variable air volume)	1.5[2] l/s,m², only running 07-19 on weekdays			1,086,358 (total)	20

[1]Classification.
[2]Assumed from Sveby (2013).
[3]Rough estimations assumed based on estimations when discussed with a professional (Karlsson, 2023). The deterioration period of option D1 depends on the current quality.

For a more detailed understanding of the costs, see table A0.2 in the appendix.

3.6 Energy Simulation in IDA ICE

The energy simulations were conducted in IDA ICE (version 4.8 (SP2)), an energy simulation program that simulates indoor climate and energy and is widely used. Its accuracy was examined by Mazzeo et al. (2020), which in comparison to two other popular energy simulation programs, EnerygPlus, and TRNSYS, concluded it to be an accurate program. Additionally, it is recommended by Sveby when simulating energy by Sveby (2013).

A challenge when creating a model for energy simulation is finding the correct information about building physics and information about a building. Moreover, constructing a detailed model is not always reasonable as it is time-consuming and might be unnecessary as it will not account for the existence of uncertainties and missing information (Augenbroe, 2019). Since there, in this case, is a lot of lacking information, assumptions of the construction have been made, our model has a simplified geometry, and the results should be interpreted accordingly. The building model is presented in figure 3.4, the data used to create the model is presented in tables A0.1, A0.4, and A0.5, in the appendix.

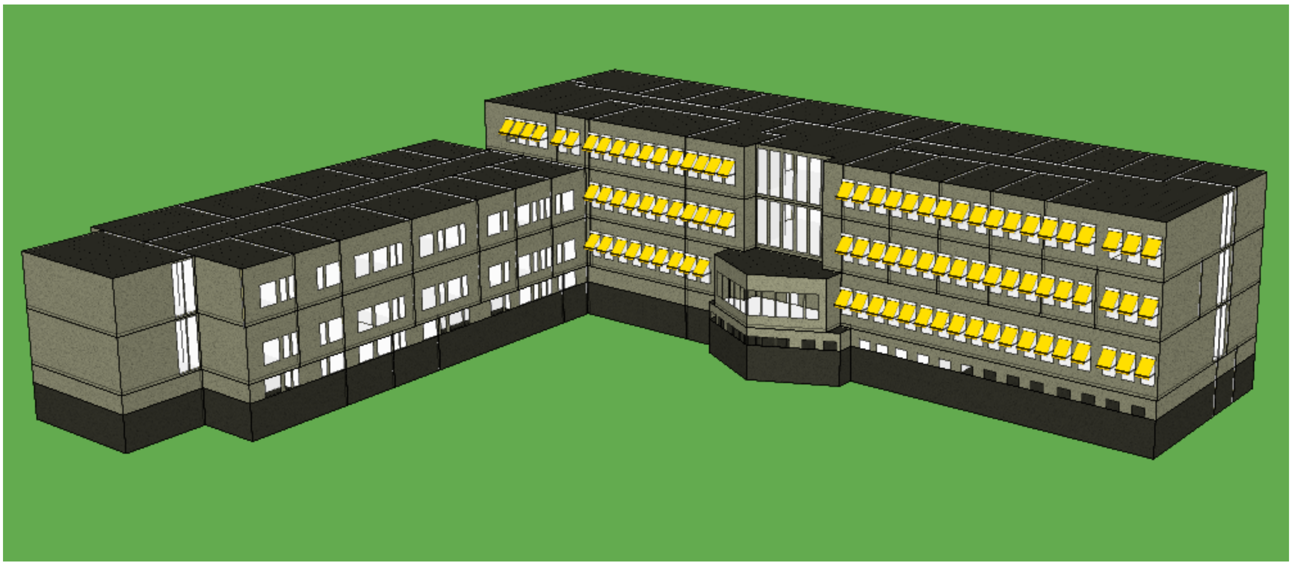


Figure 3.4: IDA-ICE simulation model.

3.7 Primary Energy Factor

The primary energy factor is used to describe a building's energy performance, which is used to classify a building's energy class. This is different from the final energy consumption, in other words, the actual consumption of a building. The primary energy factor (PE) is calculated, see equation 3.1, by summarizing the energy for heating ($E_{heat,i}$), energy for cooling ($E_{cool,i}$), domestic hot water ($E_{dhw,i}$) and operational energy ($E_{op,i}$), where i is the ith simulation. The energy for heating is adjusted with a location factor. The sum is then multiplied with a weighted factor (WF_i) dependent on the type of heating source and then divided by the heated area. The original formula summarizes these variables for different heating sources (Boverket, 2022). The examined building is assumed to only have one type of heating source.

$$PE = \frac{\frac{E_{heat,i}}{F_{geo}} + E_{cool,i} + E_{dhw,i} + E_{op,i}}{A_{temp}} * WF_i \tag{3.1}$$

A benchmark was simulated, from which the energy savings will be calculated in percentage, and gave total energy consumption of 260 kWh/m^2, year. The primary energy was calculated to be 201 kWh/m^2, year. This value differs from the one estimated in the energy declaration performed in 2019, with an energy performance of 252 kWh/m^2, year.

3.8 Economic Framework

To conduct the economic analysis, three main components are required. Firstly, a recognized method for calculating the potential savings is needed. Secondly, energy prices must be established so that the chosen economic methodology can be effectively applied. Finally, it is essential to have accurate information regarding the costs of labor and investment required to perform the necessary retrofits. Ensuring that all three factors are considered makes conducting a comprehensive and accurate economic analysis possible.

3.8.1 Net Present Value and Simple Payback Period

The net present value is a method used to determine whether an investment is economically viable. It is useful when comparing investments with a series of cash flows, as it accounts for the time value of money. One should typically choose the option with the highest NPV. If the value is below zero, it should typically be rejected as the investment has no economic gain. The NPV is defined as the present value of the costs subtracted from the present value of the benefits, and as there is a series of cash flows it can be described by the formula 3.2:

$$NPV = -C_I + \frac{C_0}{1+r} + \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + ... + \frac{C_n}{(1+r)^n} = -C_I + \sum_{i=0}^{n} \frac{C_i}{(1+r)^i} \tag{3.2}$$

Where C_I represents the total investment cost, C_i is the cash flow per year, ranging from year $i = 0$ to year n (Berk and DeMarzo, 2020). The variable n is the time frame for the NPV calculation and will be 10 years in this study. The variable r is the discount rate. Energy investments can be viewed as an upgrade of the property; lowering energy costs should result in a higher net operating income, all else equal. A study by Leskinen et al. (2020) concluded that incorporating the same discount rates used in property valuation is a reliable method for accounting for risks associated with energy investments. In the NPV calculation, a discount rate of 6.5 % will be used, as it is the average rate for offices in the building's area. The rate was obtained from Värderingsdata (2023). In our case, the benefits gained from the investment are the savings in energy costs.

Another method professionals can adopt is a simple payback period. This does not account for the time value of money but is simpler to perform. The investment cost is divided by the annual earnings from energy cost savings, which we describe as energy saving benefits. This way, one can determine how quickly an investment is repaid (Berk and DeMarzo, 2020).

3.8.2 Energy Prices

Various factors play a part in the energy prices, such as a connected energy market and changing weather conditions that lead to drought, storms, and increased demand for fossil fuels. In recent years, the energy market has been volatile, as pictured by record high prices followed by a limited capacity where the supply does not meet the demand. Furthermore, the Russian invasion of Ukraine, its impact on the energy market, and Russia's role as a distributor have enlarged these problems. There is uncertainty about how the market will develop (Svenska Kraftnät, 2023).

Predicting the future price is no easy task. To find a price used in calculating energy savings, in SEK, commodity futures prices are retrieved from Nasdaq OMX for the years 2024 to 2027. These show the system price, and to find the area-specific price EPAD futures are also used. EPAD futures (Electricity Price Area Differential), which show the sum of the system price subtracted from the area price, are used for hedging against price risk. Malmö belongs to the electricity price area SE4, and the area-specific price is obtained from EPAD futures added to future prices.

$$P_{EPAD} + P_{Future} = P_{area\ price} \tag{3.3}$$

In figure 3.5, the historical prices, tracing back to April 2018, are shown together with the prices for year-based futures, as well as the average of these futures, which will be used when calculating the cost savings. The average is 0.8536 SEK / kWh. Historical prices are obtained from Nord Pool (2023), and future prices are obtained from Nasdaq OMX (2023). The currency rate, when converted was 11.31 EUR/SEK, which took place on the date 2023-04-21.

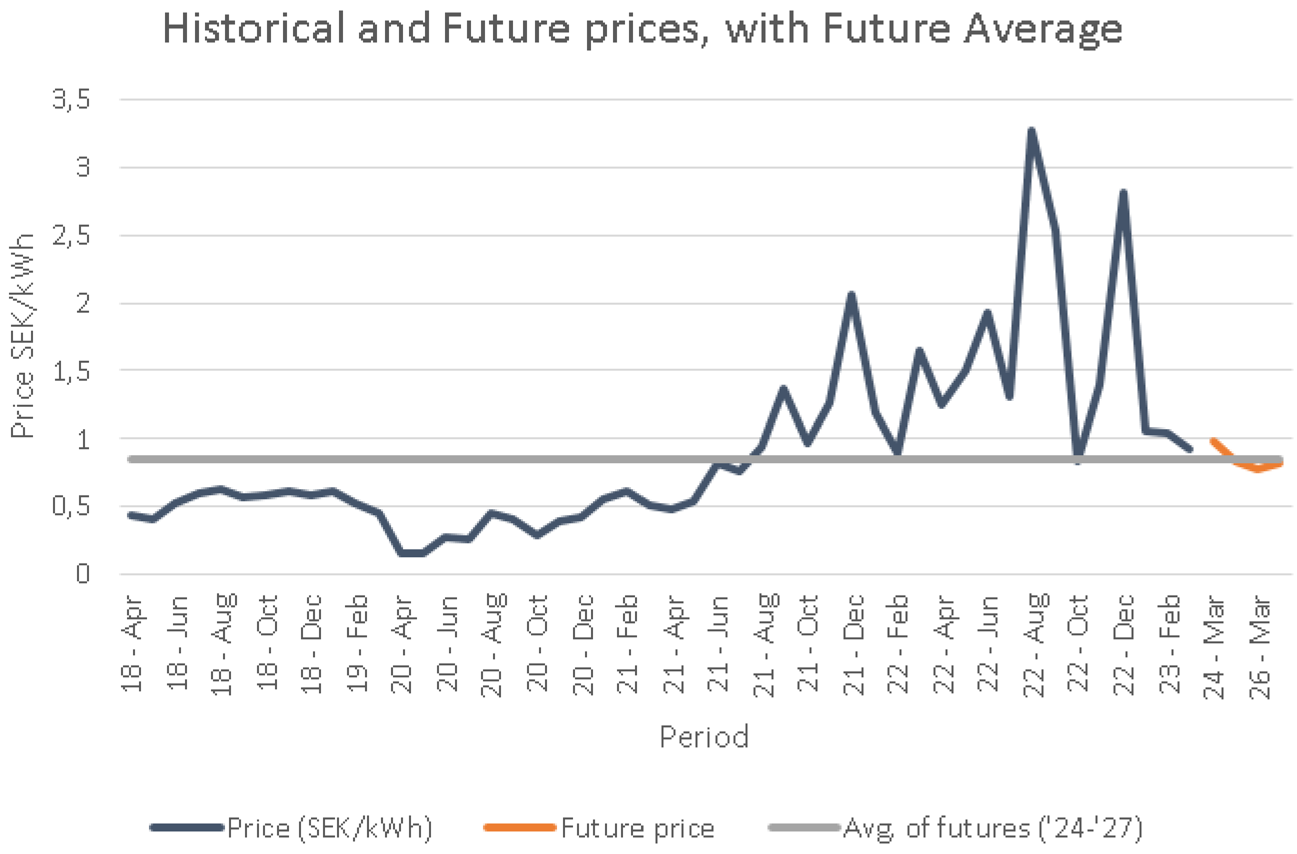


Figure 3.5: Historic energy prices, prices for futures, and the average of these futures are displayed in SEK/kWh. Historic prices from Nord Pool (2023), commodity future prices from Nasdaq OMX (2023).

3.8.3 Energy Saving Benefits

The energy price is used to calculate the NPV and the metric energy saving benefits. The metric combines the economic impact on all retrofit investments and is a metric that was used in the study by Wan et al. (2022). It is calculated according to formula 3.4:

$$ESB_{yr,i} = (E_{yr,base} - E_{yr,i}) \times C_{kWh/m^2,yr} \times A_{total}, \tag{3.4}$$

where the $ESB_{yr,i}$ is the energy saving benefits, $E_{yr,base}$ is the energy consumption per year in the benchmark case, $E_{yr,i}$ is the yearly energy consumption for the i-th simulation, $C_{kWh/m^2,yr}$ is the cost of energy. It is described in section 3.8.2, and A_{total} is the total heated area.

3.8.4 Multiobjective Optimization

Multiobjective optimization is employed in the process of decision-making when the goal is to optimize two or more objectives concurrently. The objects are often in conflict, where none of the objectives can improve, without the other being worse off (Chang, 2015).

For this study, the optimization is calculated with respect to energy saving rate and NPV. The energy saving rate is calculated as the result of the simulation, divided by the benchmark case; the quota is then subtracted from 1. This approach, utilized by Wan et al. (2022), aids readers in interpreting the findings. Using the energy saving rate instead of absolute values effectively demonstrates the magnitude of the impact and assists readers with limited knowledge of energy consumption in office buildings. The benchmark case represents the current energy consumption, where the building energy is simulated using the existing building components outlined in tables A0.1, 3.2, and 3.3.

While acknowledging the inherent relationship between energy savings and NPV. The latter is dependent on two factors: initial cost and energy cost savings, where a higher investment cost does not necessarily result in better technology and higher energy savings. Optimizing both these objectives provides a comprehensive understanding of the synergies between the trade-offs and strengthens the decision-making process. The same kind of optimization was used by Fan and Xia (2017), who employed the weighted sum method of the object's energy savings, net present value derived from the energy savings, and the payback period of investments to find the scalar maximum.

When optimizing to find a scalar maximum, the NPV must be transformed since the two objects have different magnitudes of units and scales. This issue is addressed by using a technique called Min-Max normalization, where the minimum value of an array is deducted from the i-th value and then divided by the difference between the maximum and minimum value of the array, as described in the formula 3.5:

$$x_{norm} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{3.5}$$

where x_{norm} is the normalized value, x_i is the i-th value, and x_{min} and x_{max} is the minimum and maximum of the array (Loukas, 2020).

In this study, the Weighted-Sum Method will be used, where the two objectives are combined to a single-objective scalar function, as defined in the formula 3.6

$$\max_{x \in S} u(x) = \sum_{i=1}^{q} w_i f_i(x), \tag{3.6}$$

where $u(x)$ is the unique objective function set to be maximized. The $f_i(x)$ refers to the ith objective function considered in the optimization. The optimization aims to find the value of x that maximizes both objective functions. The set of possible values of x is denoted by S. The weights w_i represent how the decision maker prioritizes the two objectives so that $\sum_{i=1}^{q} w_i = 1$, and $w_i \geq 0\forall$ (Chang, 2015).

4 Analysis

In the following section, the results from the energy simulations will be presented. To facilitate the interpretation and provide a deeper understanding, several figures and tables are presented. The analysis highlights key results and explains the potential factors contributing to them. A thorough walk-through of the total energy savings and energy savings rate will be presented for each retrofit combination, along with their NPV and payback period respectively. Finally, an optimal combination is identified.

The final energy consumption for each retrofit combination is presented in figure 4.1, where the final energy consumption ranges from 92.87 to 52.94 kWh/m^2. They are further elaborated in table 4.1, where each combination and its retrofit measures, energy consumption, energy saving rate, and primary energy are presented.

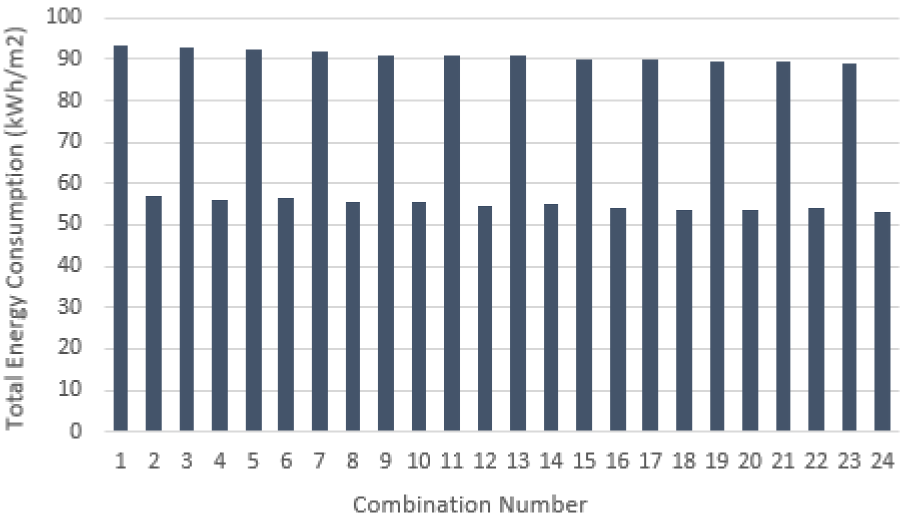


Figure 4.1: Total Energy consumption after each energy-efficient retrofit.

To provide a reminder of the construction of the combinations in table 4.1, the classification numbers presented in table3.4 are used again. In this classification, A represents insulation in exterior walls, B represents insulation in the roof, C represents windows, and D represents the HVAC system. The numbering follows an ascending order, where A1 represents the lowest additional wall insulation of 50 mm EPS, and A3 represents the highest option of 100 mm PIR. Specifically, A1 refers to 50 mm EPS added to the exterior wall, A2 represents 100 mm EPS, and A3 represents 100 mm PIR. Similarly, B1 represents 50 mm insulation added to the roof, and B2 represents 100 mm EPS. C1 represents the lowest upgrade option for windows, which involves double-paned windows with a 1.1 U-value, while C2 represents the best upgrade option with three-pane windows and a 0.9 U-value. Lastly, D1 represents a scheduled constant airflow volume system with 85 % heat recovery, while D2 represents a scheduled variable airflow system equipped with sensors to measure indoor CO_2 levels and temperature.

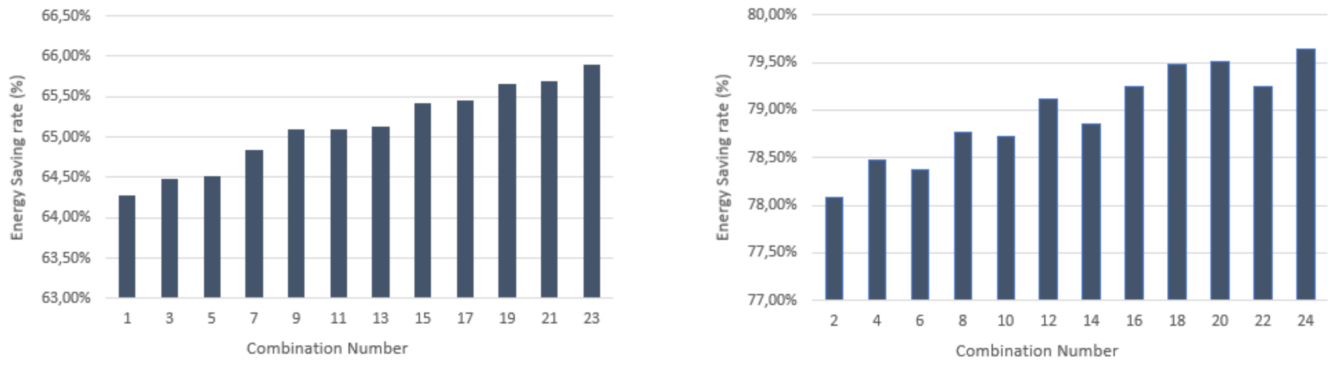
Table 4.1: Retrofit combinations. See table 3.4, for explanation of each measure.

C.No.[1]	E.W.[2]	R.[3]	W.[4]	HVAC	Total Energy Consumption, kWh/m^2	Energy Saving Rate, %	Primary Energy kWh/m^2
1	A1	B1	C1	D1	92.87	64.28	72.73
2	A1	B1	C1	D2	57.00	78.08	46.70
3	A1	B1	C2	D1	92.36	64.48	72.28
4	A1	B1	C2	D2	55.97	78.47	45.89
5	A1	B2	C1	D1	92.27	64.51	72.20
6	A1	B2	C1	D2	56.25	78.37	46.03
7	A1	B2	C2	D1	91.42	64.84	71.46
8	A1	B2	C2	D2	55.22	78.76	45.21
9	A2	B1	C1	D1	90.75	65.10	70.88
10	A2	B1	C1	D2	55.34	78.72	45.21
11	A2	B1	C2	D1	90.75	65.10	70.88
12	A2	B1	C2	D2	54.31	79.11	44.39
13	A2	B2	C1	D1	90.67	65.13	70.81
14	A2	B2	C1	D2	54.99	78.85	44.89
15	A2	B2	C2	D1	89.91	65.42	70.14
16	A2	B2	C2	D2	53.97	79.24	44.07
17	A3	B1	C1	D1	89.82	65.45	70.05
18	A3	B1	C1	D2	53.34	79.48	43.48
19	A3	B1	C2	D1	89.28	65.66	69.59
20	A3	B1	C2	D2	53.29	79.50	43.45
21	A3	B2	C1	D1	89.22	65.68	69.53
22	A3	B2	C1	D2	53.97	79.24	43.96
23	A3	B2	C2	D1	88.68	65.89	69.05
24	A3	B2	C2	D2	52.94	79.64	43.14

[1]Combination number. [2]Exterior wall. [3]Roof. [4]Windows.

From table 4.1 and from the alternating pattern in figure 4.1, it is possible to distinguish a higher energy consumption for retrofit combinations that include the HVAC option D1, i.e., a scheduled CAV-system with increased heat recovery, as well as reduced air flows. Simultaneously, the HVAC option D2, an occupancy-based VAV system with CO_2 and temperature sensors, yields a lower energy consumption. Each energy simulation with its in-going retrofit measures is presented in table A0.3 in the appendix to give further insights into how the delivered energy is distributed for each retrofit combination. The primary energy ranges between 43.14 and 72.73, meaning that some of the simulations achieve an energy class B status. In contrast, others achieve a C or D status, as presented in section 1.3.

To facilitate the interpretation of figure 4.1, the table has been split into two separate ones to highlight the energy-saving rate for each of the two HVAC system measures. Note the difference in the y-axes.



(a) Energy saving rate for each combination including D1, a CAV-System.

(b) Energy saving rate for each combination including D2, a VAV-System.

Figure 4.2: Energy Saving Rate for both HVAC measurements.

By examining the results in table 4.1 and figure 4.2, it is noticeable that the HVAC system alone greatly impacts the consumed energy. Since the only thing that differs between the two figures is the HVAC system, it can be concluded that the other measures, such as replacing the windows and adding additional insulation to the roof and exterior walls, have a marginal impact on the final energy consumption and energy saving rate. For example, comparing measures C.No.14 and C.No.16, where the only modification implemented is the replacement of windows while all other measures are kept constant, it is apparent that upgrades to window glazing yield a modest but discernible effect. Similarly, increasing insulation thickness in the roof and external walls (as seen in comparisons between measures C.No.1 to C.No.5, C.No.1 to C.No.9, C.No.9 to C.No.17, C.No.1 to C.No.17) results in lower energy consumption, albeit to a small degree (ranging from 92.27 to 89.82 kWh/m^2). It is also apparent that the retrofit combination with the lowest energy consumption and highest energy saving rate is C.No.24, with 52.92 kWh/m^2 and 79.64 %, respectively.

The costs of each combination are introduced in table 4.2, which presents each combination, together with its yearly energy-saving benefits, and total retrofit costs. Additionally, the NPV and payback period are calculated for each combination of retrofit measures to measure its economic efficiency. Note that the NPV is sensible and highly dependent on the discount rate and energy price; a higher discount rate or a lower energy price would yield fewer combinations with a positive NPV. Investment costs have been collected from an encyclopedia with estimated maintenance property cost (Repab, 2017). The costs are based on the average costs of 2017 and have been indexed with a construction cost index retrieved from (Statistics Sweden, n.d.) (Central Bureau of Statistics), which is estimated to have increased by 28 % between 2017 and 2022. See the appendix for a detailed cost calculation A0.2.

Estimating the number of components that require replacement in an HVAC system can be challenging, especially when there is a lack of sufficient information about the system. Based on inputs from Karlsson (2023), a professional in the real estate sector, it appears that the project planning phase typically involves rough estimates. The inspection of the system often highlights which components that require replacement. Changing the entire system is not always necessary (personal communication, April 24, 2023). To determine the retrofitting costs for the two HVAC system options examined in this study, the entire fan assembly is replaced to account for potential increased expenses.

Table 4.2: Each combination with the energy savings, total cost of the retrofit investment, and the NPV after ten years and each payback period.

C.No.[1]	E.W.[2]	R.[3]	W.[4]	HVAC	Energy Saving Benefits, SEK/yr	Total Retrofit Cost, SEK	NPV, SEK	Payback Period, years
1	A1	B1	C1	D1	492,880	3,084,999	458,235	6.3
2	A1	B1	C1	D2	598,664	3,422,796	880,899	5.7
3	A1	B1	C2	D1	494,384	4,703,550	-1,149,504	9.5
4	A1	B1	C2	D2	601,702	5,041,346	-715,815	8.4
5	A1	B2	C1	D1	494,650	3,113,721	442,233	6.3
6	A1	B2	C1	D2	600,876	3,451,517	868,078	5.7
7	A1	B2	C2	D1	497,157	4,732,271	-1,158,297	9.5
8	A1	B2	C2	D2	603,913	5,070,068	-728,637	8.4
9	A2	B1	C1	D1	499,132	3,141,320	446,859	6.3
10	A2	B1	C1	D2	603,560	3,479,116	859,771	5.8
11	A2	B1	C2	D1	499,132	4,759,871	-1,171,692	9.5
12	A2	B1	C2	D2	606,597	5,097,667	-736,943	8.4
13	A2	B2	C1	D1	499,368	3,170,041	419,833	6.3
14	A2	B2	C1	D2	604,592	3,507,838	838,470	5.8
15	A2	B2	C2	D1	501,610	4,788,592	-1,182,605	9.5
16	A2	B2	C2	D2	607,600	5,126,389	-758,457	8.4
17	A3	B1	C1	D1	501,875	3,537,282	70,613	7.0
18	A3	B1	C1	D2	609,458	3,875,079	506,209	6.4
19	A3	B1	C2	D1	503,468	5,155,833	-1,536,490	10.2
20	A3	B1	C2	D2	609,605	5,493,630	-1,111,281	9.0
21	A3	B2	C1	D1	503,645	3,566,004	54,612	7.1
22	A3	B2	C1	D2	607,600	3,903,800	464,131	6.4
23	A3	B2	C2	D1	505,237	5,184,555	-1,552,491	10.3
24	A3	B2	C2	D2	610,637	5,522,351	-1,133,016	9.0

[1]Combination number. [2]Exterior wall. [3]Roof. [4]Windows.

By examining table 4.2 it is clear that all retrofit combinations with the window retrofit measure C2 have a negative NPV (C.No.3, 4, 7, 8, 11, 12, 15, 16, 19, 20, 23 and 24). This is due to the high costs related to changing to three-pane windows and the many replaced windows. See table A0.2 in the appendix.

The effects of increased insulation thickness on the roof and walls indicate that changes in the insulation thickness of 50 mm EPS to 100 mm EPS (C.No.1 to C.No.5 for the roof and C.No.1 to C.No.9 for the external wall) result in small differences in NPV, specifically 11,376 SEK and 16,001 SEK. All of these three combinations have a payback period of 6.3 years. However, when comparing the effects of different insulation materials on the external walls, the differences are more pronounced; 4 combinations with the PIR material have a positive NPV (C.no. 17, 18, 21, and 22). For instance, when comparing C.No.9 and C.No.17, where the only difference is 100 mm EPS compared to 100 mm PIR, the NPV difference is 376,246 SEK and a longer payback period, 7.0 years for PIR, compared to 6.3 years for EPS.

Additionally, the difference between the two HVAC systems yields significant differences in yearly energy-saving benefits, dramatically impacting the NPV. By comparing C.No. 1 and C.No. 2, where the only retrofit implementation is the HVAC system change, the NPV difference equals 422,664 SEK. However, both combinations yield a positive NPV. Another noticeable observation that can be distinguished between the combinations with different HVAC systems is that increased investment costs only yield a marginal impact on the final energy consumption. As investment costs rise, energy consumption still approaches a limit without surpassing it; see figure 4.3.

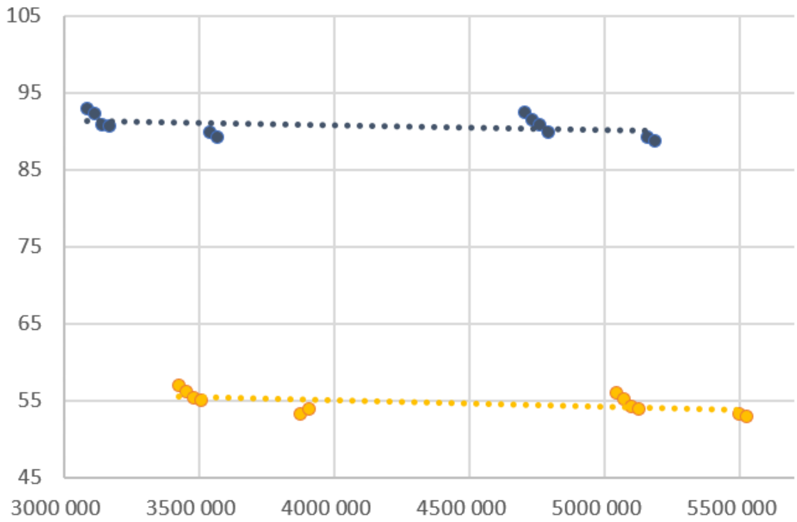


Figure 4.3: Greater investment costs only give marginal savings in energy consumption. The HVAC option D1 with a CAV system is presented in navy, and option D2 with a VAV system is presented in orange, both together with a trendline.

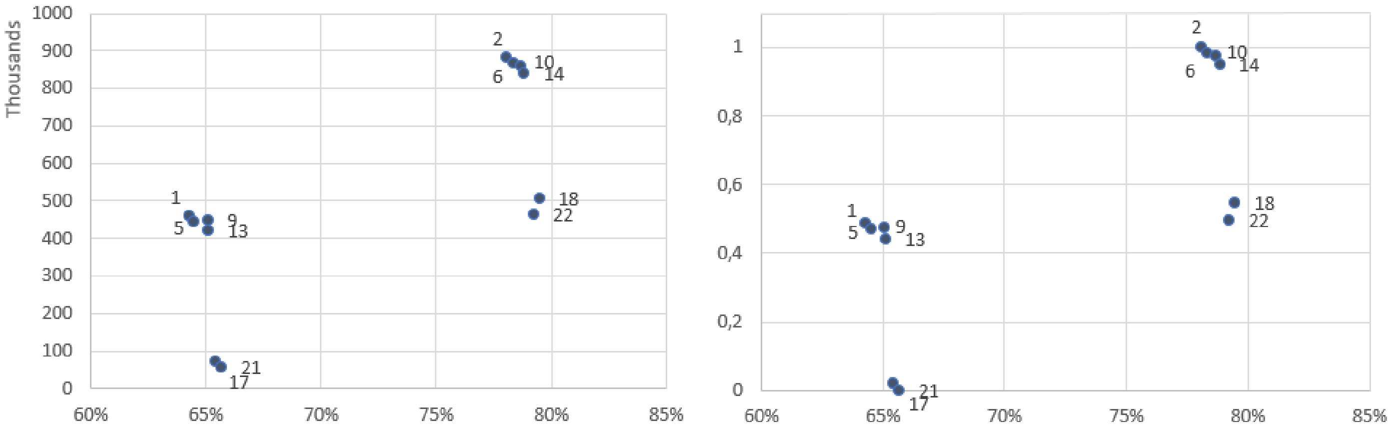
Table 4.2 displays that the combinations with the highest NPV are C.No. 2, 6, 10, and 14 range from 838,470 to 880,899. Even though table 4.1 shows that combinations 12, 16, 18, 20, 22, and 24 had the highest energy saving rate, ranging from 79.11 to 79.64%, not all of them resulted in a positive NPV. Combinations 12, 16, 20, and 24 resulted in a negative NPV. To show the retrofit combinations with a positive NPV, table 4.3 displays a filtered version of 4.2 that includes their corresponding energy consumption and energy saving rate.

Table 4.3: Filtered and extended version of table 4.2.

C.No.[1]	E.W.[2]	R.[3]	W.[4]	HVAC	Energy Saving Benefits, SEK/yr	Total Retrofit Cost, SEK	NPV, SEK	Payback Period, years	Total Energy Consumption ,kWh/m^2	Energy Saving Rate, %
1	A1	B1	C1	D1	492,880	3,084,999	458,235	6.3	92.87	64.28
2	A1	B1	C1	D2	598,664	3,422,796	880,899	5.7	57.00	78.08
5	A1	B2	C1	D1	494,650	3,113,721	442,233	6.3	92.27	64.51
6	A1	B2	C1	D2	600,876	3,451,517	868,078	5.7	56.25	78.37
9	A2	B1	C1	D1	499,132	3,141,320	446,859	6.3	90.75	65.10
10	A2	B1	C1	D2	603,560	3,479,116	859,771	5.8	55.34	78.72
13	A2	B2	C1	D1	499,368	3,170,041	419,833	6.3	90.67	65.13
14	A2	B2	C1	D2	604,592	3,507,838	838,470	5.8	54.99	78.85
17	A3	B1	C1	D1	501,875	3,537,282	70,613	7.0	89.82	65.45
18	A3	B1	C1	D2	609,458	3,875,079	506,209	6.4	53.34	79.48
21	A3	B2	C1	D1	503,645	3,566,004	54,612	7.1	89.22	65.68
22	A3	B2	C1	D2	607,600	3,903,800	464,131	6.4	53.97	79.24

[1]Combination number. [2]Exterior wall. [3]Roof. [4]Windows.

Figure 4.4 displays the combinations with a positive NPV, plotted against their corresponding energy-saving rate. As the two objectives have different scales and units, the NPV is normalized to range from 0 to 1. Although the normalization, the ratio between each point is indifferent.



(a) NPV plotted against Energy Saving Rate, for combinations with positive NPV.

(b) Normalized NPV plotted vs. Energy Saving Rate.

Figure 4.4: Combinations with positive NPV values plotted against the energy saving rates.

The optimal solution depends on the decision maker's view of what is most important. To present the sensitivity, different weights display the priorities of the two optimized objects, Energy Saving Rate and NPV. These are presented in table 4.4.

Table 4.4: Weighted sums of the two objectives, after the NPV has been normalized.

ESR[1]/NPV	0/100	25/75	50/50	75/25	80/20	85/15	90/10	95/5	100/0
C.no. 1	0.4885	0.5271	0.5656	0.6042	0.6119	0.6197	0.6274	0.6351	0.6428
C.no. 2	**1.0000**	**0.9452**	**0.8904**	**0.8356**	**0.8246**	0.8137	0.8027	0.7917	0.7808
C.no. 5	0.4691	0.5131	0.5571	0.6011	0.6099	0.6187	0.6275	0.6363	0.6451
C.no. 6	0.9845	0.9343	0.8841	0.8339	0.8238	0.8138	0.8037	0.7937	0.7837
C.no. 9	0.4747	0.5188	0.5628	0.6069	0.6157	0.6245	0.6333	0.6421	0.6510
C.no. 10	0.9744	0.9276	0.8808	0.8340	0.8246	**0.8152**	**0.8059**	0.7965	0.7872
C.no. 13	0.4420	0.4943	0.5466	0.5990	0.6094	0.6199	0.6303	0.6408	0.6513
C.no. 14	0.9487	0.9086	0.8686	0.8285	0.8205	0.8125	0.8045	**0.7965**	0.7885
C.no. 17	0.0194	0.1782	0.3370	0.4957	0.5275	0.5593	0.5910	0.6228	0.6545
C.no. 18	0.5465	0.6086	0.6707	0.7328	0.7452	0.7576	0.7700	0.7824	**0.7948**
C.no. 21	0.0000	0.1642	0.3284	0.4926	0.5255	0.5583	0.5912	0.6240	0.6568
C.no. 22	0.4956	0.5698	0.6440	0.7182	0.7331	0.7479	0.7627	0.7776	0.7924

[1]Energy Saving Rate.

The table above shows the optimal solutions for different weights in the weighted sum approach. It is divided into 9 prioritization intervals, 0/100, 25/75, 50/50, 75/25, 80/20, 85/15, 90/10, 95/5, and 100/0. For example, 25/75 implies that the decision maker has a prioritization preference of 25 % Energy Saving Rate and 75 % NPV. After the weights 75 / 25, smaller intervals were added to examine a tipping point, where weights with higher prioritized ESR changes the optimal solution. In the table, four potential combinations are presented: combinations 2, 10, 14, and 18.

Among the twelve retrofit combinations exhibiting a positive net present value (NPV), it becomes evident that Combination No. 2 emerges as the dominant choice in the majority of cases, except when a high ESR significantly influences the decision-makers prioritization. While the optimal combination may shift at weightings such as 85/15 or approaching 100/0, Combination No. 2 is considered optimal due to its ability to yield the highest scalar maximum in most instances. The combination has an NPV of 880,899 and a payback period of 5.7. Table 4.5 provides a detailed overview of the combination's components.

Table 4.5: The optimal solution, combination 2.

Combination	Exterior Wall	Roof	Windows	HVAC
2	A1	B1	C1	D2
	50 mm EPS	50 mm EPS	Two-pane , 1.1 U-value	Temp. and CO_2 VAV system

To align with the requirements set by the EU taxonomy, a building must have an energy consumption of less or equal to 80 kWh/m^2. Most simulated combinations yielded energy consumption levels that comply with this criteria. The combinations that exceeded the limit did so by a margin of up to 4 kWh/m2. According to the Swedish building standards, energy class B can be achieved by utilizing the optimal combination C.No. 2, which have a primary energy rate of 46.70 kWh/m^2.

5 Discussion

The analysis highlights that a positive NPV is achievable while decreasing energy consumption significantly. Based on the simulations, twelve out of the twenty-four simulations achieved a positive NPV while achieving energy saving rates ranging from 64.28 to 79.64 %, and NPVs ranging from 54,614 up to 880,899 SEK. In absolute measures, this corresponds to energy consumption levels ranging from 53.97 to 92.87 kWh/m^2. Half of the simulations easily fulfill the energy consumption requirement of 89 kWh/m^2, set by the EU taxonomy for office buildings, while the other half clusters around this value.

Furthermore, figure 4.3 indicates that increasing investment costs only lead to marginal improvements, if any. Major differences could be seen when comparing simulations with the two different HVAC systems, implying this is a dominant factor in energy consumption. Since all simulations are implemented as retrofit packages with several types of single retrofit measures, one cannot certainly exclude the effects of single measures. However, it is evident that single-measure retrofits only result in marginal improvements in the final consumption, all else equal. This was confirmed in section 5. For example, when comparing simulation combinations 1 and 17, where 100 mm additional PIR was compared to 50 mm additional EPS to the exterior wall, and other measures being constant, this resulted in a marginal improvement in energy consumption of 3.05 (92.87 compared to 89.82) kWh/m^2. Simultaneously, the investment cost of the PIR material was more than double that of the 50 mm EPS; see table A0.2 in the appendix. If we instead compare combinations 9 and 17, where the only difference is PIR or EPS, the difference in consumption is only 0.93 kWh/m^2 (90.75 compared to 89.82). For this comparison, the investment cost is also doubled for the PIR case. The additional 50 mm and PIR material are unlikely to be justified. The effects of additional insulation are greatly affected by the walls' current U-value. Similar results were found when comparing the two window types. However, the U-value between these differed with 0.2 W/m^{2}K and was therefore expected not to have a significant influence.

Despite the considerable energy savings achieved through all simulations, potential risks still exist due to the stringency of the EU taxonomy requirements and the level of building compliance with them. The primary energy rate of each simulation ranged from 43.14 to 72.73 kWh/m^2, which falls within the range for the energy classes B, C, and D. To achieve class B status, a building must meet between 50 % to 75 % of the requirements for a new building, which were stipulated as 70 kWh/m^2 in section 1.3. For a Swedish context, it is interesting to consider the potential implementation of regulations that can dictate which buildings will be eligible for letting, such as the case in the Netherlands, introduced in section 1.1. A building prohibited from being let would imply that it is solely a liability since it is not generating any cash flows, implying that its theoretical value would be negative.

It is worth questioning whether the NPV should be the dominant measure to evaluate green investments. There is an inherent relationship between energy savings and cost savings which contribute to higher NPVs. Finding an optimal solution by minimizing the investment cost would only account for the value of money when the investment is being executed, and it is common for investments to be evaluated with respect to their yielding returns. Together with the findings in figure 4.3, one can see that higher investment costs would not necessarily lead to greater energy savings. Furthermore, one could equate green investments with a green premium to ensure future cash flows; not carrying out the retrofits could, inversely, be a brown penalty.

Additionally, it is interesting to consider who benefits from implementing retrofits. The reduction in primary energy consumption benefits the property owner as it can increase the energy class. In contrast, the decrease in overall consumption benefits the tenant, particularly in the case of cold rent. In any case, there are incentives to implement these measures.

Another interesting aspect regarding the EU taxonomy is whether it is strict enough. Based on the simulations, it is clear that it is possible to implement measures yielding consumption levels way below the requirements set by the taxonomy. While the EU taxonomy does not impose penalties, it is reasonable to believe that businesses can be penalized for not complying with broader sustainable frameworks defied by the taxonomy. For example, investors could experience difficulties raising financial aid as institutions tighten their green initiatives.

From another point of view, where the requirements for the energy classes would be stricter, one can raise the question of how low of a consumption one can achieve and to what cost. We found two limits towards which the energy consumption converges as we increase the investment costs. This is displayed in figure 4.3 in the analysis, which shows the two limits for the two different HVAC options. This observation supports the notion that an optimal choice exists, strengthening this study's relevancy.

One optimal combination was identified from those with a positive net present value while looking at the weighted sum of the energy saving rate and net present value. Interestingly, combination 2 had the smallest upgrades, except for the HVAC system, including 50 mm EPS in walls and roof, double pane windows with 1.1 U-value, and a temperature and CO_2 controlled VAV system. The payback period is short.

All combinations with retrofit measures implemented to the existing building would result in energy classes ranging from D-B. Where the optimal combinations 2 and 18 both result in energy class B. Furthermore, one of Sweden's goals is to decrease the share of buildings with energy classes F-G, which is currently a large share of the stock. Since a limit on how low the energy consumption could reach was observed, a question arises about what will happen when these buildings undergo retrofitting. It is reasonable to assume that improving the energy efficiency of buildings with energy classes C and D will be more challenging and costly in the future. Therefore, investigating this matter proactively before it becomes a problem would be relevant for future research.

5.1 Evaluation of study

This study intended to examine a number of combinations of retrofitting measures and find the optimal combination with respect to the highest possible energy savings and minimized cost of the combination. However, the approach is not that of a life cycle assessment (LCA); operational and embodied carbon is not considered. If an LCA approach had been used, it is uncertain whether it would be worth changing all building components. While the added insulation saves leaking energy, the insulation might not be justified from an LCA perspective as the production leads to carbon emissions. The study instead focuses on energy efficiency for the in-use phase. The combinations are implemented in a simulation program utilizing data related to a single case study of a single building. The different combinations are not evaluated after being implemented in practice. Instead, the study aims to examine possible and optimal outcomes. The data combines case-specific and generalized assumptions that could limit the model's accuracy for a single case. It is still believed to represent a building of similar building types.

The approach used in this study has been homogeneous in terms of adopting retrofit measures, where all of these were implemented on both building parts, which might not be feasible in reality due to architectural limitations. Several physical issues, such as moisture and water vapor condensation problems, might arise from adding insulation to the internal part of the exterior wall. The model does not account for this. Neither does it account for different U-values of the window frames that would likely be changed with new windows. The model assumes that the building has a uniform construction, with separation of the two building parts, which in reality has different constructions of floors and walls towards the ground.

There was found to be a threshold where the effects of additional insulation did not lead to significant savings. In a future study, one could examine energy consumption where the insulation level is adjusted with respect to the U-value of walls and roofs. The insulation thickness could be adjusted to align with the limits outlined in section 2.3. Moreover, it might not be reasonable to change all of the windows if those of Building Part 2, the newer part, have lower thermal conductivity. However, simplified models are often used when conducting energy simulations, as they only account for the building elements with great impact on the building's energy consumption, i.e., building envelope, heating source, and HVAC system.

When creating the energy simulation and the building model, there was a scarcity of information about the building. The existing blueprints are of poor quality and difficult to read. It would require more resources in terms of time and professional knowledge about certain building parts to better understand how the building is constructed. Accordingly, assumptions from template data have been made. These template data origins for office buildings in general, and it is worth considering the possibility that the examined building would benefit from using different data. However, the same issue with lack of information could be a frequent problem when working with retrofitting buildings. Although the precision of energy simulations is only as accurate as the assumptions, it still provides a valuable tool for evaluating the energy performance of buildings. The building data combines to a representative building with this age and type, particularly since generic template data was used in the assumptions. With the above mentioned, the authors deem the methodology appropriate for the stated research questions.

Before the examined measures are implemented, a professional's opinion in each retrofitting field should be consolidated to better understand problems that might occur and savings that can be made. However, this study is interesting and shows significance as it presents great potential in reducing energy consumption, reaching the goals of the EU taxonomy, and saving costs from these. This study examined and found it is possible to make buildings reach the goals of the EU taxonomy and increase the energy class. Though, the time aspect of implementing the retrofit measures has not been examined and is outside the scope of this study.

Savings in expenses will be derived from the price of electricity, which has fluctuated a lot in recent years. This creates an uncertainty in the potential cost savings, which are assumed to be the same for each year when calculating the energy-saving benefits. While it may seem like a simple solution, it is hard to predict future electricity prices accurately, and if the electricity price drops drastically, it will similarly drastically affect the NPV. Nevertheless, the net present value analysis helps determine the most financially viable combinations.

Based on the pre-literature study, several retrofit measures were identified but discarded in this study due to limitations such as time, resources, software limitations, and case study building requirements.

6 Conclusion

This study set out to examine cost-effective retrofit actions that can reduce energy consumption in an existing office building and find an optimal solution with respect to energy savings and positive NPV. It was found that retrofitting an existing building can yield significant energy savings so that the building aligns with the EU taxonomy, with several optimal combinations identified that achieve high energy efficiency and positive net present value. Specifically, all 24 combinations resulted in energy savings ranging from 64.28 to 79.64 % and payback periods ranging from 5.7 to 10.3 years, with half of the combinations having a positive NPV value. It was found that the HVAC system was a dominant factor in achieving optimal outcomes, which confirms the results by Boyano et al. (2013) and Che et al. (2019), and that adding additional insulation beyond a certain point did not greatly increase energy savings, and confirms the conclusions of Wan et al. (2022) and Rodrigues and Freire (2014). Changing window types had a modest impact on energy savings but led to high investment costs for 3-pane windows, resulting in a negative NPV for all combinations tested. Using a weighted sum method for the combinations with positive NPVs, we identified combination 2 as the most optimal in most cases, having a payback period of 5.7 years with only 50 mm EPS in walls and roof, U-value 1.1 windows, and a temperature and CO_2 controlled VAV system. Moreover, we found two limits for the two HVAC options, towards which the energy consumption converges as we increase the investment costs.

All combinations with retrofit measures implemented to the existing building would result in energy classes ranging from D-B. Where the optimal combination 2 resulted in energy class B. However, our study is subject to certain limitations, as the model is only as accurate as our assumptions. Nevertheless, our findings provide practical insights and actions for building retrofits and demonstrate the importance of considering the trade-offs between energy savings and investment costs.

6.1 Contributions and Future Research

The contributions of this study encompassed significant insights into cost-effective retrofit actions for energy reduction in existing office buildings, aiming for optimal solutions in energy savings and positive net present value (NPV). The findings confirmed that the HVAC system was crucial in achieving optimal outcomes, aligned with previous research. Additionally, the study revealed a threshold regarding the energy savings from additional insulation, consistent with earlier conclusions. Notably, combination 2 stood out with minimal upgrades, except for an efficient HVAC system, yet yielding substantial energy efficiency. Moreover, the research identified two limits for HVAC options, towards which energy consumption converged with increasing investment costs. These contributions pave the way for future research, which should delve into refining and maximizing energy-efficient strategies, taking into account the identified limits and exploring other factors that influence retrofit effectiveness, ultimately enhancing sustainability and economic viability in building retrofits.

References

Abdul Hamid, A.; Johansson, D., and Bagge, H., 2020. Ventilation measures for heritage office buildings in temperate climate for improvement of energy performance and ieq. *Energy and Buildings*, 211:109822. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2020.109822. URL https://www.sciencedirect.com/science/article/pii/S0378778819320249.

Akbari, K. . and Öman, R., 2012. Radon Mitigation using Heat Recovery Ventilation system in a Swedish Detached House. *WSEAS Transactions on Environment and Development*, 8: 73–82. URL https://www.researchgate.net/publication/289302433_Radon_Mitigation_using_Heat_Recovery_Ventilation_system_in_a_Swedish_Detached_House.

Akgüç, A. and Zerrin Yılmaz, A., 2022. Determining hvac system retrofit measures to improve cost-optimum energy efficiency level of high-rise residential buildings. *Journal of Building Engineering*, 54:104631. ISSN 2352-7102. doi: https://doi.org/10.1016/j.jobe.2022.104631. URL https://www.sciencedirect.com/science/article/pii/S2352710222006441.

Annual Accounts Act (1995:1554). [Årsredovisningslag], Chapter 6, Paragraph 10.

Aslani, A.; Bakhtiar, A., and Akbarzadeh, M. H., 2019. Energy-efficiency technologies in the building envelope: Life cycle and adaptation assessment. *Journal of Building Engineering*, 21:55–63. ISSN 2352-7102. doi: https://doi.org/10.1016/j.jobe.2018.09.014. URL https://www.sciencedirect.com/science/article/pii/S235271021830319X.

Aste, N.; Angelotti, A., and Buzzetti, M., 2009. The influence of the external walls thermal inertia on the energy performance of well insulated buildings. *Energy and Buildings*, 41 (11):1181–1187. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2009.06.005. URL https://www.sciencedirect.com/science/article/pii/S037877880900125X.

Augenbroe, G. *(10 The Role of Simulation in Performance-Based Building). Building Performance Simulation for Design and Operation.* 2 edition, 2019. ISBN 9780429688546; 0429688547. URL libgen.li/file.php?md5=65cdb26e85074a481711b73cb95f5be6.

Baker, H.; Moncaster, A.; Remøy, H., and Wilkinson, S., 2021. Retention not demolition: how heritage thinking can inform carbon reduction. *Journal of Architectural Conservation*, 27: 1–19. doi: 10.1080/13556207.2021.1948239.

Bauhaus, n.d.a, Accessed on: 2023-04-19. URL https://www.bauhaus.se/cellplast-s80-600x1200x100-4-32m-6st-pk.

Bauhaus, n.d.b, Accessed on: 2023-04-19. URL https://www.bauhaus.se/isolering-recticel-eurothane-ewall-pir-100x1200x2400mm.

Bauhaus, n.d.c, Accessed on: 2023-04-19. URL https://www.bauhaus.se/cellplast-s80-600x1200x50mm-7-2m-per-paket.

Belany, P.; Hrabovsky, P., and Kolkova, Z., 2021. Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings. *Energy Reports*, 7:2470–2483. ISSN 2352-4847. doi: https://doi.org/10.1016/j.egyr.2021.04.044. URL https://www.sciencedirect.com/science/article/pii/S2352484721002602.

Berardi, U., 2013. Stakeholders' influence on the adoption of energy-saving technologies in italian homes. *Energy Policy*, 60:520–530. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2013.04.074. URL https://www.sciencedirect.com/science/article/pii/S0301421513003273.

Berk, J. and DeMarzo, P. *Corporate Finance*, volume 5. ed., Global ed. Pearson, Harlow, 2020.

Birchall, S.; Wallis, I.; Churcher, D.; Pezzutto, S.; Fedrizzi, R., and Causse, E. 2014, D2.1a survey on the energy needs and architectural features of the EU building stock. EC FP7 project iNSPiRe.

Birchall, S.; Gustafsson, M.; Wallis, I.; Dipasquale, C.; Bellini, A., and Fedrizzi, R., 05 2016. Survey and simulation of energy use in the european building stock.

Borodinecs, A.; Zemitis, J., and Palcikovskis, A., 2022. Hvac system control solutions based on modern it technologies: A review article. *Energies*, 15(18). ISSN 1996-1073. doi: 10.3390/en15186726. URL https://www.mdpi.com/1996-1073/15/18/6726.

Boverket. *Underlag till den tredje nationella strategin för energieffektiviserande renovering - Ett samarbete mellan Boverket och Energimyndigheten*. ET 2019:13). Energimyndigheten, 2019. ISBN 978-91-7563-674-0.

Boverket. September 2021, Syftet med att klimatdeklarera byggnader, Accessed on 2023-03-14. URL https://www.boverket.se/sv/klimatdeklaration/om-klimatdeklaration/syfte/.

Boverket. June 2022, Konsekvensutredning bfs 2022:3. URL https://www.boverket.se/contentassets/9ff3f2ae337140b2865c5280f435c993/konsekvensutredning-bfs-2022-3.pdf.

Boverket. April 2023a, Energideklarationens innehåll, Accessed on 2023-04-02. URL https://www.boverket.se/sv/energideklaration/energideklaration/energideklarationens-innehall/#:~:text=Energiklass%20A%20st%C3%A5r%20f%C3%B6r%20en,f%C3%A5r%20klass%20C%20eller%20b%C3%A4ttre.

Boverket. January 2023b, Utsläpp av växthusgaser från bygg- och fastighetssektorn, Accessed on 2023-03-14. URL https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/vaxthusgaser.

Boverket. January 2023c, Bygg- och fastighetssektorns energianvändning uppdelat på förnybar energi fossil energi och kärnkraft, Accessed on 2023-03-14. URL https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/energianvandning/.

Boverket. January 2023d, Energy performance certificate, Accessed on 2023-03-17. URL https://www.boverket.se/en/start/building-in-sweden/contractor/inspection-delivery/energy-performance-certificate/.

Boyano, A.; Hernandez, P., and Wolf, O., 2013. Energy demands and potential savings in european office buildings: Case studies based on energyplus simulations. *Energy and Buildings*, 65:19–28. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2013.05.039. URL https://www.sciencedirect.com/science/article/pii/S0378778813003277.

BPIE. 2011, Europe's buildings under the microscope, Published 2011-09-13, Accessed on 2023-05-02. URL https://www.bpie.eu/publication/europes-buildings-under-the-microscope/.

Chang, K.-H. 2015, Chapter 19 - multiobjective optimization and advanced topics. URL https://www.sciencedirect.com/science/article/pii/B9780123820389000193.

Che, W. W.; Tso, C. Y.; Sun, L.; Ip Danny, Y.K.; Lee, H.; Chao, C. Y.H., and Lau Alexis, K.H., 2019. Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (hvac) system. *Energy and Buildings*, 201:202–215. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2019.06.029. URL https://www.sciencedirect.com/science/article/pii/S0378778819303640.

Conejos, S.; Langston, C., and Smith, J., June 2015. Enhancing sustainability through designing for adaptive reuse from the outset: A comparison of adaptstar and adaptive reuse potential (arp) models. *Facilities*, 33:531–552. doi: 10.1108/F-02-2013-0011.

Council, European. January 2023, Fit for 55. URL https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

Cruz Rios, F.; Grau, D., and Bilec, M., October 2021. Barriers and enablers to circular building design in the us: An empirical study. *Journal of Construction Engineering and Management*, 147:04021117. doi: 10.1061/(ASCE)CO.1943-7862.0002109.

Dellgar, U. and Wänglund, C. *Typhuskatalog Byggnader [Catalogue of Type Buildings]*. Försvarets Forskningsanstalt [National Defence Research Establishment], Stockholm, 1995.

Dipasquale, C.; Fedrizzi, R.; Bellini, A.; Gustafsson, M.; Ochs, F., and Bales, C., 2019. Database of energy, environmental and economic indicators of renovation packages for european residential buildings. *Energy and Buildings*, 203:109427. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2019.109427. URL https://www.sciencedirect.com/science/article/pii/S037877881930218X.

Dubois, M.-C. and Blomsterberg, Å., 2011. Energy saving potential and strategies for electric lighting in future north european, low energy office buildings: A literature review. *Energy and Buildings*, 43(10):2572–2582. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2011.07.001. URL https://www.sciencedirect.com/science/article/pii/S0378778811002933.

EKRS. n.d.a, Fönster, Accessed: 2023-04-14. URL https://www.ekrs.se/fonster#:~:text=Ett%20%C3%A4ldre%20kopplat%202%2Dglasf%C3%B6nster,ner%20till%20ca%201%2C3.

EKRS. n.d.b, Nybyggnad av hus, Accessed on 2023-04-14. URL https://www.ekrs.se/nybyggnad#:~:text=N%C3%A4r%20det%20g%C3%A4ller%20v%C3%A4ggar%20och,det%20inte%20uts%C3%A4tts%20f%C3%B6r%20fukt.

El Saied, A.; Maalouf, C.; Bejat, T., and Wurtz, E., 2022. Slab-on-grade thermal bridges: A thermal behavior and solution review. *Energy and Buildings*, 257:111770. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2021.111770. URL https://www.sciencedirect.com/science/article/pii/S0378778821010549.

Energilyftet. n.d., Exempel på teknik och lågenergibyggnader, Accessed: 2023-03-26. URL https://energilyftet.com/block-7/index.html.

Energimyndigheten. February 2022, Gällande krav belysning, Accessed on 2023-02-06. URL https://www.energimyndigheten.se/energieffektivisering/jag-ar-saljare-eller-tillverkare-av-produkter/produktgrupper-a-o/produkter/belysning2/.

European Commission. 2021, Proposal for a directive of the european parliament and of the council amending directive 2003/87/ec establishing a system for greenhouse gas emission allowance trading within the union, decision (eu) 2015/1814 concerning the establishment and operation of a market stability reserve for the union greenhouse gas emission trading scheme and regulation (eu) 2015/757. COM(2021 0124 final, EU-decision 2021/0211(COD), section 4, page 5.

European Parliament and the Council of the European Union. *Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, amending Regulation (EU) 2019/2088*. EUR-Lex, 2020. URL https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0852&from=EN.

Fan, Yuling and Xia, Xiaohua, 2017. A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop pv system installation and maintenance. *Applied Energy*, 189:327–335. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2016.12.077. URL https://www.sciencedirect.com/science/article/pii/S0306261916318505.

Fastighetsägarna. 2021, Nya energikrav på befintliga byggnader på gång, Accessed on 2023-04-28. URL https://www.fastighetsagarna.se/aktuellt/nyheter/2021/nya-energikrav-pa-befintliga-byggnader-pa-gang/.

Fastighetsägarna. December 2022, Uppdaterade och fler gränsvärden för hållbara byggnader enligt eus taxonomi, Accessed on 2023-05-06. URL https://www.fastighetsagarna.se/aktuellt/nyheter/2022/sverige/uppdaterade-och-fler-gransvarden-for-hallbara-byggnader-enligt-eus-taxonomi/.

Flyvbjerg, B., April 2006. Five misunderstandings about case-study research. *Qual. Inq.*, 12(2): 219–245.

Goodfellow, H. D. and Wang, Y. 2021, Chapter 6 - commissioning, control, and maintenance of ventilation systems. URL https://www.sciencedirect.com/science/article/pii/B9780128166734000018.

Guo, S.; Wang, W., and Zhou, Y., 2022. Research on energy saving and economy of old buildings based on parametric design: A case study of a hospital in linyi city, shandong province. *Sustainability*, 14(24). ISSN 2071-1050. doi: 10.3390/su142416681. URL https://www.mdpi.com/2071-1050/14/24/16681.

Gustafsson, M.; Dipasquale, C.; Poppi, S.; Bellini, A.; Fedrizzi, R.; Bales, C.; Ochs, F.; Sié, M., and Holmberg, S., 2017. Economic and environmental analysis of energy renovation packages for european office buildings. *Energy and Buildings*, 148:155–165. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2017.04.079. URL https://www.sciencedirect.com/science/article/pii/S0378778816312221.

Güçyeter, B. and Murat Günaydın, H., 2012. Optimization of an envelope retrofit strategy for an existing office building. *Energy and Buildings*, 55:647–659. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2012.09.031. URL https://www.sciencedirect.com/science/article/pii/S0378778812004847.

Ho, A. M.Y.; Lai, J. H.K., and Chiu, B. W.Y., 2021. Key performance indicators for holistic evaluation of building retrofits: Systematic literature review and focus group study. *Journal of Building Engineering*, 43:102926. ISSN 2352-7102. doi: https://doi.org/10.1016/j.jobe.2021.102926. URL https://www.sciencedirect.com/science/article/pii/S2352710221007841.

Höglund, P. 2016, Impact of future usage patterns on the insulation demand for office buildings in stockholm. URL https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,uid&db=edsndl&AN=edsndl.194369&site=eds-live&scope=site.

IEA, 2013. Transition to sustainable buildings: Strategies and opportunities to 2050.

IEA, 2022. Buildings. URL https://www.iea.org/reports/buildings. Accessed on 2023-02-05.

James, G.; Witten, D.; Hastie, T., and Tibshirani, R. *An introduction to statistical learning*, volume 112. Springer, 2013.

Javid, A. S.; Aramoun, F.; Bararzadeh, M., and Avami, A., 2019. Multi objective planning for sustainable retrofit of educational buildings. *Journal of Building Engineering*, 24:100759. ISSN 2352-7102. doi: https://doi.org/10.1016/j.jobe.2019.100759. URL https://www.sciencedirect.com/science/article/pii/S2352710218312427.

Jiang, X.; Lin, A.; Ma, H.; Li, X., and Li, Y., 2020. Minimizing the thermal bridge through the columns in a refrigeration room. *Applied Thermal Engineering*, 165:114565. ISSN 1359-4311. doi: https://doi.org/10.1016/j.applthermaleng.2019.114565. URL https://www.sciencedirect.com/science/article/pii/S1359431119321076.

Karlsson, B. 2023, Explanation of retrofitting hvac systems, Personal communication, April 24, 2023.

Lee, J.; McCuskey Shepley, M., and Choi, J., 2019. Exploring the effects of a building retrofit to improve energy performance and sustainability: A case study of korean public buildings. *Journal of Building Engineering*, 25:100822. ISSN 2352-7102. doi: https://doi.org/10.1016/j.jobe.2019.100822. URL https://www.sciencedirect.com/science/article/pii/S2352710219306606.

Leskinen, Niina; Vimpari, Jussi, and Junnila, Seppo, 2020. Using real estate market fundamentals to determine the correct discount rate for decentralised energy investments. *Sustainable Cities and Society*, 53:101953. ISSN 2210-6707. doi: https://doi.org/10.1016/j.scs.2019.101953. URL https://www.sciencedirect.com/science/article/pii/S2210670719316956.

Li, W.; Koo, C.; Hong, T.; Oh, J.; Cha, S. H., and Wang, S., 2020. A novel operation approach for the energy efficiency improvement of the hvac system in office spaces through real-time big data analytics. *Renewable and Sustainable Energy Reviews*, 127:109885. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2020.109885. URL https://www.sciencedirect.com/science/article/pii/S1364032120301787.

Loukas, S. 2020, Everything you need to know about min-max normalization: A python tutorial, Accessed: 2023-04-10. URL https://towardsdatascience.com/everything-you-need-to-know-about-min-max-normalization-in-python-b79592732b79.

Lönn, E. 2023, Interpretation of poor quality blue prints, Personal communication, March 18, 2023.

Ma, Z.; Cooper, P.; Daly, D., and Ledo, L., 2012. Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings*, 55:889–902. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2012.08.018. URL https://www.sciencedirect.com/science/article/pii/S0378778812004227.

Marina, D. 2022, Everything comes with a price – including the future of the real estate sector. https://www.nordicsrealestate.com/everything-comes-with-a-price, Accessed: 2023-2-23.

Mazzeo, D.; Matera, N.; Cornaro, C.; Oliveti, G.; Romagnoni, P., and De Santoli, L., 2020. Energyplus, ida ice and trnsys predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a pcm module. *Energy and Buildings*, 212:109812. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2020.109812. URL https://www.sciencedirect.com/science/article/pii/S0378778819324521.

Menta Fönster, n.d., Accessed on: 2023-04-20. URL https://www.mentafonster.se/webbshop/aluminium-energi-fast-fonster?redirect=/produkter/aktuell-kampanj.

Moncaster, A. M.; Nygaard Rasmussen, F.; Malmqvist, T.; Houlihan Wiberg, A., and Birgisdottir, H., 2019. Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies. *Journal of Cleaner Production*, 235:378–393. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2019.06.233. URL https://www.sciencedirect.com/science/article/pii/S0959652619321985.

Nasdaq OMX. 2023, Market prices, nordic commodities, Accessed on 2023-04-21. URL https://www.nasdaqomx.com/transactions/markets/commodities/market-prices?

Nilsson, P.-E.; Aronsson, S., and Jagemar, L., 1994. Energy-efficient retrofitting of office buildings. *Energy and Buildings*, 21(3):175–185. ISSN 0378-7788. doi: https://doi.org/10.1016/0378-7788(94)90033-7. URL https://www.sciencedirect.com/science/article/pii/0378778894900337.

Nord Pool. 2023, About us, Accessed date: 2023-04-21. URL https://www.nordpoolgroup.com/en/About-us/.

Nordiska Fönster, n.d., Accessed on: 2023-04-20. URL https://www.nordiskafonster.se/fonster/tra-aluminium/norrland/fast-fonster-aluminium-2-glas.

Nutkiewicz, A.; Choi, B., and Jain, R. K., 2021. Exploring the influence of urban context on building energy retrofit performance: A hybrid simulation and data-driven approach. *Advances in Applied Energy*, 3:100038. ISSN 2666-7924. doi: https://doi.org/10.1016/j.adapen.2021.100038. URL https://www.sciencedirect.com/science/article/pii/S2666792421000305.

Ozel, M., 2012. Cost analysis for optimum thicknesses and environmental impacts of different insulation materials. *Energy and Buildings*, 49:552–559. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2012.03.002. URL https://www.sciencedirect.com/science/article/pii/S0378778812001466.

Planning and Building Act (2010:900). [Swedish Building and Planning Act (2010:900)], Chapter 9, Paragraph 2. [Plan- och bygglagen].

Poirazis, H.; Blomsterberg, Å., and Wall, M., 2008. Energy simulations for glazed office buildings in sweden. *Energy and Buildings*, 40(7):1161–1170. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2007.10.011. URL https://www.sciencedirect.com/science/article/pii/S0378778807002423.

Repab. Underhållskostnader 2017 : [mark, bygg måleri, installationer]. Mölndal, 2017.

Rodrigues, C. and Freire, F., 2014. Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house. *Building and Environment*, 81:204–215. ISSN 0360-1323. doi: https://doi.org/10.1016/j.buildenv.2014.07.001. URL https://www.sciencedirect.com/science/article/pii/S0360132314002170.

Santamouris, M. and Dascalaki, E. June 2002, Passive retrofitting of office buildings to improve their energy performance and indoor environment: the office project.

Shadram, F.; Bhattacharjee, S.; Lidelöw, S.; Mukkavaara, J., and Olofsson, T., 2020. Exploring the trade-off in life cycle energy of building retrofit through optimization. *Applied Energy*, 269:115083. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2020.115083. URL https://www.sciencedirect.com/science/article/pii/S030626192030595X.

Statistics Sweden. n.d., Byggkostnadsutvecklingen 1910-2022. Årlig förändring [data set], Accessed on 2023-04-24. URL https://www.scb.se/pr0502.

Strandberg, B. and Lavén, F. *Bygga hus: Illustrerad bygglära*, volume 3. Studentlitteratur AB, Lund, 2018. ISBN 978-91-44-12513-8.

Sveby. 2013, Brukarindata kontor, version 1.1 svebyprogrammet, Accessed: 2023-04-10. URL https://www.sveby.org/wp-content/uploads/2013/06/Brukarindata-kontor-version-1.1.pdf.

Svenska Kraftnät. March 2023, Tema: Elmarknad och elpriser, Accessed on 2023-04-03. URL https://www.svk.se/press-och-nyheter/temasidor/tema-elmarknad-och-elpriser/#:~:

text=De%20h%C3%B6ga%20priserna%20som%20vi,utsl%C3%A4ppsr%C3%A4tter%20f%C3%B6r%20koldioxid%20inom%20EU.

Sweden Green building Council. n.d.a, Vad är miljöbyggnad idrift? SGBC, Accessed on 2023-05-05. URL https://www.sgbc.se/certifiering/miljobyggnad-idrift/vad-ar-miljobyggnad-idrift/.

Sweden Green building Council. n.d.b, Vad är eu:s gröna taxonomi? SGBC, Accessed on 2023-01-31. URL https://www.sgbc.se/utveckling/eu-taxonomin/vad-ar-eus-grona-taxonomi.

Swedish Finanical Supervisory Authority. August 2022, Taxonomi, Accessed: 2023-02-23. URL https://fi.se/sv/hallbarhet/regler/taxonomi/.

Swedish Ministry of Infrastructure. 2010, Sweden's third national strategy for energy efficient renovation, [Infrastrukturdepartementet]. URL https://energy.ec.europa.eu/system/files/2020-05/se_2020_ltrs_official_translation_0.pdf.

Säfsten, K. and Gustavsson, M. *Research Methodology: For Engineers and Other Problem Solvers*. Studentlitteratur, Lund, 2020. ISBN 9789144122304.

United Nations Environment Programme. *2021 Global Status Report for Buildings and Constructions: Towards a zero-emissions, efficient and resilient buildings and construction sector*. Nairobi, 2021.

United Nations Framework Convention on Climate Change. 2015, The Paris Agreement. UN Doc FCCC/CP/2015/10/Add.1, Article 2, paragraph 1 (a).

Valdiserri, P. and Biserni, C., 2016. Energy performance of an existing office building in the northern part of italy: Retrofitting actions and economic assessment. *Sustainable Cities and Society*, 27:65–72. ISSN 2210-6707. doi: https://doi.org/10.1016/j.scs.2016.07.009. URL https://www.sciencedirect.com/science/article/pii/S2210670716301792.

Värderingsdata. 2023, Marketinformation, Accessed: 2023-04-18. URL https://www.varderingsdata.se/.

Wan, S.; Ding, G.; Runeson, G., and Liu, Y., 2022. Sustainable buildingsrsquo; energy-efficient retrofitting: A study of large office buildings in beijing. *Sustainability*, 14(2). ISSN 2071-1050. doi: 10.3390/su14021021. URL https://www.mdpi.com/2071-1050/14/2/1021.

Wang, Q.; Ploskić, A.; Song, X., and Holmberg, S., 2016. Ventilation heat recovery jointed low-temperature heating in retrofitting—an investigation of energy conservation, environmental impacts and indoor air quality in swedish multifamily houses. *Energy and Buildings*, 121: 250–264. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2016.02.050. URL https://www.sciencedirect.com/science/article/pii/S0378778816301062.

Yin, R. K. *Case Study Research and Applications*. SAGE, London, 2018. Sixth edition.

Ástmarsson, B.; Anker Jensen, P., and Maslesa, E., 2013. Sustainable renovation of residential buildings and the landlord/tenant dilemma. *Energy Policy*, 63:355–362. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2013.08.046. URL https://www.sciencedirect.com/science/article/pii/S0301421513008501.

Appendix

Table A0.1: Building properties for the entire building.

Building part 1			**Building part 2**		
Overall					
Room height	3 m				
Type of use	Office cells				
Heated area[1]	3,245				
Number of occupants[2]	1 person / 20 m^2				
Working hours[2]	08 - 17 weekdays				
Exterior walls	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$	**Exterior walls**[3]	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$
½ Brick wall	120	0.6	Concrete	80	1.7
Air gap	30	0	Wall insulation, Rockwool	200	0.037
Insulation, Rockwool	100	0.037	Concrete	90	1.7
Concrete	150	1.7	Aluminum	15	218
Total	**Thickness (mm)**	**U-value (W/m^2K)**	**Total**	**Thickness (mm)**	**U-value (W/m^2K)**
	400	0.299		385	0.1762
Exterior walls towards ground	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$	**Exterior walls towards ground**[4]	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$
Exterior wall insulation, Rockwool	80	0.037	Exterior wall insulation, Rockwool	80	0.037
LECA (Light expanded clay aggregate)	290	0.17	LECA (Light expanded clay aggregate)	290	0.17
Concrete	150	1.7	Concrete	150	1.7
Total	**Thickness (mm)**	**U-value (W/m^2K)**	**Total**	**Thickness (mm)**	**U-value (W/m^2K)**
520	0.249		520	0.249	
Roof	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$	**Roof**	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$
Flat roof insulation, Rockwool	30	0.037	Aluminium	5	218
Insulation, Rockwool	120	0.037	Wood	23	0.14
Concrete	220	1.7	Air gap	20	
			Insulation, Rockwool	2x100	0.037
			Flat roof insulation, Rockwool	60	0.037
			Concrete	200	1.7
Total	**Thickness (mm)**	**U-value (W/m^2K)**	**Total**	**Thickness (mm)**	**U-value (W/m^2K)**
	370	0.2319		508	0.1305
Slab	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$	**Slab**[4]	**Thickness** (mm)	**Thermal conductivity** $\lambda(W/mK)$
Chipboard	16	0.13	Chipboard	16	0.13
Concrete	40	1.7	Concrete	40	1.7
Insulation, Rockwool	60	0.037	Insulation, Rockwool	60	0.037
Concrete	200	1.7	Concrete	200	1.7
Total	**Thickness (mm)**	**U-value (W/m^2K)**	**Total**	**Thickness (mm)**	**U-value (W/m^2K)**
	316	0.4864		316	0.4864
Windows[5]	Window no.	Placement	Thermal conductivity, $\lambda(W/mK)$	Size (width x height cm)	
Glass brick	W1	Building part 1, facing north and south	2.9	70 x 50	
Double pane	W2[6]	Building part 1, facing north and south	2.9	70 x 140	
Double pane	W3	Building part 1, facing west and east	2.9	60 x 280	
Double pane	W4	Building part 2, facing west and east	2.9	40 x 120	
Double pane	W5	Building part 2, towards west and east	2.9	100 x 120	
HVAC					
Constant air volume flow (CAV)[7]	1.5 - 2 l/s,m^2				
Mechanical FTX system	Always running				
Heat recovery rate	60 %				
Lightning	W/m^2	Share of light sources in building			
LED	10	80%			
Older, T8[8]	18	20%			

[1]the office space (LOA) is about 80 % of this, around 2,700 m^2. All space is assumed to be heated, and the larger value is used in the analysis when computing the NPV.

[2]Assumption origins from "Brukarindata kontor" Sveby (2013).

[3]No blueprints exists, construction assumptions are based on a similar structure described by Dellgar and Wänglund (1995).

[4]No blueprints exists, construction assumed to be the same as builing part 1.

Table A0.2: Table presenting the calculation of the retrofit investments. Labor time and cost obtained from Repab (2017), and index based on statistics from Statistics Sweden (n.d.).Rounding errors might occur.

Exterior walls							
Cl.[1]		**Thickness (mm)**	**Exterior Wall Area, m^2**	**Labor Time (h/m^2)**	**Labor Cost, SEK/h**	**Material Cost[2], SEK/m^2**	**Total Cost, SEK**
A1		50 mm EPS	1,060	0.38	605	58[3]	**305,119**
A2		100 mm EPS	1,060	0.38	605	111[4]	**361,439**
A3		100 mm PIR	1,060	0.38	605	484[5]	**757,402**
Roof							
Cl.		**Thickness (mm)**	**Roof Area, m^2**	**Labor Time (h/m^2)**	**Labor Cost/h**	**Material Cost, SEK/m^2**	**Total Cost, SEK**
B1		50 mm	541	0.53	560	58[3]	**191,777**
B2		100 mm	541	0.53	560	111[4]	**220,498**
Windows[6]							
Cl.	**Window Type**	**Size**	**No. of units**	**Labor Time (h)**	**Labor Cost/h**	**Material Cost/unit**	**Total Cost, SEK**
C1	W1	0.7x0.5	41	4.5	605	2,302	97,098
C1	W2	0.7x1.4	220	4.5	605	4,091	902,733
C1	W3	0.7x2.6	38	4.5	605	8,470	324,600
C1	W4	0.4x1.2	78	2.2	605	3,401	266,574
C1	W5	1x1.2	54	4.5	605	4,552	248,537
						Total	**1,839,542**
C2	W1	0.7x0.5	41	4.5	605	5,410	224,532
C2	W2	0.7x1.4	220	4.5	605	8,196	1,805,858
C2	W3	0.7x2.6	38	4.5	605	11,848	452,940
C2	W4	0.4x1.2	78	2.2	605	6,303	492,933
C2	W5	1x1.2	54	4.5	605	8,872	481,829
						Total	**3,458,092**
HVAC							
Cl.		**Replaced components**	**No. of units**	**Labor Time (h/m^2)**	**Labor Cost/h**	**Material Cost / m^2**	**Total Cost, SEK**
D1		Fan Assembly	1	65	638	165,500	206,944
D1		Supply Air Device 160 mm	104	1.3	837	2,680	391,917
D1		Exhaust Air Device 160 mm	29	0.77	489	280	19,050
D1		Heating Battery 80 x 40 mm	1	10	640	4,230	10,632
D1		Air Vent Cleaning Costs	3,213 m^2		21	0	66,218
D1		Adjustment Cost	3,213 m^2		17	0	53,802
						Total	**748,562**
D2		Supply Air Device	104	1.3	650	2,680	366,600
D2		Exhaust Air Device	29	0.77	380	280	16,605
D2		Sensors	133	1,5	464	2,203	385,458
D2		Fan Assembly	1	65	495	165,500	197,675
D2		Air Vent Cleaning Costs	3,213 m^2		21	0	66,218
D2		Adjustment Cost	3,213 m^2		17	0	53,802
						Total	**1,086,358**

[1]Classification number.
[2]Latches are not included in the material cost.
[3]Material cost obtained from Bauhaus (n.d.c).
[4]Material cost obtained from Bauhaus (n.d.a).
[5]Material cost obtained from Bauhaus (n.d.b).
[6]Double pane windows in option C1 are obtained from

Table A0.3: Distribution of delivered energy for each simulation, together with the primary energy.

C.no[1]	**Lighting, Facility**	**HVAC Auxiliary Heat**	**District Cooling**	**District Heating**	**Equipment, Tenant**	**Total Consumption, kWh/m^2**	**Primary Energy**
1	11.26	7.90	4.51	63.96	5.24	92.87	72.73
2	11.26	1.86	3.99	34.65	5.24	57.00	46.70
3	11.26	7.90	4.49	63.48	5.24	92.36	72.28
4	11.26	1.76	3.95	33.76	5.24	55.97	45.89
5	11.26	7.90	4.51	63.36	5.24	92.27	72.20
6	11.26	1.88	4.00	33.88	5.24	56.25	46.03
7	11.26	7.80	4.49	62.53	5.24	91.42	71.455
8	11.26	1.79	3.95	32.98	5.24	55.22	45.21
9	11.26	7.90	4.50	61.86	5.24	90.75	70.88
10	11.26	1.91	4.01	32.92	5.24	55.34	45.21
11	11.26	7.90	4.50	61.86	5.24	90.75	70.88
12	11.26	1.83	3.97	32.02	5.24	54.31	44.39
13	11.26	7.90	4.52	61.76	5.24	90.67	70.81
14	11.26	1.92	4.01	32.56	5.24	54.99	44.89
15	11.26	7.90	4.50	61.02	5.24	89.91	70.14
16	11.26	1.84	3.97	31.66	5.24	53.97	44.07
17	11.26	7.90	4.52	60.9	5.24	89.82	70.05
18	11.26	1.87	3.99	30.98	5.24	53.34	43.48
19	11.26	7.90	4.50	60.38	5.24	89.28	69.59
20	11.26	1.86	3.98	30.94	5.24	53.29	43.45
21	11.26	7.90	4.52	60.3	5.24	89.22	69.53
22	11.26	1.96	4.02	31.49	5.24	53.97	43.96
23	11.26	7.90	4.50	59.78	5.24	88.68	69.05
24	11.26	1.87	3.99	30.58	5.24	52.94	43.14

Table A0.4: Building elements source data.

Windows	Measures from site visit, U-value from EKRS (n.d.a)
Exterior walls, BP1	Based on blue prints
Exterior walls, BP2	Assumptions made from Typkatalog
Roof BP1	Based on blue prints, and interpretation help from a professional (Lönn, 2023)
Roof BP2	Based on blueprints
HVAC	Based on blueprints, inquiries with the owner and template data from Sveby (2013)
Slab BP1	Based on blueprints
Slab BP2	No information, assumed same as BP1
Exterior walls towards ground BP1	Based on blueprints
Exterior walls towards ground BP1	No information, assumed same as BP1
Lamps	Based on inquiries with the owner, and assumptions made from Energilyftet (n.d.)

Table A0.5: Model design in IDA ICE for the benchmark.

Type	Explanation
Building Design and Construction	
Location	Malmö / Sturup
Weather conditions	IDA ICE Malmö Sturup Climate setting
Infiltration	Not accounted for, automatically transferred between zones
Thermal bridges	Default - Typical for all building parts
Wind profile	Default - Urban
Site shading and orientation	Accounted for
Internal walls	Software default
Internal floor	Software default
Door constructions	Software default
Window-to-wall ratio	0,27
Total number of windows	431
U-value windows	2.9
U-value window frames	2
Model design	Assumed simplified model, rectangular. Roof is in reality inclined.
Basement	Windows applied to the basement are shorter than in reality. This is due to limitations in the software. Correct size is used in the NPV.
Stairs	No stairs are added
Entrance	Only one entrance
Fan rooms	Not accounted for in the model, removed
Homogenous model assumed	Yes, assumed uniformed for model, every default applies to the entire building.
Building operation	Assumed no variability
Building materials and properties	Idealized building materials and properties assumed
Ground properties	ISO-13370
Preassure coefficients	Default
Extra energy and losses	Default, uniform distribution of hot water use
HVAC Systems and Components	
Heating source	District heating , COP 1
Cooling source	Distrcit cooling, COP 1
Domestic hot water	District heating
Air handling unit	Constant supply air
Heat exchanger	fan operation
Always on	
Heat exchanger	0,6
Heating coil	Default parameters
Cooling coil	Default parameters
Fan parameters	Default parameters
Plant	Standard plant
Ideal heater in room units (all zones)	2000 W
Ideal cooler in room units (all zones)	Not existing
Temperature min, C	21
Temperature max, C	23
Advanced parameters for each zones	Default
Supply Air flow	1.5 - 2.0 (0 for basement)
Total zones (1 room = 1 zone)	114
Atemp	3,213
Occupancy and Equipment	
Internal gains, Equipment	Default - 75 W
Internal gains, Lights	Default
Occupants	1 per 20 m2, i.e., 15 m2 gives 0.75 occupants
Units of equipment in each zone	Default
Mechanical equipment	Assumed perfectly functioning
Lights	Assumed 80 Humidity
Default	
Other	
System parameters (key tolerances and standard settings)	Software default, not changed
Number floors BP1	3 (+ basement) for BP1
Number floors BP2	2 (+ basement) for BP2
Room height	3 m, for the entire building
Schedule	
Holidays	Public Holidays Sweden from Wikipedia
Occupants	08-17 weekdays
Equipment	08-17 weekdays
Light	08-17 weekdays
HVAC	CAV - Constant
Doors	Always open