Master's thesis

NTNU
Norwegian University of Science and Technology
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Evaluation of Energy Saving Potentials in Non-Residential Buildings with Small Rehabilitation Measures

Master's thesis in Energy and Environmental Engineering
Supervisor: Natasa Nord and Rune Gjertsen
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Preface

This work is the Master's Thesis of Iren Han Thodesen written Spring 2020 for the Department of Energy and Process Engineering at NTNU.

I would like to show my appreciation to my supervisor Natasa Nord for her guidance throughout the year. Also thanks to my co-supervisor Rune Gjertsen from GK Inneklima for advisory on the technical systems and connecting me with the case building and its relevant building owners.

Also thanks to Nils Magne Vikan from E.C. Dahls Eiendom, Arne Rønning from Arne Rønning AS, Øyvind Hegvik from HUS Arkitekter AS for providing relevant documentations and advice.

Abstract

The replacement rate of existing buildings is only around 1-3% per year and most of the buildings in use in 2050 have already been built. Rehabilitating existing buildings is therefore essential for reducing the total energy use in the building sector. Simulation tools can be useful in the prediction of a building's energy performance and used in the selection process for energy measures.

It was of interest to evaluate the effectiveness of small efficiency measures at improving the energy profile and indoor climate in older non-residential buildings. The thesis aims to create a simulation model that represents the case building on Nordre Gate 10 as realistically as possible and to be used as a basis for comparison of rehabilitation measures.

The thesis is structured with a literature study on relevant topics such as historical building codes and its development, energy use in buildings and related statistics, parameters in the indoor environment, components in a HVAC system, and theory related to rehabilitation of buildings. Furthermore, a thorough investigation of the case building is conducted and used to develop a base case model with the simulation tool IDA ICE. The base case was used as a basis for further simulations 10 rehabilitation scenarios where results of energy use and thermal comfort were compared with each other.

Results showed a specific annual energy use of 215 kWh/m^2 for the Base Case, 9.8% less than measured. The rehabilitation scenario that included all evaluated measures resulted in the highest heat energy saving with up to 68% of the Base Case. Rehabilitation measures in this thesis focused only around improving the building's physical properties and compared purely base on energy savings. For future work it was suggested to to look into measures on internal loads and occupant behaviour, as well as a more detailed simulation on a demand controlled ventilation system. Economic costs of rehabilitation measures should also be taken into consideration.

Sammendrag

Årlig erstattes rundt 1-3% av eldre bygninger med nybygg. Det er estimert at de fleste bygninger som brukes i 2050 allerede er bygd. Rehabilitering av eksisterende bygninger er derfor avgjørende for å redusere det totale energiforbruket i byggesektoren. Simuleringsverktøy kan brukes til å forutsi energiytelsen i et bygg og bidra i utvelgelsesprosessen for mulige energitiltak.

Oppgaven hadde som mål å lage en simuleringsmodell av en kommersiell bygning i Nordre Gate 10 i Trondheim. Målet var å lage en grunnmodell som gjenspeilte bygningen så realistisk som mulig. Modellen ble videre brukt som grunnlag for sammenligningen av energitiltak. Det var ønskelig å evaluere forbedringspotensialer til mindre rehabiliteringstiltak, i form av energibruk og inneklima.

Oppgaven er oppbygd med litteraturstudier av relevante temaer som historiske forskrifter, energibruk i bygninger samt relevante statistikker, inneklima parametere, oppbygging av varme- og ventilasjonssystemet og relevant teori om rehabilitering av bygninger. Videre ble det gjennomført en analyse av bygget der parametere for bygningskroppen og tekniske anlegg ble bestemt og implementert i en grunnmodell med simuleringsverktøyet IDA ICE. Energibruk og termisk komfort var deretter sammenlignet og vurdert for de ulike rehabiliteringsmodellene utviklet med grunnmodellen som basis.

Grunnmodellen resulterte i et årlig energiforbruk på 215 kWh/m^2, 9.8% mindre enn faktisk forbruk. Rehabiliteringsmodellen som tok for seg samtlige energitiltak resulterte i høyest energibesparelse for oppvarming med opp mot 68% reduksjon sammenlignet med grunnmodellen. Oppgaven tok kun i betraktning energitiltak som berørte bygningens fysiske egenskaper og evaluerte resultatene ut i fra energibesparelse. Det er anbefalt ved videre arbeid å se på andre mulige tiltak som fokuserer på interne laster og brukeratferd samt en detaljert simulering med behovsstyrt ventilasjon. Tiltakets økonomiske kostnader bør tas med i betraktning.

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1 Introduction

1.1 Background and Motivation

The building sector accounts for over 36% and 39% of the energy use and energy related CO_2 world wide. Although much effort have been put into reducing the building energy intensities, the growth in the industry is offsetting the reduction such that the total energy use is still increasing [4]. In Norway, the situation is similar where nearly 40% of total energy use on the country's mainland goes to energy in buildings, of which 15% originates from non-residential buildings ([5][6]). Most of the building stock that will be in use in 2050 have already been built, 40% of buildings in Europe were built before 1960 and 90% before 1980 [7]. The replacement rate of existing buildings is only around 1-3% per year [8]. To decrease the total energy use in buildings it is therefore important to not only focus on new buildings but also determining ways to rehabilitate existing buildings.

Simulation tools can be used for prediction of a building's energy performance and be used in the selection process for energy measures. In most cases it may not be realistic for building owners to implement an unlimited amount of efficiency measures due to economic constraints. Rehabilitation measures should therefore be prioritised by its effect and costs. This ensures a maximisation in energy savings while maintaining a manageable budget.

1.2 Objectives

The main objective of this thesis is to examine how the implementation of small efficiency measures affects the energy profile and indoor climate in older non-residential buildings. The building simulation tool IDA ICE is used to model the building's performance. To achieve reasonable results requires the model to reflect its building in the most realistic way. It is therefore also of interest to calibrate crucial parameters that play a part in the building's dynamic behaviour. The project is divided into two main parts concentrating first around the case building and afterwards different rehabilitation measures.

The main tasks performed in this thesis are listed as follows:

- A literature study with focus on relevant standards, statistics and influences on energy use, indoor environment, technical systems and building rehabilitation
- Specialisation in the building simulation program IDA ICE
- Establish communication with the building owner, tenants and relevant experts
- Obtain information and collect data on the case building
- Develop a base case model that represents the case building
- Look into possible rehabilitation measures and create scenarios in IDA ICE
- Analyse possible differences in the building's performance and indoor climate for various measures
- Propose a rehabilitation plan for future implementations

1.3 Limitations

The building did not have a complete year's energy use measurement at the time the thesis was written. Missing data and a simplex Building Energy Measurement System also limited the calibration possibilities of the Base Case Model. Other limitations included lack of documentation of building body parameters and information on internal loads and occupancies. Assumptions had to be made based on values found in literature.

1.4 Outline

The thesis consists of 9 Chapters and a short description for each is presented below.

Chapter 1 Introduces the background and motivation of the thesis as well as objectives and limitations regarding the project.

Chapter 2 Covers relevant theoretical background for the project. Relevant topics include the Norwegian national building code, energy use in buildings, indoor environment parameters, HVAC systems in a building, building simulation and building rehabilitation.

Chapter 3 Describes the general methodology for completing the project and gives information of how data is collected.

Chapter 4 Gives a general description of the case building, including parameters for the building envelope, technical installations and an evaluation of the indoor environment.

Chapter 5 Goes through the establishing process of the Base Case model and its input parameters.

Chapter 6 Describes the selected rehabilitation measures and simulation scenarios.

Chapter 7 Presents and analyses results from this thesis, from the building's Energy Measurement System, Base Case Simulation and Rehabilitation Scenarios.

Chapter 8 Discussion around limitations of the thesis, rehabilitation recommendations and suggestions for future work.

Chapter 9 Conclusion and recap of main findings in the project.

2 | Theoretical Background

2.1 The Norwegian National Building Code and Development

The Norwegian National Building Code (*Byggeteknisk forskrift TEK*) is a regulation following the National Planning and Building Act. The regulation covers all technical aspects of a building and sets demands for how buildings are to be built. The first Building Act valid nationally was published in 1965, whereas the previous *Buildings Service Act* from 1924 only concerned cities and urban areas [9]. Since the first building code in 1949, regulations have been under constant development. For the purpose of the project, regulations regarding energy performance of a building is of most interest. Below is a brief overview of the main development within energy-related requirements, inspired by Kongerud's thesis [10].

The main publications of the building code to this date includes *Byggeforskrift 1949* (BF49), *Byggeforskrift 1969* (BF69), *Byggeforskrift 1987* (BF87), *Byggteknisk forskrift 1997* (TEK97), *Byggteknisk forskrift 2007* (TEK07), *Byggteknisk forskrift 2010* (TEK10), and *Byggteknisk forskrift 2017* (TEK17).

The first documents have very limited focus on energy performance in a building. BF49 does not contain any content regarding energy. A section is dedicated to heat isolation to obtain an acceptable thermal comfort. Similar information is also found in BF69. The first mention of energy comes in the form of "good energy economy". This term is first seen in the 1980's update of BF69 and continuously in BF87. Very vague instructions are given in terms of requirements to reduce the building's energy,.

BF87 is the first building code to include quantitative regulations in terms of limits for u-values of various building parts. In addition to heat isolation, a good energy economy is also emphasised under sections involving ventilation and sanitary facilities. The regulation provided little flexibility and arose as a challenge for many.

A significant increase in focus on energy and energy efficiency is seen in the publication in 1997 and onwards. An individual subchapter under §8 Environment and health was dedicated to energy use (TEK97 §8-2). The regulation also specifically mentions a requirement to "promote a *low* energy- and power demand". TEK97 further defines three alternatives in §8-21 that allows more flexibility in which regulations are met. The three alternatives include an overall energy requirement, specific heat-isolation requirements for building parts, and lastly a heat loss limit for the building. The regulation is considered met as long as one of the alternatives are achieved.

Energy requirements are emphasised even further in TEK07 and onwards. The update in 2007 substitutes the three previous alternatives with a minimum demand as well as to alternatives within energy efficiencies (TEK07 §8-21). Flexibility is given to developers to either meet the regulation in the form of net energy demand or specific demands within energy measures. In addition, renewable energy sources are put into focus and two regulations are added in §8 under energy supply and district heating.

TEK10 and TEK17 are the most recent building codes and are almost the same regarding technical requirements. Energy becomes even more important and gets its own chapter in §14. The net energy demand limit becomes stricter in each update and slowly transitions from a low-energy towards passive house level. As energy efficiency continuous to become more crucial in the building sector, it is proposed and expected that energy requirements will become even stricter in the future. A downside regarding the existing building codes is that it is adapted for new buildings. The Norwegian HVAC forum suggests in an article that the new building code TEK20 should include a separate set of regulations for rehabilitation of buildings to promote economically-, environmentally-, and energy optimal solutions [11].

Table 2.1: U-value requirements for various building parts

U value [W/m^{2}K]	1949	1969	1985	1987	1997	2007	2010	2017
External wall	0.81-1.05	0.46-1.04	0.45	0.3	0.22	0.22	0.22	0.22
Roof	0.81	0.41-0.46	0.23	0.2	0.15	0.18	0.18	0.18
Floor	-	0.41	0.23-0.3	0.2-0.3	0.15	0.18	0.18	0.18
Windows	-	-	2.1-2.7	2.4	1.6	1.6	1.2	1.2

An overview of maximum U-values from the building codes mentioned and its development are presented in Table 2.1. Values for 1997 and earlier concerns heated spaces and climate zones including Trondheim retrieved from Multiconsult's report in 2006 [9]. Values for TEK10 are from versions before the update in 2016 [12], as values in this update are consistent with values in the new regulation TEK17.

Table 2.2 presents the total net energy demand limit from 2007 and onwards for office and commercial buildings.

Table 2.2: Total net energy demand for TEK07, 10 and 17

Energy demand [kWh/m^2]	TEK07	TEK10	TEK17
Office buildings	165	150	115
Commercial buildings	235	-	180

2.2 Energy Use in Buildings

As presented in a report by NVE, the annual total energy use on Norwegian mainland in the period of 2000 to 2015 increased by 3.1%, from 221.6 TWh to 228.5 TWh. Of this, energy use in office and commercial buildings increased from 26.5 TWh to 29.7 TWh. The increase was significantly noticeable in the first years however slowly flattened out after 2011. Population and economic growth are major contributors to the increase in energy use whereas reduction in the specific energy use per floor area has restricted the rate of its development [13]. This trend is expected to continue in the future as population is expected to increase further and energy efficiency in buildings are prioritised even more.

2.2.1 Energy Use in Office and Shop Buildings

Enova's annual building statistics includes analysis and statistics of the energy use of a selection of the Norwegian building stock of the given year. Each year the portfolio consists of about three to four thousand building samples within various sizes, categories and ages. The section of specific energy use in buildings by age is especially interesting for this study as buildings of different ages varies a lot by regulations they followed and thereby technical specifications. A summary of specific energy use in office and commercial buildings built in the period 1971-1987 is presented in Table 2.3. Taking the average of the most recent 10 year period, the specific energy use for office buildings is 208 $\pm$ 34 kWh/m^2 and for commercial buildings 233 $\pm$ 35 kWh/m^2. Energy measurements have been temperature adjusted for location.

Commercial buildings includes many different types of businesses such as malls, single shops and grocery stores etc. Each business type have different energy profiles and uses. NVE's report from 2014 [14] analysed the energy use for the different categories within commercial buildings. For shops, the representative specific energy was between 200 - 220 kWh/m^2, although shops built in the period 1970-89 has a higher specific energy at 300 kWh/m^2. For shops smaller than 500 m^2 the specific energy use is 317 kWh/m^2 according to NVE and 248 m^2 according to Entro. Different locations of the shops (city centre or along the highway), opening hours, and how the business is operated will all effect the energy use. Making it hard to conclude a representative value for all shops.

The energy consuming areas in a building as categorised in NS3031 are room heating, heating of DHW, ventilation, lighting, electrical appliances and room cooling. A representative allocation of the specific energy use in office and shop buildings are shown in Figures 2.1a and 2.1b. Shops have a relatively higher share of internal loads leading to more heat gain in the building and in return reducing the demand for room heating. Shops also use more energy for ventilation, this could be due to higher air flow rates and higher pressure drops in the system. Typically higher ceiling heights in shops may be a reason for a lower cooling demand. As most shops do not have detailed energy monitoring equipment installed, the available sample consisted of fairly large buildings. Therefore the results may not accurately represent all shops in Norway.

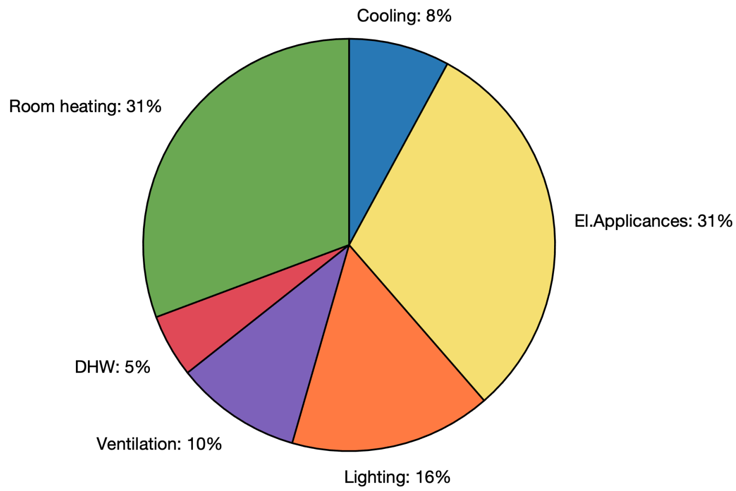
Table 2.3: Specific energy use in buildings built 1971-1987 [3]

Energy use [kWh/m^{2}K]	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average
Office building	244	257	240	235	200	175	210	170	185	165	208 ± 34
Commercial building	-	247	269	235	255	260	240	215	165	185	230 ± 35

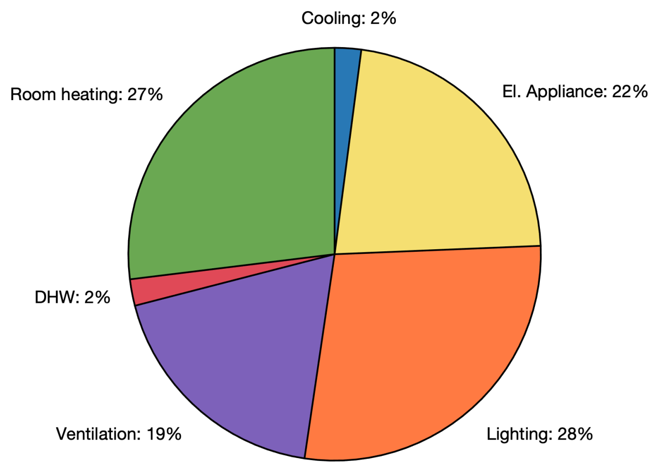
2.2.2 Influencing factors On Building Energy Use

In a review of 20 building-energy related articles, five influencing factors were drawn out as the most important for energy use in buildings: climate, building related characteristics, building systems and/services related characteristics, occupant related characteristics, and socio-economic and legal related characteristics [15]. Similar conclusions are made by Yoshino et al [16] where six factors were put into two groups in addition to a social factor as shown in Figure 2.2. An analysis by NVE also points out quality of building mass, technical solutions, indoor climate, operation and other social/economic as well as environmental motivations as drivers for energy use in buildings [5].

The technical and physical factors stays fixed during a building's operation.



(a) Office [5]



(b) Shops [14]

Figure 2.1: Representative Energy Allocation

They can give an estimate on how a building's performance will be based on scientific principles. On the other hand, human influenced factors varies by time, building type and occupant groups. These factors are much harder to predict and influences the actual energy use of a building.

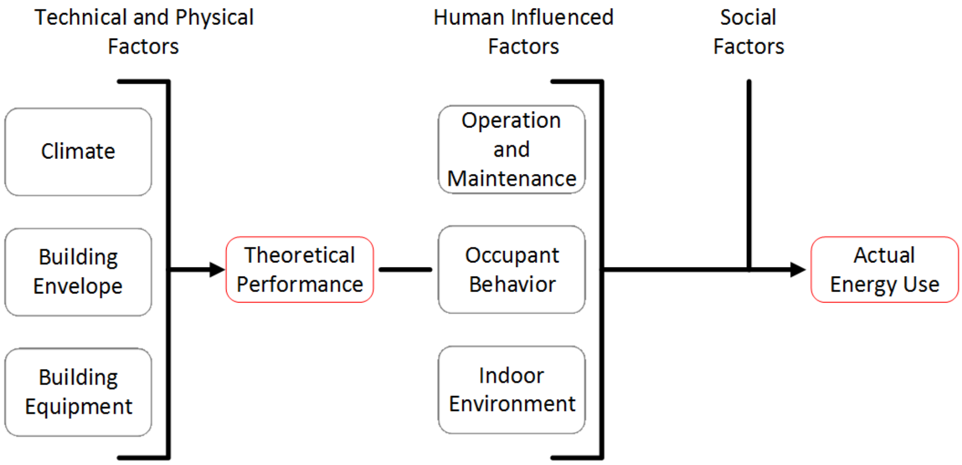


Figure 2.2: Influencing Factors in Building Energy Use

2.2.3 Heat Demand in Buildings

The building's envelope keeps the indoor environment at a constant temperature independent of the outdoors. The heat balance looks at the energy gains and losses of the building. To maintain a constant indoor temperature, the sum of all gains and losses should be equal to zero. A principle sketch of heat gains and losses in a building is shown in Figure 2.3. The corresponding heat balance equation is shown in Equation 2.1.

$$Q_{internal} + Q_{heating} + Q_{solar} - Q_{transmission} - Q_{ventilation} = 0 \tag{2.1}$$

The heat demand is therefore determined by the level of internal gains and losses through the envelope. Transmission losses are determined by the heat transmission factor (U-value) as well as temperature difference between inside and outside. Higher U-values as well as colder outdoor temperatures contribute to higher heat losses and thus a higher heating demand. In cases when the heat gains are larger than heat losses, the heat demand becomes cooling demand.

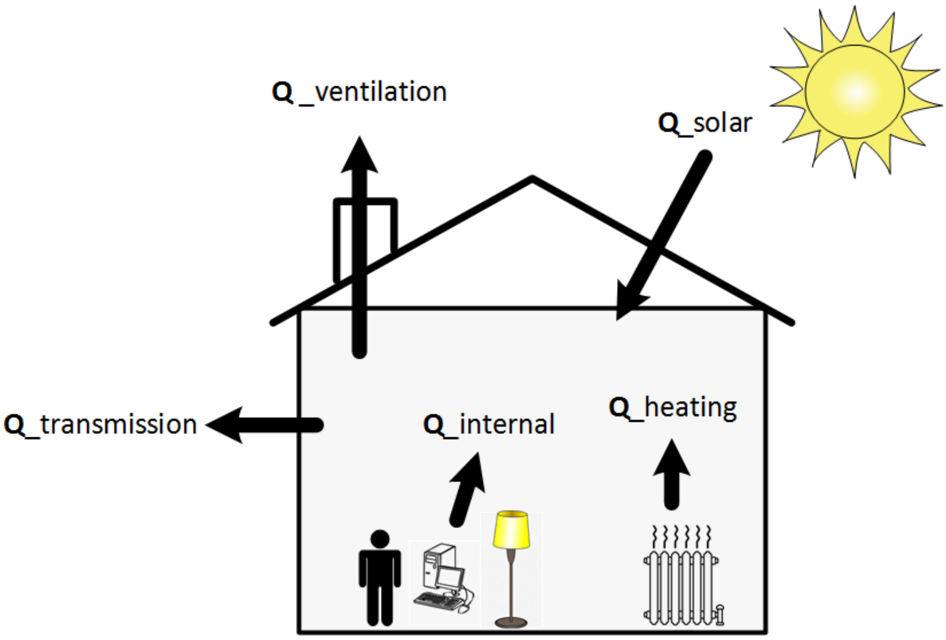


Figure 2.3: Principle Sketch of Heat Balance

2.3 Indoor Environment

2.3.1 Thermal Comfort

Thermal comfort is defined as *the condition of mind which expresses satisfaction with the thermal environment* [1]. Two people in the same room may have completely different perceptions and satisfactions of the indoor environment. It is a highly subjective evaluation dependent on both environmental and personal factors:

- Air temperature
- Mean radiant temperature
- Air velocity
- Humidity
- Clothing insulation
- Metabolic rate

Air temperature is measured by the dry-bulb temperature. Thermal sensations may vary even if the air temperature is constan, affected by the radiant temperature. The human skin has both a high emissivity and absorptivity, allowing it to lose or gain heat through radiation to the person's surroundings. The mean radiant temperature is a weighted average of the temperatures of surfaces surrounding the person and is often measured by with a globe thermometer[17]. Thermal discomfort may occur when there are high radiant temperature asymmetries present with for instance warm ceilings or cold walls. The air velocity measures the movement of air surrounding a person. The higher the velocity the greater convective heat exchange between a person and its surroundings, resulting in draught and thermal discomfort. The relative humidity is given as a ratio of the moisture content in air compared to how much air can hold at the given temperature without condensing. Humidity has relatively little influence on thermal comfort at moderate temperatures [1].

Personal factors affecting thermal comfort involves the person's activity level as well the type of clothing used which are interconnected. The metabolic rate represents a human body's heat production, measured in Met. A seated, relaxed person with 1clo has a metabolic rate of around 1 Met, given as 58 W/m^2. Clo is the unit for measuring a clothing's thermal insulation level, corresponding to 0.155 m^2K/W.

The European standard ISO7730 recommends the indoor temperature to be between 23-26 °C during the summer and 20-24 °C during the winter [1]. The Norwegian Labor Inspection recommends indoor temperatures to not exceed the lower and upper limit of 19 °C and 26 °C [18]. TEK17 recommends the same for light work and extends the lower limit to 16 °C and 10 °C for medium and heavy work. The ideal indoor temperature is heavily debated and varies for different people and activities as mentioned above. The temperature recommendations in today's standards are based on studies conducted by Fanger in the 1960s. A lot has changed in the past 60 years. Typical clothing for work has changed and more women have joined the work force. Women have a lower metabolism than men and therefore often finds the set indoor temperatures to be too low. New studies have therefore recommended to increase the indoor temperature by 3 degrees to better suit today's working environment [19].

Two commonly used measurements for thermal comfort are PMV (Predicted Mean Vote) and PPD (Predicted Percentage Disatisfied) developed by P.O. Fanger. PMV uses a scale from -3 to +3 where the lowest represents cold, 0 representing neutral and highest representing hot. The results gives an estimate of how occupants percieves the indoor environment based on the thermal balance of the human body [20]. Equation 2.2 shows the general formula for calculating PMV based on Fanger's model. Further details on calculations for each variable may be found in [21]. There are multiple user friendly calculation tools available online that helps calculate the PMV. It is also given as an output from simulations in IDA ICE.

$$PMV = (0.303e^{-2.1\cdot M} + 0.028) \cdot [(M - W) - H - E_c - C_{res} - E_{res}] \quad (2.2)$$

M Metabolic Rate [W/m^2]

W Effective Mechanical Power [W/m^2]

H Sensitive Heat Loss [W/m^2]

$\mathbf{E_c}$ Heat Exchange by Evaporation on Skin

$\mathbf{C_{res}}$ Heat Exchange by Convection in Breathing

$\mathbf{E_{res}}$ Heat Exchange by Evaporation in Breathing

The PPD is estimated based on the PMV results given in Equation 2.3 and as shown in Figure 2.4. It follows an almost parabolic shape with its bottom at 5% intersecting with 0 on the PMV scale. ISO 7730 defines three thermal environment categories A, B and C where PPD should be below 6%, 10% and 15% respectively [1].

$$PPD = 100 - 95 \cdot e^{-0.3353\cdot PMV^4 - 0.2179\cdot PMV^2} \quad (2.3)$$

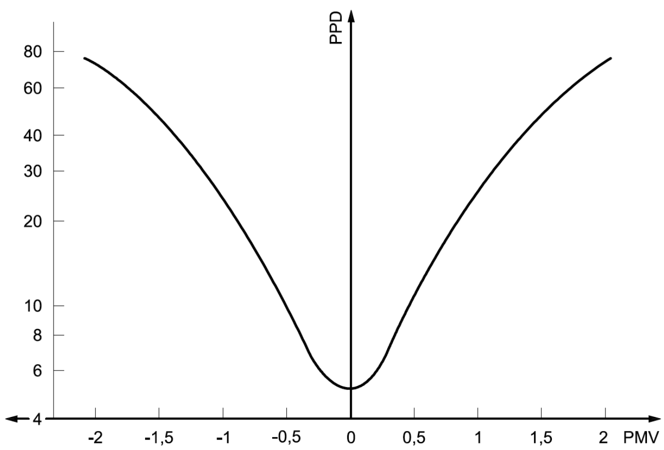


Figure 2.4: Relationship between PMV and PPD [1]

The European Standard NS-EN 16798 also defines acceptable operative temperature ranges for buildings with or without mechanical systems, at the three comfort expectation categories [2]. Temperature thresholds for buildings without mechanical systems are compensated for outdoor temperatures between 10-30°C, shown in Figure 2.5.

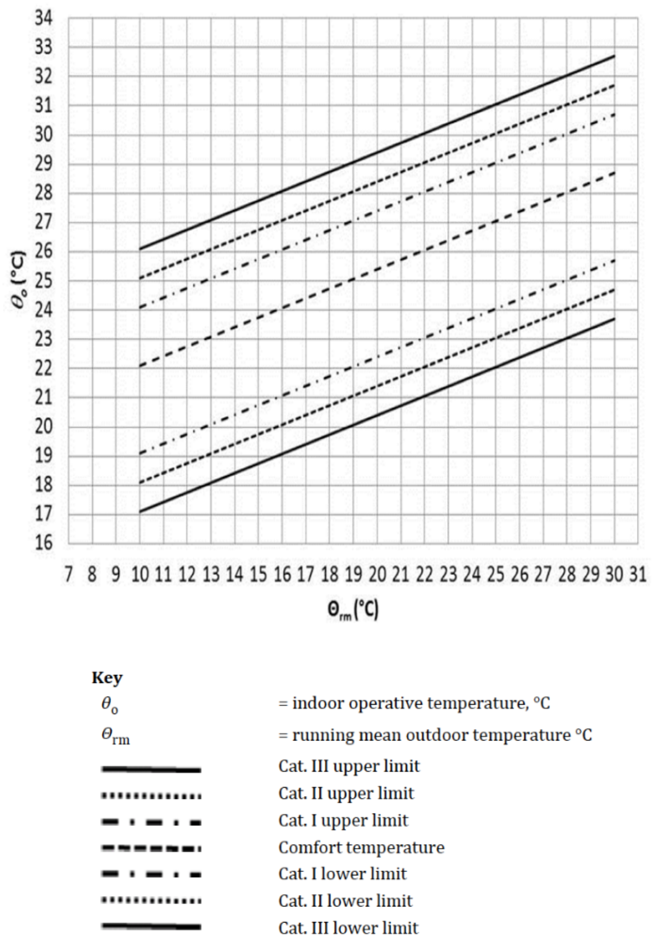


Figure 2.5: Acceptable Temperature Ranges for Thermal Comfort [2]

2.3.2 Indoor Air quality

The indoor air quality (IAQ) is dependent on generated pollutants indoors as well as the air outside of a building. ISO16814 describes three methods for accessing IAQ. Concentrations for pollutants should be kept below the recommended levels to ensure little health effects; IAQ can also be measured by satisfaction of perceived air where a low dissatisfaction indicates high air quality; lastly, IAQ may indirectly be met through satisfying a minimum requirement for ventilation rate [22]. Four main types of pollutants and examples of substances are listed below. Exposure to high concentrations of pollutants may cause both short term and long term health problems such as headaches, fatigue, respiratory problems, asthma or even cancer. TEK17 defines a maximum limit for CO_2 concentration in a room to be 1000 ppm [18].

- Inorganic gases (CO_2, Carbon monoxide, nitrogen dioxide)
- Organic gases (Volatile organic compounds, formaldehyde)
- Non-biological particles (Smoke, dust)
- Biological particles (mould, bacteria, pollen, dust mites)

The minimum required ventilation rate is calculated based on room type, occupancy and materials in the room. For low emitting materials in the room the air flow must ensure a minimum airflow of 2.5 m^3/m^2(0.7 m^3/m^2) when the space is (not) in use and 26 m^3/m per person. Standard occupancy density for offices are 15 m^2 per person and 2 m^2 per person at sales premisses [23].

2.4 HVAC System

HVAC systems are technical systems in buildings designed to ensure an optimal indoor environment. This includes maintaining a comfortable indoor temperature and ensuring enough fresh air supply to the space to keep pollutant levels low. Figure 2.6 shows the principle sketch of a typical AHU. The most common components includes air intake/exhaust grill, filters, heat recovery unit, heating and cooling coils, fans and air ducts to distribute the air.

2.4.1 Heat Recovery Units

The heat recovery unit is essentially a heat exchanger that receives heat from the return air and uses it to heat up the supply air. This way heat energy from the room is reused and less energy is required from the heating coils. The two main types of heat exchangers are regenerative and recuperative.

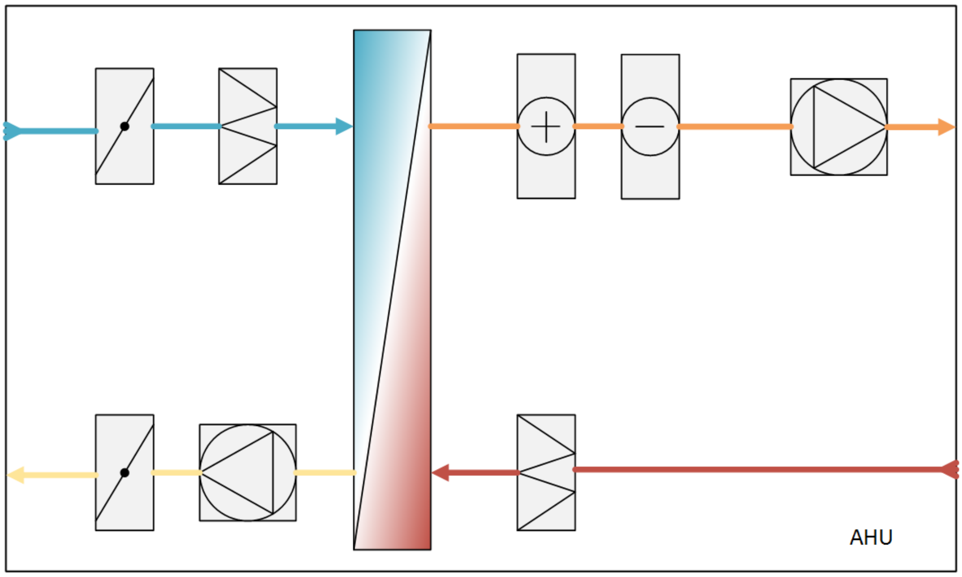


Figure 2.6: Principle Sketch of AHU

Regenerative heat recovery units operates cyclic and alternates between the cold and warm medium. Both heat and moisture are transferred which leads to risks for transfer of pollutants. This type is therefore not ideal for spaces where the return air has a high pollutant level. Recuperative heat recovery units keeps the cold and warm medium separated and only heat, not moisture is transferred through a separation wall. This type of indirect heat exchanger does not transfer pollutants however also does not have as high of a heat recovery efficiency as regenerative units.

The heat recovery efficiency is the temperature efficiency of the heat exchanger calculated based on inlet and outlet temperatures as shown in Equation 2.4. Equation 2.5 shows the calculation basis for energy efficiency which is the share of annual heat demand covered by recovered energy.

Most common types of regenerative units includes the rotary-, chamber-, and cross flow- heat exchangers. The heat recovery efficiencies usually lays between 50-80%. For recuperative units the efficiencies are around 45-65% [24].

$$\eta_T = \frac{t_{after} - t_{outside}}{t_{extract} - t_{outside}} \tag{2.4}$$

$$\eta_Q = \frac{\text{Recovered Energy}}{\text{Annual Total Heat Demand}} \tag{2.5}$$

2.4.2 Heating/Cooling Coils

The heating and cooling coils may be either electric or hydronic. The units heats up or cools the supply air to the correct set point temperature. The hydronic heating coil is a water to air heat exchanger that transfers heat from the water to air while the cooling coil uses cold water as a heat sink to extract heat from the supply air. The heating capacity is dependent on either the water temperature and flow rate for hydronic units or electric power.

2.4.3 Fans and Ducts

The air is distributed throughout the building with a network of air ducts. Pressure losses in the ducting includes friction and impact losses. Fans are electrically driven and responsible for compensating the pressure losses in both the AHU.

Fan power is dependent on the air flow rate, system's pressure drop and overall efficiency as shown in Equation 2.6. The specific fan power (SFP) is given in Equation 2.7 and represents the amount of power required to move one unit of air flow. It is directly related to the system's pressure drop and efficiency. The system's efficiency is dependent on efficiencies of the motor, belt/bearings, fan and capacity control and rarely exceeds 60% [25]. To achieve an efficient fan operation it is therefore important to design a system with low pressure drops and selecting fans with high efficiencies ([26] [27]).

$$\Sigma \mathrm{P} = \frac{\dot{V} \cdot \Delta p_{tot}}{\eta_{tot}} = [kW] \tag{2.6}$$

$$\begin{aligned} \mathrm{SFP} &= \frac{\Sigma \mathrm{P}}{\dot{V}} = [\frac{kW}{m^3/s}] \\ &= \frac{\Delta p_{tot}}{\eta_{tot}} = [kPa] \end{aligned} \tag{2.7}$$

2.5 Building Rehabilitation

To reduce the energy consumption in the building sector it is not enough to only focus on the development of low energy new buildings. Increasing the energy efficiency in existing buildings is just as important. Only 1-3% of the existing buildings are replaced annually, meaning most of the buildings in use are older [8]. It is estimated that of all energy use in buildings, the existing building stock contributes with over 80% [28].

Measures to conserve energy and promote building energy efficiencies are considered retrofit technologies. Some essential retrofit measures include:

- Installing energy efficient equipment
- Implementing advanced controls
- Updating to renewable energy systems
- Change in internal load patterns
- Advanced heating and cooling technologies

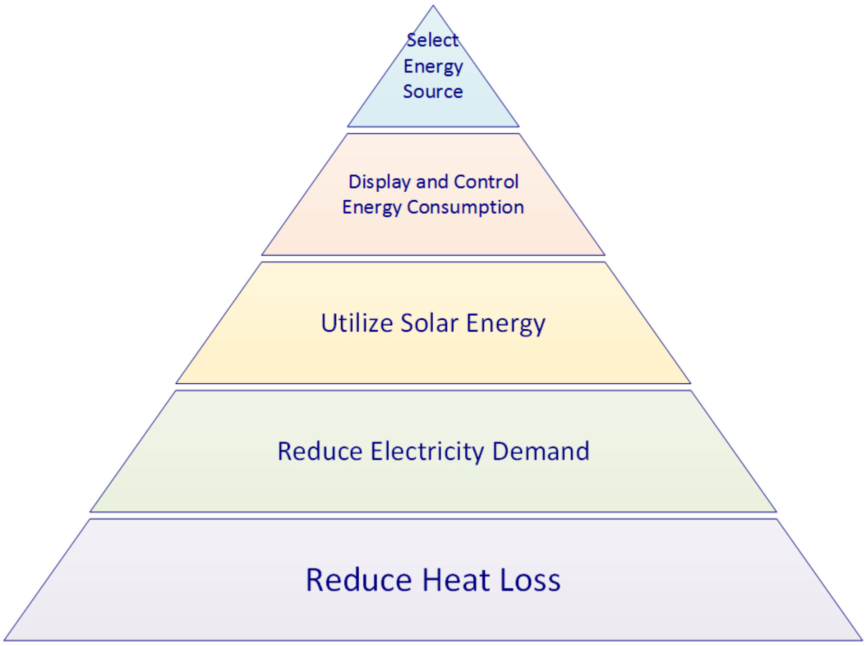


Figure 2.7: Kyoto Pyramid

Successful rehabilitation is dependent on multiple factors enabling motivation, resource and effectiveness in the measures. The measures should be considered in the order of economic payback, complexity and ease of implementation [29]. The Kyoto pyramid as shown in Figure 2.7 provides a guideline for how energy rehabilitation measures should be prioritised. One should first focus on reducing the energy demand, utilise the "free" solar energy, implement adequate control and finally select the energy source [30].

This ensures an optimal solution where the energy demand is minimised and the remaining demand is covered with a suitable energy source.

3 | Methodology

3.1 General

The goal of the project was to develop a simulation model that represented the case building's energy behaviour as realistically as possible. The model was then used in comparison and analyses of possible rehabilitation measures. The project consisted of three main areas: data collection and development of base case model and rehabilitation scenarios.

3.2 Data collection

Access to the building and communication was established with the building owner and its occupants with help of the thesis' co-supervisor, Rune Gjertsen, of GK Inneklima. Existing documentation of the building were given access to, as well as data and reports from previous inspections. Interviews were conducted with tenants in the building to obtain information on perceived indoor environment, experienced problems in the building and possible demands that should be considered. It was also given access to historical energy statistics through the Building Energy Measurement System. The accessibility and validity of the data is discussed further in Chapter 4.4.

3.3 Base Case Model

The base case model was created based on parameter values found through data collection. A detailed description of the establishment process of the model may be found in Chapter 5.

3.4 Rehabilitation Scenarios

Using information from the literature study of building rehabilitation, 10 rehabilitation scenarios were created for comparison with the base case. The rehabilitation measures chosen focused mostly on the bottom two levels in the Kyoto Pyramid: to reduce heat loss and electricity demand. Other measures related to control strategies and energy sources were not considered. As rehabilitation costs were not available, only energy and power reductions were analysed and used as comparison basis.

The scenarios consisted of single- and combination of measures. The degree of change in parameters were based on relative changes in percentage of original values used in the Base Case. Energy and power were analysed with both absolute values and relative savings.

4 | Case Building: NG10

4.1 Description of the Case Building

The case building, Nordre Gate 10 - also referred to as NG10, is a combined commercial and office building of 1260 m^2 located in Trondheim city centre. The building's area is distributed over five levels, with four levels above ground and one under. As shown in Figures 4.1 and 4.2 the east (front) facade faces Nordre gate, its west (back) facade to Stiftsgårds park and the building's north and south sides are shut between two other buildings. The east and west facing facades are coated with dark tinted glass that

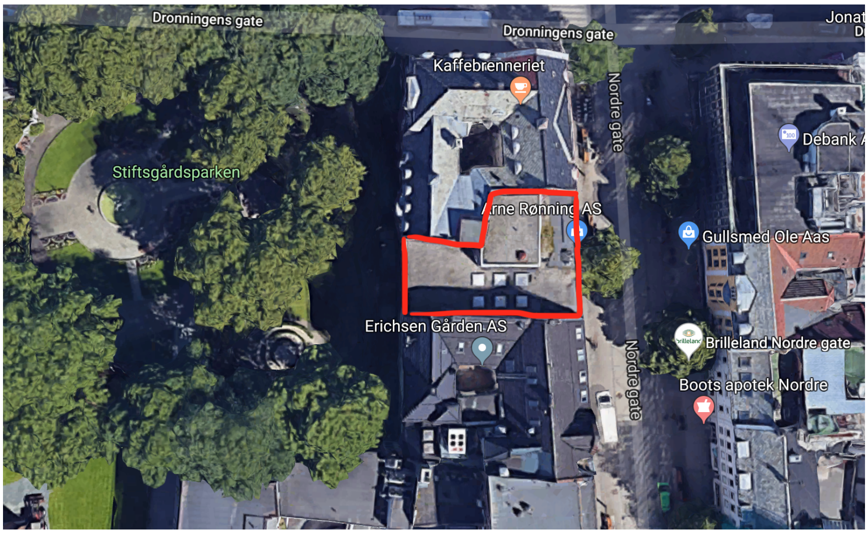


Figure 4.1: Satellite photo

gives a uniform look. Most of the building is in its original form from the construction period in the 70's except for the west facing facade that was updated in 1993. Six ceiling windows are installed on the roof to provide additional daylight into the fourth floor office area.

The building currently houses the clothing store Arne Rønning AS on its ground and basement levels, and architecture firm HUS arkiteker AS on its third and fourth floor. The second floor was previously part of the clothing store but is currently empty and expects to be rented out as an office space in the future.

4.2 Evaluation of Current Indoor Environment and Internal Loads

Seeing that the building had no temperature/air quality monitoring devices installed, feedback from tenants were therefore used as the only source of determining the state of the indoor environment. Analysis were based on results from a survey distributed to employees at the architecture firm in addition to interviews with both the CEO of HUS Arkiterkter AS, Øyvind Hegvik, and owner of the clothing store, Arne Rønning.

A seven point Likert scale was used to determine opinions of the office's indoor environment. Out of 30 employees, 22 responded, giving a response rate of 73%. Results on satisfaction of the indoor temperatures and air quality as well as to what extent draught from windows and noise from the ventilation is experienced as a problem is presented in Figure 4.3. For questions about satisfaction, 1 was set to *Extremely dissatisfied*, 7 to *Extremely satisfied* and 4 being *Neutral*. Questions about draught and ventilation noise were formulated as "To what degree do you experience ___ as a problem" where 1 represents *Very little problem*, 7 *Very big problem* and 4 *Neutral*.

4.2.1 Indoor Environment

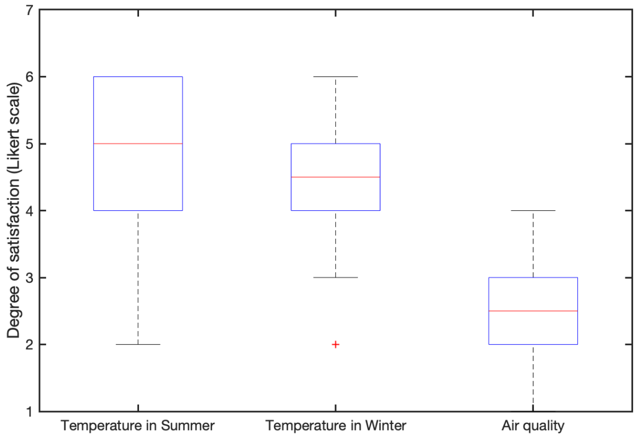
In accordance to the intervju with Hegvik, temperature levels in the building are maintained at an acceptable level. The air quality however, is drawn out as a big problem. Especially in the large meeting room on the fourth floor, employees have experienced high discomfort during meetings to the extent that the firm has sometimes had to rent external spaces for long meetings. At one point, ORAS AS was involved to document air qualities and temperatures at the office. Results showed that CO_2 levels reaching up to 1300 ppm at its peak. Measured ventilation air flow values were found to highly deviate from designed values. Conclusions were made that the space most likely had too low air flow rates and advice was given to review the

(a) From Nordre gate

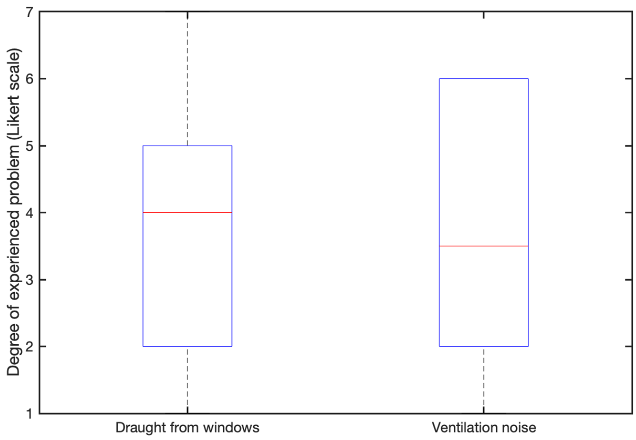
(b) From Stiftsgårds park

Figure 4.2: Nordre Gate 10 Facade

entire ventilation system to determine faults or to find that the system is in fact under-dimensioned. Results from the survey does not indicate draught from windows to be a big problem. However Hegvik explicitly mentioned that the east/west facades were experienced to be extremely poorly insulated. In addition to experiencing high heat loss from the walls, noise from the main street is also very noticeable from the office, reducing productivity at work. Ventilation noise is not a direct annoyance for the tenants but is especially noticeable during the evening when the fan is turned off.



(a) Results of satisfaction on indoor temperatures and air quality



(b) Level of draught and ventilation noise as experienced problem

Figure 4.3: Indoor Environment Survey Results

4.2.2 Internal Loads

The same survey also included questions regarding the use of technical equipment and working hours. Results showed that office hours usually started between 08:00-09:00 and employees were distributed with 55% on the fourth floor and 45% on the third. A typical day ended between 16:00-17:00 where the majority of employees worked five days a week and overtime work often varied between once or twice a month to several times a week. 91% reported that they are at the office more than 80% of the time. All work spaces are in open landscapes. Figure 4.4 shows the number of responses at each time interval for perception on when most people are at work. Most people are in the office between 09:00 and 13:00 and slightly decaying in the 13:00-15:00 interval.

Everyone have at least one computer stationed at their work space. 41% reported to have one additional computer screen and 23% reported to have two. 14% of respondents have more than 80% of the equipment turned on after working hours while 50% reported to have all equipment shut down.

The clothing store is open from 10:00-18:00 on all days except for Sunday.

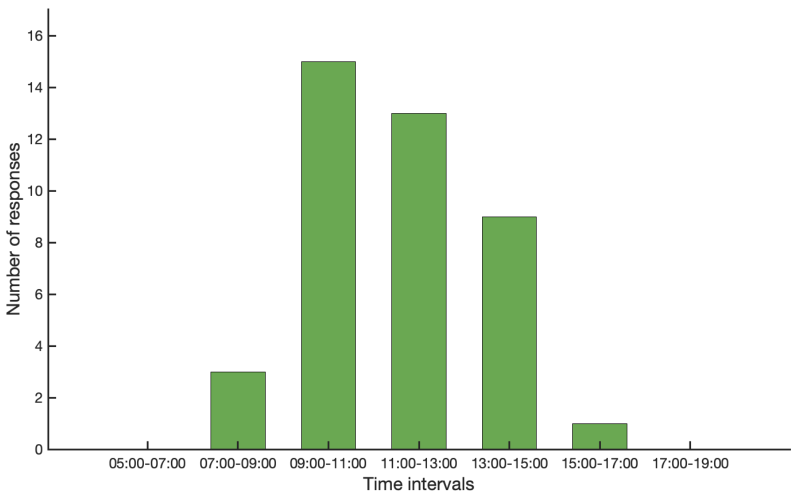


Figure 4.4: Time intervals with most people at work

4.3 Technical Installations

The ventilation system is a balanced mechanical system with an existing air handling unit of estimated 12 000 m^3/h capacity. The system was designed and installed during original construction in the 70's. A rotary heat exchanger ensures a heat recovery from the extracted air and additional heating is achieved through re-heating coils located in distribution ducts on each level. Technical specifications of the air handling unit is presented in Table 4.1. The heating coil capacities were given in system drawings while SFP and recovery efficiencies are empirical values selected based on the unit's age. The ventilation system operates with constant air flow rates and the same operational time for the entire building, from 06:00 to 18:00. It was presumed that the air handling unit, AHU, is turned off outside of operating hours except for when the indoor air temperature fall below 17 °C to avoid excessive heat loss at night.

Table 4.1: Technical specifications of AHU

	U1	L1	L2	L3	L4
Heating coil capacity [kW]	7	14	10	6	6
SFP [kW/m^3s]			3.5		
Heat Recovery Efficiency [%]			55		

Electric heating panels are installed locally to cover the remaining heating demand on the third and fourth floor. The clothing store levels were not equipped with heat panels as historically a high heat gain was achieved through lighting equipment. A downside to heat gain through lighting is high radiant heat asymmetry which causes discomfort to occupants. Through a recent update all lights in the store were upgraded to LEDs. In an interview from the store owner, Arne Rønning, this solution has proven to be much more energy efficient and has given a more comfortable working environment in terms of lighting level and temperature. A warm air curtain by the entrance is used during the winter to avoid additional heat losses through constant openings of the front door. Heating coils on each level are regulated through set point room temperatures of the given level, except for the basement which is controlled by a fixed supply air temperature. Figure 4.5 shows a schematic of the ventilation and room heating system, not including building automation.

Air flow rates were found through old HVAC system drawings of the building. Drawings were available for each floor with air flow rates except for the basement level. All drawings dated back to 1969 in the design phase of the building. Alterations of distribution ductwork has been performed to

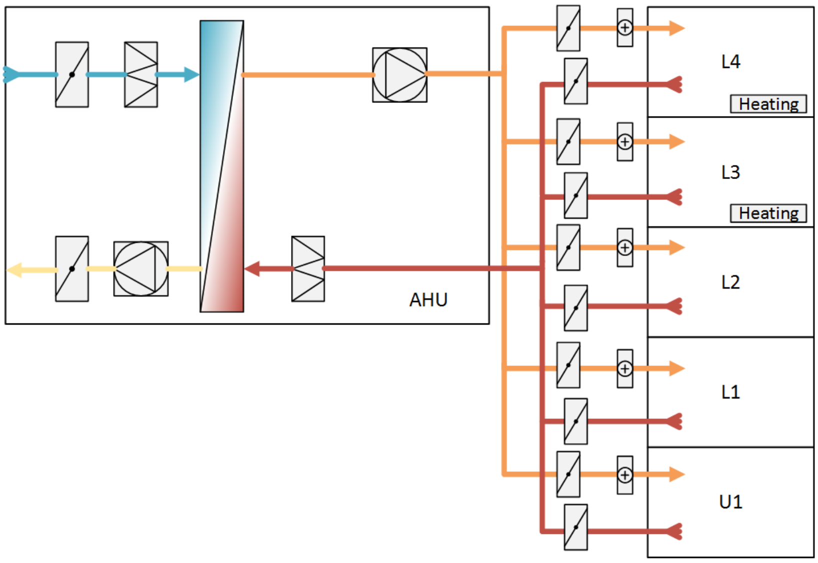


Figure 4.5: HVAC system in NG10

Table 4.2: Air flow rates of NG10

	U1	L1	L2	L3	L4	Total
Designed air flow rates [m^3/h]	2711	4000	2700	2800	2520	14731
80% of designed values [m^3/h]	2169	3200	2160	2240	2016	11785

accommodate various tenants and room layouts throughout the years which were not documented. As the basement level drawing did not give sufficient information to determine its designed air flow rate it was assumed to have the same specific air flow rate as the floor above.

ORAS noticed in their report that the average measured air flow rate was around 80% of the design values. This was taken into account when air flow rates for the model were selected. The designed air flow rates as shown in Table 4.2 sum up to nearly 15 000 m^3/h. Using ORAS' average measured rate, the actual air flow rate is estimated to just below 12 000 m^3/h which is reasoned to be more realistic. Explanations for the oversized flow rates could either be wrong interpretations of the technical drawings or that the air handling unit has a lower capacity than expected.

A detailed zone-based air flow rate calculation based on various bases for occupant loads may be found in Appendix A. Occupancy in TEK17 is based on a design criteria of 2 m^2 and 15 m^2 floor area per occupant for commercial and office buildings. Realistic capacities were based on architectural drawings and normative values. Air flow rates were calculated using minimum requirements of TEK17 as presented in Chapter 2.3.2. Normative air flow rates uses a normative specific air flow rate based on the use of each zone. Given values were obtained through experiences from similar HVAC engineering projects.

The air flow rate should be in compliance with TEK17 to fulfil the Norwegian Building Code. Table A.1 allows for comparison in design values for air flow rates. It's observed that calculations based on realistic occupancy in rooms are lower than TEK17 and are higher using normative specific air flow rates. Minimum requirements of TEK17 only account for removing indoor pollutants and not potential heating or cooling capacity expected through ventilation. Required air flow rates for the building is therefore expected to be higher than TEK17 and lie closer to calculations based on normative values. Indoor environment simulations were run in IDA ICE to ensure acceptable indoor air qualities and temperature. These are presented and analysed further in Chapter 7.5.

The estimated existing ventilation capacity in the building was found to be around 11785 m^3/h. It exceeds the minimum requirements and should therefore ensure a sufficient indoor air quality. The existing AHU was therefore found to be of enough capacity. Drawbacks of the existing system relates to air flow rates that were uniformly distributed on each level without dimensioning to different room's uses. This contributed to poor indoor environment in rooms with a high occupant concentration. The system is also not likely to be dimensioned for cooling purposes, resulting in rooms with high indoor temperatures and troublesome CO_2 concentrations that led to complaints from occupants.

4.4 The Building Energy Monitoring System

Figure 4.6 shows a simplified version of the Building Energy Monitoring System (BEMS). The system measures hourly energy consumption for the building tenants and public area automatically except for levels 2 and 3 that still requires manual readings off of the energy meter. The available measurements are evaluated and analysed further in Chapter 7.1. Energy measurements for the rental area included energy use for equipment, lighting, as well as the reheating coils in each level's distribution duct. Energy use for fans in the AHU was assigned as part of the public area measurement. The public area measurement also consisted of lighting in common areas, other technical systems in the building such as elevator, heating, and the snow melting system. The snow melting system is operated manually to ensure a frost-free walkway outside of the building. Heating and the snow melting system contributes to significant energy use during winter months.

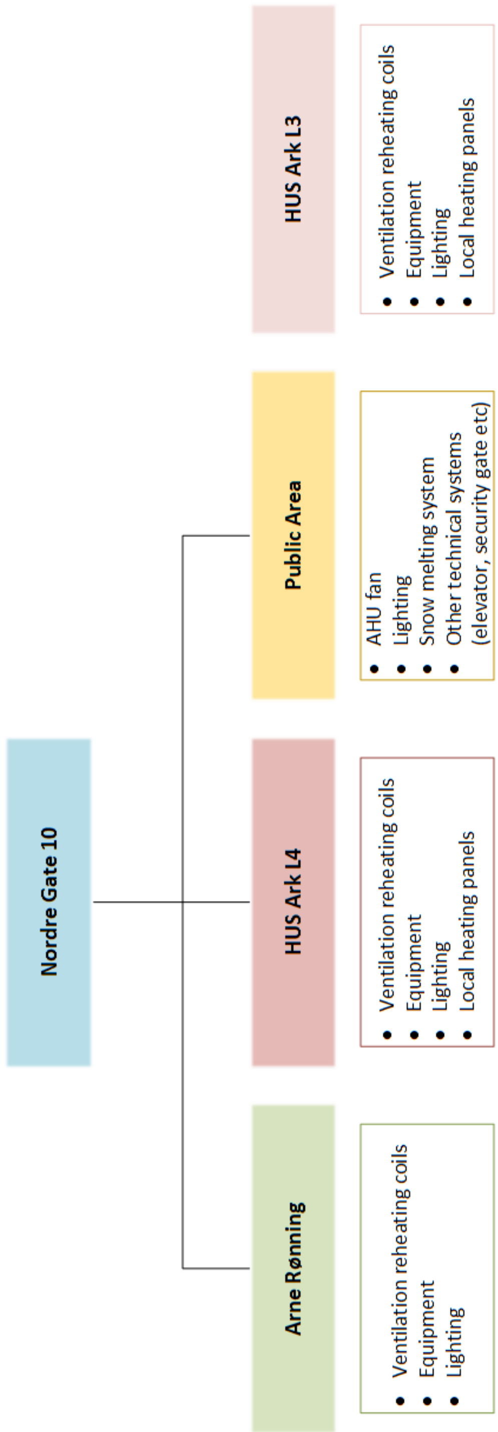


Figure 4.6: BEMS Structure

5 Establishing the Base Case Model

The purpose of the base case was to obtain a model that imitated the building's energy behaviour in a most realistic way. This would set a comparison basis for results from the rehabilitation scenarios. Potential variations in performance between the model and building are laid forward such that further results may be interpreted accordingly.

The model went through numerous updates before being approved as the appropriate base case. The first phase focused on defining proper building parameters in the model. This included U-values for the building envelope and performance specifications of the AHU. Zones were aggregated to one per level in addition to the stairway. Normalised internal loads from NS3031 were applied to zones based on whether they belonged to the clothing store or office. Ideal heaters were installed on each level to cover the heat demand. All other relevant inputs were retrieved from standards and building codes. Results from this phase were used to decide appropriate building parameters. The simulated energy performance was compared against measured data and checked for correct behaviour in relation to outdoor temperature.

Once the physical parameters of the model were defined, the second phase centralised around dividing the space into more detailed zones and inserting more realistic air flow rates, set points and internal loads into each zone. The model was repeatedly calibrated against measurements from the building. At the same time, window opening and operation strategies were under continuous revision. The below sections go into more details on specifications of the completed Base Case model.

5.1 Building's Thermal Performance Parameters

Correctly input building properties play a central role in making a model as realistic as possible. Unlike in newer buildings where structures of the building are well documented and readily available, documentation of older buildings generally have more missing pieces and may have been lost over the years. In the case of NG10, although some documents were kept from the initial building period, information on materials used and facade structures were not available. It was also not possible to know what quality of work the carpenter carried out which makes determining infiltration and thermal bridge heat losses very hard.

As the building was constructed in the 1970's, the applicable building code is TEK69 [31] which defines the upper limit of the heat-transfer properties of building parts. In most cases insulation properties in materials will decay over time and it was therefore expected for the building to have a higher heat loss factor than requirements given by the building code. NVE included a summary of typical values found in the "energy labelling system" as a guide for energy labelling buildings [32]. The values are based on a combination from standards and empirical data.

Building parameters used in the simulation model are presented in table 5.1. Values were based on suggestions from the *Energy labelling system library*, building codes and through inspection of the building and available documents.

Table 5.1: Input parameters for NG10 simulation model

Building property	Input values
External walls [W/m^{2}K]	0.66
Windows [W/m^{2}K]	2.8
Roof [W/m^{2}K]	0.6
External floor [W/m^{2}K]	0.7
Thermal bridge [W/m^{2}K]	0.08
Infiltration [ACH]	7

5.2 Facade and Zone Divisions

3D views of the model in IDA ICE are presented in Figure 5.1. The model replicates the real building by its shape, size, facade as well as modelling the neighbouring buildings. The shaded screen in Figure 5.1b represents buildings on the opposite side of NG10 along Nordre Gate. The framed structures on each side of the model is to resemble the adjacent buildings. These were featured to simulate a more realistic wind/pressure profile and thermal performance on NG10's external walls.

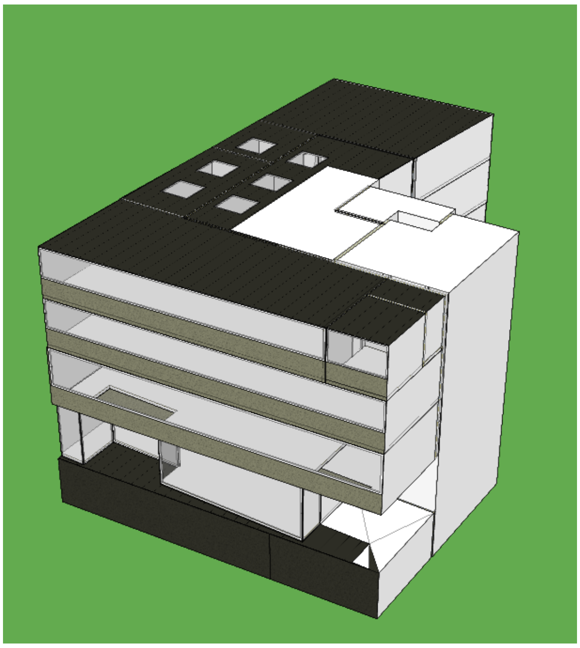
Figures 5.2 and 5.3 shows the zone divisions in the model. These were assigned based on existing rooms in the building and their function. This information was obtained through inspection of the building as well as architectural drawings provided by the tenants. The clothing store consisted of shops on two levels and a connected storage area. The storage area was defined as an individual zone to distinguish between varying internal loads and occupancies. The same applies to the stairway which was defined as a common area shared by all tenants. This also made it easier to later group the simulation results according to the BEMS structure as shown in Figure 4.6. Although L2 was not occupied during the scope of this project it was still defined as a zone in the model. The zone was defined with no internal loads or connection to the HVAC system. The main purpose was to include thermal connections between its adjacent floors/ceilings and the stairway.

The office levels were divided into more zones than the levels below due to more variation in types of activities and uses of each room. Large openings were established between zones where there were no real partitions. Perks of doing so is the possibility to define more realistic load profiles and set points. However a major drawback is that air is not mixed between zones and the computation time increases compared to more aggregated zones.

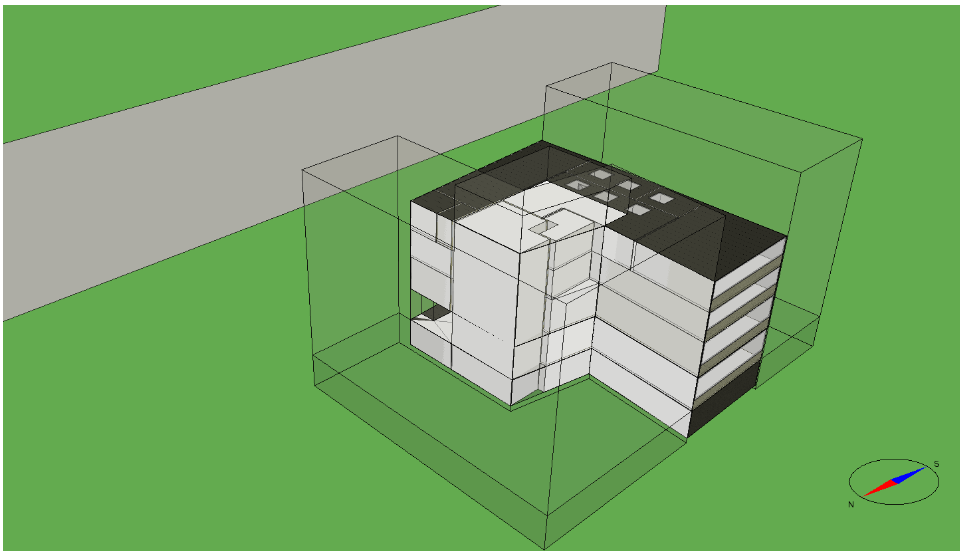
5.3 Occupancies

5.3.1 Arne Rønning

It was difficult to determine a realistic occupancy for the clothing store as customer loads varies greatly by the day of week and time of day. Since it was not possible to obtain real statistics from the store an algorithm was used to generate a fictional load profile for the entire year. The algorithm created semi-randomised half-hourly occupancy for the store's opening hours. Threshold values as presented in Table 5.2 were established to imitate varying customer loads for different days of the week. It was assumed that the store would be busiest during Saturdays, followed by Fridays. The minimum value indicates the assumed number of store employees always present. The developed profile was normalised to be implemented on both L1 and U1. Full occupancy was assumed to be 10 occupants in an half-hour period on the first floor and 6 occupants for U1.



(a) Building Facade

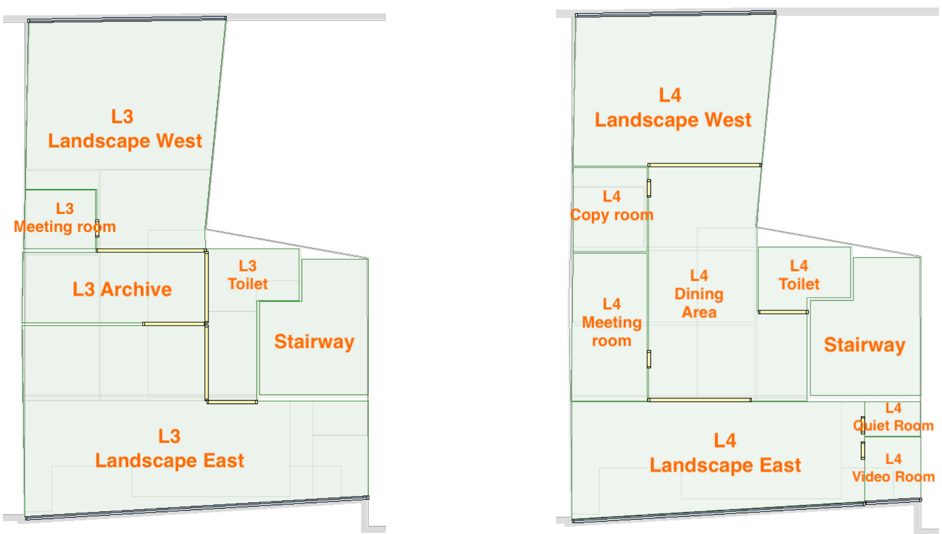


(b) Model with Shading and Adjacent Building

Figure 5.1: NG10 3D Model

(a) U1 (b) L1 (c) L2

Figure 5.2: Arne Rønning Zones



(a) U3 (b) L4

Figure 5.3: HUS Ark Zones

Figure 5.4 illustrates the developed load profile for the first two weeks in January as an example. The occupancy hits higher peaks during weekends as compared to the rest of the week, illustrated in green for Friday and orange for Saturdays. The randomness of the algorithm allowed some variation of the same weekday throughout the year to better reflect the unpredictability of shop customers.

Table 5.2: Arne Rønning Occupancy Profile Threshold Values

Day of Week	**Threshold Values**	
	min	**max**
Monday Tuesday Wednesday Thursday	2	5
Friday	3	8
Saturday	3	10
Sunday	-	-

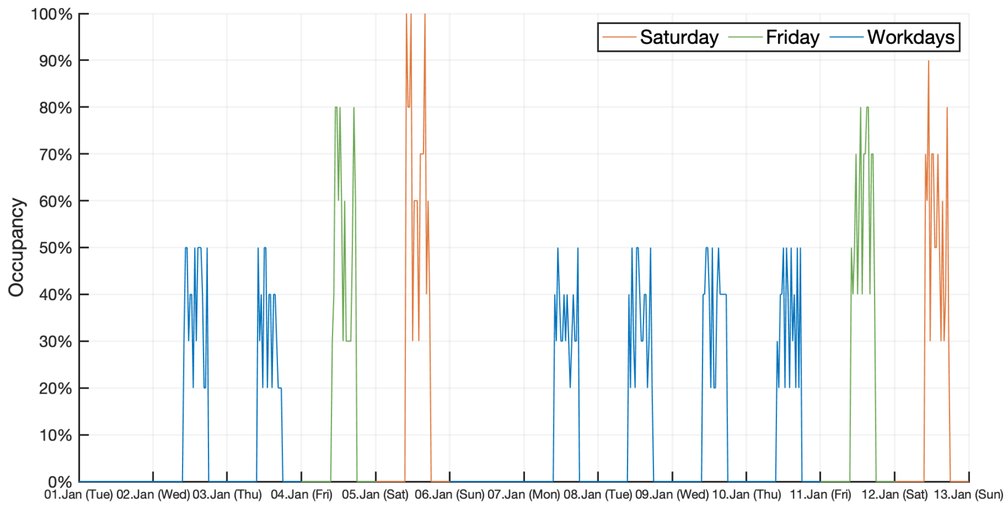


Figure 5.4: Example of Clothing Store Occupancy

5.3.2 HUS Arkitekter

The total occupant capacity for HUS Arkitekter were found to be 42 based on furnishing plans provided by the tenants. Occupied zones in the office were categorised into 3 main types: landscape, meeting rooms, and dining area. Occupancies in these zones are dependent on both the overall office occupancy as well as each other. A fictional office occupant schedule was created based on survey results as discussed in Chapter 4.2.2. In addition to an overall office occupancy, a normalised meeting room occupant profile was created in collaboration with another master student involved in a project evaluating realistic internal loads of a selected office building [33]. Large dataset was obtained by the use of multiple sensors installed. Although the building was both larger and occupied by different type of tenants than NG10, the dataset formed a basis for an applicable schedule to simulate.

The normalised meeting room occupancy profile contained half-hourly data for an entire year. Holidays, weekends and evenings could be observed with promptly lower occupancies. To simplify the simulation model it was decided to generate 24-hour schedules for three type of periods: normal work days, summer holiday and Easter. The overall office occupancy for summer and easter were relative to a normal work day consequently 37.5% and 72.2% lower. All zone occupancies were assumed to be proportional hence adjusted with the same factor. Additionally, all weekends were assumed to have no occupants. The schedules should reflect some of the personnel load diversity even though it did not include all holidays through out the year. It is also possible that there are some occupancy during weekends which was not simulated.

Figures in Appendix B shows the developed schedules for the overall office, meeting rooms, dining room, and landscape for workdays, summer and Easter holiday. The summer schedule was defined to apply for workdays in the period 1 July - 31 August 2019 and Easter schedule for the week of 15 April - 19 April 2019.

5.4 Internal Loads

5.4.1 Office

Equipment

Equipment loads in the office levels were categorised into five main profiles based on its usage: Landscape, Meeting rooms, Video rooms, Copy room and Dining Area. Capacities per zone were defined based on the number of occupants and size of room in accordance to the guideline by [34]. An overview of equipment capacities for relevant zones as well as load profile categories are presented in Table 5.3.

Table 5.3: Overview of Equipment Capacity in Office Zones

Zone	Capacity [W]	Category
L3 Landscape W	1080	Landscape
L3 Landscape E	1440	
L4 Landscape W	1080	
L3 Landscape E	1440	
L4 Copy Room	200	Copy Room
L4 Video Room	200	Video Room
L4 Quiet Room	200	
L4 Dining Area	200	Dining Area
L4 Meeting Room	600	Meeting Room
L3 Meeting Room	300	

To simulate the equipment use in various zones several control systems based on occupancies were defined. Equipments in the landscape zones were dependent on the number of occupants present in the office. Taking into account that occupants may move around zones during the day yet still have computers on at their desk. It was assumed that 15% of equipment remained on during the night. Equipment use in meeting rooms were defined to operate on three levels: 100% when the occupancy is higher than 20% capacity, 60% for occupancies between 0-20% occupancy and a 30% constant base load when the room is not in use. Smaller work rooms such as the video room was defined without a base load and assumed to operate 100% when the room is in use. The copy room operates with a 70% base load at night and 100% between 08:00-17:00. The dining room was assumed to have a base load of 60% and full equipment load when in use.

Lighting

Normalised lighting load from NS3031, 9.62 W/m^2, was applied over all office zones. No lighting strategies were implemented and it was assumed that all lights were on between 7:00-17:00 for all work days.

5.4.2 Clothing Shop

Less information were available for the the internal loads in the clothing shop. Equipment was assumed to be operating 100% of the time and the load was determined by the average measured daily energy use on Sundays, found to be 6.25 W/m^2. Light was assumed to be turned on and off 30 minutes before and after the shop's opening hours to take into account the store workers opening and closing the store. Load was calculated based on measured daily energy use during the summer when there is no heat demand and the constant equipment load, resulting in 15.3 W/m^2, slightly lower than the normalised values from NS3031.

5.5 HVAC System

5.5.1 Ventilation

As discussed in Chapter 4.3 the ventilation system consisted of an air handling unit with a rotary heat exchanger and reheating coils located in each each level's distribution ducts. Air flow rates were selected based on values in Table 4.2: 3.22 L/s m^2 for Arne Rønning and 2.15 L/s m^2 for HUS Arkitekter.

Using "Advanced Mode" in IDA ICE it was possible to replicate the HVAC system realistically. Figure 5.5 shows the AHU schematics in IDA ICE while schematics for the building may be found in Appendix C. Heating coils were removed from the standard AHU model and later installed between the supply air from AHU and entering air to zones. The defined operating time of the system where the AHU runs at full capacity is between 06:00 to 18:00 on all days except for Sundays. An embedded sensor turns on the system as required to ensure the indoor air temperature not subceeding 17 °C at non-operating hours. This was implemented as a fan control structure sending operation signals to both the supply and return fan. The general structure of the model's heating system is laid out in Figure 5.6 which shows the four active reheating coils and its connection to building zones as well as additional room heating units on office levels. Air-split chambers after the heating coils allowed for a heating coil to heat up air for multiple zones.

Set point temperatures for the shop and office areas were respectively 18°C and 22°C. A lower temperature was allowed in the clothing store considering that occupants generally are more active and tends to stay for a shorter period of time. It was also expected that office workers should prefer a higher indoor temperature seeing that they are mostly stationary at their desks. Both set point values are within recommendations presented in Chapter 2.3.1.

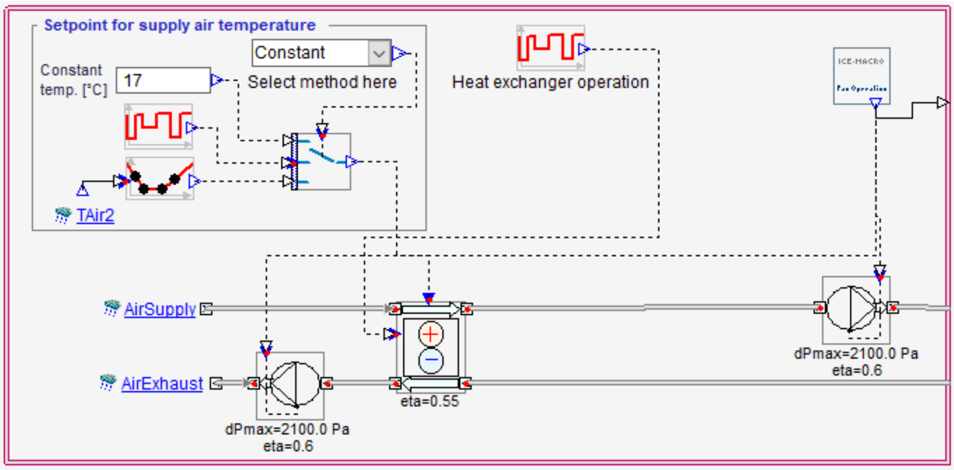


Figure 5.5: AHU Schematics in IDA ICE

Reheat Coil

The heating coil on U1 maintains a constant supply air temperature of 21 °C to both the shop area and storage. The rest of the heating coils are PI-controlled to maintain the room's set point temperature. Figure 5.7 shows a connection diagram for the PI controlled reheat coils in the model.

Maximum supply air temperature is kept at 3 °C above the room set point during operating hours and 27°C at night. The minimum temperature is kept at 17 °C. This was to ensure proper air circulation and avoid thermal discomfort caused by vertical air temperature gradients. Supply air temperature was allowed to be higher during night time for more efficient heating without having to worry about occupant's comfort. The PI control unit compares the level's average room temperature with set point and generates an output signal between 0 to 1. The signal is then transformed linearly to a heating coil set point within the defined temperature interval.

5.5.2 Heating

Figure 5.6 also shows the electric radiators connected to office landscapes on levels 3 and 4. It was assumed that radiators in each zone had a total capacity of 3kW, corresponding to around 3-4 wall mounted radiators. These radiators covered additional heating demands for the level and were simulated to be proportionally controlled. This differed slightly to the real life situation where radiators were manually controlled by the occupants. Occu-

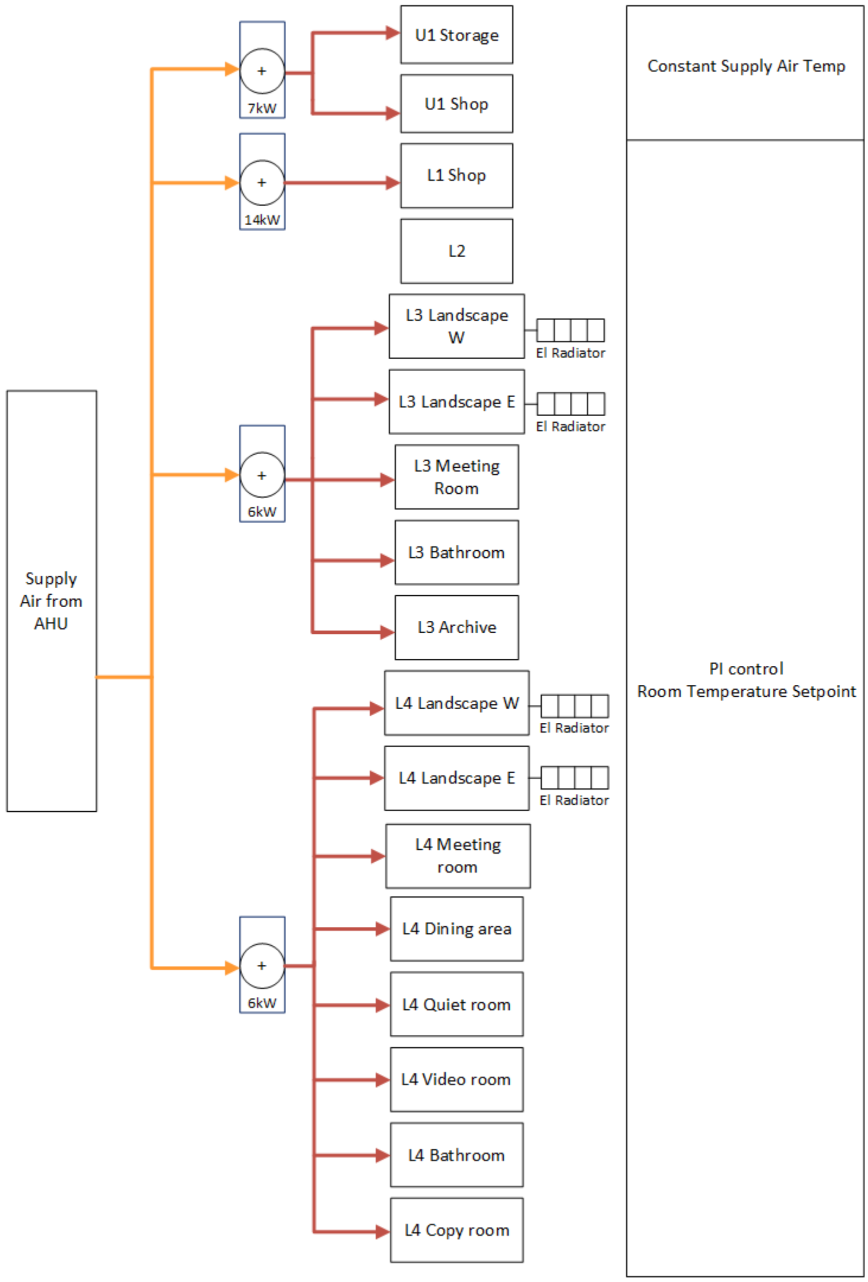


Figure 5.6: Principle Sketch of Modelled Heating System in Base Case

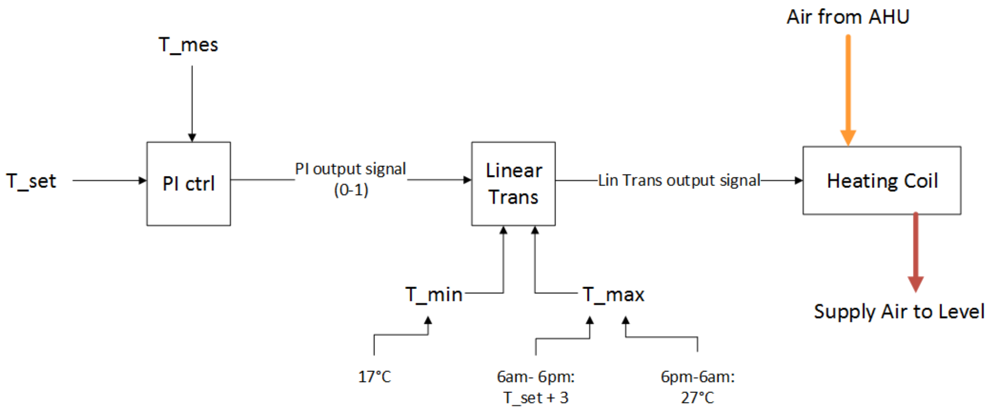


Figure 5.7: Reheat Coil Connection Diagram

pants would most likely not adjust the radiator as often and rigid. It was expected that there may be a lag in response by the users, especially during summer times in combination with opening of windows. Users may forget to turn off the radiator and choose to open windows at the same time. An attempt to simulate this was implemented by setting a long time constant for the controller to 3600s, representing the time between each input signal.

5.6 Openings

5.6.1 Windows

It was assumed that 30% of windows on both building facades were openable on the office levels. A schedule and control system tried to simulate the occupant's response to open the windows for cooling and ventilation in warmer months. The control process is shown in Figure 5.8. The time schedule signals positive for when the office level is occupied between April and September, only then can the window be opened. PI control was used to resemble the user's behaviour with a time constant of 1800s. It was expected that occupants would need some time to react to the temperature before opening or closing the window yet still more frequent than controlling the radiator.

The cooling set point was defined to be 24 °C when windows were previously closed and 3 °C lower for when the window is already open. This approach tried to resemble occupant's choice of leaving the windows open for longer during summer months partially for convenience and also to achieve better thermal comfort.

Windows were defined to either be opened fully or 50%. Control signals from the PI controller were therefore transformed into three possible signals: 0 for signals less than 0.25, 0.5 for signals between 0.25 and 0.75 and 1 for signals over 0.75. Lastly a comparator was put in so windows are kept closed when the outdoor air temperature is higher than inside.

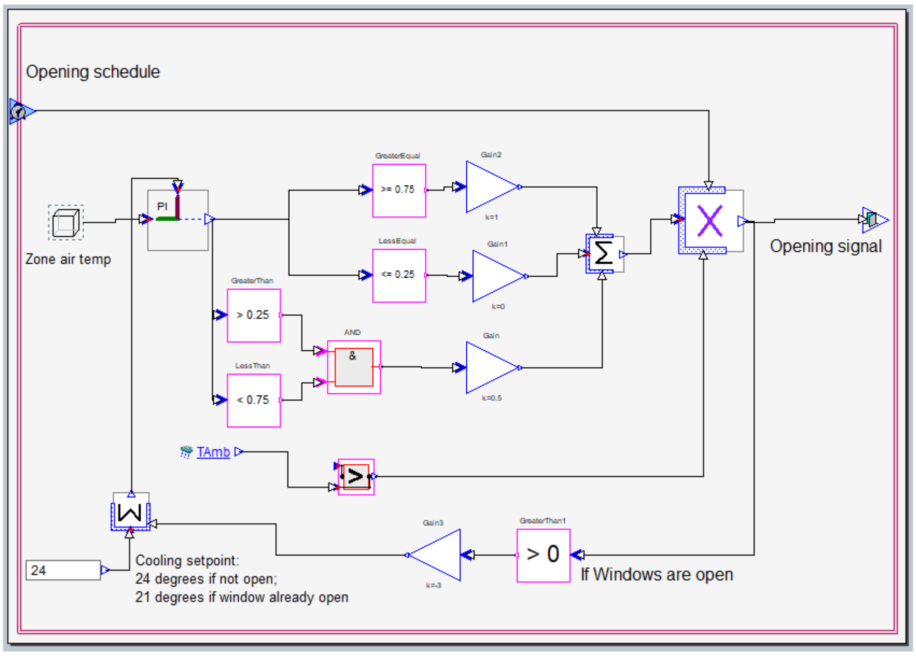


Figure 5.8: Office Window Opening Control

Shading

Shading of windows on levels three and four were in the form of internal blinds regulated by a time schedule and sun exposure. The time schedule was defined such that blind can only be drawn in the period when the office is occupied. The internal blinds reduces solar gain through windows by 35% without reduction in the window's U-value.

5.6.2 Shop Entrance

The shop entrance on the first floor is equipped with an air curtain to reduce heat loss during winter months. This was however not implemented in the model as specifications of the air curtain was not available. Instead, a generic opening schedule of 5 minute openings every half hour between 09:30 to 18:30 as shown in Figure 5.9 was used on all operating days. Through discussion with the thesis supervisor from GK Inneklima it was brought up that air curtains in rooms with higher ceilings does not necessarily provide sufficient insulation due to not enough air velocities.

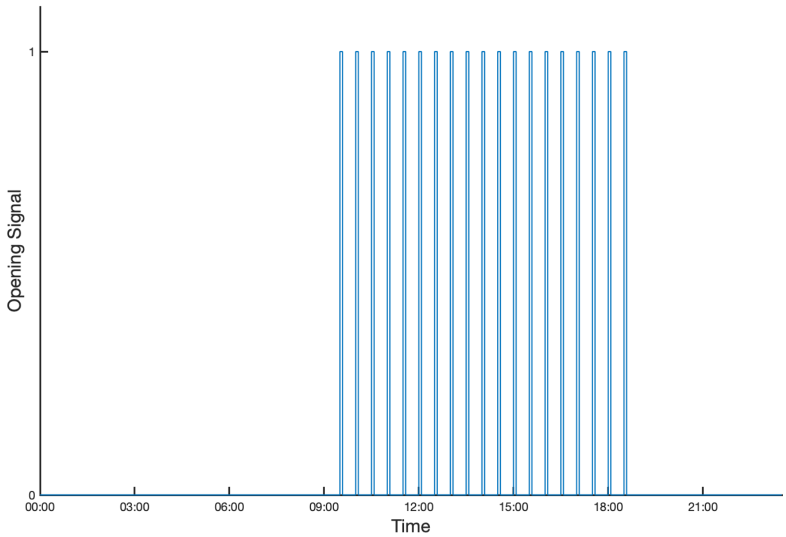


Figure 5.9: Shop Entrance Opening Schedule

6 | Rehabilitation Measures

The Kyoto Pyramid as presented in Chapter 2.5 was used as a guideline for the selection of possible rehabilitation measures for the building. This thesis focused on the first two levels of the pyramid, to reduce heat loss followed by reducing the electricity demand. To reduce heat loss implies that one should try to improve the physical properties of the building. Once the heating need is minimised it is then possible to improve the energy use even further by upgrading the technical systems and internal loads.

The following sections presents scenarios for various rehabilitation measures and combinations to be compared in terms of their relative energy savings and/or improvement in the indoor environment.

6.1 Rehabilitation of the Building Envelope

Five scenarios were created to analyse potential energy savings through rehabilitation of the building envelope's physical parameters, presented in Table 6.1. The scenarios consisted of individual and combinations of these measures. The building owners had explicitly stated that upgrading facades and the technical system is part of their plans in the near-future. This analysis could therefore be especially useful to them when prioritising and dimensioning how much rehabilitation is required to meet their energy ambitions. Each scenario consists of some parameters that are altered while the rest remains as modelled in the base case. There are three sub-scenarios (a, b, c) under each with varying degrees of change. All measures were taken as a percentage change of the original value from Table 5.1.

Table 6.1: Building Envelope Rehabilitation Scenarios

Scenario		Rehabilitation	Changed parameter	Relative Change
1	a b c	Windows	U-value	-20% -40% -60%
2	a b c	Walls and Windows	U-value	-20% -40% -60%
3	a b c	Roof and Floor	U-value	-20% -40% -60%
4	a b c	Infiltration	ACH	-20% -40% -60%
5	a b c	All Envelope Properties	-	-20% -40% -60%

Table 6.2: AHU Rehabilitation Scenarios

Scenario		Rehabilitation	Changed parameter	Relative Change
6	a b c	Heat Recovery	Recovery Efficiency %	+20% +35% +50%
7	a b c	SFP	kW/m^3s	-20% -35% -50%
8	a b c	Improved AHU Performance	Recovery Efficiency % kW/m^3s	±20% ±35% ±50%
9	a b c	All Envelope Properties and AHU	All	±20% ±35%/40% ±50%/60%
10		TEK17		

6.2 Improvement of AHU

The existing air handling unit in the building is nearly 50 years old and have a much lower performance efficiency than installations today. An improved AHU may reduce both the building's heat loss by recovering a larger portion of heat from extract air as well as lower the fan electricity use. Table 6.2 presents the relevant scenarios and conditions for evaluating potential energy savings. Scenario 9 and 10 included rehabilitation scenarios of the building envelope to consider all mentioned measures and minimum requirements defined by TEK17. Input values of each scenario are listed in Appendix D.

7 Results

7.1 Evaluation of the Building Energy Measurement System

Manual readings of BEMS were made inconsistently and with large time intervals, leading to challenges in modelling a detailed energy consumption performance. As the second level was not occupied, the space was neglected. Level three is occupied by HUS Arkitekter and was therefore assumed to have a similar energy profile as the floor level above. An energy adjustment factor of 0.7 was obtained by analysis of the total energy use for the HUS Arkitekter and obtained energy use for L4.

7.1.1 Measurement: HUS Arkitekter

As mentioned previously only one level of the architect office is connected to the BEMS. Also, data for the fourth floor were only available from 17. July 2019 and onwards meaning that there were not a full year of data available. To overcome this issue, linear regression was used to determine any missing data.

To not overcomplicate the regression model two parameters were selected to be most influential, outdoor air temperature and whether it is a workday (Monday - Friday) or weekend. The available data was first filtered for workdays and weekend. Two separate regression models were then created with outdoor air temperature as the dependent variable. Daily energy values were used to phase out differences in hourly values.

Figure 7.1 shows the regression model for three instances: workday, weekend and all days combined. As seen in the last subfigure the energy use is lower during weekends and increases in difference for lower outdoor temperatures. Taking into account the day of week increases the model's sensitivity and reliability. The regression model is only valid for temperatures below 20 °C as energy consumption evens out at around 20 kWh/day for warmer temperatures. This did not have immediate influence when completing the missing data from 2019 as temperatures were all below threshold values.

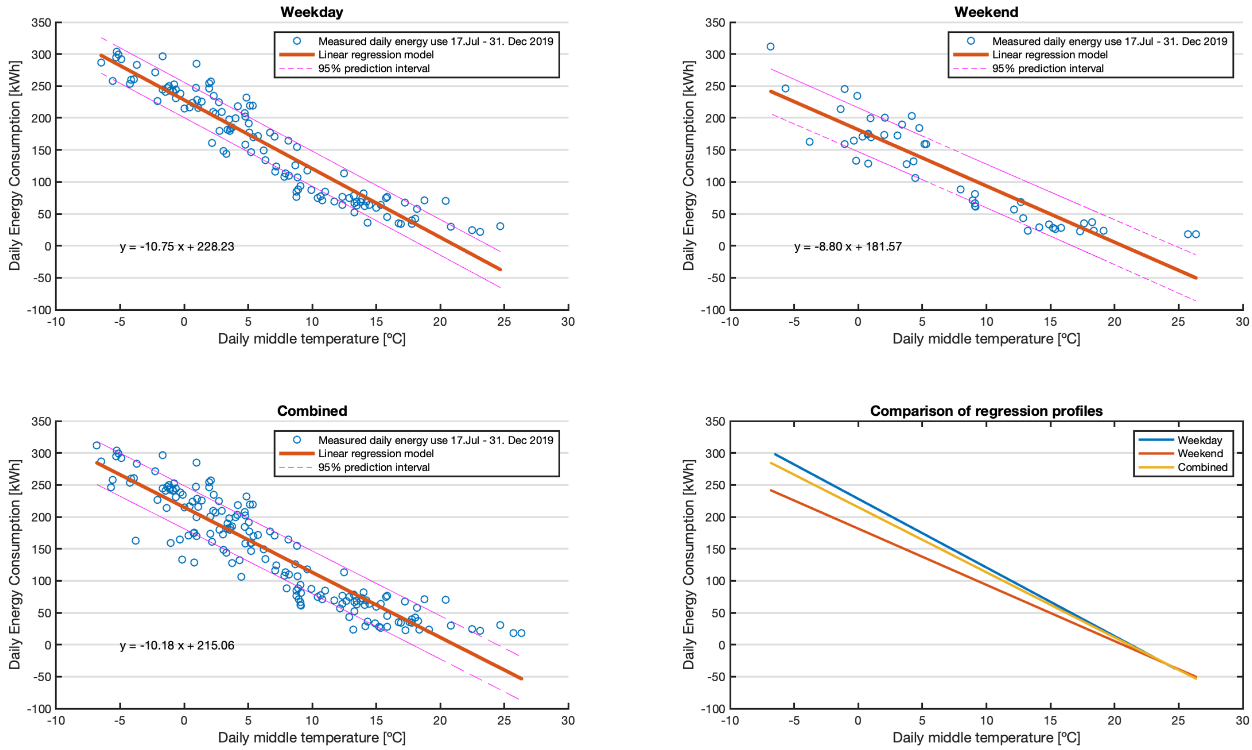


Figure 7.1: Regression models for HUS Ark L4

The complete energy profile for HUS Ark level four is displayed in an ET-diagram in Figure 7.2. The diagram shows the daily energy consumption in relation to the outdoor temperature. The model proved to be solid during winter months when heating demand is high. During warmer months it's observed that internal loads and office operations may be more influential on the energy use. The regression model did not take into account holidays and other "low"-periods in the office. This is a limitation that may explain how the predicted energy consumption for June/July lies higher than measured values for July/August. Since no other form of measurement of activity and user operation is available in the building it was difficult to obtain a more accurate regression model for the scope of this project.

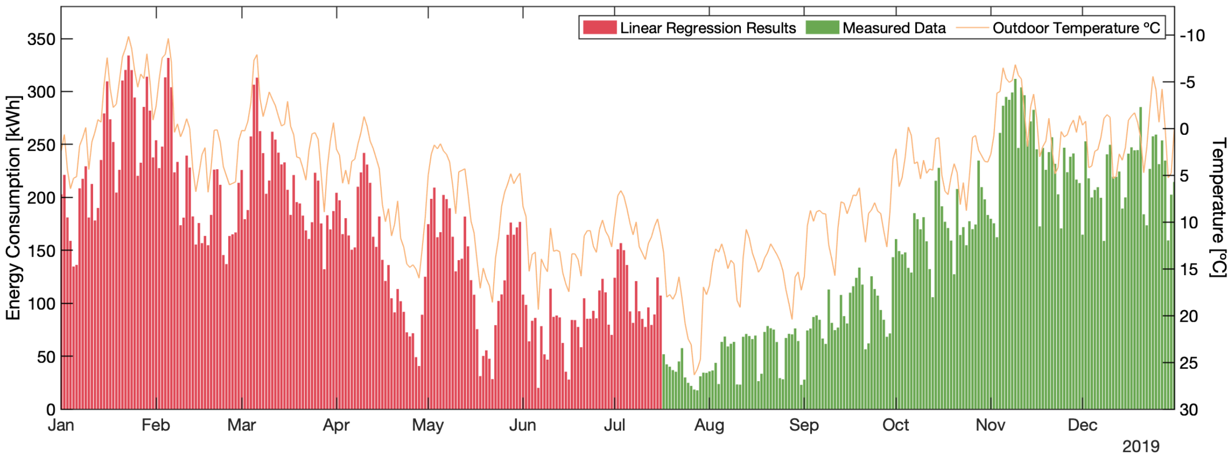


Figure 7.2: Completed annual energy profile for HUS Ark Level 4

7.1.2 Measurement: Arne Rønning

Similar to the office levels, measurements for Arne Rønning included energy use of reheating coils on the shop levels as well as internal loads. Evaluation of the correctness of the measurement data for 2019 is evaluated further in Chapter 7.3.3

7.1.3 Limitations of the Existing BEMS

The main limitation of the existing BEMS was its low measurement structure complexity. Measurements were only given up to the scale of one level or one tenant and did not provide information on allocation of its energy use. It was therefore not possible to assess how much each load (equipment, lighting and heating) contributed to its total consumption. This also restricted the possibility for a more detailed calibration of the base case model.

7.2 Evaluation of the Building's Measured Energy Performance

The measured annual energy use for the entire building in 2019 was 258 437 kWh. Figure 7.3 shows the allocation of energy use to each tenant and common area. Energy use for level three was calculated by subtracting energy use for level four from the total annual energy use for the entire office. A 30% lower energy use on level three may be explained by a lower occupancy in the office landscape as well as more movement to the fourth floor during lunch and meetings.

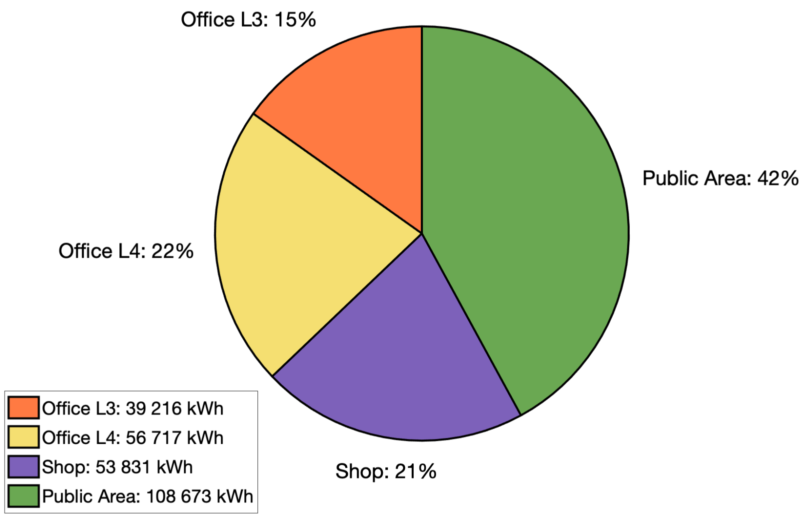


Figure 7.3: Annual Energy Allocation of NG10

Measurements show that the Public Area accounts for most of the building's energy use during the year, followed by office levels. The specific energy use for office levels is also higher than for the clothing store, respectively 158.8 kWh/m^2 and 112.2 kWh/m^2. Measurements deviate from statistical energy uses for office and commercial buildings presented in Chapter 2.2.1 where the specific energy use are both on the lower side of its statistical reference. This is most likely linked to missing AHU energy use in the tenant's energy measurements. As the AHU energy is capsuled within the Public Area measurements it was not possible to isolate it from the BEMS data.

According to standards, commercial buildings are expected to have a higher energy demand than offices. This was not the case for NG10. One explanation could be that the shop has a higher ventilation energy use as shown in Figure 2.1. It is also possible that the shop had a lower temperature set point and more efficient internal loads. It was however also noted a possible glitch in the measurement system or some operation problem during the fall season which could have effected the shop's annual energy use. This is justified further in Chapter 7.3.3 with comparison to the simulation results.

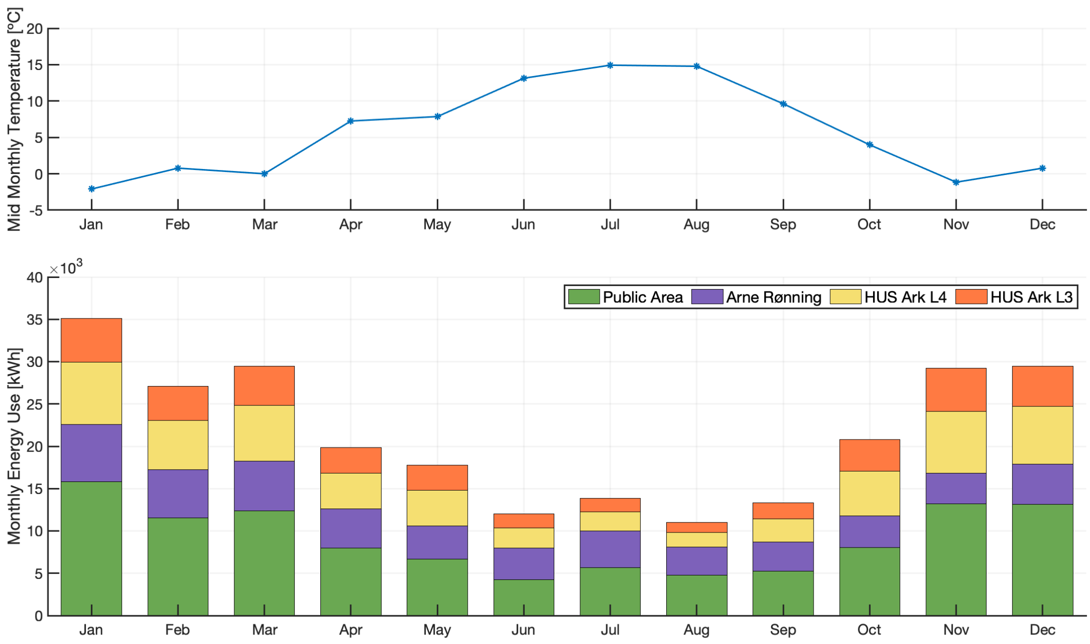


Figure 7.4: NG10 Monthly Energy Use

Figure 7.4 shows the monthly energy use of the building and mid temperatures. The energy use was at its highest during the winter months when there is a considerable heating demand. The figure also illustrates how heating need is highly reliant on the outdoor air temperature. The monthly mid temperature in February was higher than in March which corresponded to a lower energy use in February compared to March. Energy use registered for Public Area had the highest change in energy use between seasons due to the snow melting system. Energy use during the summer months were dominated by internal loads and the AHU's fan energy consumption.

7.3 Base Case Results

7.3.1 Simulated Building Annual Energy Use

The simulated annual energy use for the base case was 233 070 kWh, including energy use for heating, internal loads and AHU fan. This corresponded to a specific energy use of 215 kWh/m^2 (area for L2 not included), 23.4

kWh/m^2 less than measured. Figure 7.5 shows the simulated monthly energy use with measured values in the background where the difference in monthly energy were highest for winter months. Energy uses per measurement level are analysed in more detail in the following subsections.

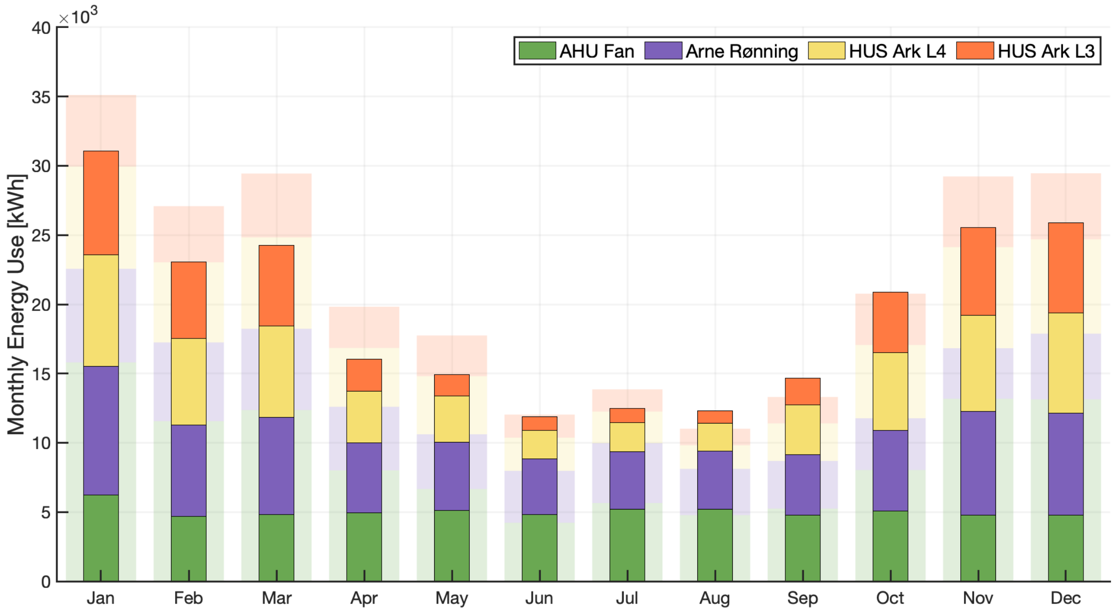


Figure 7.5: Base Case Monthly Energy Use

The simulated heating duration curve is presented in Figure 7.6. The base load consists of mostly heat from the electric radiators on the office levels and accounts for 70% of the year. Around 600 hours of the year (7%) operates with the maximum installed heat capacity, both radiator and reheat coil. This indicates that the HVAC system may be under-dimensioned, which is supported by the indoor temperature measurements as presented in Figure 7.22. The duration curve also shows that there is a heat demand for nearly 90% of the year, also for large parts of the summer. This was due to the simulated lag in response time for closing windows and assumption that occupants would forget to turn off the radiators. With a more appropriate control strategy during the summer it could be possible to reduce some of the excess heat demand.

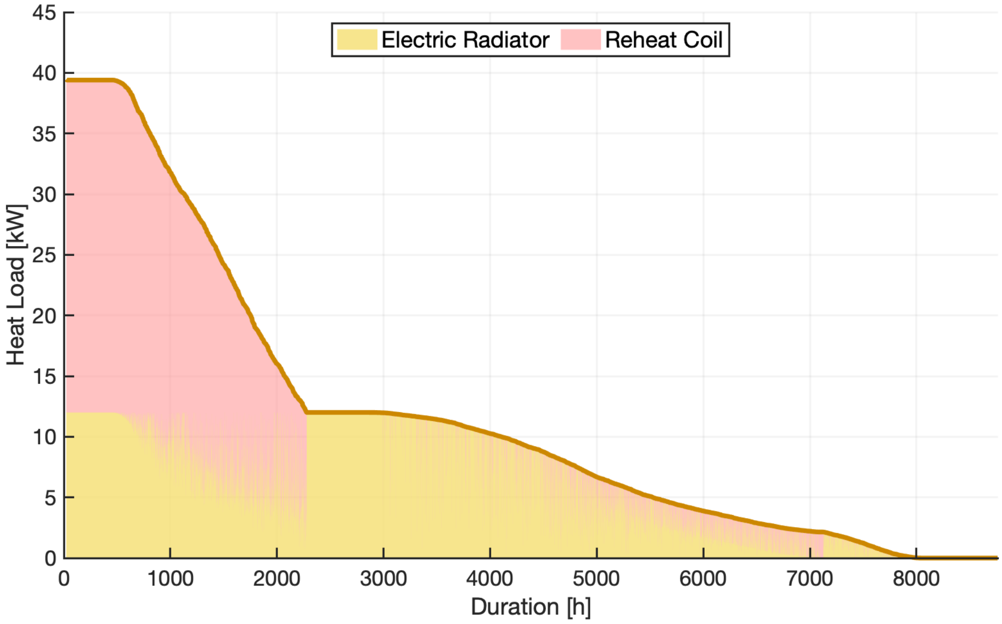


Figure 7.6: Base Case Heating Duration Curve

7.3.2 Comparison of Office Energy Results

Figure 7.7 shows the relationship between simulated and measured daily energy use for office level four. The third level was not included in this analysis due to no appropriate measurement data. A linear regression model shows an almost perfectly linear correlation between measured energy use and simulation. Similarly, the same trend may be seen in figure 7.8 where both simulated and measured energy use have a matching regression line to the daily mean outdoor air temperature. The analysis indicates that the base case model is well calibrated against real measurements and should represent the building's energy performance well.

Measured and simulated monthly energy use are compared in Figure 7.9. Results show a slightly higher simulated energy use during the winter months and lower during spring/summer months. The largest monthly energy difference was in September with an overestimated energy use of 871 kWh (33 kWh/m^2), followed by May where the model underestimates the energy use by 834 kWh (31 kWh/m^2). A higher measured energy use in May could possibly be explained by a higher radiator heat load. One could expect that occupants are more reluctant to turning down the radiator after a cold winter and varying temperatures during spring months. Similarly, right after

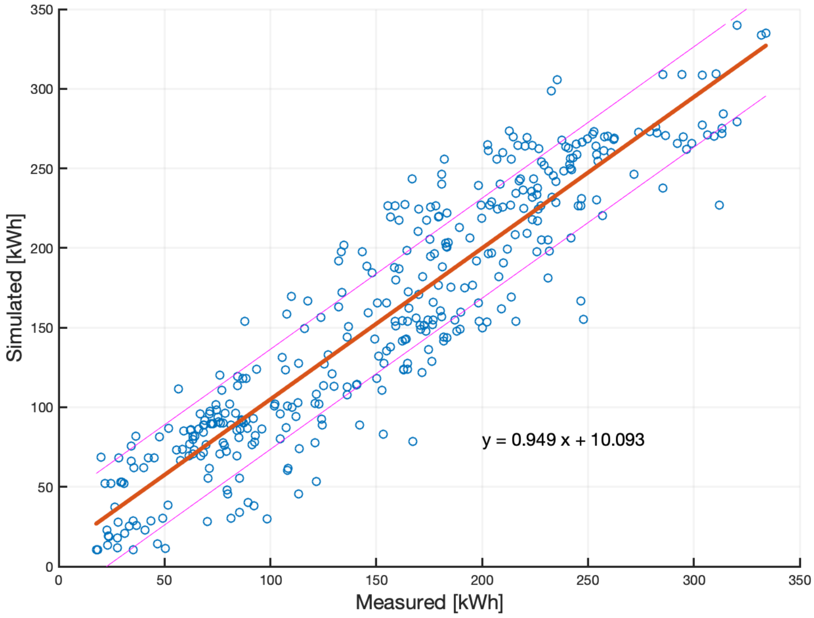


Figure 7.7: HUS Ark L4 Measured vs Simulated: Linear Regression Model

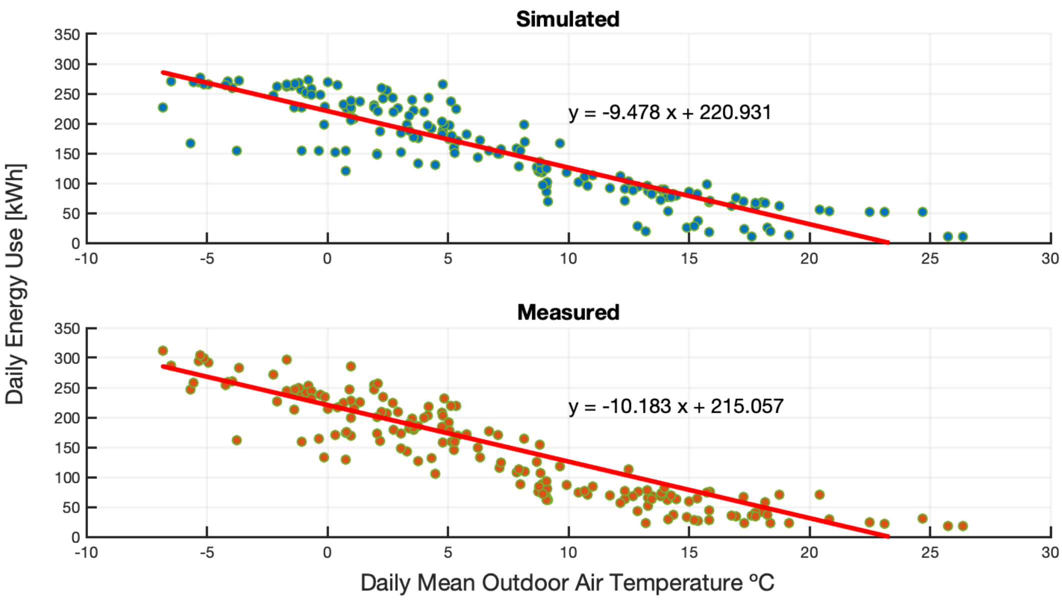


Figure 7.8: HUS Ark L4 Measured vs Simulated:

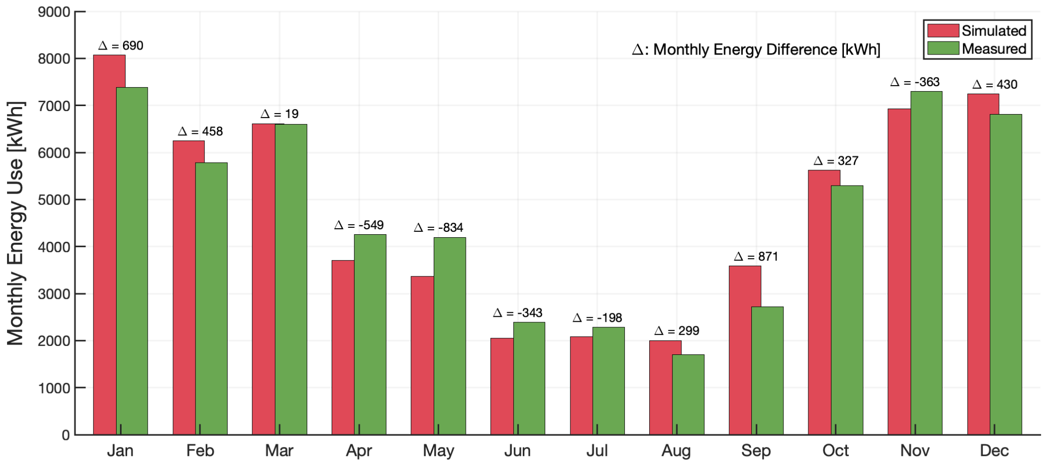


Figure 7.9: HUS Ark L4 Measured vs Simulated: Monthly Energy Use

summer when the temperature starts to drop it's possible that radiators are turned on immediately. It is also possible that the heating set point is slightly higher in the model than in real life, resulting in a larger heating demand during the winter. As mentioned in Chapter 7.1.1, energy measurements prior to 17. July 2019 were not available and were determined based on linear regression. It is therefore also a possibility that potential imprecisions in the predicted measurements led to greater deviation in the simulation.

Simulated energy use for the third level was 78% of energy use for level four, 8% higher than the relation between measured values. This difference is most likely due to a higher simulated occupancy and equipment use.

7.3.3 Comparison of Clothing Shop Energy Results

Figure 7.10 shows the relationship between measured and simulated results of the entire year for the clothing store. Greater deviations were found in comparison to the office levels. Although the relationship is close to linear with a gradient of 0.931, there is a high offset of 55 indicating a higher simulated energy use. The linear model is also less representable as the dataset was much more spread. The model's result deviation from measurement is seen more clearly in Figure 7.11. It is apparent that the simulated energy use exceeds measured values greatly during the heating season. It was also noticed that the measured energy use in fall was generally lower than the rest of the year, also the summer period. The figure suggests that the shop is less sensitive to outdoor temperatures than simulated.

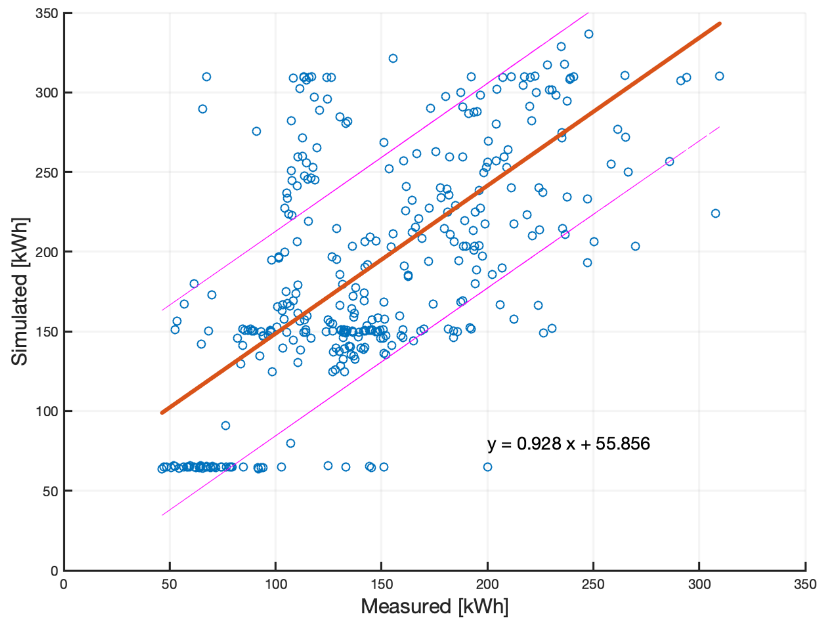


Figure 7.10: Arne Rønning Measured vs Simulated Linear Regression

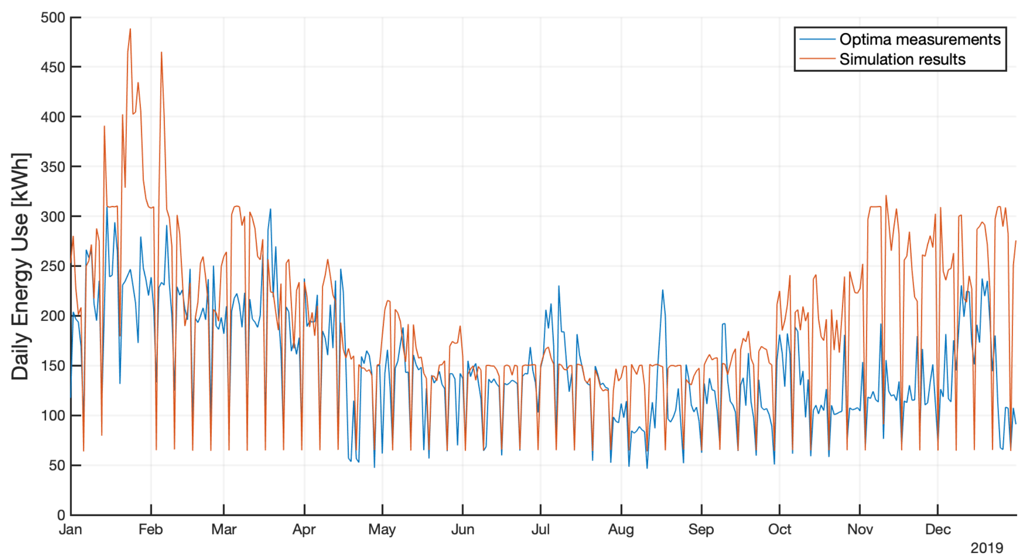
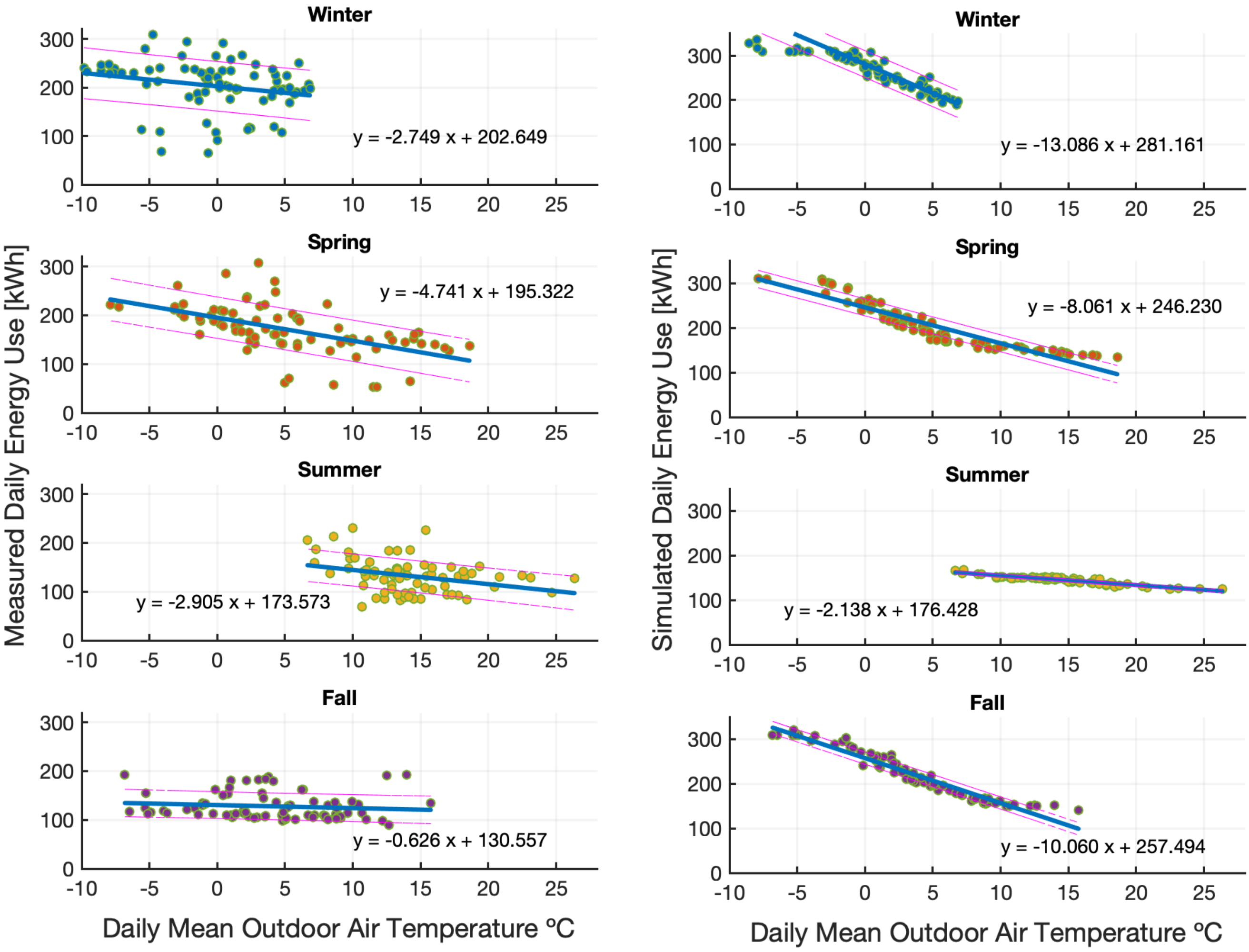


Figure 7.11: Arne Rønning Measured vs Simulated Daily Energy Use

An attempt to study the variance in results further is shown in Figure 7.12. The figure shows an analysis of the measured and simulated daily energy use for the clothing store in relation to the daily mean outdoor air temperature, grouped by seasons. Apart from the summer season, measured energy was much less dependent on the outdoor temperature compared to the simulation. Measurements were also much more spread out with a higher variance than the model.

The plot for fall amplified concerns for a much lower energy use at the end of the year. The energy use had almost no dependency on the outdoor temperature even though they fall within a similar range as in the winter and spring. Results implied that the heating system may not have been operating functionally or that there was some aberration in the BEMS. It was not possible to verify the validity of the measurements as no other information was available. Considering that the model matched the office levels well and that energy use for the clothing store during summer corresponded well, it was assumed that the problem should not lie within the building's input parameters. The current base case model was therefore accepted for further use in simulation of the rehabilitation scenarios.



(a) Measured (b) Simulated

Figure 7.12: Arne Rønning Seasonal Analysis of Measured and Simulated Energy Use

7.3.4 Public Area Energy Results

As mentioned in Chapter 4.4, the Public Area measurement in the building's BEMS includes measurements for the AHU's fan and other technical systems such as the snow melting system. Figure 7.13 shows the simulated fan energy in comparison to measured Public Area energy use. The fan energy is maintained at relatively constant level through out the year while the total Public Area energy use in significantly higher during the winter. During winter months with hight heat demand, the fan energy only accounts for around 40% of the total energy use. The share of fan energy then gradually increases during spring and makes up for all of the energy use in the summer. The fan energy exceeds the measured energy use in June and Aug by around 500 kWh each month. Results indicate that the AHU fans in the building may be slightly more efficient than simulated and have a marginally lower SFP.

January had the highest fan energy use of all months due to some cold nights and days causing the AHU to run outside of normal operating hours.

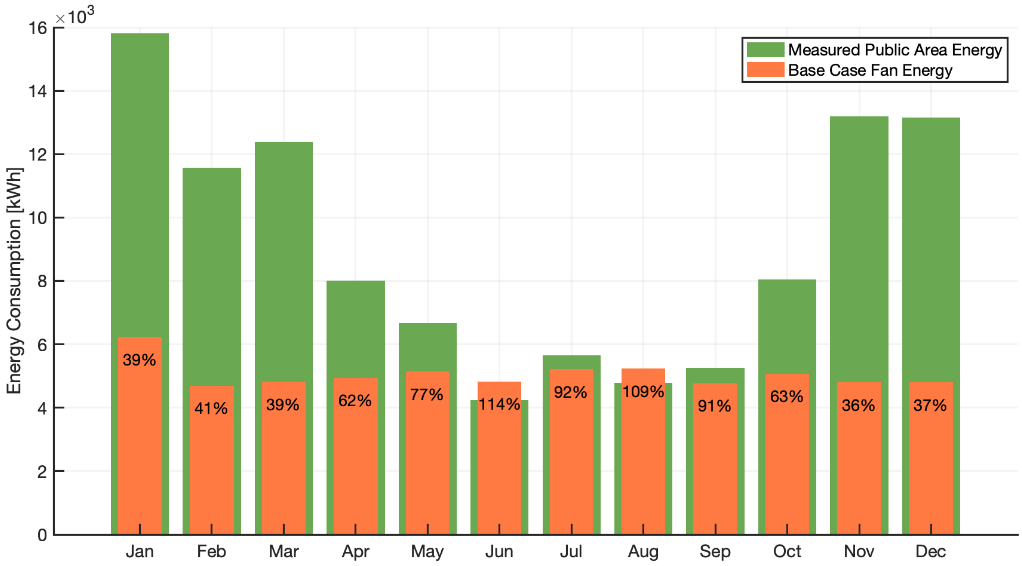


Figure 7.13: Public Area vs Simulated Fan Energy

7.4 Rehabilitation Scenario Results

7.4.1 Specific Heat Energy Need

Table 7.1 gives a summary of the simulated heating energy for the rehabilitation scenarios defined in Chapter 6. The specific heat energy use is calculated for the whole building. A visual representation of the relative saving in energy of the building is shown in Figure 7.14.

Table 7.1: Rehab Scenarios Heating Energy

Scenario	Heating Energy [kWh/m^2] (Rel. Change to Base Case)					
	a		b		c	
Base Case	98.3					
1	88.7	(-9.7%)	82.4	(-16.2%)	75.5	(-23.2%)
2	88	(-10.5%)	80.7	(-17.9%)	79.8	(-18.8%)
3	95	(-3.4%)	91.8	(-6.6%)	89.1	(-9.4%)
4	95.9	(-2.5%)	93.7	(-4.7%)	90.3	(-8.1%)
5	83.7	(-14.8%)	71.2	(-27.5%)	65.1	(33.7%)
6	84.4	(-14.1%)	75.9	(-22.7%)	69.4	(-29.4%)
7	98.3	(-0%)	98.3	(-0%)	98.3	(-0%)
8	84.4	(-14.1%)	75.9	(-22.7%)	69.4	(-29.4%)
9	71	(-27.7%)	49.5	(-49.6%)	38.2	(-68.2%)

It was observed that S9, rehabilitation of all parameters, resulted in undoubtedly the highest reduction of heat energy for both premises, over 60% saving for the whole building with 60% parameter improvement. Results for the scenario was equal to the sum of results from S5 and S8, showing the importance of improving both building parameters and the technical system. However, the relative saving in heat energy for improving the AHU (S8) was only a few percent higher in case b and c compared to S5 and identical for case a. It is therefore possible to obtain almost the same energy saving by only increasing the heat recovery efficiency. Thus if only one rehabilitation measure was to be implemented, upgrading the AHU would give the most energy saving for the least complexity.

Figure 7.15 shows the specific heat energy saving for each rehab scenario case. The figure also shows the allocation of energy saving between shop and office. Results showed that energy reduction for all cases originated primarily from the office, especially for the building envelope related parameters in Scenarios 1-5. This may be linked to a higher temperature set point in the office zones. The energy savings for improved heat recovery efficiency in the AHU (S6 and S8) at each premise were proportional to each level's air flow rate,

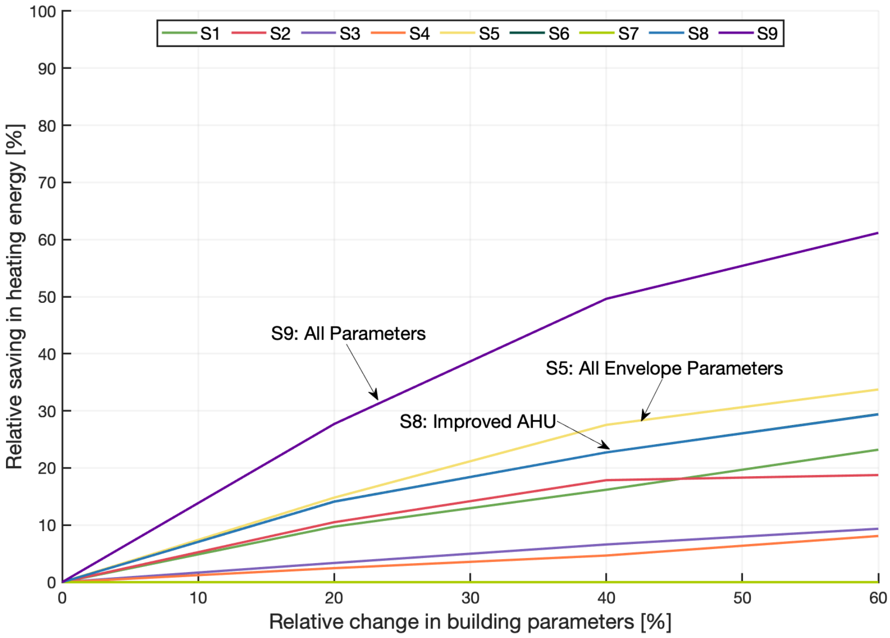


Figure 7.14: Comparison of Relative Heat Energy Saving of Rehab Scenarios

explaining a slightly higher share for the shop. The least efficient scenarios were S3 and S4, implying that it is more rewarding to rehabilitate windows and external walls than the floor and infiltration rate. Results for S1 and S2 also showed that windows contributed the most to the energy saving of the building facade. This is most likely specific to the building as the proportion of window area was high.

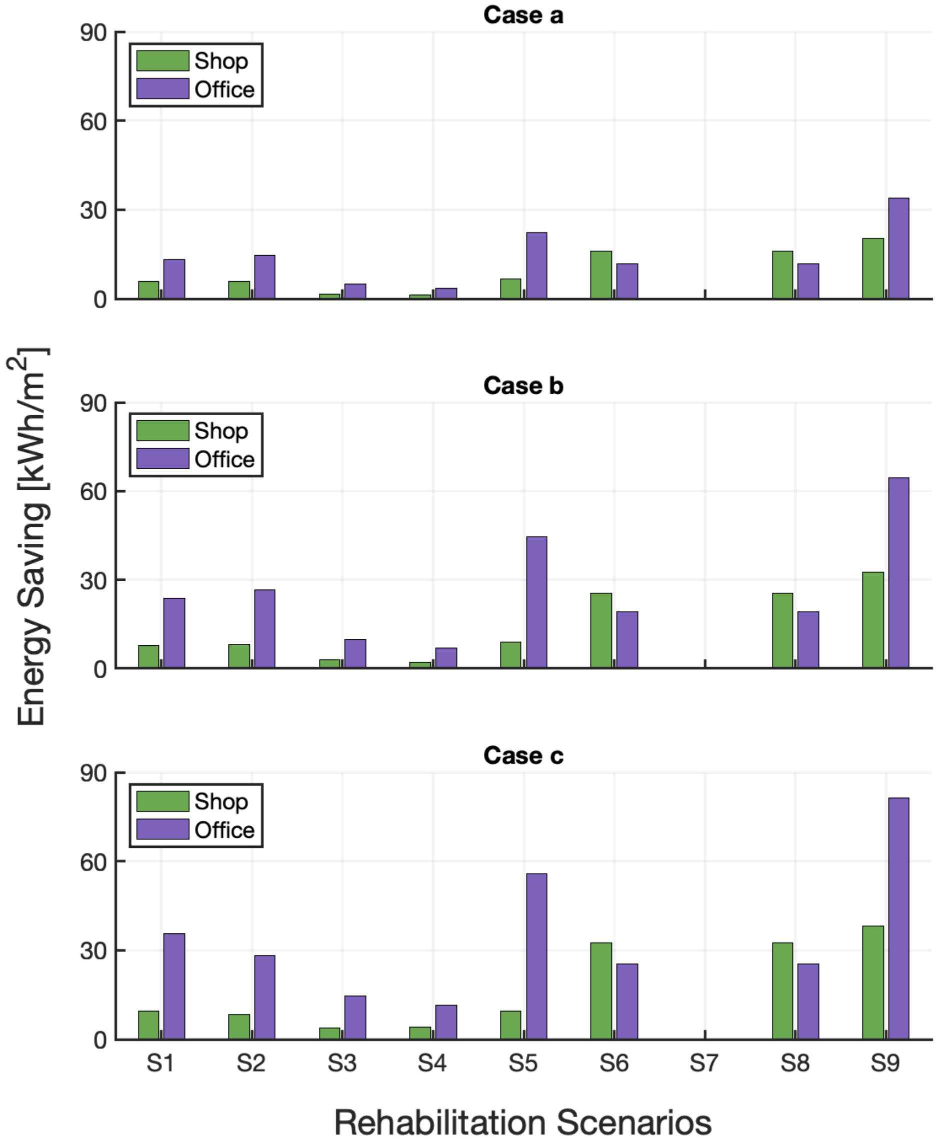


Figure 7.15: Heat Energy Saving for Rehab Scenarios

7.4.2 Ventilation Energy

The only scenarios effecting the ventilation energy are S7 and S8, which uses the same SFP values. Figure 7.16 shows the energy saving through improved fan performance in comparison to the Base Case. As SFP defines the specific fan energy use per unit of air, the ventilation energy saving is directly proportional to the scale of improved performance. This was also due to the fact that the model had constant air flow in all its zones. If a variable air flow strategy was implemented, the effect of ventilation energy could be influenced accordingly.

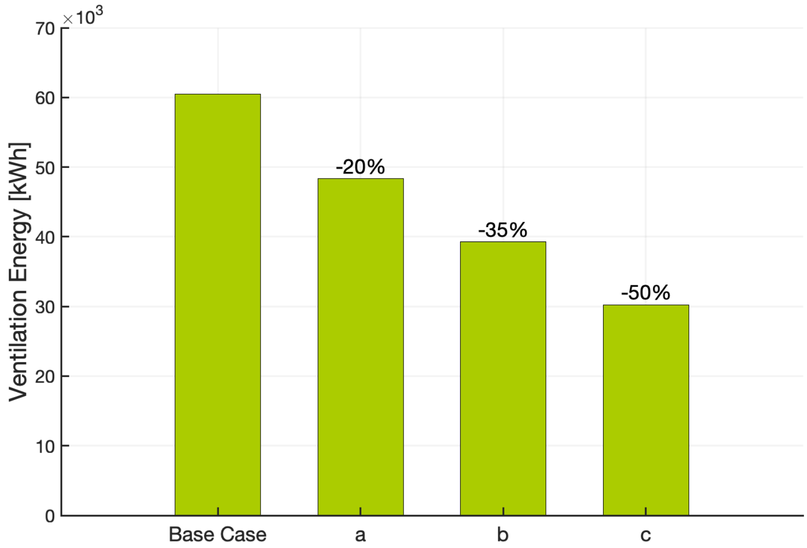


Figure 7.16: Ventilation Energy Comparison of Base Case and S7

7.4.3 Heat Load

The heat duration for cases of Scenarios 5, 8 and 9 in comparison to the Base Case are illustrated in Figures 7.17, 7.18, and 7.19. The rehabilitation scenarios contributed to various degrees of reduction in the peak load. The main differences between each scenario and case within were the peak load duration. For case a, S5 and S8 followed an almost identical curve reducing the peak load duration by around 23%, whereas S9 reduced the peak load duration by 38%. The duration curves for all scenarios still followed a similar shape as the base case, with a near linear fall in the peak load and smoother curve at the base.

The difference between each scenario escalates in Case b and c. The curve for S9 becomes smoother at the transition between peak and base load. The peak load is also reduces by both the maximum load and duration. The maximum load falls by 3 and 7 kW while the duration is is reduced to 60% and 78% respectively of the Base Case. It was also noticed that overall heat duration was reduced in the scenario by up to 400 hours.

It seemed that although the two curves were similar in case a, they developed differently in the the next to cases. An upgrade of AHU proved efficient to reduce the building's peak heat duration. In comparison the improvement of envelope parameters did not reduce the peak load as quickly, however the base load is kept more stable than S8.

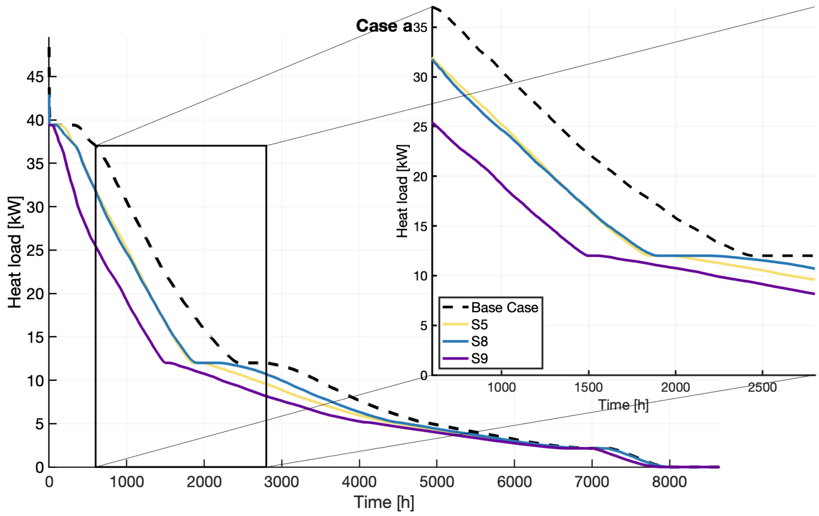


Figure 7.17: Rehabilitation Heat Duration Curve: Case a

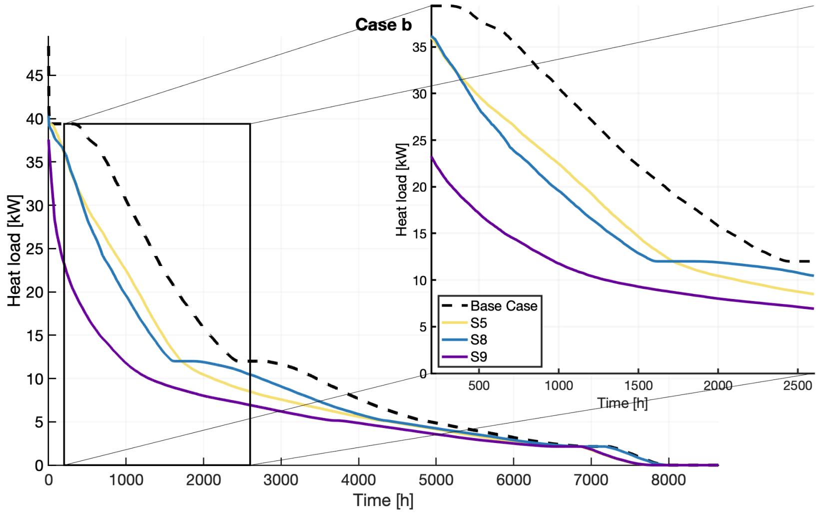


Figure 7.18: Rehabilitation Heat Duration Curve: Case b

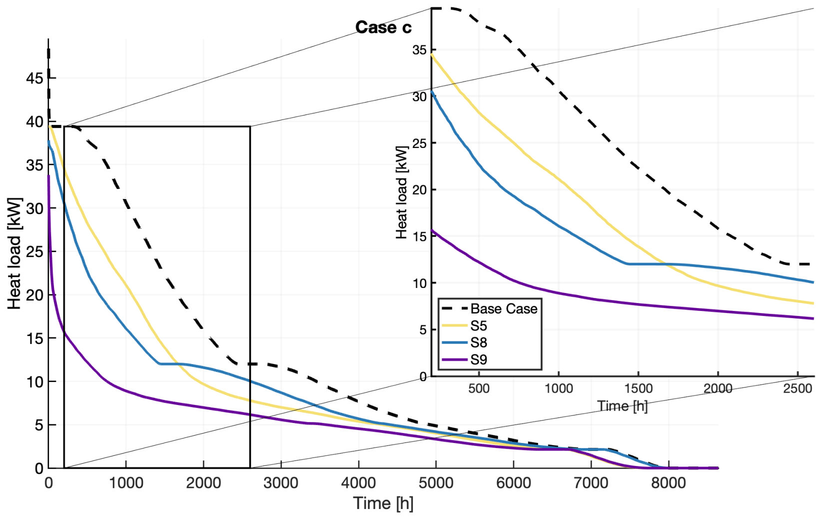


Figure 7.19: Rehabilitation Heat Duration Curve: Case c

7.4.4 Scenario 10: TEK17

The rehabilitation scenario S10 used input values according to the building code TEK17. The scenario was simulated to obtain an energy saving potential of the building if it was to be built according to today's standards. Figures 7.20 and 7.21 compares the energy use in S10 with Base Case results, monthly and annually by measurement category.

The simulated annual energy use for S10 was 79 781 kWh, a 66% reduction from the Base Case. Results showed that the fan energy was reduced by 58%, energy use in the shop was down by 16% and the office 17%. The reduction of fan energy is directly related to the improvement of SFP while energy reduction in the tenant zones were linked to the reduced heat loss by improved building envelope as well as a higher heat recovery efficiency in the AHU.

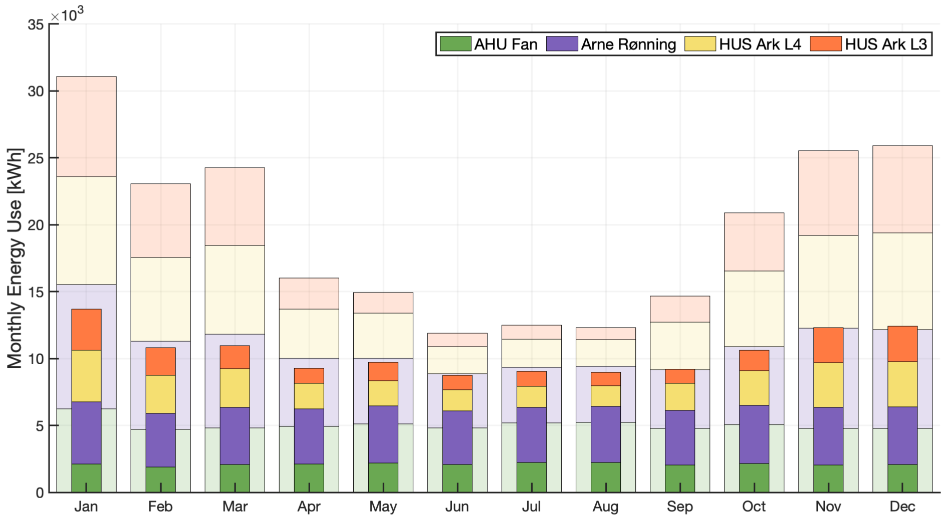


Figure 7.20: S10 Monthly Energy Use Comparison
with Base Case

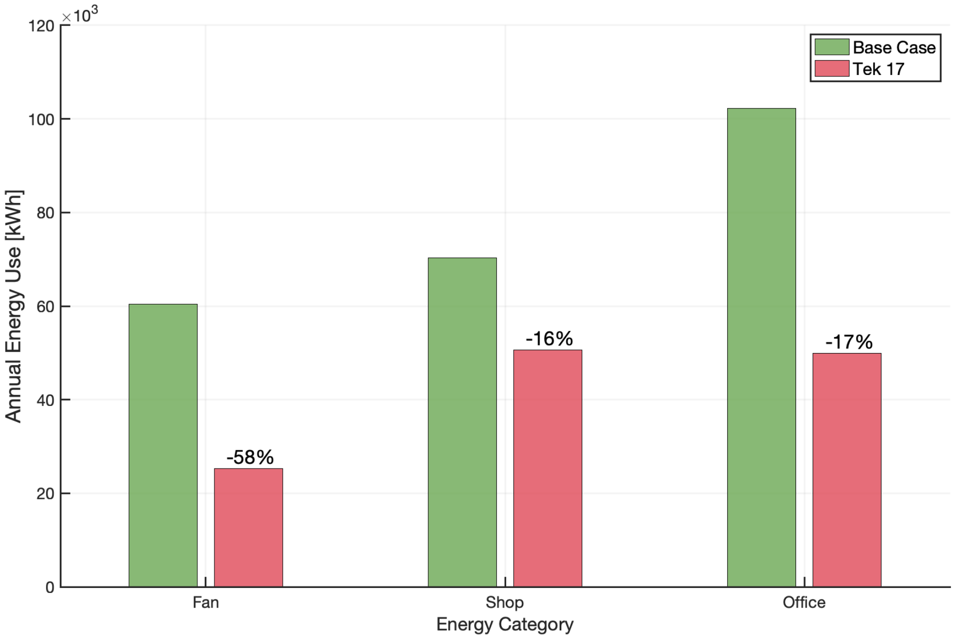


Figure 7.21: S10 Annual Energy Use Comparison with Base Case

7.5 Indoor Environment

7.5.1 Base Case Thermal Comfort

Four zones of different usages were selected to evaluate the building's thermal environment. Figure 7.22 shows the daily average PPD of each zone along with its operative temperature. The average only included values during the operating hours of the HVAC system.

The three office zones maintained a low PPD (between 6-10%) for the majority of the year with some peaks in the winter and summer. Peaks in PPD during the summer were concentrated around a week with unusually high outdoor temperatures. The same trend is seen for the clothing shop however with more extreme variations in the PPD values. It was observed that all zones reached an abnormally low operative temperature at the end of January, reaching down to 14 °C and 16 °C for the shop and office. This was most likely caused by an under-dimensioned heating system combined with extremely low outdoor temperatures over a longer period of time.

It should be noted that the model assumed all occupants to be sedentary and with normal "office"-level clothing. This could've influenced the PPD values for shop zones slightly as occupants there may have more clothes on and are more active. Yet, even by taking this into consideration, a temperature level of 14 °C is still on the boundary to be considered "comfortable".

By comparing the clothing shop's indoor temperatures and thermal comfort levels with the energy simulation, it was observed a significant peak in energy use as illustrated in Figure 7.11. The simulated energy results were also much higher than measured, as discussed in Chapter 7.3.3. The poor thermal comfort in January supports the suspicion that the clothing store's energy measurements are insufficient.

It is also possible that the model's heat resistance was simulated lower than real life. This was however hard to evaluate due to lack of indoor temperature measurements in the building.

L4 Meeting Room

Analyses of the indoor environment for the meeting room on level 4 was performed with regards to complaints from the office occupants. Figure 7.24 shows a comparison of both the indoor temperature and CO_2 levels in the room with varying occupancies for a hot day in July. Fictional occupancy

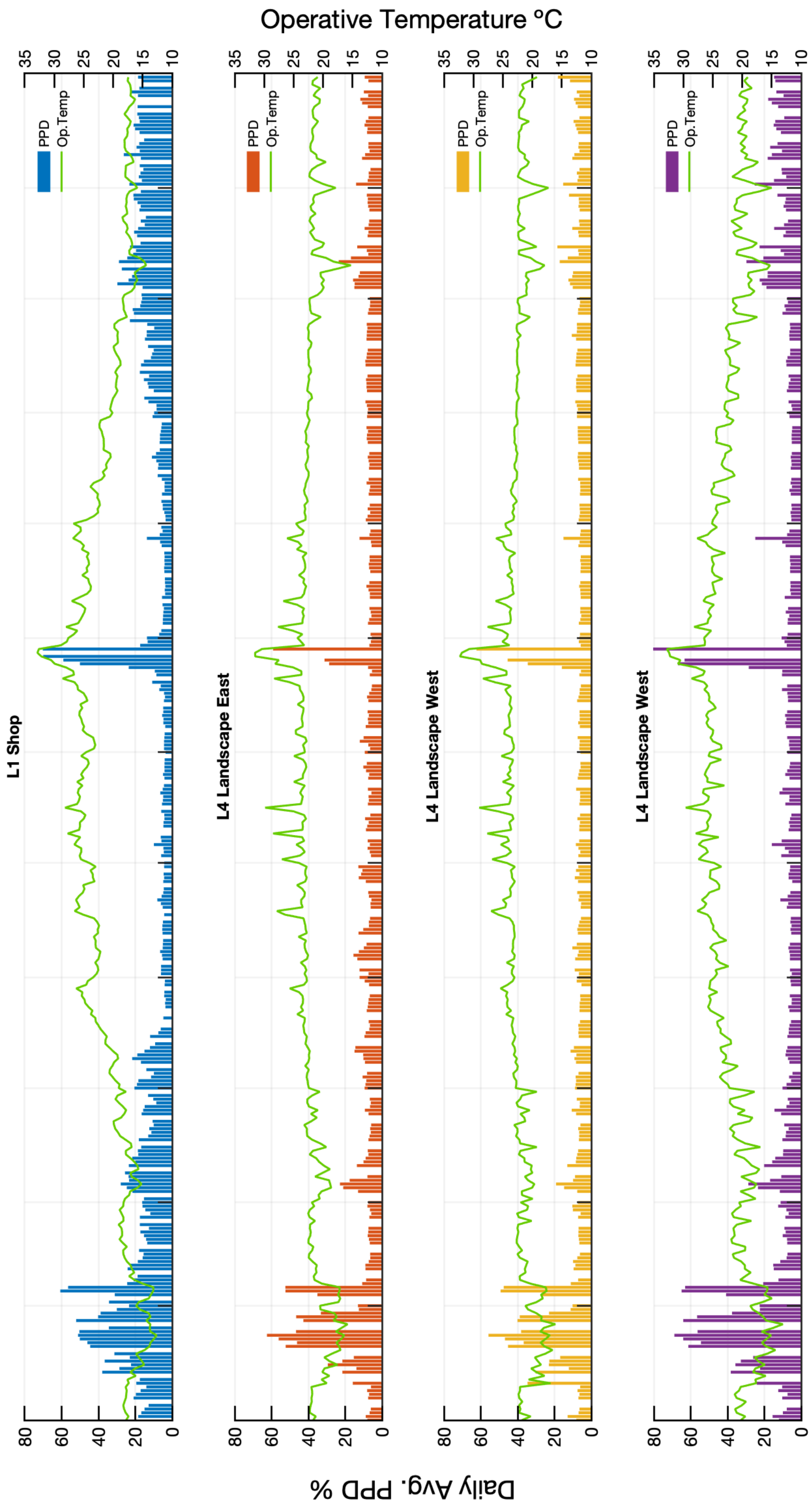


Figure 7.22: PPD and Operative Temperature for Selected Zones in Base Case

profiles of 1 hour durations at three different times during the day were defined with respectively 50%, 75% and 100% occupancy load. A simulation was also run with no occupants to determine the building performance without internal heat contribution from people.

Simulation showed that CO_2 levels are directly related to the occupancy loads achieving up to 700 ppm with 100% occupancy, within the recommended threshold on 1000 ppm. A more serious problem is the temperature levels within the room. Results showed that the indoor air temperature rises significantly with the number of occupants and outdoor temperatures. It is also troublesome that the temperature level is not able to decline at the same rate once the room is empty. This indicates a too low air change rate in the room caused by low air flow rates. In comparison to today's standards, the modelled air flow is less than half of the minimum requirement.

Two more simulations with improved air flow rates, 20 $m^3/h\ m^2$ and 25 $m^3/h\ m^2$ based on the HVAC industry's common used air flow rates for meeting rooms, were run at 100% occupancy load. Figure 7.23 shows a comparison of the zone's indoor temperature throughout the day. Both air flow rates contributed positively to reducing the indoor temperatures, most significantly with 25 $m^3/h\ m^2$ which cooled down the room with over 1 °C.

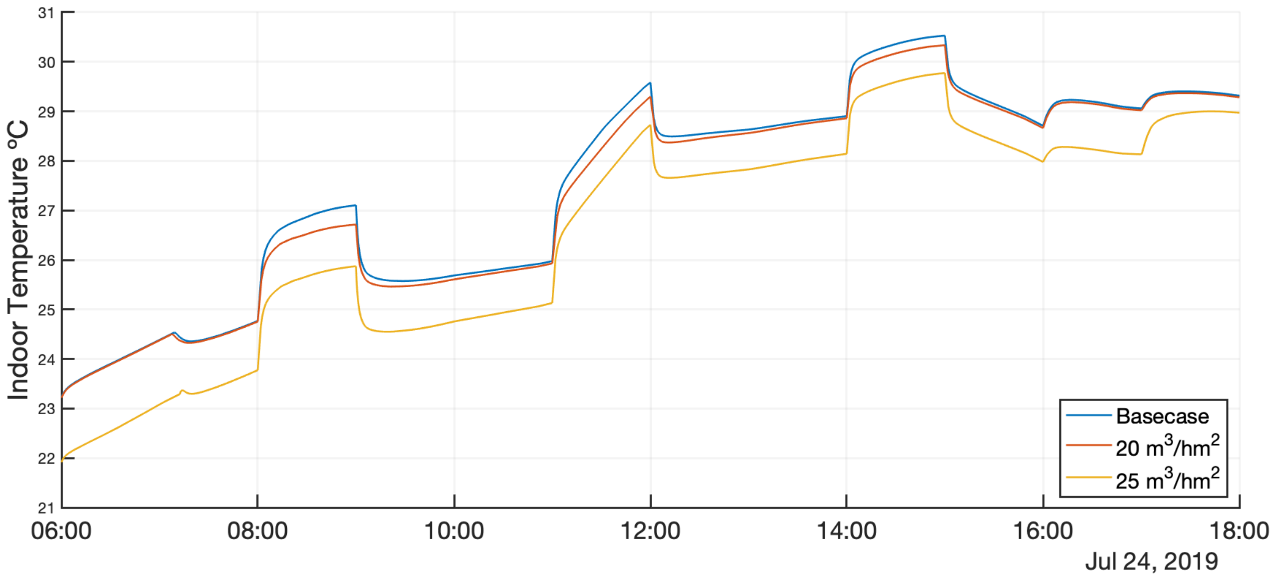


Figure 7.23: L4 Meeting Room Indoor Temperature With Improved Air Flow Rates

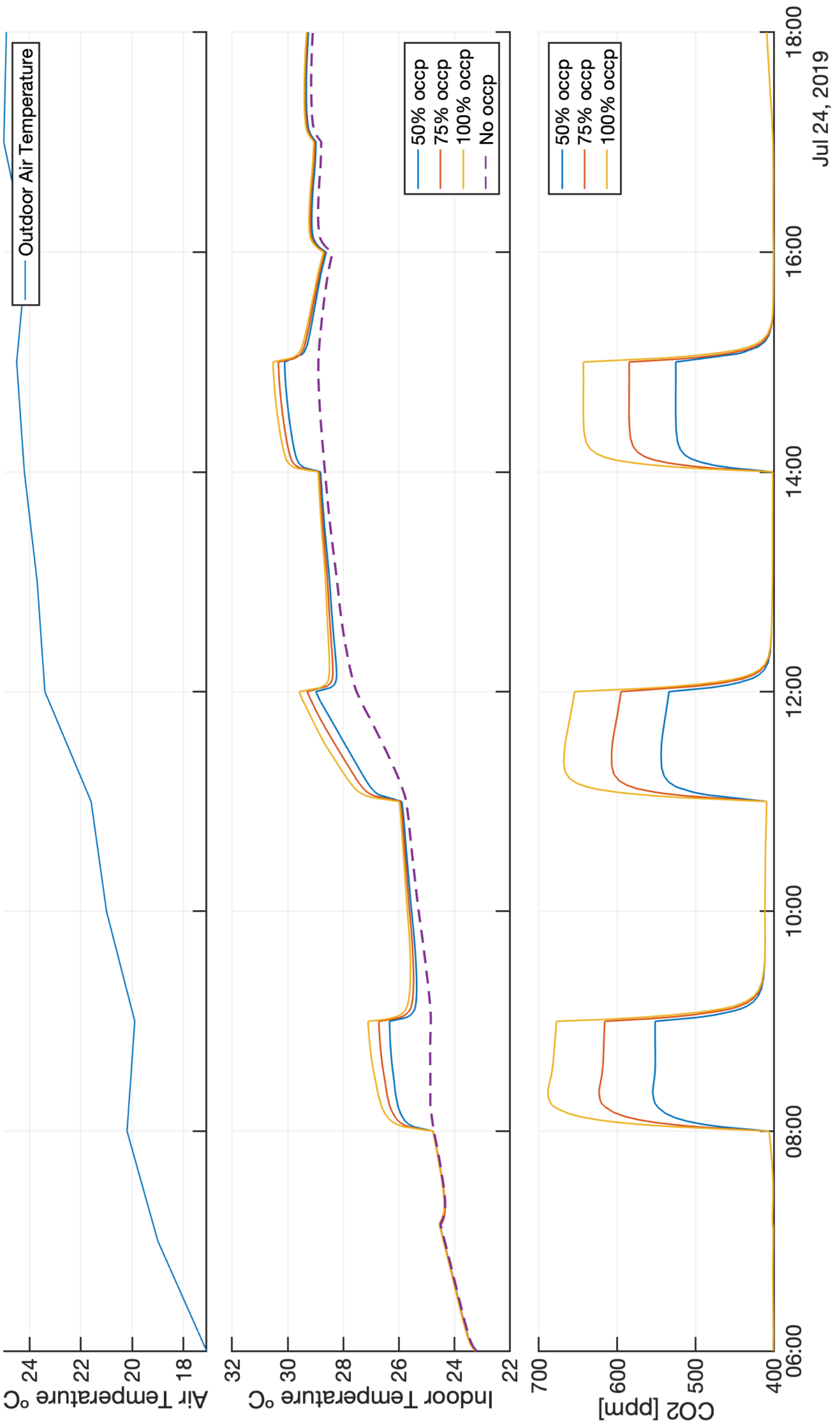


Figure 7.24: L4 Meeting Room Indoor Environment With Various Occupancies

7.5.2 Rehab Scenario 10 Thermal Comfort

The heat loss in Scenario 10 was much lower than the Base Case due to a more air tight building envelope and higher heat recovery through the AHU. Figure 7.25 compares the operative temperature in selected zones in the model. The temperature levels for S10 were observed to have less fluctuations throughout the year. This was especially noticeable during the end of January where temperatures in the Base Case were uncomfortably low.

Figure 7.26 shows the number of hours in a year meeting the thermal comfort categories as defined in Chapter 2.3.1. There number of unacceptable hours for L1 shop was more than halved and the number of hours in Category I increased for all zones. Table 7.2 provides an overview of the number of unacceptable hours grouped by season. Winter was defined between October and March while Summer included the period between April and September. The table showed that the total number of unacceptable hours for all zones were reduced in S10. However it was also noticed an increase in unacceptable hours during the summer, due to an increased indoor temperature during the summer for S10.

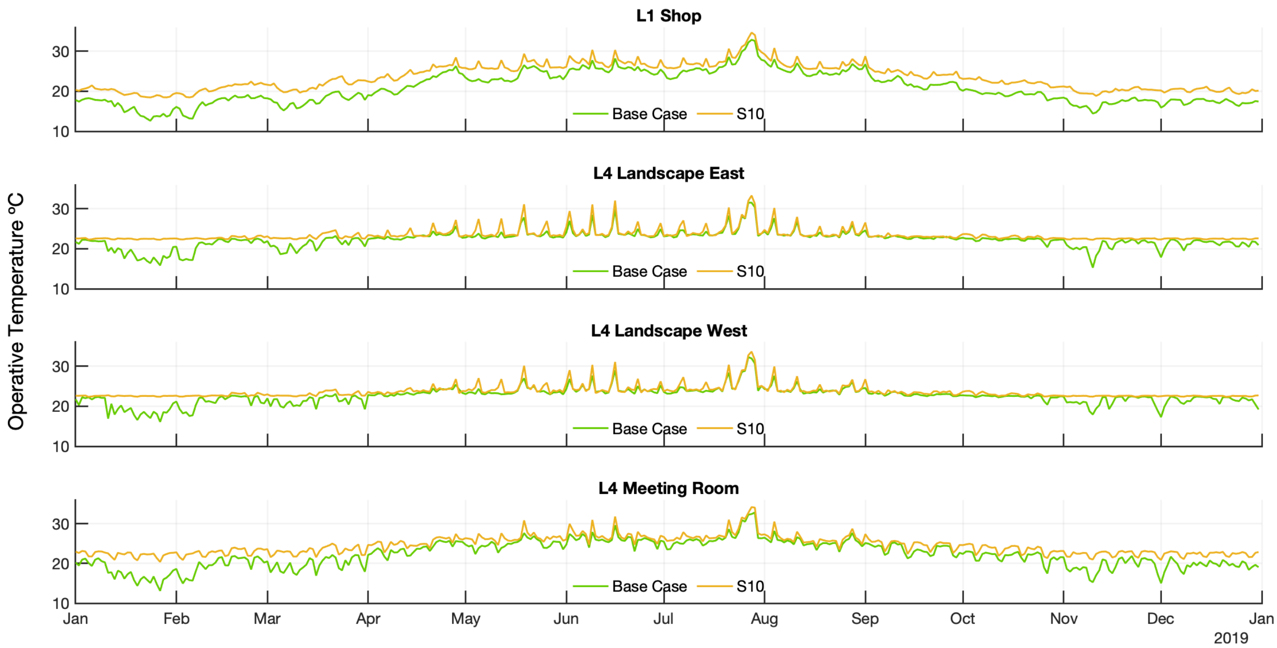


Figure 7.25: Operative Temperatures for Base Case and Rehab Scenario 10

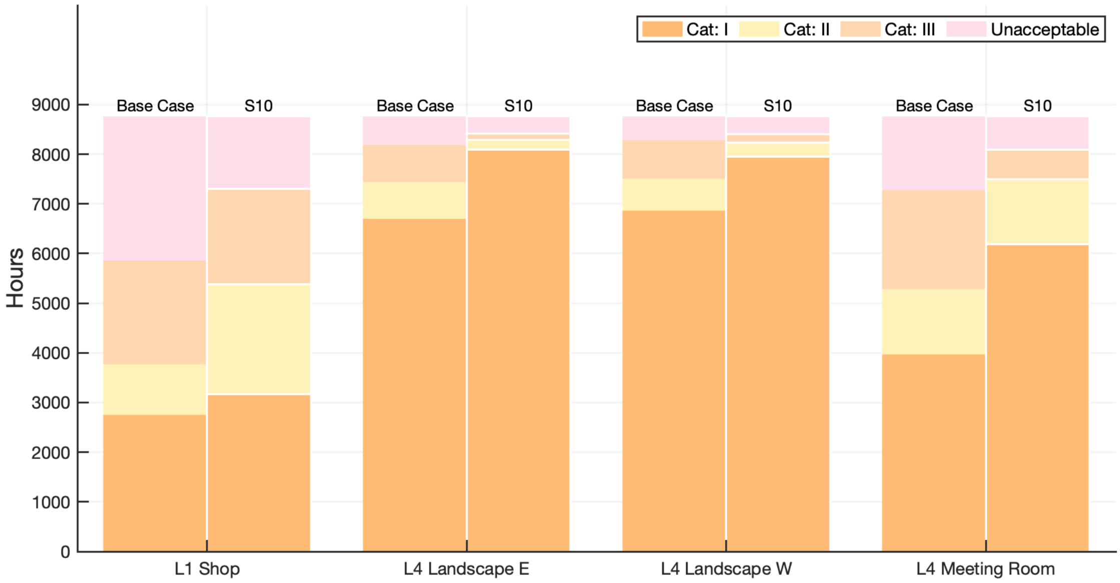


Figure 7.26: Thermal Comfort Comparison of Base Case and Rehab Scenario 10

Table 7.2: Base Case and S10 Number of Unacceptable Thermal Comfort Hours

	L1 Shop			L4 Landscape East			L4 Landscape West			L4 Meeting Room		
	Base Case	S10	Diff	Base Case	S10	Diff	Base Case	S10	Diff	Base Case	S10	Diff
Summer	226	1336	+1110	90	308	+218	108	313	+205	237	593	+356
Winter	2677	117	-2520	484	38	-446	372	40	-332	1244	75	-1169
Tot	2903	1453	-1450	574	346	-228	480	453	-27	1481	668	-813

8 Discussion

As mentioned in Chapter 7.1, the low complexity of the BEMS limited the possibility to calibrate the Base Case model more accurately. Ideally, measurements of the indoor temperature could have helped with the evaluation of the building's heat loss. It would have also been useful to gain access to more information of the internal loads per zone. It's easier to define the model's improvement potential when there are more comparative parameters. A recommendation is therefore to implement a more exhaustive BEMS as part of the rehabilitation plan. This way to gain more control and overview of the building's energy behaviour which is useful for both the operation of the building and for other energy analysis in the future.

The rehabilitation results gave an indication of the parameters that have the most influence on the building's energy performance. It should however be noted that the rehabilitation measures were based on relative percentage changes in building parameters and did not consider if the resulting values were achievable or not. In some cases it might even be possible to improve the parameters further than suggested. One should therefore interpret the results based on the measure's realisticness. If possible, it's suggested for further work to establish a closer contact with contractors and collaborate on some scenarios using real manufacture data as parameter input for the model.

Economic costs for each measure were also not evaluated in this thesis and measures were compared purely on their energy and heat load saving potential. It would have been interesting to evaluate the marginal costs for each measure in light of its saving potential. This could've also helped provide an better comparison basis for the measure's feasibility.

Results from the previous chapter implied that the highest energy savings were achieved when all measures was implemented, as in S9. This scenario also resulted in the highest reduction in peak heat duration. However if only one measure was to be considered, it is recommended to focus on improving the AHU's fan and heat efficiency as this gave the highest relative saving in heat demand in addition to contributing to a lower fan energy. Among the building envelope parameters, the most efficient measure was to upgrade the windows.

The rehabilitation measures evaluated in this thesis focused only on the physical parameters in a building. Mainly concentrated around reducing the building's heat loss and ventilation energy. Other possible measures that should also be considered are parameters around the efficiency of internal loads and occupant behaviour that also have significant influence on the electricity use. The thesis also did not get the opportunity to evaluate the effect of different ventilation control strategies. A variable air flow strategy with demand control would most likely be more appropriate for the building than with the current CAV. As occupancies and operation hours differs with both the tenants and hours during the day. A control strategy considering the occupant concurrency could possibly reduce the total air flow rate need, allowing for possibly a smaller AHU and less fan energy. The system will also be more flexible at each room to ensure enough fresh air depended on both occupancy and temperature levels.

The thermal comfort analysis of Base Case and Rehabilitation Scenario 10 gave an indication of new issues that arises with a reduced building heat loss. Results showed that although temperatures during winter could be kept at a steady level with lower heat load, the number of hours where the indoor temperature was too high in the summer had increased. It will therefore be increasingly important to evaluate the cooling demand in the building and establish a cooling strategy, either by a more integrated window opening control or possibly installing mechanical cooling devices. More efficient internal loads may also play a role in reducing internal heat gains.

9 | Conclusion

The main objectives of the project were to develop a simulation model that represented the case building as realistically as possible. This model was then further used to create multiple rehabilitation scenarios to analyse the energy saving potentials of the rehabilitation measures. Some of the main tasks performed for the project were literature studies of relevant topics, specialisation in using the simulation program IDA ICE, establishing communication with contacts relevant to the building to collect information on the case building and developing both simulation models for the base case and rehabilitation scenarios.

The case building is located on Nordre Gate 10 in the city centre of Trondheim. Most of the building is still in its original form from the 70's while the west facing facade was updated in 1993. The building is a combined commercial and office building occupied by the clothing store Arne Rønning AS on levels U1 and 1 and the architecture firm HUS arkiteker AS on levels 3 and 4. The second floor is currently unoccupied and is being prepared to be rented out as an office space. The space has previously been a part of the clothing store. The building lacked some documentation of existing building properties, and no measurements of the indoor environment. Values for the project were based on relevant building codes and guidance reports of similar building types. A better understanding of the indoor environment and internal loads were achieved through a survey for the tenants and interviews with owners of the two businesses.

The developed Base Case model intended to replicate the building's parameters as realistically as possible and went through multiple calibrations with energy measurements of the building. Custom control strategies and schedules were defined in IDA ICE's advanced mode as an attempt to model occupants' behaviour and the technical system. The model was divided into zones based on its usage and internal loads.

Suggested rehabilitation measures included insulation of windows, walls, roof, floor, reducing infiltration, improving heat recovery efficiency and reducing electricity use in the air handling unit. The effect of different internal loads were also analysed. A total of ten rehabilitation scenarios were created that consisted of both individual and combination of measures with relative change of between 20 %-60 % divided each scenario into three cases each.

The Base Case model had an annual energy use of 233 070 kWh (215 kWh/m^2), 25 367 kWh (23.4 kWh/m^2) lower than measured energy use in 2019. The main cause of variance was the lack of simulated snow melting system and other technical systems included in the Public Area measurement. Analysis of the rehabilitation scenarios found that the most energy efficient solution was to implement all measures which gave an heat energy use reduction of up to 68%. If due to limitations only one measure could be implemented, improving the performance of the AHU alone could reduce the heating energy with up to 30% and additionally reducing the fan energy.

Simulation showed that the indoor temperature in the Base Case suffered from longer periods of uncomfortably cold temperatures due to high heat losses and an undersized heating system. Rehabilitation results showed that once the building's heat loss was reduced the indoor temperature was kept at a much more stable level. Nonetheless, the building's cooling demand would increase and should be considered as part of the rehabilitation plan.

A | Detailed Air Flow Rate Calculation

Table A.1: Air flow rates based on TEK17 and (room occupant capacity)

Level	**Zone**	**Area [m^2]**	**Occupancy**	**Air Flow Rate [m^3/h]**		**Normative values [m^3/h]**	
				Max	Min	Basis [/m^2]	Air flow rate
U1	Arne Rønning	187	93.5 (30)	2898.5 (1247.5)	130.9	15	2805
L1	Arne Rønning	245	122.5 (30)	3797.5 (1392.5)	171.5	15	3675
L2	(Office space)	270	18 (21)	1143 (1221)	189	10	2700
L3	Archive	29.9	2 (2)	126.7 (126.7)	20.9	5	149.3
L3	Landscape East	120	8 (12)	508 (612)	84	10	1200
L3	Landscape West	89.5	6 (9)	378.9 (457.8)	62.7	10	895.1
L3	Meeting room	9.6	0.6 (4)	40.8 (128.1)	6.8	15	144.7
L3	Toilet zone	21.3	1.4 (2)	90.3 (105.3)	14.9	0	0
L4	Copy room	14.1	0.9 (1)	59.6 (61.2)	9.8	5	70.4
L4	Landscape East	76.8	5.1 (12)	325 (503.9)	53.7	10	767.6
L4	Landscape West	65.8	4.4 (9)	278.4 (398.4)	46.0	10	657.6
L4	Meeting room	23.5	1.6 (16)	99.6 (474.8)	16.5	20	470.4
L4	Dining area	64.6	4.3 (24)	273.4 (785.5)	45.2	10	645.8
L4	Quiet room	5.7	0.4 (1)	24.1 (40.2)	4.0	10	56.87
L4	Toilet zone	10.2	0.7 (2)	43 (77.4)	7.1	0	0
L4	Video room	7.9	4	33.4 (123.7)	5.5	10	78.9
Total		1240.8	269.9 (179)	10119.8 (7755.9)	868.5	-	14316.6

B | Office Occupancy Schedules

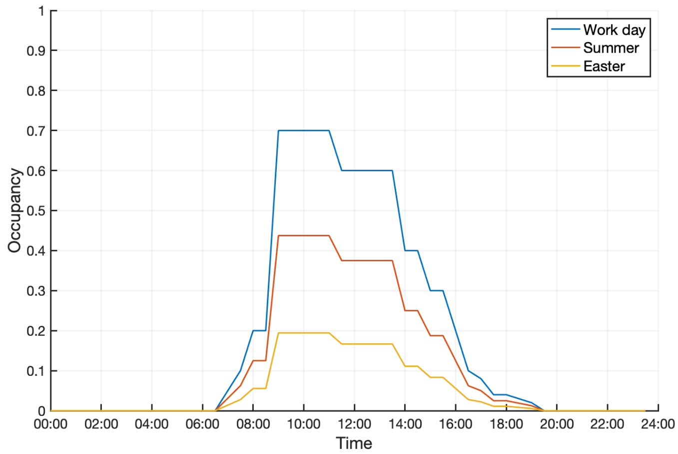


Figure B.1: HUS Ark Office Occupancy

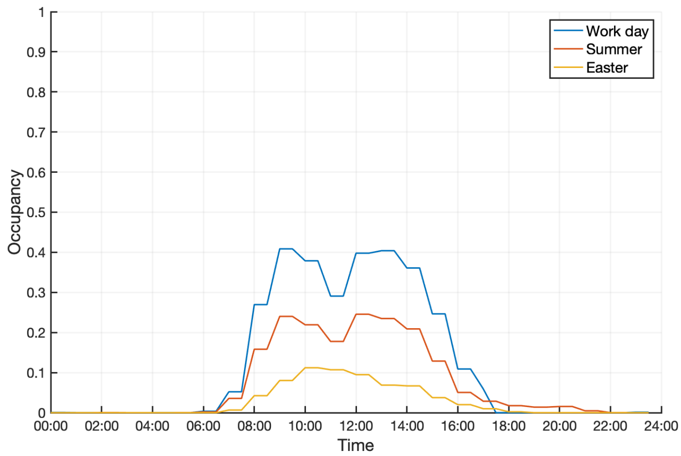


Figure B.2: Meeting Rooms Occupancy

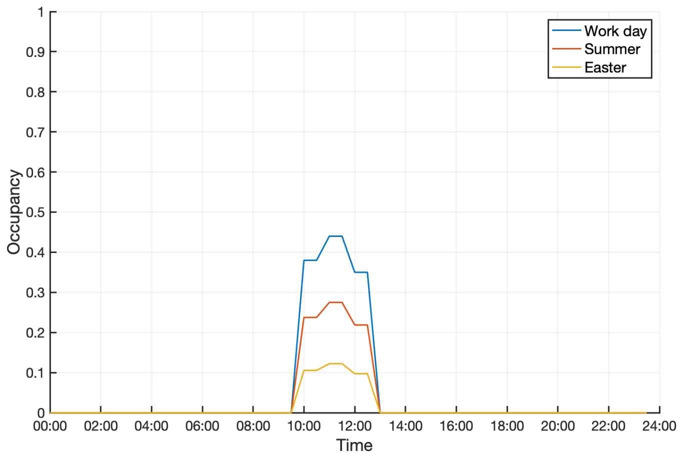


Figure B.3: Dining Room Occupancy

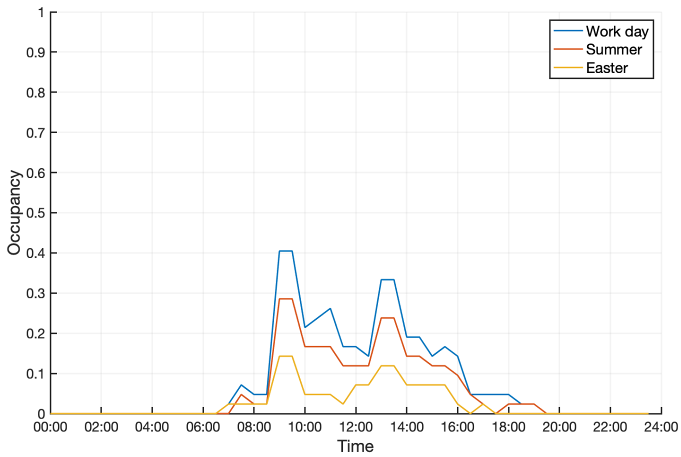


Figure B.4: Office Landscape Occupancy

C | Base Case IDA ICE Schematics Diagram

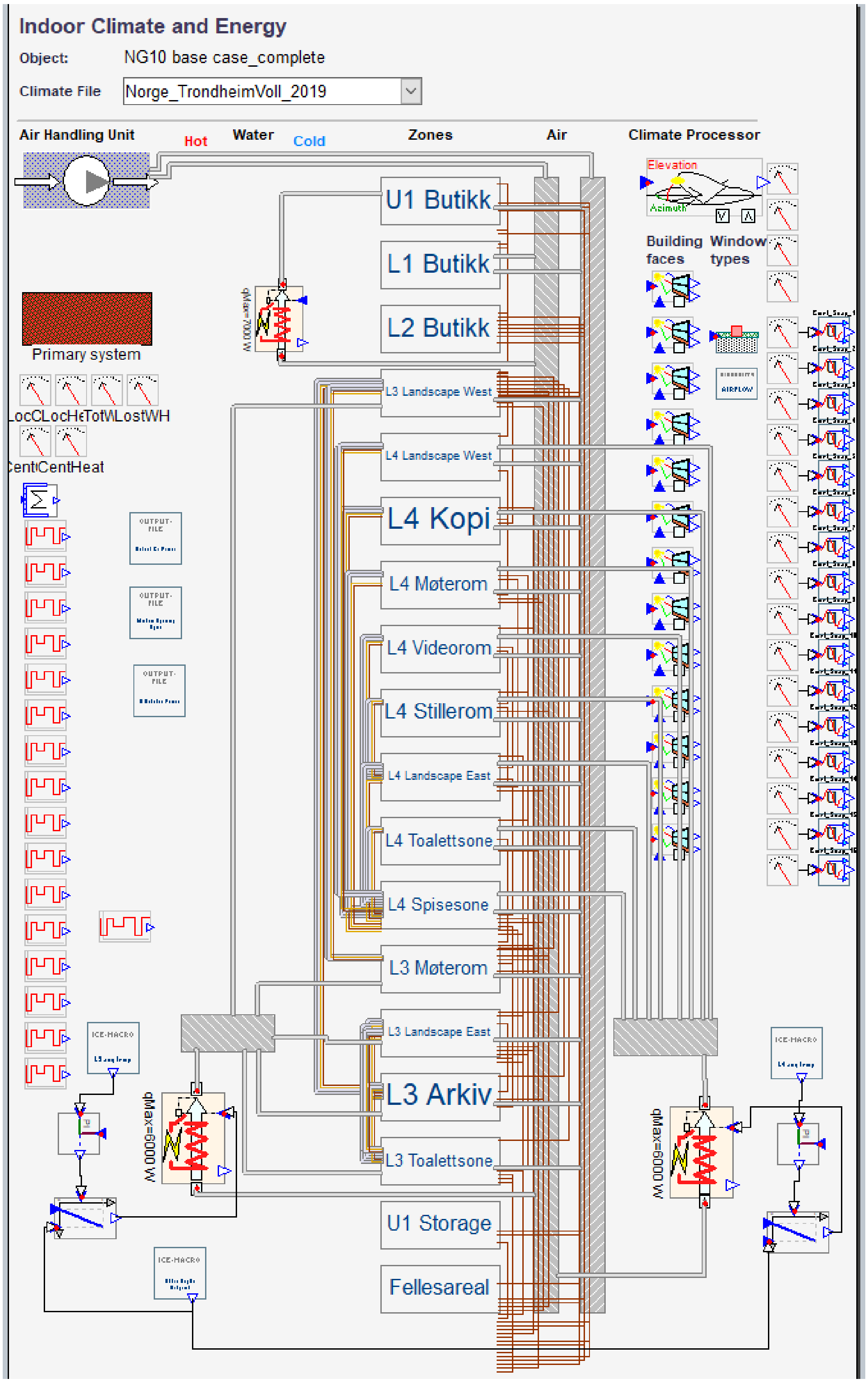


Figure C.1: Base Case Schematics Mode Interface

D Rehabilitation Scenario Input Values

Table D.1: Rehabilitation Scenario Input Values

Scenario		Rehabilitation Parameters						
		External Walls [W/m^{2}K]	Windows [W/m^{2}K]	Roof [W/m^{2}K]	External Floor [W/m^{2}K]	Infiltration [h^{-1}]	Heat Recovery Efficiency	SFP [kW/m^3]
Base Case		0.66	2.8	0.6	0.7	7	55%	3.5
1	a	-	2.24	-	-	-	-	-
	b	-	1.68	-	-	-	-	-
	c	-	1.12	-	-	-	-	-
2	a	0.528	2.24	-	-	-	-	-
	b	0.396	1.68	-	-	-	-	-
	c	0.264	1.12	-	-	-	-	-
3	a	-	-	0.48	0.56	-	-	-
	b	-	-	0.36	0.42	-	-	-
	c	-	-	0.24	0.28	-	-	-
4	a	-	-	-	-	5.6	-	-
	b	-	-	-	-	4.2	-	-
	c	-	-	-	-	2.8	-	-
5	a	0.528	2.24	0.48	0.56	5.6	-	-
	b	0.396	1.68	0.36	0.42	4.2	-	-
	c	0.264	1.12	0.24	0.28	2.8	-	-
6	a	-	-	-	-	-	66%	-
	b	-	-	-	-	-	74.3%	-
	c	-	-	-	-	-	82.5%	-
7	a	-	-	-	-	-	-	2.8
	b	-	-	-	-	-	-	2.275
	c	-	-	-	-	-	-	1.75
8	a	-	-	-	-	-	66%	2.8
	b	-	-	-	-	-	74.3%	2.275
	c	-	-	-	-	-	82.5%	1.75

	a	0.528	2.24	0.48	0.56	5.6	66%	2.8
9	b	0.396	1.68	0.36	0.42	4.2	74.3%	2.275
	c	0.264	1.12	0.24	0.28	2.8	82.5%	1.75
10		0.22	1.2	0.18	0.18	1.5	80%	1.5

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Evaluation of Energy Saving Potentials in Non-Residential Buildings with Small Rehabilitation Measures

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