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Robustness Assessment Methods to Identify Robust High-Performance Building Designs

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Extract:

Robustness assessment is a method that evaluates the robustness of building designs based on uncertainties in building operation and external conditions. These uncertainties lead to deviations between actual and planned performance of buildings, e.g. in level of thermal comfort or energy use. In the design phase, together with building performance simulations, this assessment can be used to ensure that a building performs as desired. Thus, different stakeholders, as policymakers, designers and homeowners, know that the building meets their requirements.

This master thesis uses this method to evaluate different designs of an apartment located at Løren in Oslo. The robustness assessment provides three different indicators that measure robustness in different ways, and all of them are evaluated in this thesis. In the assessment, several designs of the apartment are tested in different scenarios to check how the scenarios affect the performance. The robustness of the designs is measured in terms of two key performance indicators, overheating and heating energy demand.

The research questions this master thesis considers are the following:

- **RQ1** Which design is the most robust in terms of the two key performance indicators, heating energy demand and overheating?
- **RQ2** Does the robustness of the designs differ from which robustness indicator (performance spread, performance deviation or maximum performance regret) and key performance indicator that are considered?
- **RQ3** Which design is the most optimal for the three different stakeholders: policymakers, homeowners and designers?

Keywords:

1. Robustness assessment
2. High-performance building designs
3. Overheating
4. Heating energy demand

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Preface

This master thesis has been completed in the last semester of a five-year study in Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). It has been written during the spring of 2018 within the specialization of TBA4905 Building and Material Engineering.

The interest for this theme began in 3rd grade at NTNU with exciting subjects, e.g. building physics and building technology. The 4th year of my education I went to San Diego State University. In San Diego, many of the subjects were about building performance simulations and sustainable buildings, which caught my interest. This has led to the choice of subject for this thesis.

The master thesis is based on the specialization project in TBA4521 Building and Material Engineering written in the Fall of 2017. Similarly to the specialization project, this thesis also deals with “Robustness Assessment Methods to Identify Robust High-Performance Building Designs”. It is an extension of the specialization project with integration of the software Matlab. The purpose of this thesis is to consider the robustness of different designs based on various scenarios, which consist of combinations of climate changes and occupant behavior. To conduct this robustness assessment, the tools Matlab and IDA ICE have been used.

I am very thankful for all the support and help I have received when completing my master thesis. I would like to thank my supervisor Associate Professor Mohamed Hamdy for guidance. He has helped me a lot with this subject in the specialization project and the master thesis. This applies to use of IDA ICE, Matlab and conducting the robustness assessment. Additionally, he has been very good at helping me step by step by reaching the goal of the master thesis. I would also like to thank Multiconsult Oslo, especially Petter Martin Skjeldrum and Vibecke Lea, for helping me with the content of the thesis and allowing me to work at their office. Furthermore, I want to thank Håkon Eggebø, working at Multiconsult Stavanger, for all technical help in Matlab, IDA ICE and customizing his algorithm to my thesis. This has helped me greatly in carrying out my master thesis. Finally, I would of course thank my family and my boyfriend, Henrik Mørk, for the support and for reviewing the master thesis. I am especially thankful for all technical help I have received by my boyfriend when it comes to handling Matlab.

Trondheim, June 2018

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Abstract

Robustness assessment is a method that evaluates the robustness of building designs based on uncertainties in building operation and external conditions. Although environmentally friendly buildings are planned to have low energy consumption, the actual values are often higher due to these uncertainties. In the robustness assessment, different scenarios based on the uncertainties are created to test how robust the designs are. Three different robustness indicators (RI) are evaluated: performance spread, performance deviation and maximum performance regret.

In this master thesis, an apartment at Løren in Oslo is studied, and different designs of this apartment are evaluated in terms of robustness. The designs consist of two standards, TEK 17 and passive house, in combination with different shading types. Furthermore, the scenarios are based on combinations of occupant behavior (OB) and climate changes. The occupant behavior consists of how much opening of windows is used, while the climate changes are based on to climate files for Oslo: current climate and assumptions on how the climate will be in 2050.

Through a link between IDA ICE and Matlab, an algorithm in Matlab runs all the simulations for each model in parallel in IDA ICE. The models consist of different OBs, while the simulations vary in design and climate. The output values from the simulations, heating energy demand and overheating (measured in degree hours), are used as key performance indicators (KPI). Based on the KPIs, robustness indicators (RIs) are defined to assess the robustness of each design.

The results from the robustness assessment show that the robustness of the designs vary from which RI and KPI that are considered. The most robust design according to overheating across all RIs is TEK 17 with external blinds. Furthermore, the most robust design in terms of heating energy demand according to performance spread is TEK 17 without shading and internal blinds. On the other hand, according to the two other RIs, performance deviation and maximum performance regret, the most robust design is passive house with no shading. The results also show that which design that is the most beneficial for stakeholders varies with which RI that suits them best and what they emphasize highly in buildings. For example, thermal comfort, low energy consumption or investment costs.

Sammendrag

Robusthetsvurdering er en metode som kan brukes for å vurdere robustheten til et bygningsdesign, basert på usikkerheter når bygningen er i bruk og eksterne forhold. Selv om energieffektive bygninger planlegges å ha et lavt energibruk, er de faktiske tallene ofte høyere på grunn av usikkerhetene. Robusthetsvurderingen går ut på å lage forskjellige scenarier, ut ifra usikkerhetene, for å sjekke hvilket design som er mest robust. Det brukes tre forskjellige robusthetsindikatorer (RI) i denne metoden: «performance spread», «performance deviation» og «maximum performance regret».

I denne masteroppgaven er en leilighet på Løren i Oslo studert, og robustheten til forskjellige bygningsdesign av denne leiligheten er vurdert. Disse designene består av to standarder, TEK 17 og passivhus, i kombinasjon med forskjellig typer solskjerming. Scenarioene er basert på en kombinasjon av brukeroppførsel og klimaforandringer, hvor brukeroppførsel går ut på hvor mye vinduslufting som benyttes. Klimaforandringene er basert på to klimafiler i Oslo: en for dagens klima og en basert på antagelser om hvordan klimaet er i 2050.

Gjennom en kobling mellom programmene IDA ICE og Matlab, kjører en algoritme i Matlab alle simuleringene for hver modell parallelt i IDA ICE. Modellene består av forskjellig brukeroppførsel, mens simuleringene varierer i design og klima. Verdiene fra simuleringene er energibehov til oppvarming og overoppvarming (målt i gradtimer). Disse verdiene blir videre brukt som indikatorer i robusthetsvurderingen for å evaluere hvor robust hvert design er.

Resultatene fra robusthetsvurderingen viser at hvor robust hvert design er, varierer fra hvilken robusthetsindikator som er vurdert og om man vurderer overoppvarming eller energibehovet til oppvarming. Med tanke på overoppvarming er det mest robuste designet, ifølge alle robusthetsindikatorene, TEK 17 med utvendige persienner. Når det gjelder energibehov til oppvarming, er det mest robuste designet ifølge «performance spread» TEK 17 uten skjerming og innvendige persienner. I følge «performance deviation» og «maximum performance regret» er passivhus uten skjerming det mest robuste designet. Resultatene viser også at hvilket design som er mest gunstig for de ulike interessentene varierer ut ifra hvilken robusthetsindikator som passer dem best, samt hvilke faktorer de synes er mest viktige i bygninger. For eksempel kostnader, termisk komfort eller energibruk.

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Abbreviations

IDA ICE	IDA Indoor Climate and Energy. Building performance simulation software.
MATLAB	Matrix Laboratory. Mathematical computing software.
Revit	A building information modeling software.
TEK 17	Norwegian building regulation from 2017.
NS 3031	Norwegian standard about calculation of energy performance of building – method and data (Standard Norge, 2016).
NS-EN 15251	Norwegian standard (based on European) about indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Standard Norge, 2014).
RI	Robustness indicator
KPI	Key performance indicator
OB	Occupant behavior

1. Introduction

1.1 Background

To decrease the global warming in the world, the focus on being a more sustainable society has become bigger. From 1990 to 2016, Norway has decreased the green gas emissions from heating of buildings by 57 %. In 2016, heating of Norwegian buildings only constituted 2.1 % of the total green gas emissions. The reason for this decrease is the increased use of electricity and sustainable solutions as heating pumps and district heating. Currently, the green gas emissions are mainly from wood burning and oil furnaces (Miljødirektoratet, 2018).

Although the green gas emissions from buildings have decreased significantly, buildings still account for 40 % of the total energy consumption in Norway. By building more environmentally friendly buildings, the goal is among other things to decrease the energy use. Energy-efficient buildings are more sustainable than other buildings, but the decreased energy use may adversely affect the thermal comfort. Therefore, it is important to consider these two parameters together. A building that uses little energy is not satisfactory if the thermal comfort is not good.

Because of many uncertainties in building operation and external conditions, buildings often do not meet the requirements that were planned, both when it comes to energy use and thermal comfort (Fichman, A., & Melton P., 2015). To avoid these deviations between planned and actual performance of a building, the solution is a robust building design.

1.2 Purpose

The purpose of this master thesis is to conduct a robustness assessment of an apartment with the highest risk of overheating. The robustness assessment is based on several designs of the apartment tested in various scenarios, which consist of combinations of various occupant behavior (OB) and climate files. The assessment uses key performance indicators (KPI) to evaluate the robustness of the designs. In this thesis, the KPIs are heating energy demand and overheating (measured in degree hours).

Based on this, the overall goal for the master thesis is represented in the following research questions:

- **RQ1** Which design is the most robust in terms of the two key performance indicators, heating energy demand and overheating?
- **RQ2** Does the robustness of the designs differ from which robustness indicator (performance spread, performance deviation or maximum performance regret) and key performance indicator that are considered?
- **RQ3** Which design is the most optimal for the three different stakeholders: policymakers, homeowners and designers?

1.3 Procedure

This master thesis is divided into five parts (except the introduction). The first part introduces important theory about terms and definitions that are later used in the thesis. The second part contains the method to conduct the robustness assessment. Additionally, it presents information about the case study and what the different designs and scenarios are based on. This part also presents how Matlab and IDA ICE are implemented in this thesis as tools to perform the robustness assessment.

The next part presents the results from the simulations, in terms of heating energy demand and overheating (KPIs). In the beginning of this part, several figures of the performance of the different designs are presented. Thus, it is possible to study how the different variables affect the performance of the apartment. Thereafter, the results from the robustness assessment are presented through the three different robustness indicators (RI): performance spread, performance deviation and maximum performance regret. In the end, these RIs are compared to the average performance of each design.

The fourth part includes the discussion. First, it discusses how the different designs perform when considering various climate and occupant behavior. Both the designs, climate changes and occupant behavior are evaluated in detail. Thereafter, the robustness assessment is discussed in terms of the research questions. The last part includes a conclusion of the master thesis and future work.

2. Theory

In this chapter, important concepts and definitions that are relevant for this thesis are explained and described. Hopefully, this knowledge makes it easier to understand the later parts.

2.1 Robustness

The term «robustness» is frequently used in this master thesis, and it is therefore important to know how this word is connected to buildings.

2.1.1 Robustness and Resilience

With the ever-increasing problem of global warming, terms as sustainability, robustness and resilience have become more commonly used words. Sustainability is all about the quality of not being harmful or depleting natural resources, and thereby supporting long-term ecological balance (*Sustainability*, 2017). Robustness and resilience are closely linked to this term. Although robustness and resilience may seem like similar terms, it is important to distinguish between these two in this master thesis:

- Robustness: "Robust is a characteristic describing a model's, test's or system's ability to effectively perform while its variables or assumptions are altered, so a robust concept can operate without failure under a variety of conditions." (*Robust*, n.d.)
- Resilience: "Resilience is the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance. It is the capacity to bounce back after a disturbance or interruption." (*What is resilience?*, n.d.)

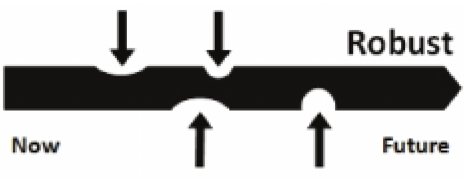


*Figure 1: A robust system (*Husdal, J., 2015*)*

*Figure 2: A resilient system (*Husdal, J., 2015*)*

As underlined and what figure 1 and 2 show, the main difference between these two terms is that resilience demands more than robustness. A resilient building requires more than the ability to withstand an interruption (e.g. extreme weather as flood, earthquake etc.). It also requires the ability to cope immediately and recover quickly (*Resilient building design*, 2014), while a robust building should function under a variety of conditions, but has no requirement when it comes to recovery. If a robust system is broken, it is broken.

In this master thesis, the focus is on robust building designs.

2.1.2 Robust Building Designs

In recent years, the focus on building environmentally friendly buildings has increased. Construction has made up a big part of total energy use in Norway. According to "UngEnergi", today's buildings account for 40 % of the total energy consumption in Norway (*Energieffektivisering*, 2017), where 22 % of this energy consumption goes to residential buildings, while 18 % goes to non-residential buildings (Nord, N. et al., 2017). Thus, if the society should be more environmentally conscious, it is crucial to decrease the energy use in Norwegian buildings. One of the actions Norway does to achieve this, is to establish stricter standards and requirements for building components and performance. On the other hand, energy-efficient buildings with low U-values and increased air tightness, may impact negatively on the thermal comfort (Pomfret, L., & Hashemi, A.,2017). Therefore, thermal comfort is an important factor to consider in combination with energy use.

Although there has been an increase in the construction of environmentally friendly buildings, these buildings do not always perform as expected, e.g. variations in thermal comfort, energy and/or costs. Designers calculate how a building should perform, but these numbers often deviate from the actual numbers when the building is in operation. The reason why the deviations are large can be poor construction, various occupant behavior and varying climate. To avoid this, it is necessary to build robust buildings, which means that the building performs as planned despite these uncertainties. To achieve a robust building, a robustness assessment should be included in the design phase to avoid major deviations between planned performance and actual (Kotireddy, R., Hoes, P., & Hensen, J. L., 2017).

This master thesis is focusing on uncertainties regarding occupant behavior and climate changes. It is proven that occupant behavior may cause major uncertainties in a building's performance. Some occupants are major energy consumers, while others use less energy. On the other hand, climate changes are more uncertain in how it will affect the performance of a building. Exactly how the climate will develop in the future is unclear.

2.1.3 Key Performance Indicators (KPIs)

Robustness of designs may be evaluated in terms of different indicators. In this thesis, it is measured with respect to two KPIs, heating energy demand and overheating.

2.1.3.1 Heating Energy Demand

Heating energy demand is how much energy that is needed to heat rooms in a building to a desired temperature, and is divided into ventilation heat and space heating. According to SINTEF Energiforskning AS, approximately 64 % of total energy consumption in Norwegian households is used on space heating (Feilber, N., & Grinden, B., 2006). As previously mentioned, climate is one of the variables that make up the scenarios. Lighting, technical equipment and domestic hot water are independent of outdoor temperature and are therefore not that important to consider. On the other hand, heating of spaces and ventilation air depend on the outdoor temperature.

2.1.3.2 Thermal Comfort (Overheating)

Thermal comfort is an important factor in buildings. Energy robust buildings are only effective when the users of the building feel comfortable. Thermal comfort means that the users of the building are satisfied with the environment in the building and do not want it warmer or colder. There are various factors that affect thermal comfort, as metabolic rate (met) and clothing insulation (clo). Metabolic rate means how much energy that is generated from a person, for example through activity level. Clothing insulation means how much clothes a person is wearing and their insulating effect. Other factors are air temperature, jet temperature, air velocity and relative humidity (*Human Thermal Comfort*, n.d.).

There are different ways to consider the thermal comfort, and in this thesis, overheating is used. Overheating is the result of too high temperatures in a building. More specific information about this KPI is presented in “3.1.1 Key Performance Indicators”.

2.1.4 Stakeholders

Robust building designs may be of interest for several interest groups and stakeholders. A stakeholder in a building project is a person or organization that has an interest in the project or the project outcome (Pondent, C., 2017). Different stakeholders have various interests of outcomes and what they think is important regarding building designs.

Policy makers are some stakeholders that may be interested in robust building designs and a robustness assessment. For example, they can use this assessment as a basis for defining energy performance requirements for future buildings to achieve the goal of being a more sustainable society. Policymakers prefer a robust design that has low environmental impacts, as low CO_2 emissions and low energy use, as well as low investment costs.

In addition, robust buildings are of interest for homeowners, who are concerned about robust designs with good thermal comfort, and both low operational and investment costs. When buying a building, they can predict how much energy it will use in operation and if it has good thermal comfort. On the other hand, if the building is not robust, it may lead to higher energy consumption than expected, which leads to more expensive electricity bills and dissatisfaction.

Other stakeholders that may be interested in robustness assessments are designers. Designers are concerned about satisfied customers, and that the buildings meet the requirements in the standards they follow. Using a robustness assessment, it is more likely that the contractors and designers deliver a building that functions as planned, which leads to satisfied customers (Kotireddy, R., Hoes, P., & Hensen, J. L., 2017).

2.2 Case Study

The case study is based on an apartment building, which is one of the buildings at Gartnerkvartalet. Gartnerkvartalet is an ongoing project with a total of five apartment buildings at Løren in Oslo. In this thesis, building 5, which contains 46 apartments, is studied closer (Gartnerkvartalet, n.d.). Figure 3 is obtained from Revit and shows building 5. This building has been received from Multiconsult, which is a Norwegian firm consisting of consulting engineers and designers. They are responsible for consultancy in building physics and performance for this project. The planned completion of the building is during 2019.

Figure 3: Building 5, Gartnerkvartalet

Only one apartment in this building is evaluated - the one with the highest risk of overheating, which is assessed in the method. To evaluate the robustness of this apartment, different designs are considered. The designs are made up by some changing variables. The changing design variables are primarily based on recommendations and requirements in standards, different shading, and what is manageable to do in the algorithm in Matlab.

2.2.1 Building Designs

In this thesis, the different designs are based on two standards, TEK 17 and passive house, in combination with different shading types. The difference between the two standards is as follows:

- TEK 17: A newer edition of the Norwegian building technology regulation. This regulation contains the minimum requirement of characteristics a building must have to be legal in Norway. Builders that have delivered building permits before January

1st 2019, can choose to follow TEK 10 or TEK 17 (Kunøe, 2017). After this, the builders must follow TEK 17.

- Passive house: A building designed to use less energy than a regular building. To meet the requirements for passive house, there are stricter rules in the design phase and the building project (*Passivhus*, n.d.).

The standard of passive house has a specific requirement linked to maximum net heating energy demand for residential buildings. For a floor area of (A_{FA}) < 250 m^2 and an outdoor mean air temperature of ≥ 6.3 °C (Standard Norge, 2013), the requirement is:

$$15 + 5.4x(250-A_{FA})/100$$

The unit is $kWh/m^2/yr$. On the other hand, TEK 17 has no specific requirement when it comes to heating energy demand, but only in total energy consumption. For residential buildings the maximum requirement is 95 $kWh/m^2/yr$ (*Byggteknisk forskrift (TEK 17)*, n.d.).

Additionally, the standards contain recommendations and/or requirements for different building components in the building envelope and ventilation system. The two next subchapters explain these building components. Furthermore, "3.2.4.2.1 TEK 17 and Passive House" presents the specific values of the components that are recommended/required in the two standards.

More information about the shading is provided in "2.2.1.3 Windows and Shading".

2.2.1.1 Building Envelope

Some of the design variables that are changing are related to the building envelope. The definition of a building envelope is that it separates the interior and the exterior of a building (*Building Envelope*, n.d.).

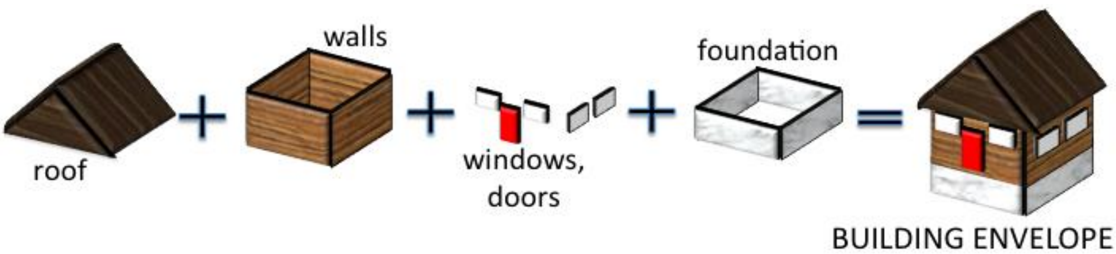


Figure 4: Building envelope (Building envelope, n.d.*)*

2.2.1.1.1 U-value

In standards, recommended or required U-values for external walls, roof, floor, windows and doors are given. U-value means thermal transmittance and is a measure of the rate of transfer of heat through a structure, divided by the difference in temperature across the structure (Lymath, A., 2015). The unit is W/m^2K. The better insulated building, the lower the U-value, and the building retains the heat better. Thus, the building needs less energy for heating, resulting in lower energy consumption.

2.2.1.1.2 Thermal Bridges

A thermal bridge is a part of a building that has lower thermal resistance than the rest of the building, which leads to higher heat loss in this area. In an energy efficient building, it is beneficial to have the least possible amount of thermal bridges to reduce the heat loss and the energy used on heating of the building (*Hva er en kuldebro?*, 2016). Thermal bridges may also affect the thermal comfort of the occupants of the building, such as cold floors. Other examples of thermal bridges are window frames and intermediate floors.

2.2.1.1.3 Leakage Rate

Leakage rate is a factor that indicates if a building is sufficiently dense. This number shows how many times the air is replaced during an hour when there is overpressure or underpressure of 50 Pascal. For example, if a building has a volume of 100 m^3 and a leakage rate of 1 at a pressure of 50 Pascal, the building replaces 100 m^3/hour (*Trykktesting*, 2016). Thus, a lower leakage rate is equivalent to a denser building.

2.2.1.2 Ventilation System

The other part of the standards applies to the ventilation system. The standards contain requirements about two variables in the ventilation system:

2.2.1.2.1 Energy Efficiency of Heat Recovery

The energy efficiency of the heat recovery is the ratio between the energy supplied to the building and the useful energy from the extracted air in the ventilation system. The higher this factor is, the more efficient heat recovery (*Slik får du et energieffektivt ventilasjonsanlegg*, 2016).

2.2.1.2.2 Specific Fan Power

Another requirement in the standards, is the specific fan power (SFP). SFP-factor specifies how much power that is necessary to move 1 m^3 air per second through the ventilation system. The lower the SFP-factor is, the more efficient ventilation system (*Slik får du et energieffektivt ventilasjonsanlegg*, 2016).

2.2.1.3 Windows and Shading

What kind of shading that is used in a building may affect the overheating and the heating energy demand significantly. There are four different parameters that are relevant when considering different shading types:

- <u>Solar Heat Gain Coefficient (g-value/SHGC):</u> Measures the ability of a window to transmit solar energy into a room. The value ranges from 0 to 1. The lower the value, the less heat gain is going through the window (*Measuring Performance: Solar Heat Gain Coefficient (SHGC)*, n.d.).
- <u>Solar Transmittance (T-value):</u> Is the fraction of the sun's radiation that is transmitted through the glazing (*Solar Transmittance*, n.d.)
- <u>U-value:</u> As written in "2.2.1.1 Building Envelope", the U-value is a measure of the rate of transfer of heat through a structure, divided by the difference in temperature across the structure (Lymath, A., 2015). For windows, this value only accounts for the glazing (without the frame).
- <u>Diffusion Factor:</u> IDA ICE defines this factor as the fraction of transmitted directed solar radiation that is diffused by the shading. A value of 1 is fully diffuse, while 0 is no diffusion.

Directed solar radiation means the proportion of the almost straight-line solar radiation from the sun to the earth's surface, while diffuse radiation is the sunlight that arrives on the surface of the earth after single, or repeated, dispersion (scattered by molecules/particles) in the atmosphere (Becker, S., 2001) (Direct, Diffuse and Reflected Radiation, n.d.).

The diffusion factor applies directly to shading, while the three others apply to windows. On the other hand, these three are affected if shading is used. This is further explained in "3.2.4.2.2 Shading".

2.2.2 Scenarios

The various scenarios are based on different occupant behavior and climate changes.

2.2.2.1 Occupant Behavior (OB)

Occupant behavior is defined as how occupants of a building use it. It is one of the biggest factors that impact the building's energy consumption and it contributes to a big uncertainty when designing the energy need of a building. This often leads to the calculated energy consumption not matching with the actual energy consumption when the building is operational (DELZENDEH, E. et al., 2017).

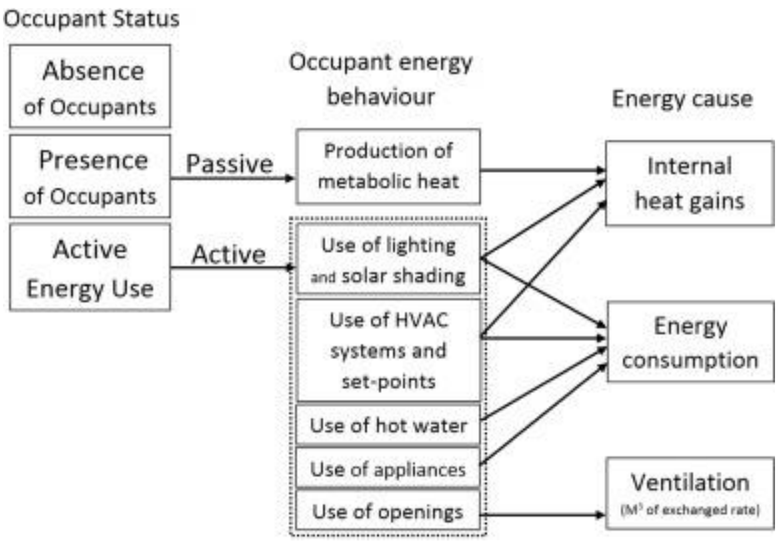


*Figure 5: Different factors in occupant behavior (*DELZENDEH, Elham et al., 2017*)*

Figure 5 shows what factors of occupant behavior that affect the energy consumption of a building. According to SINTEF and their EU-project, through help of hundreds of Norwegian households, they have mapped where buildings use the most energy. The result they found was that heating constitutes 64 %, which means that it constitutes a lot of the total energy consumption of a building. Additionally, 15 % is used on hot water and 6 % on lighting. The rest of the electricity is used on the kitchen, electrical devices and washing machines/dishwasher (Feilber, N., & Grinden, B., 2006). In this thesis, the occupant behavior consists of different occupancy schedules, window opening schedules and window opening strategies.

2.2.2.1.1 Occupancy and Window Opening Schedules

Mainly, occupancy schedules may be provided in two different ways - deterministic models or stochastic models. Stochastic models contain randomness. Different input parameters and initial conditions lead to a collection of several outputs. On the other hand, deterministic models represent a fictional behavior of a building occupant during a day and contain no randomness.

Occupant behavior includes randomness and should be stochastic modeled, but these models are very complicated. Therefore, building performance simulations use the deterministic approach. The actions of humans are typically modeled with predefined fixed schedules and/or predefined rules (Carlucci, S., 2017). In this thesis, the occupancy is based on the deterministic approach, and the window opening schedules are based on the occupancy schedules.

2.2.2.1.2 Window Opening Strategies

Households and residential buildings in Norway usually do not have mechanical cooling, and therefore it is important, especially during the summer, to use ventilation through windows. The ventilation is important to provide good indoor climate. Little replacement of air may lead to tiredness and also moisture damage in the building.

Since comfort is determined by many subjective feelings, how much people ventilate through windows differs from one person to another. This thesis takes into account that people are ventilating differently, and therefore, the window openings are based on four different strategies. Two of them are based on the adaptive model.

<u>Adaptive Model</u>

Use of window openings may depend on several comfort parameters, e.g. operative temperature, CO_2 concentrations and humidity. Standard NS-EN 15251:2007 defines acceptable “summer indoor temperatures” based on the adaptive model that are shown below. This model is based on the operative temperature. Operative temperature is the temperature humans experience in a room. It is a combination of the air temperature and the mean radiant temperature (Bean, R., 2012).

The adaptive model applies to buildings without mechanical cooling. Since households and residential buildings in Norway usually do not have mechanical cooling, the adaptive model is relevant for such buildings. Figure 6 shows the adaptive model, where the y-axis represents the operative temperature, while the x-axis represents the running mean outdoor temperature. The running mean outdoor temperature is based on the weighted outdoor air temperature during the previous days, as occupants adapt to their environment over time (*Adaptive Comfort Temperatures*, n.d). The formula for calculating the running mean outdoor temperature(ϑ_{rm}) is (Hamdy, M., 2018):

$$\vartheta_{rm} = (\vartheta_{red-1} + 0.8\vartheta_{red-2} + 0.6\vartheta_{red-3} + 0.5\vartheta_{red-4} + 0.4\vartheta_{red-5} + 0.3\vartheta_{red-6} + 0.2\vartheta_{red-7})/3.8$$

ϑ_{red-1} is the daily mean air outdoor temperature (°C) for the previous day, and ϑ_{red-2} is the daily mean outdoor temperature for the day before. In total, when calculating the running mean outdoor temperature, the formula considers 7 days before the day that is calculated. As figure 6 and table 1 show, the adaptive model divides into three different temperature limits: category I, category II and category III. Category I is the strictest. Temperatures higher or lower than category III are categorized as unacceptable thermal comfort.

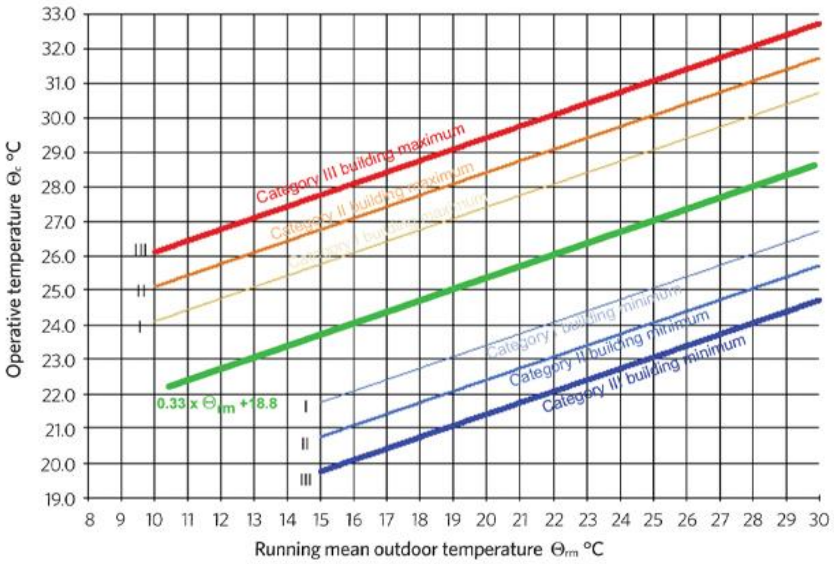


Figure 6: The adaptive model (Modul 113: Determining thermal comfort in naturally conditioned buildings, 2017)

Table 1: The three categories in the adaptive model

Category I	Upper limit	$\vartheta_{i\,max} = 0.33\vartheta_{rm} + 18.8 + 2$
	Lower limit	$\vartheta_{i\,min} = 0.33\vartheta_{rm} + 18.8 - 2$
Category II	Upper limit	$\vartheta_{i\,max} = 0.33\vartheta_{rm} + 18.8 + 3$
	Lower limit	$\vartheta_{i\,min} = 0.33\vartheta_{rm} + 18.8 - 3$
Category III	Upper limit	$\vartheta_{i\,max} = 0.33\vartheta_{rm} + 18.8 + 4$
	Lower limit	$\vartheta_{i\,min} = 0.33\vartheta_{rm} + 18.8 - 4$

The upper limit means the highest acceptable operative temperature ($\vartheta_{i\,max}$), while the lower limit represents the lowest acceptable operative temperature ($\vartheta_{i\,min}$). The operative temperature depends on the running mean outdoor temperature. For each of the categories, the acceptable temperature is when the operative temperature is between the lower and upper limit (Standard Norge, 2014).

The adaptive comfort approach has received some critique. One is that it oversimplifies the comfort chart into a two-dimensional representation and is not considering other comfort parameters. Another critique is that it lacks experimental or survey data (Halawa, E., & Van Hoof, J., 2012). Despite this criticism, in this thesis, two of the window opening strategies are based on the adaptive comfort approach.

2.2.2.2 Climate Changes

In Norway, the Norwegian climate center (“Norsk klimaservicesenter”) has established an estimate of how the climate is expected to be in the years up to 2100. These estimates are based on assumptions about future emissions, and global and regional climate models. As mentioned earlier, this study is focusing on an apartment building in Oslo. According to “Norsk klimaservicesenter”, if the RCP is 8.5, the average temperature in Eastern Norway in 2050 will be 2.2 °C higher than it was in the 1980s. In 2100, the average temperature will be almost 4.7 °C higher. If the RCP is 4.5, the average temperature will be 1.7 °C higher in 2050 and almost 2.6 °C higher in 2100 than in the 1980s (*Klimaframskrivninger*, n.d.).

RCP means representative concentration pathways and represents the four greenhouse gases. The different RCPs represent different scenarios of greenhouse gas concentrations in the future. An RCP of 8.5 means high concentration in the future, while an RCP of 4.5 has lower concentration. (Nye scenarier gir bedre forskning, 2013). How much the temperature will rise for these two cases the next hundred years is shown in figure 7 and 8. In addition to the temperature rise, other climate changes will probably also occur in Oslo, such as heavier rainfall. Despite these changes, this thesis only focuses on temperature rise and how it affects the heating demand and overheating.

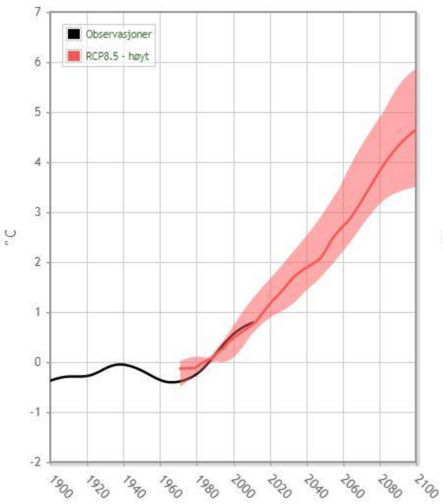


Figure 7: RCP 8.5

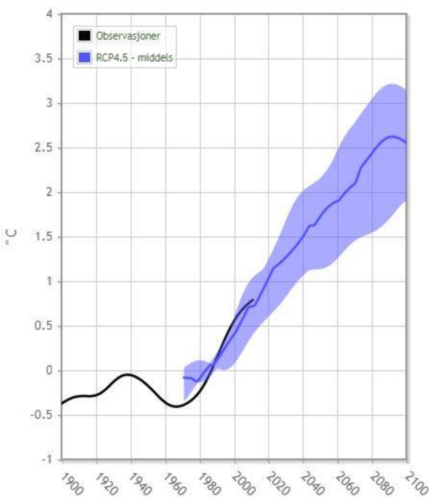


Figure 8: RCP 4.5 (Klimaframskrivninger, n.d.)

The information presented in this part, “2. Theory”, provides a basis for further understanding the implementation of the robustness assessment. The following chapter, “3. Method”, contains more specific information about how the robustness assessment of the apartment was conducted.

3. Method

To consider which design that is the most robust regarding the apartment with the greatest risk of overheating, a robustness method has been used. This method is retrieved from the paper by Rajesh Kotireddy, “Simulation based comparison of robustness assessment methods to identify robust low energy building design” (Kotireddy, R., Hoes, P., & Hensen, J. L., 2017). Several designs have been compared to each other in different scenarios, which consist of varying occupant behavior in combination with different climate files. Most of the values, both for designs and occupant behavior, are based on different standards, e.g. TEK 17, passive house and NS 3031.

At the beginning of this chapter, information about the process of the robustness assessment is given. Furthermore, the case study is presented, and what values and combinations that make up the scenarios and the designs. Additionally, information about how Matlab and IDA ICE are implemented in this thesis is provided.

3.1 Robustness Assessment

This part presents first the KPIs that are used as input values in the assessment to measure the robustness of the designs. The robustness can be measured in different ways, and the assessment uses three different RIs: performance spread, performance deviation and maximum performance regret. These are presented after the KPIs.

3.1.1 Key Performance Indicators

As earlier mentioned, the two KPIs are *heating energy demand* and *overheating*. Heating energy demand has been measured in how many kilowatt hours per square meter during a year (kWh/m^2/yr) the ventilation system and space heating use to achieve a desired temperature in the apartment.

The other KPI is overheating, measured in degree hours. The definition of degree hours is the number of hours the hourly average indoor temperature is below or above a standard temperature (*Degree hour*, n.d). In this thesis, degree hours have been based on how many hours the operative temperature is above 27 °C (overheating). Thereby, the degree hours are not evaluating the thermal comfort in terms of cold/low temperatures. The unit used is degree hours per year. The reason why the degree hours are based on the temperature of 27 °C is because IDA ICE categorizes values above this temperature as unacceptable. Additionally, NS-EN 15251, table A.3, recommends a maximum operative temperature of 27 °C for category III in households (Standard Norge, 2014).

Using these KPIs and this robustness method have in the end lead to a conclusion of the robustness of the designs. However, which design that is most robust may depend on which RI one evaluates:

1) Performance Spread
2) Performance Deviation
3) Maximum Performance Regret

3.1.2 Performance Spread

The RI "performance spread" is based on the difference between the maximum performance (A) and minimum performance (B) across all scenarios. To find out which of the designs that is most robust regarding this indicator, the difference between the maximum performance and minimum performance of each design has been calculated. The design with the smallest difference is the most robust one.

$$A_m - B_m$$

3.1.3 Performance Deviation

Performance deviation is based on the difference between the the maximum performance of each design (A) and the best performance of all designs across all scenarios (D). The design that has the smallest difference between these two factors is most robust.

$$A_m - D$$

The best performance of all designs across all scenarios is defined as when the minimum performance of each scenario (C) equals the minimum performance across all designs (B). D is the absolute best solution of a combination of a specific scenario and a specific design.

$$D = \min(B) = \min(C)$$

3.1.4 Maximum Performance Regret

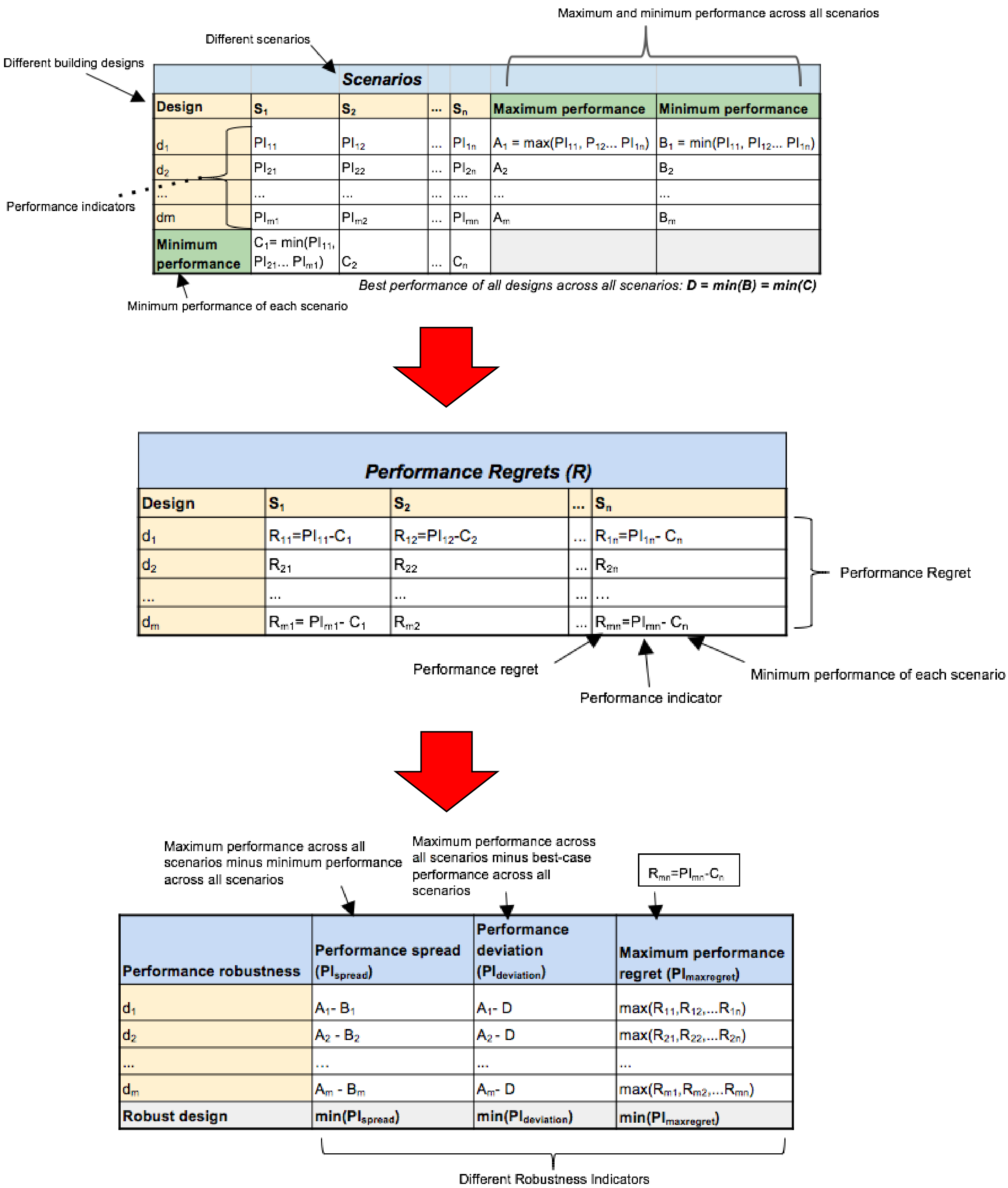
Performance regret means the difference between each individual performance indicator (PI) and the minimum performance of each scenario (C). PI is based on a specific combination between a scenario and a design.

$$PI_{mn} - C_n$$

The maximum performance regret locates the biggest deviation in each design, which means the difference between the worst performance and the best performance. To define the most robust design, the minimum of the maximum performance regret across all designs have been calculated. The design with the lowest value is most robust. This method defines the most robust design based on the minimum of the biggest deviations across all designs (Kotireddy, R., Hoes, P., & Hensen, J. L., 2017).

$$\min(PI_{maxregret})$$

The robustness method is further explained in figure 9 below. This assessment has been conducted two times – for both KPIs.



Scenarios						
Design	S_1	S_2	...	S_n	Maximum performance	Minimum performance
d_1	PI_{11}	PI_{12}	...	PI_{1n}	A_1 = max(PI_{11}, P_{12}... PI_{1n})	B_1 = min(PI_{11}, PI_{12}... PI_{1n})
d_2	PI_{21}	PI_{22}	...	PI_{2n}	A_2	B_2
...	...	...	...	....	...	...
dm	PI_{m1}	PI_{m2}	...	PI_{mn}	A_m	B_m
Minimum performance	C_1= min(PI_{11}, PI_{21}... PI_{m1})	C_2	...	C_n		

Performance Regrets (R)				
Design	S_1	S_2	...	S_n
d_1	R_{11}=PI_{11}-C_1	R_{12}=PI_{12}-C_2	...	R_{1n}=PI_{1n}- C_n
d_2	R_{21}	R_{22}	...	R_{2n}
...	...	...	...	...
d_m	R_{m1}= PI_{m1}- C_1	R_{m2}	...	R_{mn}=PI_{mn}- C_n

Performance robustness	Performance spread (PI_{spread})	Performance deviation ($PI_{deviation}$)	Maximum performance regret ($PI_{maxregret}$)
d_1	A_1- B_1	A_1- D	max(R_{11},R_{12},...R_{1n})
d_2	A_2 - B_2	A_2 - D	max(R_{21},R_{22},...R_{2n})
...	...	...	...
d_m	A_m - B_m	A_m- D	max(R_{m1},R_{m2},...R_{mn})
Robust design	min(PI_{spread})	min($PI_{deviation}$)	min($PI_{maxregret}$)

Figure 9: The robustness assessment

3.2 Case Study

As previously mentioned in the theory, the case study is based on an apartment building located at Løren in Oslo. Figure 10 is retrieved from the software Revit and it shows how the building will look like when the project is finished. In total, the building has eight floors. Figure 11 is retrieved from IDA ICE and it shows how the building is oriented in relation to south and north. The longest sides of the building are oriented toward southeast and northwest, while the shortest sides are toward northeast and southwest.

Figure 10: The apartment building

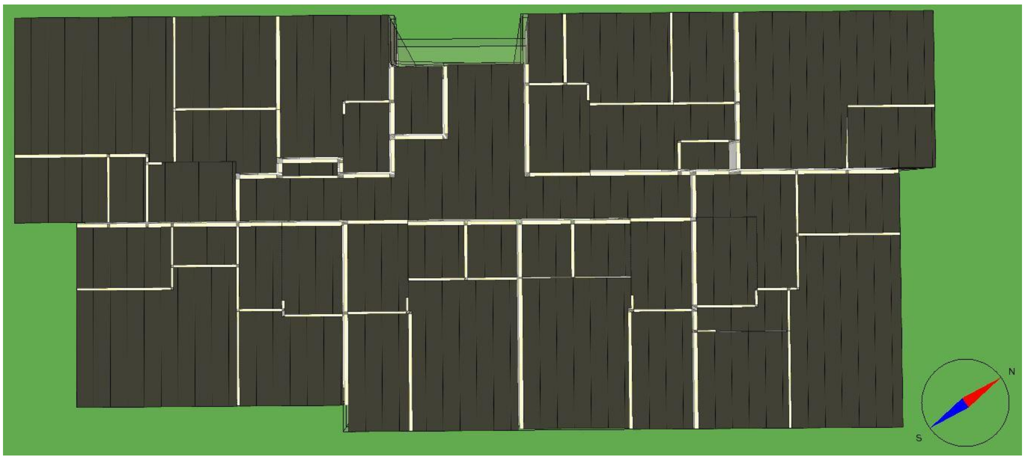


Figure 11: Orientation of the building

Only one apartment, with the highest risk of overheating, should be considered in the robustness assessment. Therefore, it was necessary to simulate several floors of the building to detect which apartment that has the highest risk.

3.2.1 Preparatory Work in IDA ICE

All the floors, except the first floor, are the same in the building. The shape, number of apartments and the layout of the apartments are identical from the 2nd floor and up to 8th floor. Therefore, to simplify the model, two different floors have been evaluated in terms of overheating. The two floors that were evaluated, were the 5th and 8th floor. The 5th floor is in the middle of the building and is a representative floor of the entire building. The 8th floor represents the floor that is the most critical in terms of overheating. All apartments on these two floors were evaluated.

3.2.1.1 Zones

As mentioned earlier, this building is a project Multiconsult is working on. First, an IFC-file from Multiconsult was received. The building did not have marked rooms in IDA ICE, which is very beneficial. Therefore, the IFC-file was opened in Revit and the rooms on 5th and 8th floor were tagged with room tags. In this way, all the rooms were created with boundaries and names. When this was completed, the IFC-file was imported into IDA ICE.

Thereafter, thermal zones were needed to be created in IDA ICE. In this way, the software knows what the calculations should be based on, and it is also possible to use different settings for each zone. In this thesis, when the two floors were compared, each floor worked as one zone. Thus, there were similar settings for all the rooms. Figure 12 shows the floor plan and what rooms the building consists of from 2nd and up to 8th floor. The thin black line represents the boundaries between the different apartments. The room surrounded by the dark grey line is a common hallway, while the light gray line surrounds the elevator and the light pink mechanical space.

● Livingroom and kitchen ● Bathroom/Toilet ● Bedroom ● Hallway ● Storage

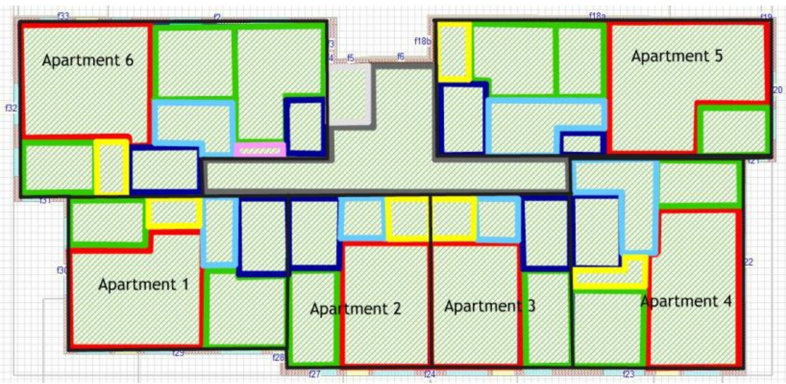


Figure 12: Floor plan of each level in the building

3.2.1.2 The Most Overheated Apartment

When simulating the 5th and 8th floor in IDA ICE, it was assumed that there was no ventilation through the windows and no shading. Additionally, the building was simulated with TEK 17 values and the current climate file for Oslo. All the rooms had the same settings, and they were based on schedules and the values in “3.2.5 Fixed Variables” from NS 3031. All other values were based on default settings in IDA ICE.

The room that was found to be the most overheated was bedroom 3 in apartment six on the 8th floor. Figure 13 shows where this room is in the apartment. The second worst room was the living room/kitchen in the same apartment. The highest registered operative temperature in bedroom 3 was 43.4 °C at 5 pm on August 15th. In the living room and kitchen the highest operative temperature was 41.9 °C on July the 16th at 6.45 pm.

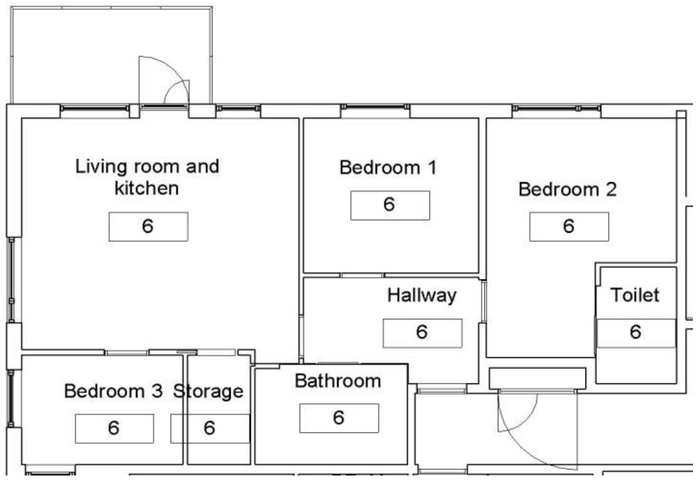


Figure 13: Floor plan of apartment six

Figure 14 below shows where the sun is in relation to the building on 10th of August in the afternoon. Apartment six is marked in red. Bedroom 3 and the living room/kitchen are facing southwest and towards the sun most of the day and might therefore be at high risk of overheating.

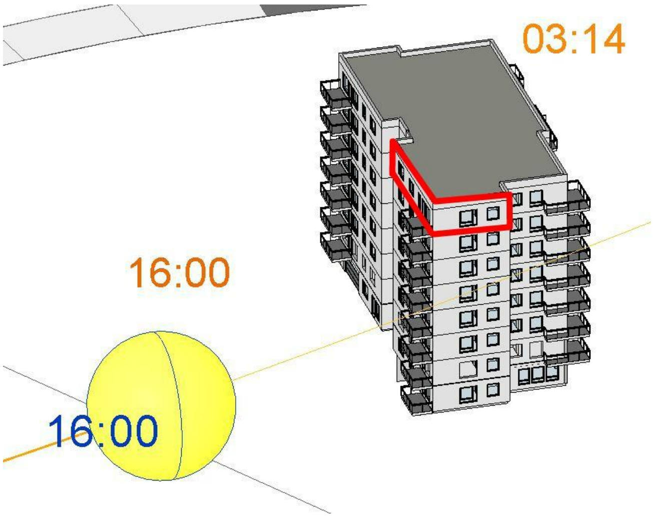


Figure 14: Position of the sun relative to the building in the afternoon

After the apartment with the most overheating was detected, all the other apartments were deleted. The chosen apartment was to be further evaluated in terms of degree hours and consumption of heating energy. The most overheated apartment, apartment six on 8th floor, has a floor area of 84 m^2. It has a balcony and the following rooms:

- Combined living room and kitchen
- Three bedrooms
- Two bathrooms
- Hallway
- Storage room

In total, the apartment has six windows. They are facing southwest and northwest. For the further evaluation of this apartment, all rooms were divided into separate zones. Thus, the eight rooms correspond to eight zones. More details about the zones are explained in “3.2.5 Fixed Variables”.

3.2.2 Design and Scenario Variables

When further simulating and evaluating this apartment, several scenarios and designs had to be defined. The different scenarios consist of occupant behavior variables and two climate files, while the designs are made up of two different standards and three kinds of shading. The designs and scenarios consist of the following variables:

Design Variables

- Two standards: TEK 17 and passive house
- Three kinds of shading

Scenario Variables

- Four different window opening strategies
- Three window opening schedules based on occupancy schedules
- Two different climate files for Oslo: current and estimated climate in 2050

In total, there are 144 combinations based on six designs and 24 scenarios. The designs are presented in table 4, while the scenarios can be found in appendix A. The 144 combinations were further simulated in terms of heating energy demand and overheating. The algorithm in Matlab cannot handle all the mentioned variables. Therefore, some were needed to be implemented in several models. The other variables were processed by Matlab.

3.2.3 Creation of 12 Models in IDA ICE

The twelve different models created in IDA ICE were based on different scenarios of occupant behavior (OB), which were made up of four window opening strategies (controls) and three window opening schedules based on occupancy schedules. A weakness of the algorithm in Matlab is that it is difficult to change window opening controls and schedules, i.e. when people are at home and not. To avoid a lot of work on creating a new algorithm in Matlab, twelve models were created manually in IDA ICE.

The opening schedules of windows are based on occupancy schedules, when people are at home or not. The windows are only operable when people are at home, except for the strategy of Multiconsult. As table 2 shows, the only difference between OB3, OB7 and OB11, which are based on the strategy of Multiconsult, is the presence of occupants. The twelve different models/occupant behaviors are as follows:

Table 2: The twelve models

Number of Models/OBs	Occupant Behavior	Window Strategy	Window Opening Schedule	Occupancy Schedule
1	OB1	Adaptive (I)	NS 3031	NS 3031
2	OB2	Adaptive (III)	NS 3031	NS 3031
3	OB3	Multiconsult	Multiconsult	NS 3031
4	OB4	IDA ICE	NS 3031	NS 3031
5	OB5	Adaptive (I)	House living	House living
6	OB6	Adaptive (III)	House living	House living
7	OB7	Multiconsult	Multiconsult	House living
8	OB8	IDA ICE	House living	House living
9	OB9	Adaptive (I)	Iranian schedule	Iranian schedule
10	OB10	Adaptive (III)	Iranian schedule	Iranian schedule
11	OB11	Multiconsult	Multiconsult	Iranian schedule
12	OB12	IDA ICE	Iranian schedule	Iranian schedule

The first column in the table represents the number of models. The second column represents the name of each occupant behavior scenario, while the third and fourth columns show what window opening strategy and schedule that are used. Fifth column represents the occupancy schedules, which the window opening schedules are based on. What all these names mean are explained in “3.2.3.1 Window Opening Strategies” and “3.2.3.2 Window Opening Schedules”.

The apartment also has a balcony and a balcony door. Since there is no control implemented in IDA ICE and it is not possible to specify the criteria when the door should be open, ventilation through the balcony door is neglected in all cases.

3.2.3.1 Window Opening Strategies

When it comes to window opening strategies, there are four different types, where two of them are based on the adaptive model. The third strategy is based on a principle Multiconsult uses, while the fourth strategy is an implemented control in IDA ICE. With the exception of the control implemented in IDA ICE, the three other strategies were manually created in IDA ICE. The different opening schedules the strategies use is explained in "3.2.3.2 Window Opening Schedules".

All six windows in the apartment follow the strategies. No window has its own strategy. The only difference is in the schedule of the third control (Multiconsult), which is explained in "3.2.3.1.2 The Strategy of Multiconsult".

3.2.3.1.1 The Two Strategies Based on the Adaptive Model

As written in "2.2.2.1.2 Window Opening Strategies", the adaptive model provides both upper and lower limits. In this thesis, only the upper limits are used. In figure 15, the x-axis represents the running mean outdoor temperature, while the y-axis represents the operative temperature. Originally, there are three different categories, but only two of these are used in this thesis. The two strategies for opening windows are based on category I and category III, where category I opens windows at a lower temperature. For example, in category I, if the running mean outdoor temperature is 10 °C and the operative temperature inside is higher than 24.1 °C, the windows open. For category III the temperature must be higher than 26.1 °C.

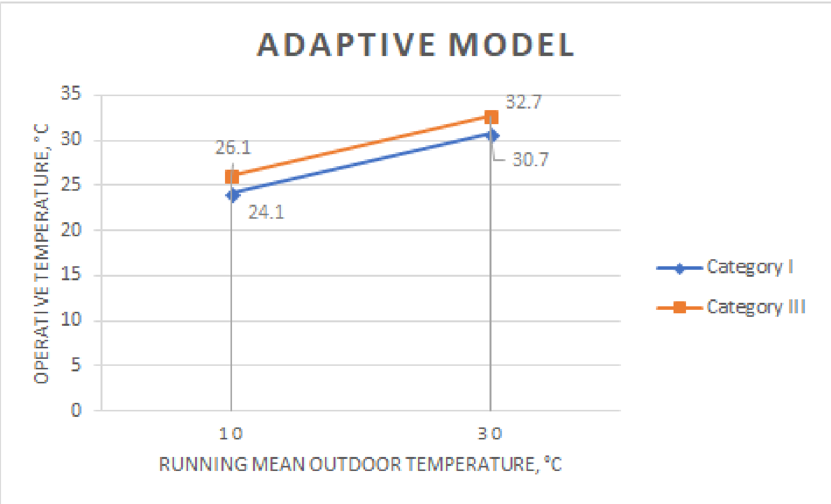


Figure 15: Two of the limits defined in the adaptive model

Figure 16 shows the structure of these two strategies in IDA ICE. If the windows open depend on three different factors: operative temperature, outdoor temperature and window opening schedule. The windows open if the temperature inside is higher than the outdoor temperature, if it is within the opening schedule and if the operative temperature is higher than one of the graphs in the adaptive model, shown in figure 15. If one of these three is the opposite: outdoor temperature is higher than inside, people are not at home or the operative temperature is lower than the graphs of category I/category III, the windows will not open. All the windows in the apartment use the same control - similar temperature and schedule.

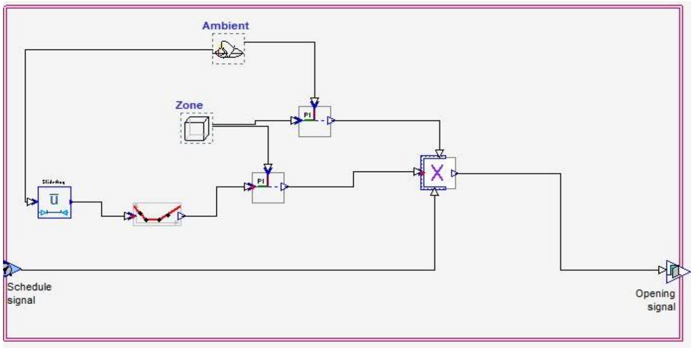


Figure 16: The strategies based on the adaptive model

The box with the ū in figure 16 calculates the sliding average of the air temperature, which gives the running mean outdoor temperature. Thereafter, this temperature is further sent to the graph in the adaptive model. The controller compares the operative temperature in the room/zone with this graph. Figure 17 shows the air temperature and the running mean outdoor temperature on the 10th of August. The red line represents the air temperature, while the running mean outdoor temperature is represented by the green line. As the figure shows, the green line is displaced and has lower variation than the red line.

🔴 Outdoor air temperature 🟢 Running mean outdoor temperature

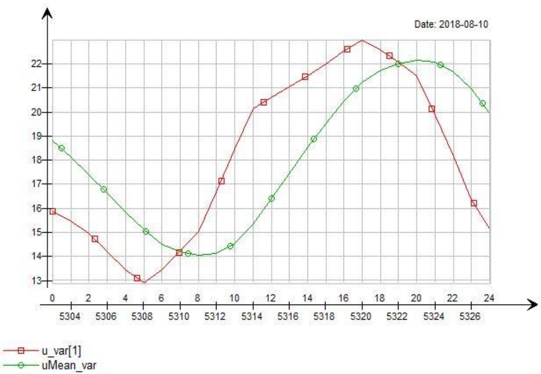


Figure 17: Temperatures 10th of August

3.2.3.1.2 The Strategy of Multiconsult

This window opening strategy is not using the same opening schedules as the three other strategies. Multiconsult defines the opening schedules themselves, and therefore the models based on this strategy do not follow the other schedules. Additionally, in contrast to the three other controls, this opening strategy varies from if it is a window in the bedroom or in the living room. The criteria this strategy uses are the following:

1) Monday - Friday: The windows are 25 % open from 11 pm until 8 am, closed from 8 am until 4 pm, and 100 % open from 4 pm until 11 pm.
2) Saturday - Sunday: The windows are open 25 % at all times.
3) The windows are only open if the air temperature is above 18 °C in the bedrooms and 20 °C in the living room.

Figure 18 shows the strategy for the windows in the living room and kitchen. The windows are open if the air temperature in the zone is higher than 20 °C, and if the time is between 4 pm and 8 am. How much the window is open depends on what time of the day it is. The control for the windows in the bedrooms is exactly the same, except that 20 °C is replaced by 18 °C.

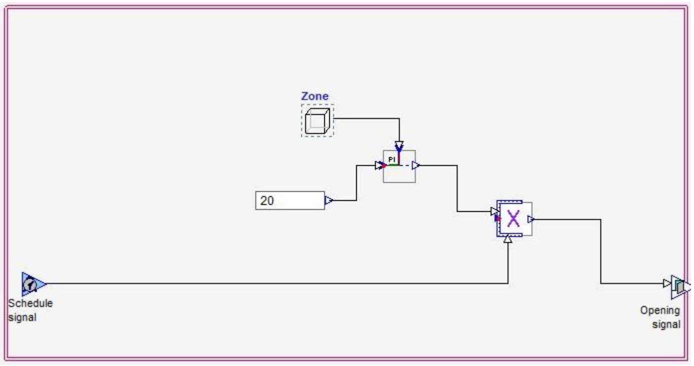


Figure 18: Strategy based on Multiconsult

3.2.3.1.3 The Integrated Strategy in IDA ICE

The integrated strategy in IDA ICE, shown in figure 19, is quite similar to the strategies based on the adaptive model. It is also based on the fact that the outdoor temperature must be lower than the zone temperature and that it must be within the opening schedule. The difference between this strategy compared to the others is that this strategy is based on that the zone air temperature must be higher than the maximum temperature of the thermostat, cooling setpoint. It is not usual that Norwegian apartments contain any other cooling than opening of windows. Therefore, the windows open if the air temperature in the zone is higher than 24 °C. This value is based on the cooling setpoint from the standard of NS 3031.

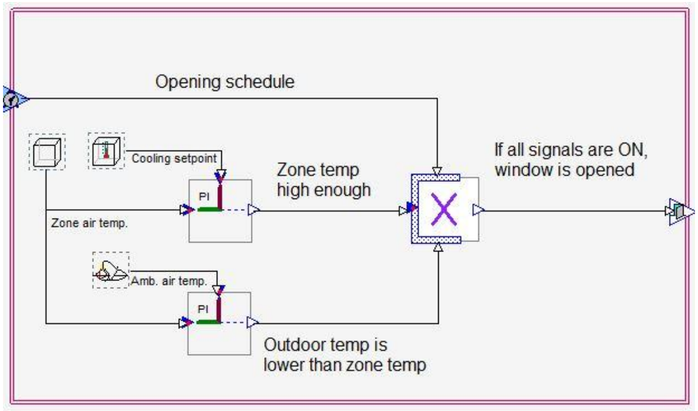


Figure 19: Implemented strategy in IDA ICE

3.2.3.1.4 Comparison of the Four Strategies

The figures below present a comparison of the four strategies. They are based on the first four models/OBs (ref. table 2), and how much the southwest window in the living room is open during 10th of August. Three of the strategies are based on that the opening schedule is all day long, while the strategy of Multiconsult follows its own schedule. The climate that is used is the reference file for Oslo (current climate). The outdoor air temperature and running mean outdoor temperature for 10th August are shown in figure 17.

Adaptive Model: Category I

Figure 20 and 21 show how the window in the living room is functioning on the 10th of August. Figure 20 shows the upper limit of category I in the adaptive model as the red line, while the green line represents the operative temperature in the living room/kitchen. From approximately 10 am until 8 pm, the green line covers the red line. This is reflected in the figure to the right, the window is open from approximately 10 am until 8 pm.

Category I from adaptive model   Operative temperature in the living room

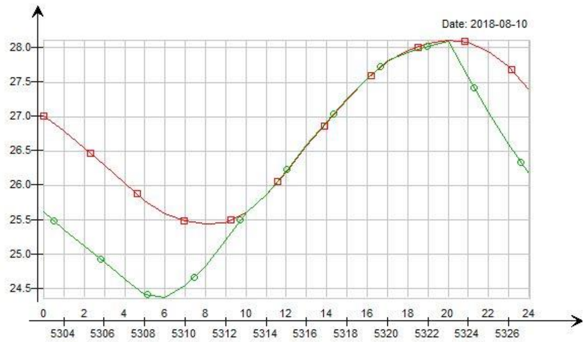


Figure 20: The operative temperature and the upper limit(I)

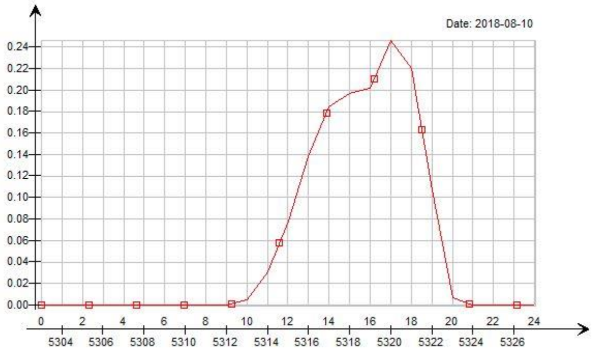


Figure 21: Window Opening (I)

Adaptive Model: Category III

Figure 22 and 23 show the same as the previous ones, except that these apply to category III in the adaptive model. The green line covers the red line from approximately noon until 8 pm. The window is also open during this time. The y-axis in the right figure also shows that the percentage of how much the window is open is less than for category I.

Category III from adaptive model   Operative temperature in the living room

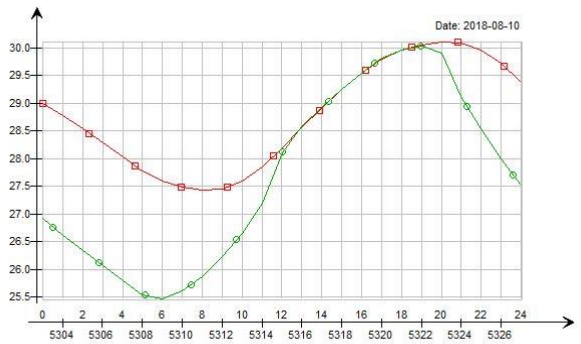


Figure 22: The operative temperature and upper limit(III)

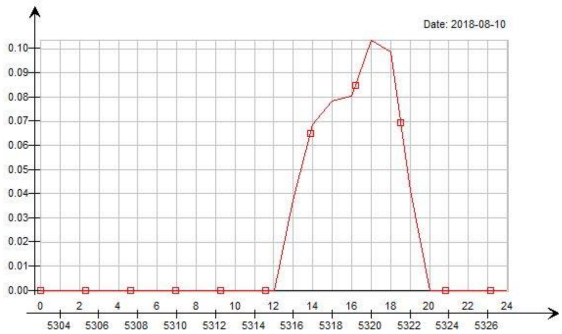


Figure 23: Opening of window (III)

Strategy of Multiconsult

This window opening strategy differs from the two presented above. In figure 24, the red line marks which limit the air temperature must cross to open the window (also depends on if it is within the opening schedule of Multiconsult). Since this window is in the living room/kitchen, the red line lies on 20 ^{o}C. The green line shows the air temperature in the room. As figure 25 shows, the window is a bit open from midnight until 8 am, while from approximately 4 pm until 11 pm it is nearly 100 % open.

The limit, 20 ^{o}C   Air temperature in the living room

Figure 24: The air temperature and the limit (20 ^{o}C)

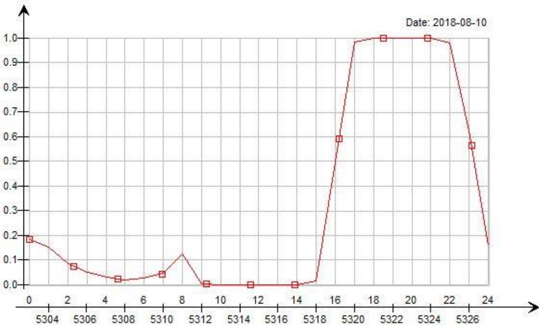


Figure 25: Window opening (Multiconsult)

IDA ICE

Figure 26 and 27 show how it works for the window in the living room in terms of the implemented control in IDA ICE. The green line represents the air temperature in the room, while the red line is the cooling setpoint. As the figures show, the air temperature is above 24 ^{o}C from approximately 10 am until 10 pm. The window opens and closes also at the same time.

Cooling setpoint, 24 ^{o}C   Air temperature in the living room

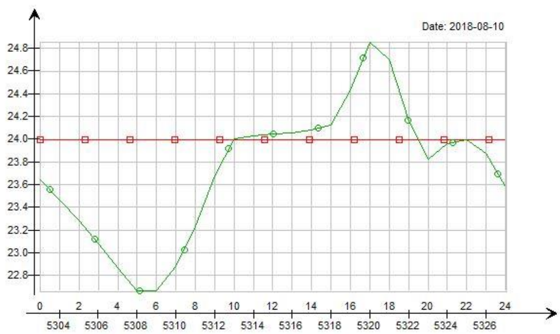


Figure 26: The air temperature and the setpoint (24 ^{o}C)

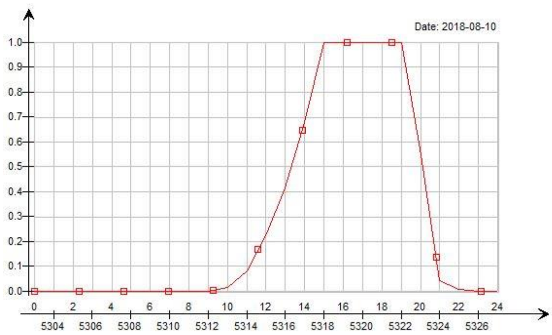


Figure 27: Opening of window (IDA ICE)

The strategies based on the adaptive model open the window in terms of how high the operative temperature in the living room is, while the two others use air temperature. According to the y-axis, the window that is the most open follows the third strategy (Multiconsult) and the fourth strategy (IDA ICE). The window that is least open is the one that uses the second strategy (category III). When it comes to the strategy based on category I, the window is open much of the time during the day, but the maximum opening of the window is 24 %.

3.2.3.2 Window Opening Schedules

The three different opening schedules the opening strategies use, are based on occupancy schedules from the Norwegian standard NS 3031, IDA ICE and the paper "A study of the impact of occupant behaviors on energy performance of building envelopes using occupants' data" (Yousefi, F., Gholipour, Y., & Yan, W., 2017). When the line is at 1 on the y-axis, all the occupants are at home. When it is at 0 no one is at home. If it is 0.5, half of the residents are at home. The three different occupancy schedules are presented like this in IDA ICE:

<u>NS 3031</u>

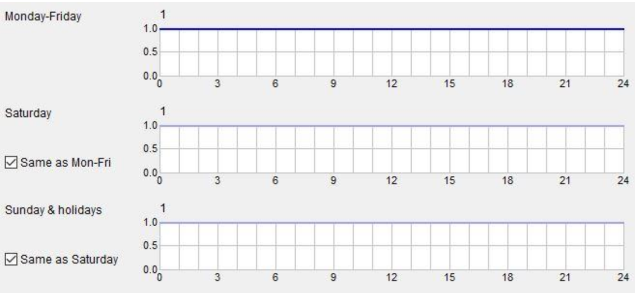


Figure 28: Schedule based on NS 3031

This schedule is recommended by NS 3031, and one assumes that the users of the building are constantly home, both on weekdays and weekends.

IDA ICE

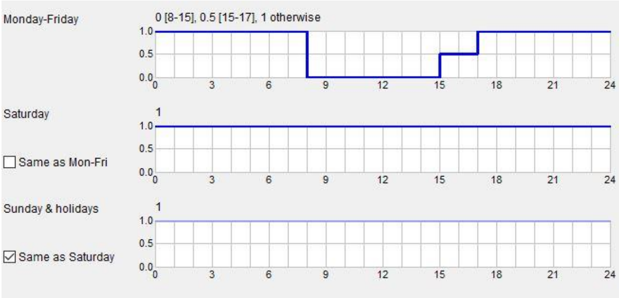


Figure 29: Schedule based on IDA ICE

This schedule is implemented in IDA ICE and is called "house living". During the weekdays, the users are home from 5 pm until 8 am in the morning. From 8 am until 3 pm no occupants are home, while between 3 pm and 5 pm half of the residents are home. During the weekends, the users are constantly at home.

Paper: Iranian Schedule

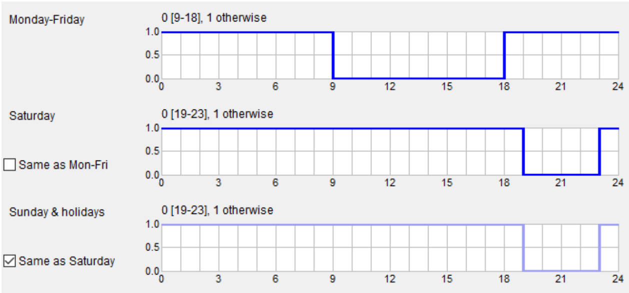


Figure 30: Iranian schedule

Figure 30 shows a schedule from the paper "A study of the impact of the occupant behaviors on energy performance of building envelopes using occupants' data" (Yousefi, F., Gholipour, Y., & Yan, W., 2017), and is in this thesis called "Iranian schedule". Finding an occupancy schedule from Norway, which was different from NS 3031 and IDA ICE, was very difficult. Therefore, this schedule is from an apartment building in Iran, and is based on a field survey provided by the occupants living there. Based on various reasons, e.g. culture, this schedule might differ from what is usual in Norway. On the other hand, there may be many people in Norway who follow a schedule like this. From Monday until Friday, the users are gone from 9 am until 6 pm. In the weekends, the residents are gone from 7 pm until 11 pm.

3.2.4 Matlab

An algorithm in Matlab is used to simulate in parallel all the combinations of scenario and design variables in each model. In total, there are 12 models (ref. table 2) and 12 combinations (ref. table 3). Manually running all these combinations through 12 different models in IDA ICE is demanding. Thus, Matlab makes it possible to save a lot of time and effort by running all the combinations at the same time.

Originally, this algorithm was made by Håkon Eggebø in his master thesis, "Sensitivity analysis for investigating the energy performance of a retrofitted kindergarten under different weather scenarios", during the spring of 2017 at NTNU (Eggebø, H., 2017). More specific information about this algorithm, than what is presented in this thesis, can be read in his master thesis.

This algorithm consists of one "main algorithm", called "master script", and several functions. Figure 31 shows a flow chart of the algorithm. First, this algorithm uses a function called "Collect design variables" that collects the variables from a diff-script (difference script). IDA ICE creates a script when changes in a model are conducted. In this thesis, the diff-script was created based on which variables Matlab should change in the models in IDA ICE. The values Matlab should use for each variable in the diff-script is retrieved from a sample file by the function "Open Sample File". This file contains the combinations and actual values of the variables. Thus, Matlab can change the values of the variables from one simulation to another. Furthermore, all the simulations were simulated in parallel and the degree hours were calculated for each simulation. In the end, the heating energy demand was calculated and printed to a file.

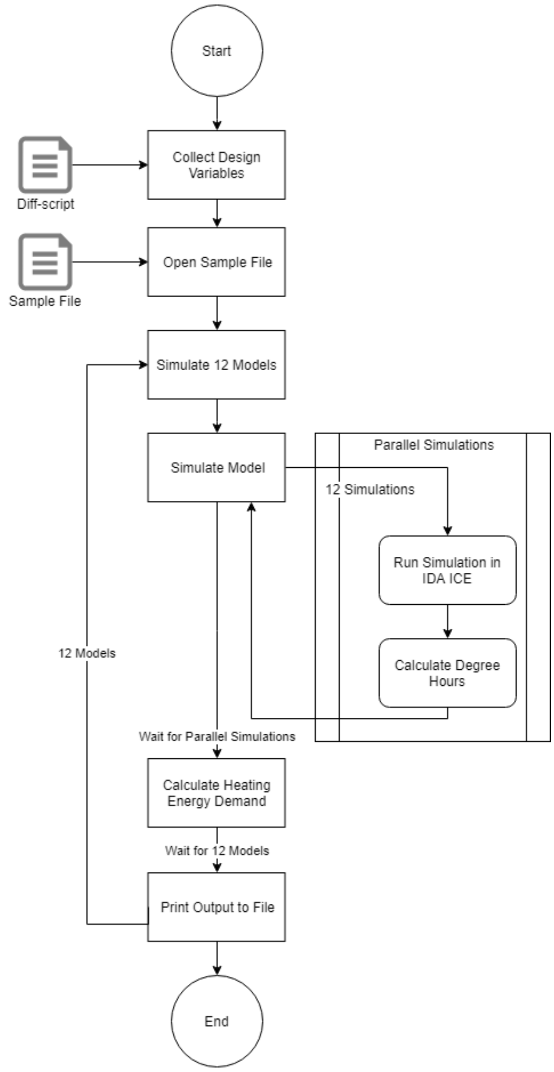


Figure 31: The algorithm in Matlab

Calculation of degree hours was originally not included in this algorithm. Considering the purpose of this thesis, it was needed to be implemented. Additionally, there were several other parts of the algorithm that needed to be added or customized to this thesis. These are explained in the next section.

3.2.4.1 Changes in Matlab

Following parts had to be added and/or customized to this master thesis:

1) Diff-script: The first necessary step was to make a new diff-script in IDA ICE that was based on the chosen design and scenario variables that were going to be changed.
2) Climate files: Originally, this algorithm was created to read numbers. In this thesis, it also had to read letters and words.
3) Sample file: A new file including all the combinations and values of the variables had to be created.
4) Twelve models: The algorithm was only created for reading one IDA ICE model. In this thesis, twelve models had to be simulated.
5) Output values: Degree hours had to be added.

3.2.4.1.1 Diff-Script

The first step when choosing the variables was to consider which of the design and scenario variables that play an important role in overheating and heating energy demand of buildings. In addition, it was necessary to test the variables in the diff-script in IDA ICE and check if they were easy to use in the algorithm. The values that had to be changed were replaced by the number 0.333333. If the change ended up with a “simple” code without errors, this variable was chosen. For example, the thickness of an external wall was easy to change. The code for the thickness was presented like this in the diff-script:

```
((WALLDEF :N "Rendered l/w concrete wall")
 ((WALL-LAYER :N "layer-2")
  (:PAR :N THICKNESS :V 0.333333)))
```

3.2.4.1.2 Reading Climate Files

Originally, the algorithm was made to only read numbers. This thesis also includes climate files, which are defined in the diff-script with the code shown below. These lines of code do not contain any numbers for the original algorithm to look for. Therefore, some adjustments in the function "Collect design variables" were necessary so it could read climate files. In the diff-script in IDA ICE, the code for the reference file for Oslo look like this:

```
(:RES :N CLIMATE-DEF :V "Oslo/Fornebu_ASHRAE")
 (SOURCE-FILE :DOCUMENT-PATH "clim:014880_IWC.PRN" :SF
"clim:014880_IWC.PRN" :N CLIMATE-FILE)
```

For the external wall or other building components, "Collect design variables" collects the variables when reading the number "0.333333". Some lines were added to this function to recognize the climate files. In addition to "0.333333", "CLIMATE-FILE" was used as a recognizer for this function.

The for-loop that run the simulation in parallel contains a function called "Change Design Variables". This function replaces the number "0.333333" for a variable in the diff-script with the desired value from the sample file. A "switch/case" block was added to the function in order to change the definition of climate files. Two text documents of the current climate file and the one for 2050 were created. These contained the associated code in the diff-script. When the "switch/case" block recognized an associated name for one of the climate files, it inserted the associated code into the model that ran.

3.2.4.1.3 Sample File

The sample file was created manually in a text document. Table 3 shows roughly the sample file for this thesis, without the specific values. For example, the first model had to run twelve simulations with the combinations shown in the table. The first simulation consists of the first row, the second simulation runs the second row and so on. The 12 combinations did all run through the 12 models, but the 12 combinations of each model were simulated at the same time, which saved a lot of time. A more detailed sample file, which Matlab used, can be found in appendix B.

Table 3: Combinations in the sample file

Simulation Number	Standard	Shading	Climate File
C1	TEK 17	No shading	Current
C2	TEK 17	No shading	2050
C3	TEK 17	Internal	Current
C4	TEK 17	Internal	2050
C5	TEK 17	External	Current
C6	TEK 17	External	2050
C7	Passive house	No shading	Current
C8	Passive house	No shading	2050
C9	Passive house	Internal	Current
C10	Passive house	Internal	2050
C11	Passive house	External	Current
C12	Passive house	External	2050

3.2.4.1.4 Twelve Models

In the beginning of the master script, the twelve models were inserted with their path to the correct folder on the computer. For the algorithm to be able to simulate all the 12 combinations/simulations for 12 models, a double for-loop structure was chosen. The outer for-loop iterates over 12 models, and for each iteration of the outer loop the inner for-loop runs through the simulations for each model in parallel.

3.2.4.1.5 Output Values

In the code that writes the output values from the simulations, it had to be added degree hours as an output value, in addition to the heating energy demand that already was implemented. The results from each model had to be written in different text documents, so the values were not overwritten. When it comes to heating energy demand, Matlab uses an ida_lisp.end file to find the amount of energy used on different areas. The algorithm found the separate values of energy used on ventilation and heating, and summed these two. For degree hours, IDA ICE creates a temperature file, which consists of air temperature and operative temperature for each zone. The algorithm went through all these files and summed all hours for all zones where the operative temperature was above 27 ºC. Thereafter, the total number of degree hours was divided by the number of zones.

3.2.4.2 Designs

Matlab handled the switch between the different designs. The six designs that were considered are as follows:

Table 4: The six designs

Designs	Standard	Shading
1	TEK 17	No shading
2	TEK 17	Internal blinds
3	TEK 17	External blinds
4	Passive house	No shading
5	Passive house	Internal blinds
6	Passive house	External blinds

Both the standards and shading contain several different variables that had to be changed simultaneously when simulating the scenarios. Matlab changed these as “a package”. It means that some values from TEK 17 and passive house or values from different shading types were not mixed.

3.2.4.2.1 TEK 17 and Passive House

The two different standards that were tested in terms of robustness and compared to each other, were TEK 17 and passive house. When it comes to the standard of TEK 17, all the values are requirements. On the other hand, the passive house standard distinguishes between recommendations and requirements. These two standards are quite similar, but differs in some areas, as U-value for walls, roof, floor and the normalized thermal bridge value. Since the apartment is on the 8th floor, the difference in the U-value of the floor was neglected. The components that are highlighted/bold are the changing variables that were replaced by Matlab. The others remained the same in all the simulations, as the requirements for these are similar for both standards.

TEK 17

*Table 5: The standard of TEK 17 (*Byggteknisk forskrift (TEK 17), n.d.*)*

Building Components	TEK 17	IDA ICE
U-value, wall (W/m^2K)	**≤ 0.18**	**0.18**
U-value, roof (W/m^2K)	**≤ 0.13**	**0.13**
U-value, floor (W/m^2K)	≤ 0.10	-
U-value, windows and doors (W/m^2K)	≤ 0.8	0.8
(Windows + doors)/floor area (%)	≤ 25 %	21 %
Efficiency of heat recovery (%)	≥ 80 %	80 %
SFP-factor ($kW/(m^3/s)$)	≤ 1.5	1.5
Leakage rate (per hour at 50 Pa pressure difference)	≤ 0.6	0.6
Normalized thermal bridge value (W/m^2K)	**≤ 0.07**	**0.07**

Passive House

*Table 6: The passive house standard (*Standard Norge, 2013*)*

Building Components	Passive House	IDA ICE
Recommendations		
U-value, wall (W/m^2K)	**0.10 - 0.12**	**0.118**
U-value, roof (W/m^2K)	**0.08 - 0.09**	**0.083**
U-value, floor (W/m^2K)	0.08	-
(Windows + doors)/floor area (%)	≤ 25 %	21 %

Requirements		
U-value, windows and doors	≤ 0.8	0.8
Efficiency of heat recovery (%)	≥ 80 %,	80 %
SFP-factor (kW/(m³/s))	≤ 1.5	1.5
Leakage rate (per hour at 50 Pa pressure difference)	≤ 0.6	0.6
Normalized thermal bridge value (W/m²K)	**≤ 0.03**	**0.03**

3.2.4.2.2 Shading

In total, three different types of shading were used: no shading, internal and external blinds. Matlab changed between these three packages. The control for when the shading was drawn was based on the sun, which is an implemented control in IDA ICE. When the incident solar radiation exceeded 100 W/m^2 on the outside of the glazing the shading was drawn.

When there is shading in a building, multipliers for g-, T- and the U-value are used. The definitions of g-, T- and U-value are described in "2.2.1.3 Windows and Shading". T_effective, g_effective and U-effective become the "new" values for the windows, where the effect of the shading is included:

- g_effective = g (SHGC) * multiplier for g
- T_effective= T * multiplier for T
- U_effective= U * multiplier for U

The three different types were based on implemented shading types in IDA ICE. Table 7 shows the difference between the shading types:

Table 7: Mulitpliers for g-, T- and U-value

Type of Shading	Multiplier for g	Multiplier for T	Multiplier for U	Diffusion factor
No shading	1.0	1.0	1.0	0
Internal blinds	0.65	0.16	1.0	1
External blinds	0.14	0.09	1.0	1

Figure 32 shows the properties of the windows in the apartment. If internal or external blinds were used, the g-value, T-value and U-value of the windows were multiplied by the multipliers shown in table 7.

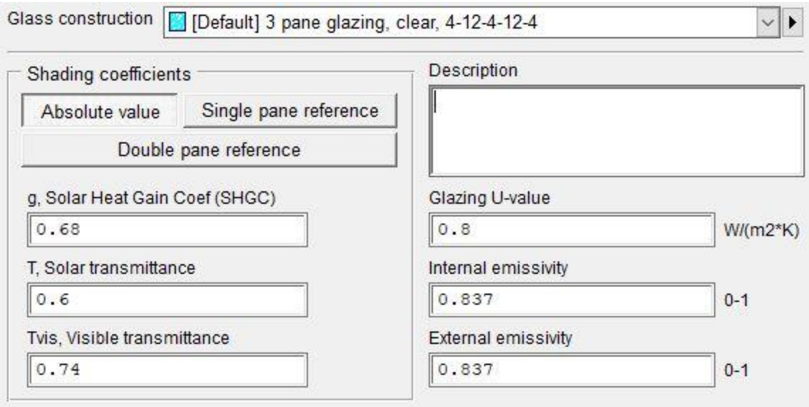


Figure 32: Properties of the windows

3.2.4.3 Climate

In addition to occupant behavior, two different climate files from Oslo have been used. One of them is the reference file from IDA ICE, while the other is a future climate file. This file is based on assumptions on how the climate will be in 2050. In this thesis, the word “climate file” is used when describing the files that IDA ICE uses to define the climate for a given simulation. In academic publications that concern the same subject as the one researched here, the word “weather file” is also used. IDA ICE uses both words to describe essentially the same entity.

The future climate file is retrieved from the master thesis written by Håkon Eggebø. This file is based on morphing by the software tool CCWorldWeatherGen and the climatic model HadCM3 that is developed by the Hadley center. HadCM3 offers a series of future scenarios based on different human emission scenarios developed by The Intergovernmental Panel on Climate Change. In total, they have established four different socioeconomic future scenarios for how much humans influence climate change.

When it comes to the future climatic files that has been used in this thesis, it has been produced by CCWorldWeatherGen morphing a local climatic file for Oslo with the HadCM3 climate change model for the second socioeconomic future scenario, called A2. A2 represents following:

- A heterogeneous world where self-reliance is the most important factor. A continuous increase in population and an economic development regionally oriented.

(Eggebø, H., 2017)

3.2.4.3.1 Comparison of Climate Files

In IDA ICE it is possible to retrieve information about the different climate files, e.g. temperatures. The reference file (current climate) and the climate file for 2050 were studied closer to see what the difference between them is.

<u>Air Temperature</u>

Figure 33 shows the difference in air temperature in Oslo between today's climate and in 2050. The mean value during a year for the reference file is 6.7 ^{o}C, while for 2050 it is 9.1 ^{o}C. This corresponds to an increase of 2.4 ^{o}C. Compared with today's climate, the figure shows that the temperature in 2050 is higher throughout the year.

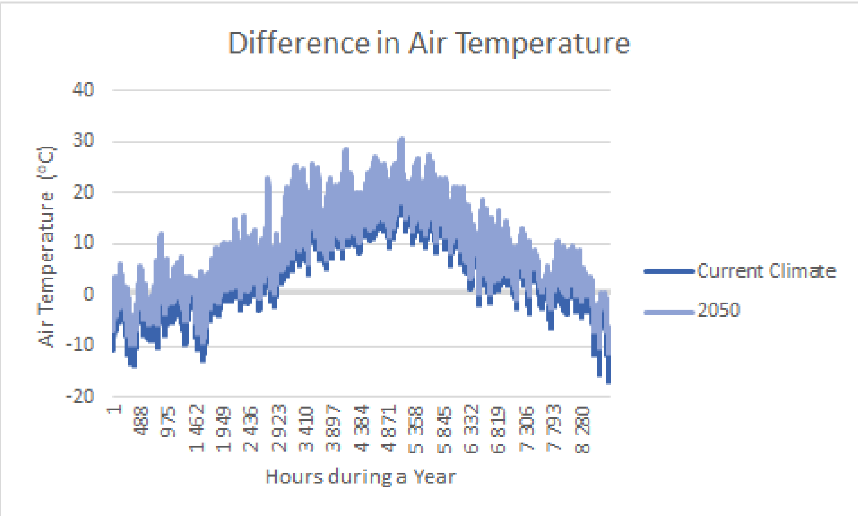


Figure 33: Comparison of air temperatures

Figure 34 shows a load duration curve of the two different climate files. The shape of the two graphs is similar, but the grey line (2050) is always some celsius degrees above the blue line (current climate).

Today 2050

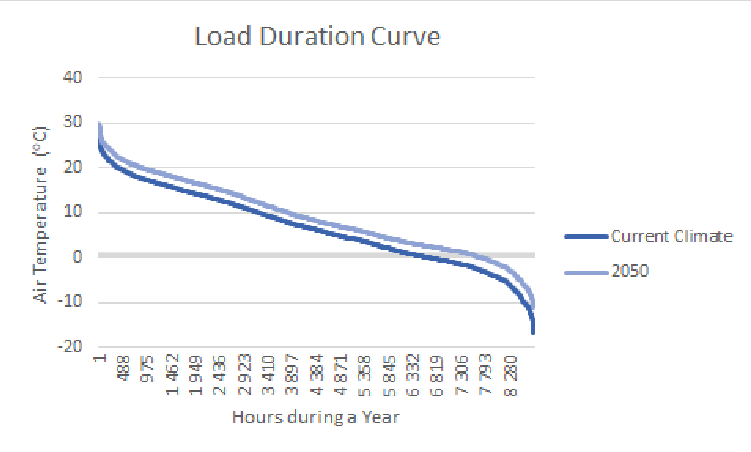


Figure 34: Load duration curve of the two climate files

<u>Other Parameters</u>

Additionally, there are other parameters in the climate files, as humidity, wind speed, and diffuse and direct solar radiation that are presented. Humidity and wind speed is not so important when considering overheating and heating energy demand. On the other hand, diffuse and direct solar radiation are relevant. The mean value for direct radiation is 79.7 W/m^2 for the reference file, while it is 79.2 W/m^2 for the climate file of 2050. In addition, the mean value of the diffuse radiation is 58.8 W/m^2 for the reference file and 58.6 W/m^2 in 2050. More solar radiation leads to higher surface temperature. That said, the difference between today and 2050 in solar radiation is very small.

3.2.5 Fixed Variables in the Simulations

Everything in the apartment that adds heat is relevant to know about, since the heat gain affects the heating energy demand and overheating. Table 8 shows the fixed values that did not change in the simulations. Overall, these values are based on NS 3031. All the rooms in the apartment used the values in table 8, except the storage room. It is not usual for occupants to stay in this kind of room. Therefore, it was assumed that lighting, equipment, space heating and ventilation are very rarely used in this room, and they were set off in IDA ICE. Additionally, it was assumed that the occupants are never present, and therefore there are no heat gains from occupants in this room.

Table 8: Fixed values based on NS 3031 (Standard Norge, 2016)

Energy Consumption Areas	**Values**	**Heat Gain**	**Operating Time (hrs/days/weeks)**
Setpoint temperature, heating (°C)	Operating time: 22 Else: 20		16/7/52
Technical appliances (W/m^2)	2.0	60 %	24/7/52
Lighting (W/m^2)	1.84	100 %	17/7/52
Ventilation - minimum specific airflow ($m^3/h*m^2$)	1.2 (Supply temperature 18 °C)		24/7/52
Occupants		100 %	

Both the space heating, lighting, technical appliances and the ventilation receive their energy from an electric heating coil. Since the apartment is quite big and it has three bedrooms, it was assumed that there are four people living there. The metabolic rate (met) and clothing insulation (clo) for persons are based on the standard settings in IDA ICE, where met is set to be 1.0 and the clo is 0.85 ± 0.25. The occupancy schedules are described in chapter "3.2.3.2 Window Opening Schedules".

3.2.5.1 Electric Radiators

In the apartment, the space heating is based on electric radiators. Originally, the inserted power in each room unit is based on the ideal heater that is implemented in IDA ICE. The ideal heater and the capacity is inserted as default when new zones are created. The default value for the capacity is 100 W/m^2. In the apartment the ideal heaters were deleted, and electric radiators added, which relate to the electric heating coil. In the ideal heaters, the maximum power (W), is automatically calculated in the software by multiplying the area of each room with the default value of the capacity. This value, maximum power, was copied from the ideal heaters to the electric radiators. The maximum power for each room is presented in the following table:

Table 9: Electric radiators in the apartment

Rooms	**Area (m^2)**	**Maximum Power (W)**
Bathroom	6.52	652.1
Bedroom	11.66	1166
Bedroom 2	16.24	1624
Bedroom 3	7.59	758.8
Hallway	7.11	711
Livingroom	27.84	2784
Storage	2.95	0
Toilet	3.99	398.8

It was assumed that there was no electric radiator in the storage room. In addition, in Norway there are often floor heating system in bathrooms and toilets. In this thesis, it has been simplified that there are electric radiators in the toilet and the bathroom instead of floor heating system.

3.2.7.2 Ventilation

The ventilation system that is used in the building is CAV (constant air volume), which means that the rate of the supply air is constant. As table 8 shows, the air volume is 1.2 $m^3/h*m^2$, which is based on the Norwegian standard NS 3031. As mentioned in "3.2.4.2.1 TEK 17 and Passive House", TEK 17 and passive house have the same requirements about heat recovery and the SFP-factor. Therefore, the efficiency of the heat recovery in all models is 80 % and the SFP-factor is 1.5 kW/(m^3/s).

The results from the simulations and the robustness assessment are presented in the next chapter "4. Results".

4. Results

In this part of the thesis the results from the simulations are presented. Matlab has in tandem with IDA ICE simulated all 144 combinations for a year and returned heating energy demand and degree hours for all the combinations. Heating energy demand is a sum of energy used on space heating and ventilation, while degree hours are the number of hours where the operative temperature during a year is above 27 ºC. This number is an average of the whole apartment.

The degree hours collected are somewhat limited since it is independent of occupancy hours. To provide more information about the thermal comfort, the 12 models (OBs) in combination with the values from simulation number 1 have been run in IDA ICE. The output value retrieved from IDA ICE is unacceptable hours during occupancy and is based on thermal comfort according to the standard EN-15251. This standard divides the thermal comfort into four different categories: I (best), II (good), III (acceptable) and IV (unacceptable). When it comes to residential buildings, EN-15251 defines the range for each category in the following way:

Table 10: Recommended values for indoor temperature (Standard Norge, 2014)

Categories	**Minimum Operative Temperature (°C)**	**Maximum Operative Temperature (°C)**
I	21	25.5
II	20	26
III	18	27

The thermal comfort is unacceptable when the operative temperature is below 21 ºC or above 27 ºC. The number of unacceptable hours is based on the thermal comfort in the living room/kitchen. Studying this output value and comparing it with degree hours makes it possible to compare the different window opening strategies and schedules. Additionally, to study if there is a correlation between degree hours and unacceptable hours.

First, the degree hours and thermal comfort according to EN-15251 are compared. Thereafter, box plots of TEK 17 and passive house are presented to detect how much the two standards, different shading types, occupant behavior and climate changes can affect the performance of the apartment. When it comes to degree hours, there is added a red line at 150 degree hours and unacceptable hours. This number is from EN-15251 and is based on allowed deviations from the standard as acceptable number of hours, or weighted hours, during a year (Standard Norge, 2014). When it comes to heating energy demand, the requirement for passive house is maximum 24 kWh/m^2/yr, which is based on the formula presented in "2.2.1 Building Designs". A red line in the figures represent this number. On the other hand, TEK 17 has no specific requirement about maximum heating energy demand, but has a requirement about maximum 95 kWh/m^2/yr in total energy consumption. Since there is no specific requirement for TEK 17, no line is added to these figures.

In the end, the results from the robustness analysis are presented in terms of three different RIs: performance spread, performance deviation and maximum performance regret. First the robustness in terms of both degree hours and heating energy demand is presented. Thereafter, the robustness of the designs is linked with performance.

4.1 Thermal Comfort (Overheating)

When it comes to thermal comfort, IDA ICE only provides files with temperatures, e.g. operative temperatures, that Matlab can use when extracting information about the simulations. Therefore, to evaluate the thermal comfort in more detail, degree hours are compared to the thermal comfort defined in IDA ICE.

4.1.1 Correlation between EN-15251 and Degree Hours

Figure 35 shows the twelve models/OBs with the first combination of values (c1) (ref. table 3). The description of the twelve different OBs is shown in table 2. Additionally, more detailed information about figure 35 can be found in appendix C. Overall, the model with the best thermal comfort in terms of degree hours is OB4 with only 0.11 % degree hours during a year. OB4 consists of the opening schedule based on NS 3031 and the strategy based on IDA ICE. The second and third best are OB7 and OB11, where both are based on the strategy of Multiconsult, but OB7 uses the occupancy schedule of house living and OB11 uses the Iranian schedule.

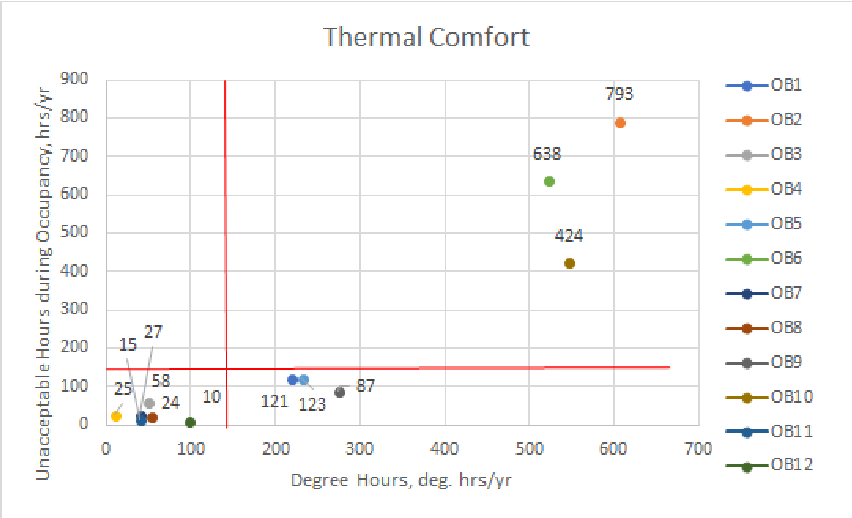


Figure 35: Thermal comfort of the twelve models (OBs)

The output in IDA ICE shows that the thermal comfort is worst during June, July and August for all the models. Figure 36 is an example of how it looks like in IDA ICE. This figure represents OB12, which has the best thermal comfort with only 0.17 % unacceptable hours during occupancy for a year. Thereafter, OB11 is the best with a percentage of 0.25 % and then OB8 with 0.35 %. OB12 and OB8 use the strategy of IDA ICE, while OB11 uses the strategy of Multiconsult. OB11 and OB12 follow the Iranian schedule, while OB8 follows house living that is the implemented schedule in IDA ICE.

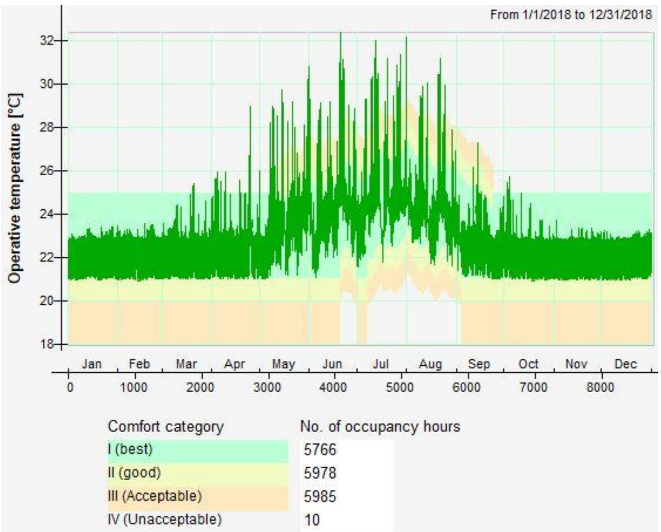


Figure 36: Unacceptable hours for model 12

Figure 35 shows that the model that is the worst in terms of degree hours is OB2 with a percentage of 6.92 %. OB2 uses category III from the adaptive model and the schedule based on NS 3031. The worst model in terms of unacceptable hours is OB6 (9.2 %). This one is also based on category III, but uses the schedule of house living. The figure also shows that six of the OBs, based on the strategies of Multiconsult and IDA ICE meet the requirements for both maximum 150 degree hours and unacceptable hours. When it comes to category I, the three OBs fulfill the requirement about unacceptable hours, but not degree hours. On the other hand, the OBs based on category III meet none of the requirements.

Figure 35 showed the different OBs as separate points. It is a bit difficult to create a regression line based on separate points, thus figure 37 is created to show a regression line between degree hours and unacceptable hours. For all the 144 cases, it requires a lot to have unacceptable hours as an output value, since Matlab cannot retrieve this value. Therefore, only degree hours are used as output values for all 144 cases. Since the unacceptable hours only apply for the 12 models with c1, it is interesting to see if there is a correlation between unacceptable hours and degree hours. According to the figure 37, the R squared has a value of 0.86. The greater the R squared value is, the more correlation there is.

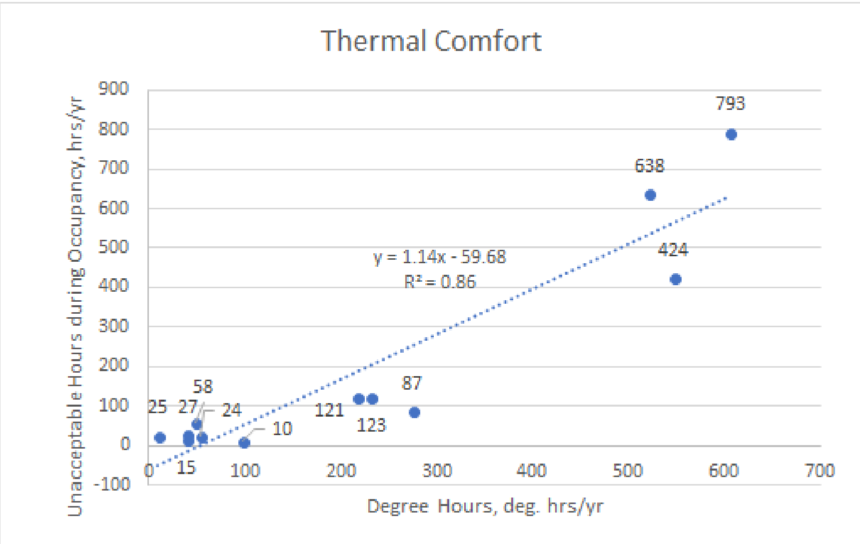


Figure 37: A regression line based on degree hours and unacceptable hours

4.1.2 Window Shading and Opening Strategies

In this section, several figures present the results of the box plots based on two standards, TEK 17 and passive house. These figures are the results of degree hours for the 144 combinations. More information about the specific value of mean, median and range can be found in appendix D. Two box plots of each standard are presented, where one is based on shading and the other on the different window opening strategies. The one that is divided into shading, the three green colors represent the different shading type. When it comes to the strategies, the different colors represent the four strategies. Additionally, the boxes are divided into which climate file that is used - reference file (current climate) or the file of 2050. The x-axis represents the climate files, while the y-axis represents the amount of degree hours. Description of the strategies and the shadings can be found in “3.2.3.1 Window Opening Strategies” and “3.2.4.2.2 Shading”.

4.1.2.1 Window Shading

In this thesis, window shading is one of the variables that makes up the designs. Creating and studying box plots of different shading types can show how much shading may influence the performance of overheating.

4.1.2.1.1 TEK 17

Figure 38 shows the results of TEK 17. There are several important aspects to notice in terms of these two, one of them is the increased degree hours in 2050 compared to today. For all shading types, the amount of degree hours is more than doubled in 2050.

Another important aspect, which the box plot shows, is that the degree hours depend greatly on which shading type that is used. For example, for the current climate, the mean for no shading is 224 degree hours during a year, while for external blinds it is 14 degree hours during a year. According to figure 37, 224 degree hours equal approximately 200 unacceptable hours during occupancy over a year, while 14 degree hours equal no unacceptable hours. Additionally, the range is much smaller for external blinds than the two others.

The mean, median and the range increase when there is less shading used and when the climate becomes warmer.

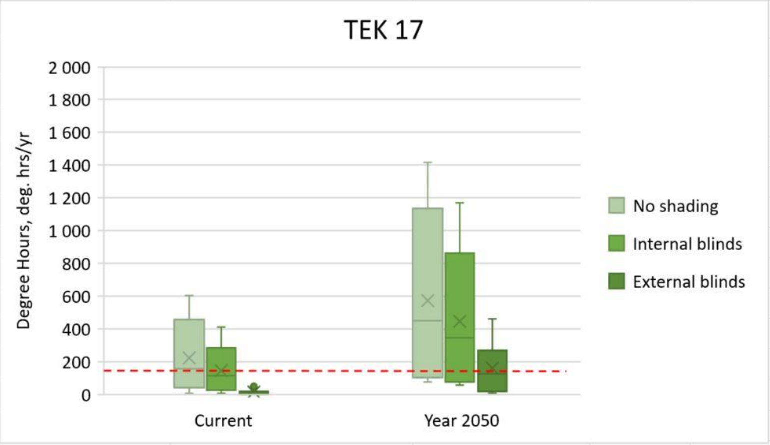


Figure 38: Box plot of TEK 17 considering degree hours

4.1.2.1.2 Passive House

Figure 39 shows the same as figure 38, only for the standard of passive house. As the figure of TEK 17, this box plot also shows that there will most likely be more degree hours in 2050 than today. The range is also larger in 2050 than today.

Also, the number of degree hours depends a lot on which type of shading that is used. In 2050, the mean of no shading is 694 degree hours during a year, while with external blinds it is 235 degree hours.

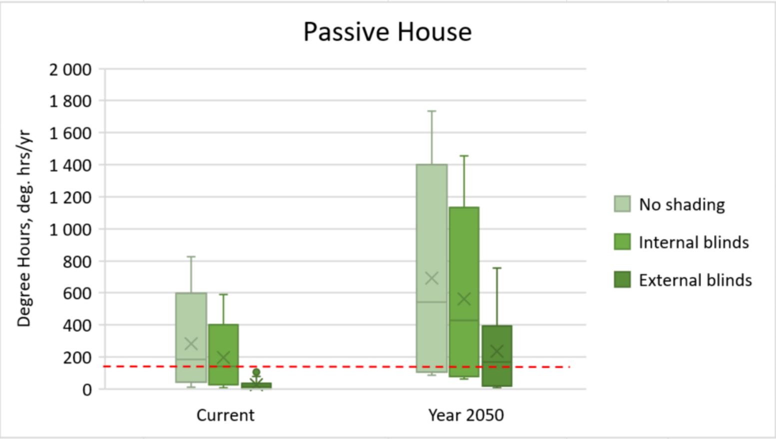


Figure 39: Box plot of passive house considering degree hours

For all shading types, both the median, mean and range are generally greater for passive house than TEK 17. The difference in mean between external blinds between these two for the current climate is 12 degree hours/yr, while in 2050 it is 74 degree hours/yr. For internal blinds, the difference is 61 degree hours/yr for the reference file and 119 degree hours/yr in

2050. Thus, one can expect more overheating and more variation in degree hours for passive house than a TEK 17 building. Additionally, the difference between the performances of TEK 17 and passive house becomes greater when the climate is warmer.

4.1.2.2 Window Opening Strategies

Unlike shading, window opening strategy is one of the variables in the occupant behavior. Following box plots show how much the strategies may influence the performance of degree hours for TEK 17 and passive house.

4.1.2.2.1 TEK 17

As what the previous box plots have showed, figure 40 also shows that there are more degree hours and greater range for all the strategies in 2050 than today. When it comes to the strategies based on Multiconsult and IDA ICE, both the mean and median today and in 2050 are within 150 degree hours. For the current climate, the mean and median for category I are approximately 150 degree hours, while in 2050 the median and mean for this strategy are more than three times as much as for the current climate. Category III does not meet the requirement of 150 degree hours today or in 2050. Additionally, the mean and median for this strategy are much greater in 2050 than today.

According to the current climate file and the one based on 2050, the strategy based on Multiconsult is the best, followed by IDA ICE. The third best is category I and then category III.

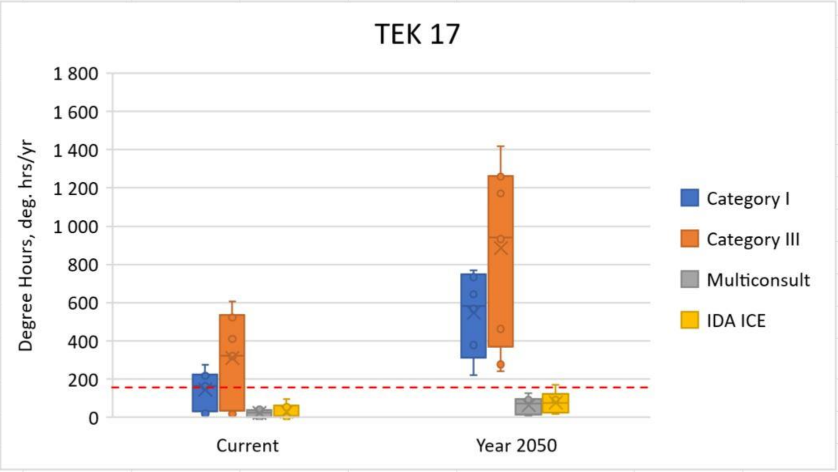


Figure 40: TEK 17 and the four strategies with regard to degree hours

4.1.2.2.2 Passive House

Figure 41 of the passive house shows the similar pattern as TEK 17 - overheating becomes worse in 2050 compared to today. The mean and median for the strategies based on Multiconsult and IDA ICE are within 150 degree hours for the current climate and in 2050. When it comes to the mean and median for the two other categories, category I and category III, they do not fulfill this requirement today or in 2050. Category III is the worst with a mean of 434 degree hours today and 1 149 degree hours in 2050.

Compared to TEK 17, passive house generally has more overheating. How much worse it becomes depend on which strategy that is used. For example, for the current climate, the strategy of Multiconsult has a mean of 24 degree hours and a range of 48 degree hours for TEK 17. When it comes to passive house, the mean is also 24 degree hours, while the range is 49 degree hours. With that said, the range is only 1 more for passive house than TEK 17 for this strategy. When it comes to the worst category, category III, the mean and range are 146 and 259 degree hours for TEK 17. For the passive house, the mean is 185 degree hours and the range is 304 degree hours. The range is approximately increased with 50 degree hours.

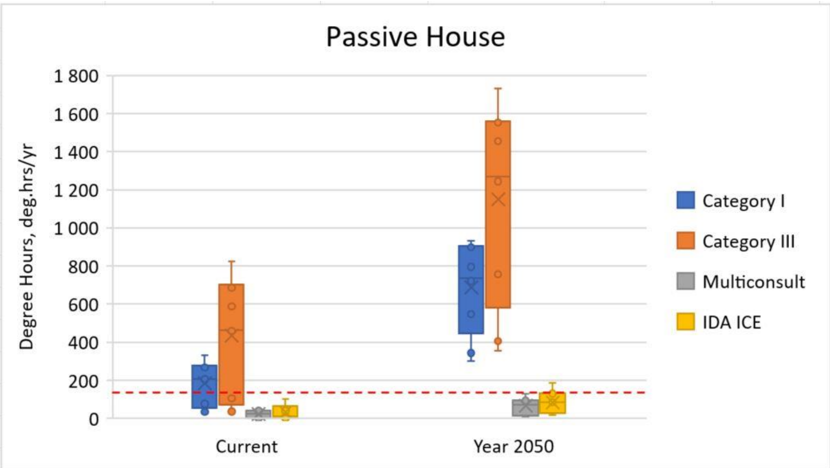


Figure 41: Passive house and the four strategies with regard to degree hours

4.2 Heating Energy Demand

Box plots of heating energy demand are organized exactly as the box plots of degree hours. The tables with the values of mean, median and range can be found in appendix E. The ventilation supplies the rooms with an air temperature of 18 ºC all day, while the electric radiators have a setpoint of 22 ºC sixteen hours a day and 20 ºC the rest of the day. When simulating how much energy that is used on the ventilation and the heating units, the results show that the energy consumption of the ventilation only varies by which climate file that is used. For the current climate file, the ventilation uses 683.1 kWh/yr, while for the climate file of 2050 the ventilation uses 686.7 kWh/yr, which represents a small difference.

Thereby, it is the energy used on space heating that varies depending on which designs and scenarios that are simulated. Ventilation only varies by the climate, while the space heating varies by standard, shading type, climate and occupant behavior.

4.2.1 Window Shading

4.2.1.1 TEK 17

Figure 42 shows the results of heating energy demand for the two climate files and the three shadings. Unlike the overheating, the boxes show that the consumption is higher today than in 2050. For example, the mean for no shading is 206 kWh/m^2/yr today, while it is 181 kWh/m^2/yr in 2050. This is equivalent to a decrease of 2 100 kwh/yr from today to 2050. Both the mean, median and maximum decrease when there is less shading, and the climate is warmer.

Additionally, this box plot shows that heating energy demand does not vary as greatly as it did with overheating when it comes to which shading type that is used. For example, for the current climate, the difference between the mean for external blinds and no shading is 11 kWh/m^2/yr, which is 924 kWh/yr for the apartment of 84 m^2. In addition, the range is approximately similar for all the three shading types.

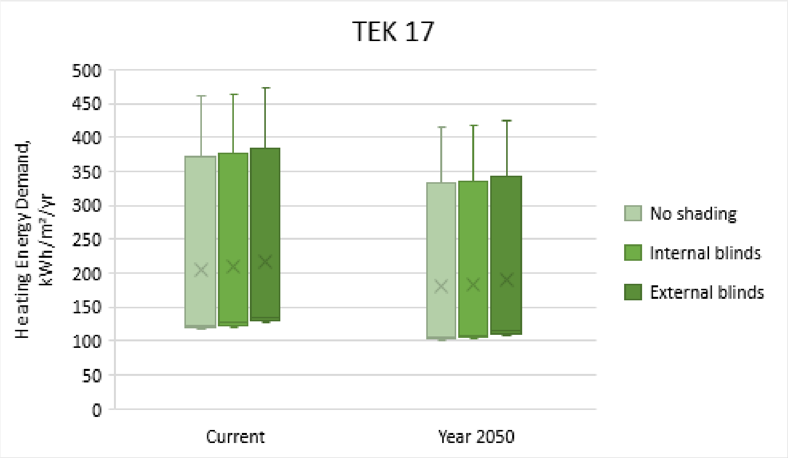


Figure 42: TEK 17 considering heating energy demand

4.2.1.2 Passive House

As for TEK 17, figure 43 of the passive house shows that the heating demand is decreasing in 2050, both in terms of median, mean and range. The box plot also shows that the range for all the shading types is very similar. External blinds have the greatest mean and median, and no shading has the smallest. On the other hand, the differences in mean and median between these two are quite small.

When comparing TEK 17 and passive house with each other, generally the mean and median are smaller for passive house than for TEK 17 for all the shading types and both climates. For the current climate, the difference in mean for the external blinds between passive house and TEK 17 is 17 kWh/m^2/yr, which constitutes 1 428 kWh/yr. On the other hand, the range is smaller for TEK 17 for all six cases. For the same case, the difference in range between TEK 17 and passive house with external blinds is 14 kWh/m^2/yr, which means that the passive house has 1 176 kWh/yr more variation than TEK 17.

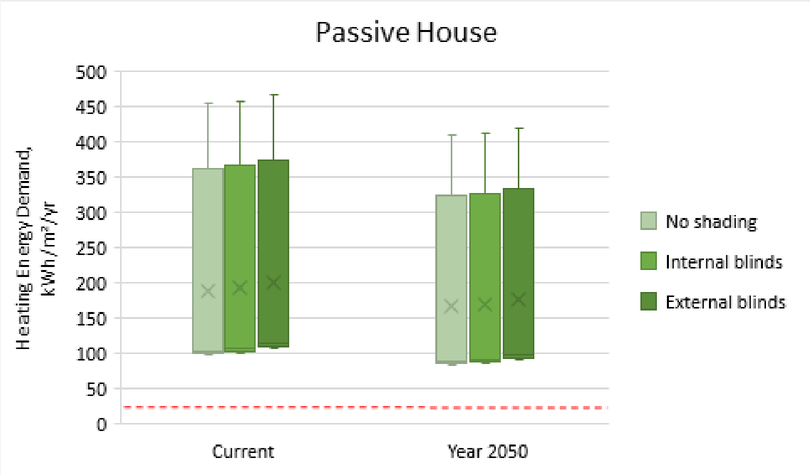


Figure 43: Passive house considering heating energy demand

4.2.2 Window Opening Strategies

Instead of dividing the boxes into shading, the following boxes are divided into what window opening strategy that is used.

4.2.2.1 TEK 17

Figure 44 is quite different from the previously shown box plots. All the boxes for all strategies are much smaller, which means smaller ranges. This means that the different shading types and window opening schedules do not affect the performance of the designs very much. Additionally, what the previous box plots showed, this box plot also shows that the heating demand in the future will most likely decrease. On the other hand, the range of all four strategies is quite similar both for the current climate and in 2050.

When it comes to the different strategies, the one based on Multiconsult is much worse than the others. For today's climate, the mean for category I and III are 126 kWh/m^2/yr, while for IDA ICE it is 127 kWh/m^2/yr. On the other hand, the mean for the strategy based on Multiconsult is 464 kWh/m^2/yr. Thus, the mean is more than three times as much for this strategy compared to the others. The difference between category I and Multiconsult constitutes 28 392 kWh/yr.

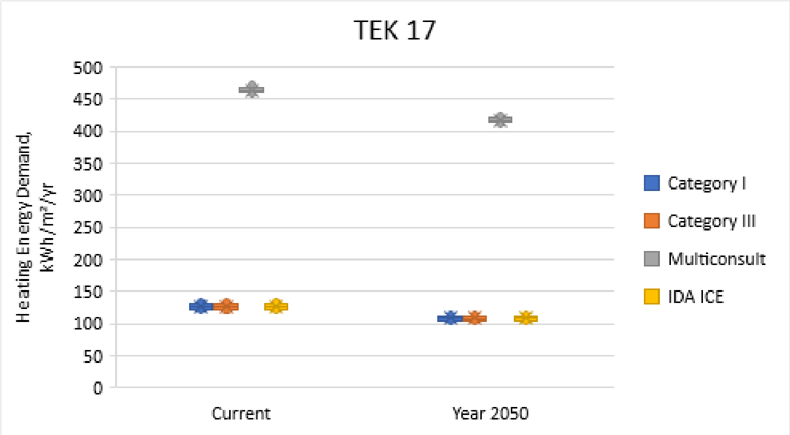


Figure 44: TEK 17 and the four strategies with regard to heating energy demand

4.2.2.2 Passive House

Similarly to what the three previous box plots have shown, figure 45 also shows that the heating demand will most likely decrease in future. It also shows that the strategy based on Multiconsult leads to much higher consumption. For passive house, the mean for category I is 106 kWh/m^2/yr, while the mean for the strategy of Multiconsult is 457 kWh/m^2/yr. This constitutes a difference of 351 kWh/m^2/yr, which is 29 484 kWh/yr for the apartment of 84 m^2.

Compared to TEK 17, as also the previous box plots have shown, the mean and median is lower for passive house than TEK 17. Unlike the box plots of shading, the ranges for the different strategies of the passive house are less than for the strategies in TEK 17. This box plot also shows that the range, mean and median are quite similar for each strategy, both for the current climate and in 2050.

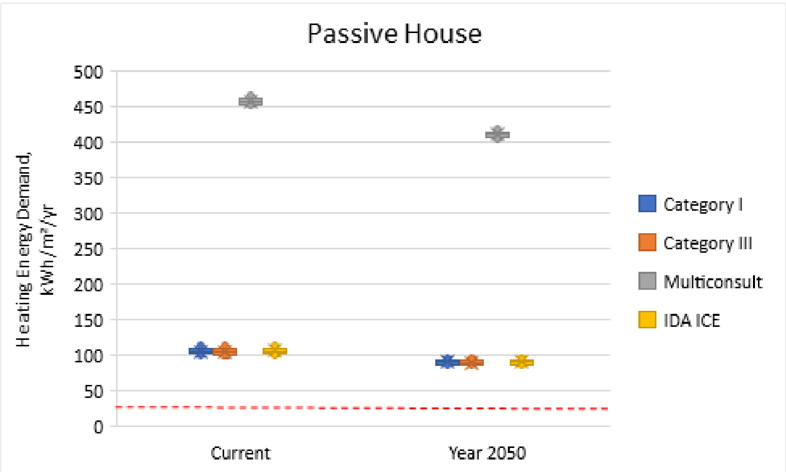


Figure 45: Passive house and the four strategies with regard to heating energy demand

4.3 Robustness Assessment

The following section is divided into three different parts. The first part presents the maximum and minimum performance of both overheating and heating energy demand. This might provide a better understanding of the results from the RIs, which is presented in the second part. The last part consists of the robustness of the designs being compared to the overheating and heating energy demand performance. The complete robustness assessment is attached in appendix F.

4.3.1 Maximum and Minimum Performance

This part presents first the performance of the six designs in terms of degree hours, and then the same for heating energy demand.

4.3.1.1 Overheating

Figure 46 and 47 show the maximum and minimum performance across all scenarios in terms of degree hours. The first figure shows the maximum performance. For all the designs, the maximum of degree hours is OB2 in combination with the climate of 2050. OB2 is based on the opening strategy of category III and the schedule of NS 3031.

Passive house with no shading is the design with most degree hours. The second worst is the passive house with internal blinds, followed by TEK 17 with no shading. The one that has the least maximum performance is TEK 17 with external blinds.

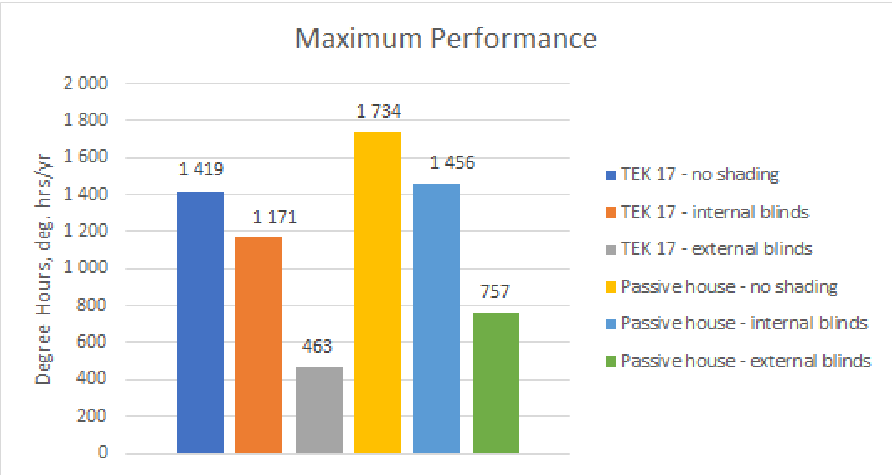


Figure 46: Maximum performance considering degree hours

When it comes to the minimum performance of the designs, it does not follow the similar pattern as the maximum performance. The minimum of degree hours for all the designs is not from the same occupant behavior, but from two different ones. TEK 17 and passive house with no shading and internal blinds have the minimum performance in OB4, which is using the implemented control in IDA ICE in combination with the opening schedule of NS 3031. TEK 17 and the passive house with external blinds have the minimum performance of OB11. OB11 is based on the occupancy schedule of NS 3031, and the opening strategy and schedule of Multiconsult. The minimum performance applies to today's climate.

As figure 47 shows, passive house and TEK 17 with external blinds have the minimum of degree hours. Passive house with no shading has the highest minimum performance with 10 degree hours/yr, while TEK 17 with no shading has the second highest with 9 degree hours/yr.

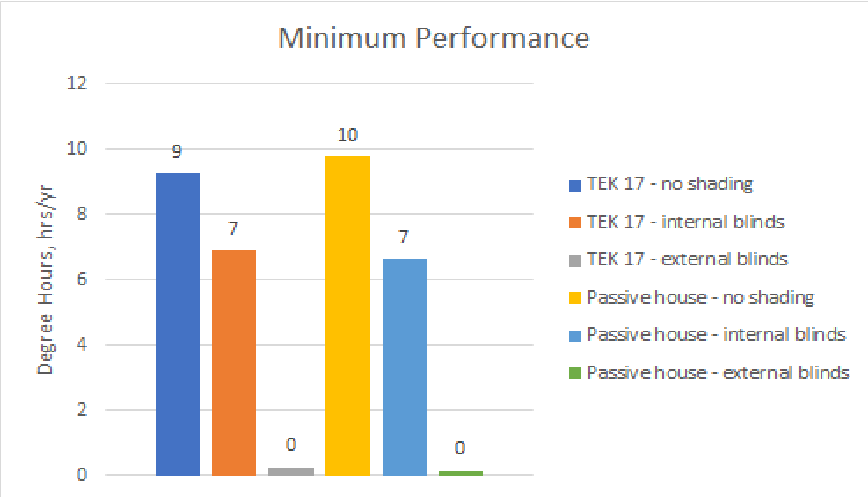


Figure 47: Minimum performance considering degree hours

4.3.1.2 Heating Energy Demand

Figure 48 and 49 show the maximum and minimum performance in terms of heating energy demand. When it comes to maximum performance, all the designs that are presented in the figure are from OB11, which is based on the opening strategy and schedule retrieved from Multiconsult. Additionally, they are all using the current climate file. The design that has the maximum performance is TEK 17 with external blinds. The second worst is the passive house with external blinds. Passive house with no shading has the lowest maximum performance in terms of heating energy demand.

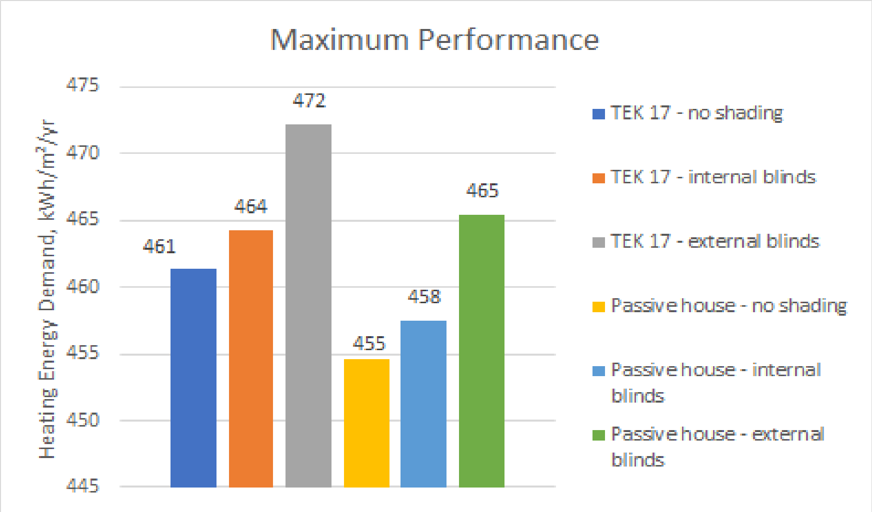


Figure 48: Maximum performance considering heating energy demand

In terms of minimum performance, the results are quite similar for all the designs. These numbers are based on OB2, except TEK 17 with external blinds, which is based on OB1. OB1 uses the strategy of category I in combination with the opening schedule of NS 3031. OB2 is also based on the opening schedule of NS 3031, but uses category III instead of category I. The results shown in figure 49 are all based on the climate file for 2050. The design that has the lowest minimum performance is the passive house in combination with no shading. The second and the third with the best minimum performance are passive house with internal and external blinds, as the figure shows. TEK 17 with external blinds has the worst minimum performance.

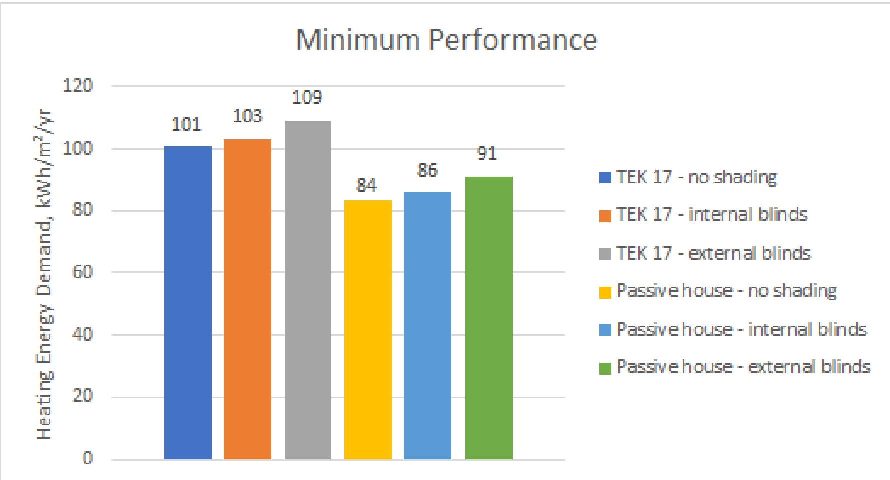


Figure 49: Minimum performance considering heating energy demand

4.3.2 Robustness Indicators

There are three different RIs: performance spread, performance deviation and maximum performance regret. The figures in this section show the robustness of the designs in terms of degree hours combined with heating energy demand. In this way, it is easier to get an opinion about which design is most robust in terms of both criteria. The points encircled represent the designs based on TEK 17.

Which stakeholder that is interested in which RI is discussed in the “5.3 Robustness Assessment and Stakeholders”. Additionally, which design that suits each stakeholder best.

4.3.2.1 Performance Spread

The first RI shows the spread in performance, which means the maximum performance minus the minimum performance in each design. In terms of degree hours, TEK 17 with external blinds is the most robust design with a spread of 462 degree hours/yr. When it comes to heating energy demand, TEK 17 with no shading and internal blinds are the most robust designs. The spread is 361 kWh/m^2/yr.

Figure 50 shows that the designs based on passive house are located further up in the figure than the designs based on TEK 17. This means that the designs based on TEK 17 are generally more robust in terms of heating energy demand. On the other hand, the difference is very small. For example, the difference between TEK 17 with no shading and passive house with no shading is 10 kWh/m^2/yr. When it comes to overheating, TEK 17 and passive house with external blinds are located more to the left in the figure than the others. Thus, these two are more robust in terms of overheating than the others. The difference in robustness in overheating is much greater than for heating energy demand. For example, the difference between TEK 17 with external blinds and TEK 17 with no shading is 947 degree hours/yr. On the other hand, the difference between these two designs in terms of heating energy demand is 2 kWh/m^2/yr.

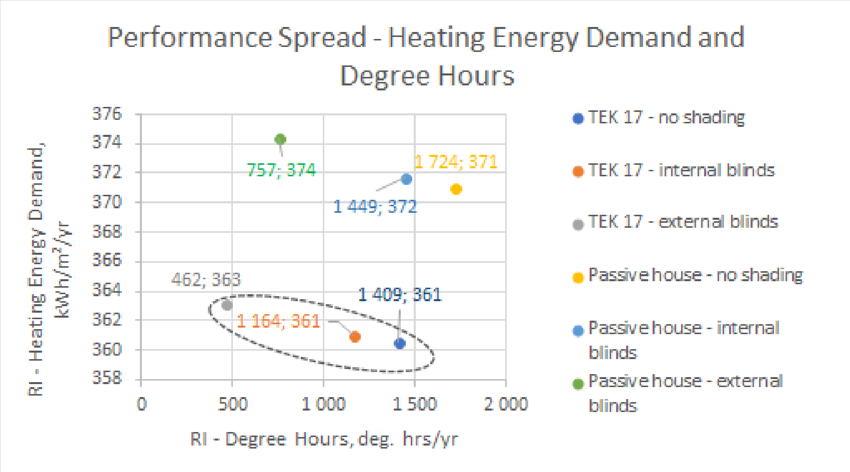


Figure 50: Performance spread

4.3.2.2 Performance Deviation

While performance spread measures the robustness only in terms of the one design, performance deviation compares all the designs with the design that is the best of all designs across all scenarios. Performance deviation uses the difference between the maximum performance across all scenarios and the best design. The ”best” design, which all the designs are compared to, is in terms of overheating the passive house and TEK 17 with external blinds with 0 degree hours, as shown in “4.3.1.1 Overheating”. When it comes to heating energy demand, the best design is passive house with no shading, with 84 kWh/m^2/yr, which was presented in “4.3.1.2 Heating Energy Demand”.

This RI gives another pattern than performance spread. Now, the designs based on TEK 17 are more scattered in figure 51, from top let to further down to the right. This also applies to the designs based on passive house, but these are located further down than the designs based on TEK 17. Passive house with external blinds is in the middle left, while the others are located down in the right corner. As for performance spread, the difference between the designs are greater for degree hours than heating energy demand. Also, for this RI, the designs with external blinds are located further to the left than the others.

The most robust design in terms of degree hours is TEK 17 with external blinds with a deviation of 462 degree hours/yr. When it comes to heating energy demand, the most robust design is passive house with no shading. It has a deviation of 371 kWh/m^2/yr.

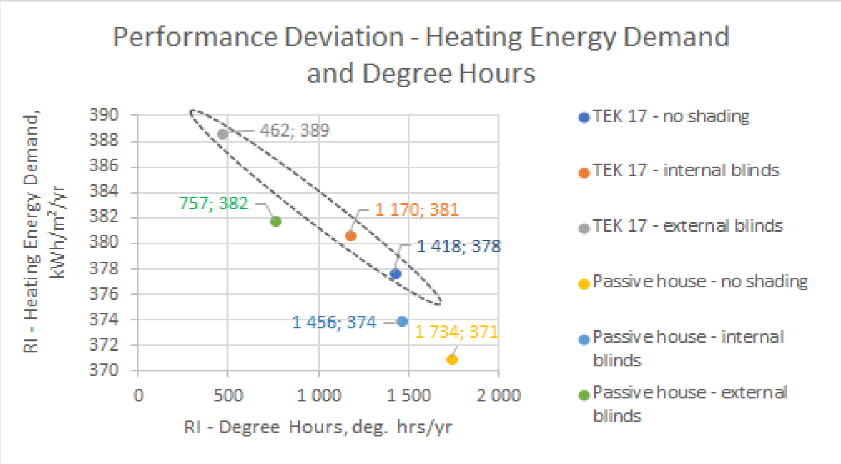


Figure 51: Performance deviation

4.3.2.3 Maximum Performance Regret

As explained in "3.1.4 Maximum Performance Regret", the performance regret takes the difference between each individual performance indicator and the minimum performance of each scenario. Thereby, the maximum of the performance regret in each design is used in the robustness assessment. Figure 52 shows that TEK 17 with external blinds has the lowest maximum performance regret when it comes to overheating, with only 1 degree hour. When it comes to heating energy demand, passive house with no shading is the most robust design.

In terms of this RI, the designs based on TEK 17 are located from the middle of the figure to the top left. The designs based on passive house are further down in the figure and go from the middle left to the bottom right. With that said, the designs based on passive house are more robust in terms of heating energy demand. In terms of overheating, the designs with external blinds are more robust.

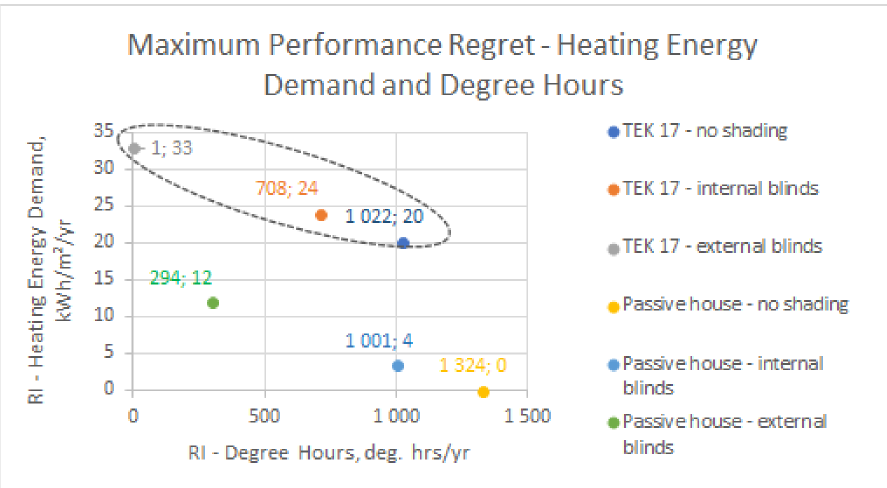


Figure 52: Maximum performance regret

4.3.3 Comparison of Robustness and Performance

Another aspect that is interesting to consider in combination with robustness is the performance of the designs and whether these two correlates. The performance of each design is calculated as an average of all the scenarios.

4.3.3.1 Overheating

The three RIs in terms of overheating are all included in the same subchapter since they all show quite similar patterns.

4.4.3.1.1 Performance Spread, Performance Deviation and Maximum Performance Regret

According to figure 53, 54 and 55, the designs show some correlation between the robustness and the performance. The more robust the design is in terms of degree hours, the better performance it has. TEK 17 with external blinds is the design that is the most robust and has the best performance across all the RIs.

The designs that fulfill the requirement about maximum 150 degree hours during a year are the ones with external blinds. The designs move from the bottom left to the top right, where TEK 17 is the best of the standards and external blinds is the best shading type.

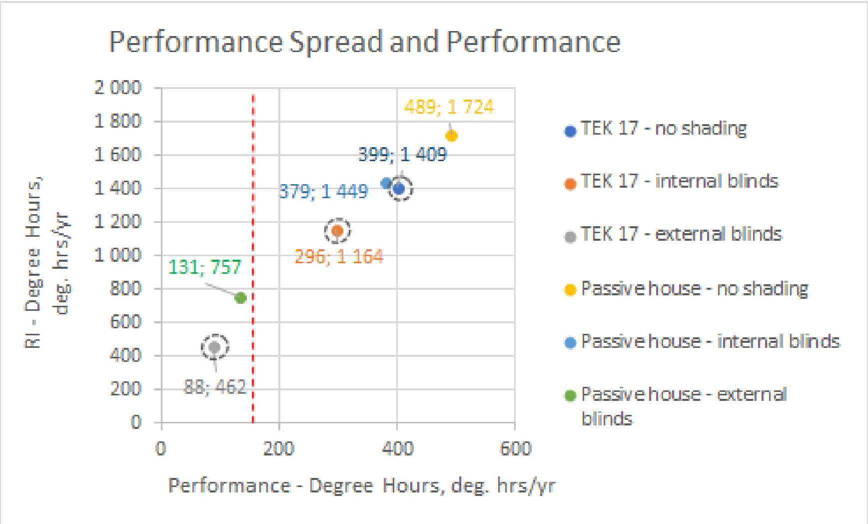


Figure 53: Performance spread in comparison with performance of degree hours

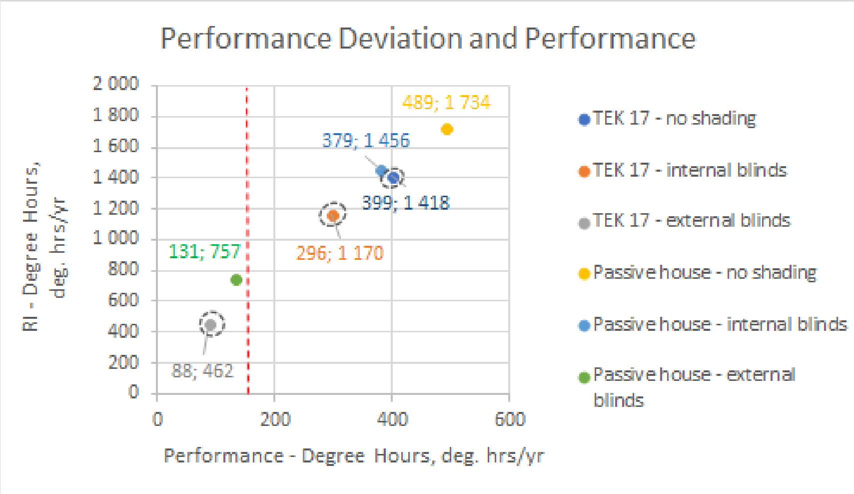


Figure 54: Performance deviation in comparison with performance of degree hours

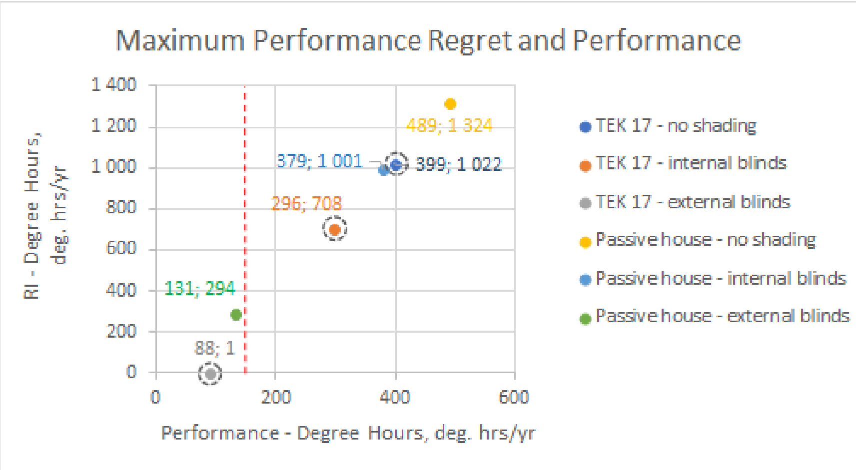


Figure 55: Maximum performance regret in comparison with performance of degree hours

4.3.3.2 Heating Energy Demand

Unlike the overheating, the figures in terms of heating energy demand show more variation.

4.3.3.2.1 Performance Spread

Figure 56 shows that the designs based on TEK 17 are located at the bottom right, while those based on the standard of passive house are located in the top left. This means that the designs based on TEK 17 are more robust in terms of this RI, while the ones based on passive house have better performance. The designs that are most robust are TEK 17 with no shading and internal blinds, while the design with the best performance is passive house without shading. The difference in performance from the best design (passive house with no shading) to the worst (TEK 17 with external blinds) is 26 kWh/m^2/yr, which constitutes 2 184 kWh/yr for this apartment. The difference in robustness between these two is 11 kWh/m^2/yr that is 924 kWh/yr, where TEK 17 with external blinds is more robust.

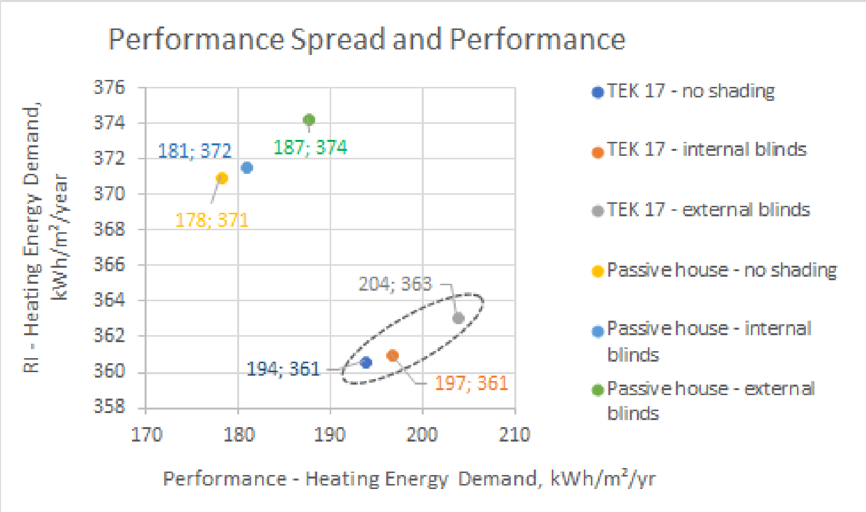


Figure 56: Performance spread in comparison with performance of heating energy demand

4.3.3.2.2 Performance Deviation

Figure 57 has a different pattern than figure 56. When it comes to the two standards, the TEK 17 designs go from the middle and up to the right. The designs based on passive house goes from down to the left and to the middle in the figure. These designs are located further down than the designs based on TEK 17 and thus they have better performances. The best design in terms of both robustness and performance is passive house with no shading. The worst design is TEK 17 with external blinds.

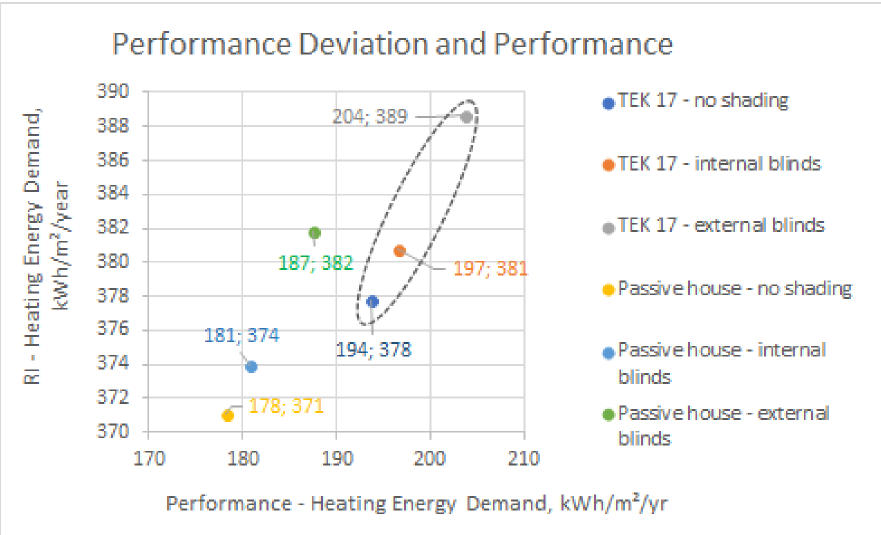


Figure 57: Performance deviation in comparison with performance of heating energy demand

4.3.3.2.3 Maximum Performance Regret

Figure 58 gives quite a similar pattern as the one based on performance deviation. All the designs are located on an approximately linear line. This means that the better the performance is, the better the robustness, and vica versa. The designs based on passive house are located further down and to the left in the figure than the designs based on TEK 17, which means that passive house is better in terms of robustness and performance. The optimal design is passive house with no shading. The worst design is TEK 17 with external blinds.

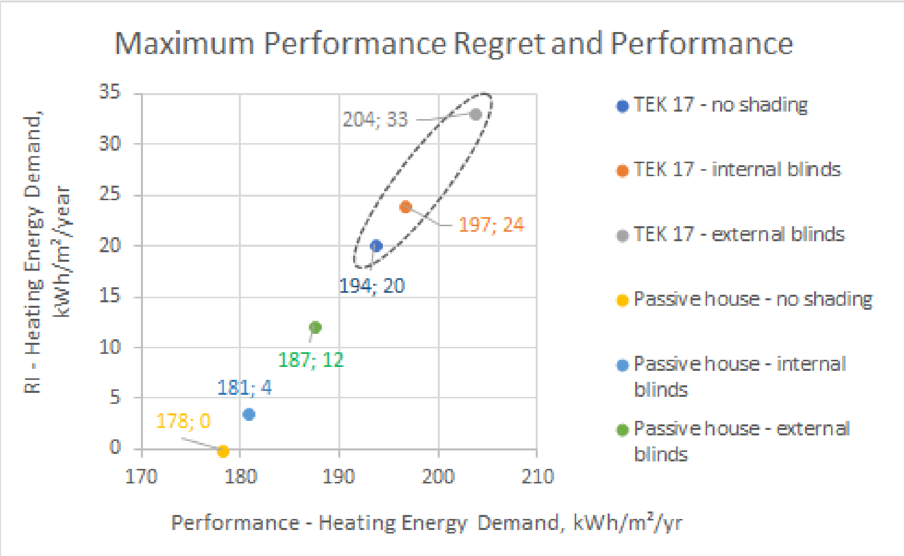


Figure 58: Maximum performance regret in comparison with performance of heating energy demand

The results presented in this chapter are further discussed in the following chapter "5. Discussion".

5. Discussion

The results show that overheating and heating demand give opposite results - the design that is most robust in terms of degree hours is worst regarding heating energy demand, and vica versa. The same apply to the performances. As mentioned in the introduction, the research questions in this thesis are:

- **RQ1** Which design is the most robust in terms of the two key performance indicators, heating energy demand and overheating?
- **RQ2** Does the robustness of the designs differ from which robustness indicator (performance spread, performance deviation or maximum performance regret) and key performance indicator that are considered?
- **RQ3** Which design is the most optimal for the three different stakeholders: policymakers, homeowners and designers?

These research questions are discussed in this part of the thesis.

5.1 Thermal Comfort (Overheating)

The following subchapters discuss the most important results that were presented in the "4. Results" regarding overheating.

5.1.1 Correlation between EN-15251 and Degree Hours

Figure 37 of the degree hours and the thermal comfort defined by EN-15251 has an R squared value of 0.86, which means that there is a correlation between degree hours and unacceptable hours during occupancy. The more degree hours, the more unacceptable hours during occupancy. Figure 36 shows that the thermal comfort is unacceptable in June, July and August. Thus, the unacceptable thermal comfort is connected to overheating, and not due to low temperatures inside the apartment in the winter months.

Figure 35 shows that there are six models located down to the left, where all of them are based on the window opening strategies of IDA ICE and Multiconsult. These six also fulfill the requirement about maximum 150 degree hours/yr. OB4 is best in terms of degree hours, while OB12 is the best one in terms of unacceptable hours. The three designs based on category I are placed slightly to the right, and the three designs based on category III are located at the upper right in the figure. Why the designs based on IDA ICE and Multiconsult have the best performance might be because of the figures shown in “3.2.3.1.4 Comparison of the Four Strategies”. These show that the window is in the living room/kitchen is much more open when it follows the strategy of Multiconsult or IDA ICE compared to the two other strategies.

When it comes to the three schedules the strategies follow, except Multiconsult, it do not seem like these influence the degree hours neither positively or negatively. The reason might be that degree hours are independent of the occupancy. OB4, which is the best design in terms of degree hours follows NS 3031. OB7 and OB11 are the second best in terms of degree hours, and they follow the schedule of house living and the Iranian schedule. The strategy influences the overheating quite more.

On the other hand, it may seem like the schedules influence the unacceptable hours during occupancy. OB12 is the best one when it comes to unacceptable hours during occupancy. This model follows the Iranian schedule. The second best is OB11, which also uses the Iranian schedule. The third best is OB4, which is based on NS 3031. According to the study of which apartment that was the most overheated, the results registered the highest operative temperature in the afternoon at 5 pm in the living room/kitchen. Due to this, it seems like the highest operative temperature is in the afternoon. Therefore, OB12 and OB11 might be the best since the occupants are not coming home before 6 pm, which means that they have been avoiding the worst time of the day considering the overheating of this room.

Overall, based on figure 35, it might seem like the window opening strategies influence the performance in terms of both degree hours and unacceptable hours more than the schedules.

5.1.2 Climate

When it comes to the two climate files, the results in terms of degree hours show that the expected warmer climate in 2050 adversely affect the overheating. There is significantly higher risk for overheating, but also the range is much higher, which means that it is more difficult to predict how a building performs in terms of degree hours.

Another important aspect in the results, due to climate changes, is what kind of shading one chooses in the future. As mentioned above, the mean, median and range increase a lot from today's climate until 2050. To keep the temperature at a respectable level it is important to use shading that prevents overheating, e.g. external blinds. The mean for external blinds is much better than the two others, both today and in 2050. On the other hand, the mean of TEK 17 with external blinds increases with 91.3 % from today until 2050, while TEK 17 with internal blinds increases with 67 %. Despite this percentage increase, external blinds have much better performance than internal blinds.

In 2050, one can expect more risk of overheating independent of which standard one follows. Therefore, what kind of shading the buildings have plays an important role.

5.1.3 Occupant Behavior

When it comes to the occupant behavior, as mentioned in "5.1.1 Correlation between EN-15251 and Degree Hours", the window opening strategies based on IDA ICE and Multiconsult give the best thermal comfort. Both category I and category III are based on the adaptive model in terms of EN-15251, but they are still the worst in terms of degree hours.

Unlike the three other strategies, the only difference between the three models/OBs based on Multiconsult is the heat gain from people. Both in terms of unacceptable hours and degree hours, it seems like the heat gain influence both negatively the more people are at home. On the other hand, this is perhaps not surprising since they all follow the similar schedule of when the windows can be opened. That said, in the weekdays the windows are closed from 8 am until 4 pm. This means that for the schedule of NS 3031, people are at home all day long and produce heat, but they cannot open the windows. On the other hand, the lowest presence of people are the models that follow the Iranian schedule. In these models, the people are not coming home before 6 pm, which means that they do not need to open the windows between 8 am until 4 pm. OB11 follows the occupancy schedule of the Iranian schedule and the window opening schedule of Multiconsult, which means the windows may be opened between 4 pm - 6 pm, which is a bit unrealistic since there are no one home in this time interval.

The box plots of the different strategies show that which shading type that is used is much more important for category I and category III in future than for the others. The designs that are based on the strategies of Multiconsult and IDA ICE have very good thermal comfort both today and in 2050 independent of which design one evaluates. Therefore, what kind of shading that is used is not that important for these two strategies. For the others, it is much more important. For example, the mean for category III increases with 574 degree hours/yr from the current climate until 2050.

On the other hand, use of windows are rarely something designers can predict, since it is an occupant behavior. Therefore, it is much better to plan how a building design can be robust and have good performance considering these uncertainties.

5.1.4 Designs

When it comes to the designs, the box plots show that TEK 17 with external blinds is the best design in terms of overheating, both in terms of performance and variation in degree hours. In comparison with passive house, TEK 17 has greater thermal bridge, and less insulation in external walls and roof. As mentioned in “2.2.1.1.2 Thermal Bridges”, if the normalized thermal bridge value is high in a building, the thermal resistance is low. Additionally, buildings with less insulation leads to higher U-value, which again means that the building is worse at keeping the heat inside the building. That said, because of less insulation and higher thermal bridge values, TEK 17 is most likely better than passive house in terms of overheating since the passive house retains the heat better than TEK 17. The risk of overheating is greater for a passive house.

When it comes to shading, external blinds are the best solution out of the three in terms of overheating. External blinds have lower multipliers for g- and T-value than the two others, which mean that the windows transmit less energy and less solar radiation into the apartment. External blinds also fully diffuse the directed solar radiation. Based on the assumptions about how the climate will be in future, the design one should aim for in terms of overheating is TEK 17 with external blinds.

On the other hand, the performance of the designs in terms of heating energy demand shows some other results than in terms of overheating.

5.2 Heating Energy Demand

The ventilation varies only with regard to the climate and not the occupant behavior. For the reference file, ventilation uses 683.1 kWh/yr, while in 2050 it uses 686.7 kWh/yr. Normally, one would think that the consumption in terms of ventilation would decrease from today until 2050 since the temperature is rising. Then the ventilation needs less energy to increase the temperature to desired supply air temperature (18 °C). From the study of the climate files in the theory, “3.2.4.3.1 Comparison of Climate Files”, it was written that the mean temperature during a year for the reference file is 6.7 ^{o}C, while in 2050 it is 9.1 ^{o}C. Despite this, the simulations show that the ventilation system uses approximately the same amount of energy independent of climate, which seems a bit odd.

On the other hand, it means that the electric radiators are most affected by the different scenarios, and they influence the heating energy demand more than the ventilation.

5.2.1 Climate

In contrast to overheating, the warmer climate in 2050 influences the heating energy demand positively. Based on all box plots, independent of shading type and opening strategy, all the designs use less energy in 2050 than today. On the other hand, the difference from today until 2050 is not as huge as it is for degree hours.

When it comes to shading type, no shading gives less heating energy demand than any of the others. On the other hand, the difference between the three shading types are very small. In terms of overheating, shading influences the performance in degree hours quite much. For heating energy demand, the difference between these three are not critical. Therefore, the most optimal, both for passive house and TEK 17, is to use external blinds or something similar to provide good thermal comfort.

5.2.2 Occupant Behavior

When it comes to the different window opening strategies, category I, category III and IDA ICE give very similar results. The difference between these three, in terms of mean and median, is very small and they produce equally good results in terms of heating energy demand. The strategy based on Multiconsult differs negatively compared to the others. On the other hand, in terms of both climate files, the range for all four strategies is small and similar. This means that opening schedule and shading do not affect the heating demand very much.

The reason why the strategy based on Multiconsult is so bad is probably because of the heating setpoints of the electric radiators, and at what temperature the windows open according to this strategy. As mentioned earlier, the heating setpoint is 22 ^{o}C when in operation and 20 ^{o}C anytime else (air temperature). When it comes to this strategy, the windows open in the living room/kitchen when the air temperature is above 20 ^{o}C (18 ^{o}C for bedrooms) and within opening schedule. That said, the electric radiators and this strategy counteract each other. The electric radiators want to achieve a temperature of 22 ^{o}C, but the strategy makes it difficult since it does not want it warmer than 20 ^{o}C. This leads to the electric radiators using much more energy on heating than necessary, and the apartment loses and wastes a lot of energy. Therefore, this case seems a bit unrealistic. Most likely, people do not have a setpoint of 22 ^{o}C on the electric radiators and at the same time want a temperature of 18 ^{o}C/20 ^{o}C.

5.2.3 Designs

Unlike overheating, the design that has the best performance in terms of heating energy demand is passive house with no shading. As mentioned in “5.1.4 Designs”, the difference between TEK 17 and passive house regarding heating energy demand is most likely because of insulation thickness and the normalized thermal bridge value.

When it comes to the requirement of TEK 17 about maximum 95 kWh/m^2/yr in total energy consumption, the box plots show that the different designs do not fulfill this requirement. For example, TEK 17 with no shading has an average heating energy demand of 206 kWh/m^2/yr for today’s climate. This design is a far from meeting this requirement. The same applies to the passive house, which has a specified requirement in heating energy demand. The requirement for the apartment is 24 kWh/m^2/yr. For passive house without shading and current climate, the mean heating demand is 189 kWh/m^2/yr.

As explained in the previous chapter, "5.2.2 Occupant Behavior", the strategies based on Multiconsult use a lot more energy than the others. The mean for TEK 17 and passive house with no shading, without this strategy, is 121 kWh/m^2/yr and 101 kWh/m^2/yr. On the other hand, they still do not fulfill the requirements. The reason might be the setpoints in each room. As explained in "3.2.5 Fixed Variables", it has been simplified that all rooms except the storage have the same setpoints. Most likely, this is not realistic. Often bedrooms are quite colder than the other rooms.

From heating demand point of view, which shading that is used is not as important as it is for overheating. Based on this, the heating demand performance of the six designs are quite similar in comparison to overheating. The optimal design in terms of heating energy demand is passive house with no shading, but the overheating is very bad for this design. The question is how the tradeoff between overheating and heating energy demand is for the different designs. Additionally, which design that is the best in terms of both overheating and heating demand regarding robustness. This is discussed further in the next section.

5.3 Robustness Assessment and Stakeholders

The figures of the minimum and maximum performance show that the design that is the best in terms of overheating is TEK 17 with external blinds, while the worst is passive house without shading. On the other hand, the design that is the best according to heating energy demand is passive house with no shading. The worst is TEK 17 with external blinds.

Which design that is the most robust vary after which RI and KPI, heating energy demand or overheating, that are evaluated. The importance of the following chapters is to find out which design and RI that is the best for which stakeholder. The following discussion is based on a Norwegian context.

5.3.1 Performance Spread and Designers

The most important for designers, such as energy performance consultants, are satisfied customers and that the designed buildings perform as predicted. Designers must ofen follow requirements according to standards, which is partly developed by policy makers. On the other hand, operational costs and investment costs are not that important for designers since they not are paying anything during the construction or when the building is in operation.

This means that, for the KPIs that are considered in this thesis, the most important for designers are both overheating and heating energy demand. They must follow the requirements in terms of maximum overheating and how energy-efficient the buildings should be. In this thesis, overheating can be compared to the requirement of 150 degree hours. When it comes to heating energy demand, none of buildings meet the requirements. The strategy based on Multiconsult increases the average consumption a lot, in addition to the apartment generally consumes more than it should.

When it comes to the different RIs, performance spread is most likely the best indicator for designers. This indicator is better when it comes to lower risks in performance variation. Additionally, this indicator is only optimized in terms of the best performing scenario in each design. Often, designers know what type of building they should design, e.g. passive house or TEK 17, since they follow building standards. In addition, often the owner of a building that gives the designers the responsibility of the design, have an opinion of what the targets for the building are, e.g. in terms of how energy-efficient it should be. Therefore, designers are most interested in which design that is the best compared to itself based on extreme scenarios of maximum and minimum performance.

Based on the results from the figures of performance spread, the design that is most likely the best for designers is TEK 17 with external blinds. One reason is because this was one of two designs (passive house with external blinds) that meet the requirement of maximum 150 degree hours during a year. Additionally, this design is more robust than passive house with external blinds both when it comes to overheating and heating energy demand. On the other hand, the performance in heating demand is better for passive house than TEK 17, but neither of these meet the requirements from the standard. The performance affects the operational costs and the average energy consumption in the household, but this is not important for designers.

5.3.2 Performance Deviation and Policymakers

The most important criteria for policy makers are robust designs that has low CO_2 emissions, use little energy and have low investment costs, as e.g. on materials. In Norway, energy is most relevant, since almost all of the energy use in Norwegian households is based on electricity. As mentioned in “1.1 Background”, buildings account for 40 % of the total energy consumption in Norway. Therefore, it is crucial to decrease the energy use. Policymakers are interested in creating a sustainable society and defining energy performance requirements in future building regulations.

Performance deviation is a good RI for policymakers since it compares different designs with each other. This RI compares all six designs with each other, and the robustness is optimized in terms of the best performing case of all designs and scenarios. In addition, this indicator contains little risk in variability in performance. Policymakers want to achieve national and international targets for e.g. energy use, and therefore it is important that the variation is low.

When studying figure 51, the design that is the optimal for policymakers is a bit difficult to determine. None of the designs excel very positively in terms of the performance deviation. Which design that is the best for policymakers depends on which tradeoff they want between heating energy demand, overheating and investment costs. Passive house demands often higher investment costs due to the use of more materials than TEK 17. Additionally, external blinds are the most expensive shading type. According to the performance deviation, the most robust design in terms of heating energy demand is passive house without shading, but it is the worst in terms of performance and robustness in overheating. The average number of degree hours for this design is 339 higher than the requirement of a maximum of 150 degree hours. If there is a lot of overheating, the occupants most likely use ventilation through windows more frequently, which increases the energy use on heating.

On the other hand, the policy makers might be more interested in the designs that have another tradeoff between robustness of degree hours and heating energy demand. For example, passive house with internal blinds, TEK 17 with no shading or passive house with external blinds. Passive house with external blinds is the second best in terms of robustness in overheating, the performance in overheating fulfills the requirement about maximum 150 degree hours/yr, and it is the third best in heating demand performance. On the other hand, this design has most likely the highest investment costs, while TEK 17 with no shading is most likely the design with the lowest investment costs. Based on this, it is difficult to determine which design that is the best for policymakers. It all depends on which tradeoff they want.

5.3.3 Maximum Performance Regret and Homeowners

The criteria homeowners are most interested in are a robust design that provides good thermal comfort, low investment costs and operational costs. Low operational costs may be the result of cheap electricity bills. One might expect that passive house has lower operational costs than TEK 17 since it generally uses less energy. Considering thermal comfort and operational costs, which design that is the best for homeowners depend on how good they want the thermal comfort to be compared to the operational costs.

Most likely, homeowners accept a certain risk of overheating as a tradeoff for operational costs. Therefore, the most appropriate indicator for homeowners is maximum performance regret that has higher risk than the two other indicators. TEK 17 with external blinds is the design that is the most robust and has the best performance in terms of overheating. On the other hand, when studying maximum performance regret (ref. figure 52), passive house with external blinds is a good tradeoff between overheating and operational costs (lower heating energy demand), but passive house has presumably higher investment costs.

In terms of performance of heating demand, passive house with external blinds is the third best. The difference in performance between this design and the one that is the best in terms of overheating, TEK 17 with external blinds, is 17 kWh/m^2/yr. According to "Trondheim Kraft", the price for electricity and gridline, excluding fixed costs, is 0.98 NOK/kWh (*Strømpriser*, n.d.). This means that using passive house instead of TEK 17 save the homeowners 1 400 kr/yr for this apartment. For a year, it might not seem that much, but over several years one can save a lot of money. The question is whether the savings cover the increased investment costs for a passive house in the long run.

Anyway, based on the good tradeoff passive house with external blinds has, this design is most likely the best for homeowners.

5.4 Closing Discussion

This thesis shows that climate changes, occupant behavior and various designs can influence the performance of a building a lot. Additionally, which design that is the most robust depends on which KPI, heating energy demand or overheating, and RI one considers. Compared to other countries, the risk of overheating in Norwegian buildings has not been that important before. Today, the standards in Norway demand more insulation than before, e.g. to decrease the heating energy demand. The new standards, along with the increasing temperature, lead most likely to less energy used on heating. On the other hand, the standards and the warmer climate increase the risk of overheating drastically, which means that it is very important to consider this aspect in future. The results show that for the apartment based on TEK 17 with external blinds the heating demand decreases with 12.5 % from today until 2050, while the overheating increases with 91.3 %. Thus, overheating of buildings will most likely be a bigger problem in future.

When it comes to the occupant behavior, the window opening strategies affect the performance of the apartment more than the opening schedules. From the perspective of overheating, the strategies based on IDA ICE and Multiconsult give the best results. They fulfill the requirement about maximum 150 degree hours both today and in 2050, while category I and category III do not fulfill this requirement. The overheating for these two become much worse, both in terms of performance and variability, when the climate is warmer. Therefore, effective shading is crucial for these two. Regarding the heating energy demand, the strategy of Multiconsult uses more energy than the others. The three others have approximately the same performance and variation. The reason why Multiconsult is so different might be of various reasons, e.g. settings in IDA ICE.

In terms of the designs, type of shading impacts the performance of overheating a lot, but do not affect the heating energy demand quite as much. When it comes to the two standards, TEK 17 has generally better performance in terms of overheating, but passive house is better when it comes to heating energy demand. Overall, shading affects the performance of overheating more, while the standard is the most crucial in terms of heating energy demand.

The most robust design in terms of overheating is TEK 17 with external blinds. When it comes to heating energy demand, the most robust design varies after which RI one studies. In terms of performance spread, the most robust design is TEK 17 with no shading and internal blinds. According to performance deviation and maximum performance regret, passive house with no shading is the best. Why the three RIs give different results is most likely because performance spread only measures the robustness in terms of each design, which means that it does not compares all the other designs. Passive house has generally lower performance than TEK 17. Therefore, passive house is more robust compared to the designs based on TEK 17. On the other hand, TEK 17 is more robust than passive house when compared to itself.

When it comes to performance spread, this indicator is best suited for designers. It has low risk in terms of variations, and it only compares the robustness to its own design. Based on the indicator and the interests of the designers, satisfying customers and fulfilling requirements, the best design for them is TEK 17 with external blinds. When considering the performance spread, it is the most robust design in terms of overheating and the third most robust design in terms of heating energy demand. Additionally, it has the best overheating performance.

On the other hand, performance deviation suits policymakers the best. It also has low risks when it comes to variation in performance, and it compares all the designs with each other. Which design that is the best for policymakers depends on what trade off they want to have between heating energy demand, overheating and investment costs. For example, passive house with external blinds has probably the highest investment costs, but has a good tradeoff between overheating and heating energy demand. The other designs most likely have lower investment costs, but they have another tradeoff between heating energy demand and overheating.

The best indicator for homeowners is maximum performance regret. This indicator has higher risks when it comes to variation in performance, but most likely it is not a problem for homeowners with cheaper electricity bills and a bit more overheating, or the opposite. The best design for homeowners is most likely passive house or TEK 17 with external blinds, but it depends on the tradeoff between overheating and operational costs. Considering figure 52, passive house with external blinds has a good tradeoff between these two. Therefore, this design is most likely the best for homeowners.

6. Conclusion

The robustness assessment of the apartment located in Oslo ended up with different results in which design that is the most robust. With regards to overheating, TEK 17 with external blinds is without a doubt the most robust design. On the other hand, when evaluating the robustness in terms of heating energy demand, the most robust design stands between passive house, TEK 17 without shading and TEK 17 with internal blinds. TEK 17 without shading and internal blinds are the most robust in terms of performance spread, while passive house with no shading is most robust according to the two other RIs.

This thesis shows how much uncertainties in occupant behavior and climate changes can affect the performance of a building. The degree of overheating and heating energy demand strongly depend on how much the windows are open and the climate. Additionally, the robustness assessment shows how much the design may influence the performance of the apartment. Use of external blinds decrease the number of degree hours drastically and keep the thermal comfort more stabilized.

In the building industry, the focus on building more sustainable buildings that use little energy is widespread. In the future, the governmental focus has been on moving on from TEK 17 to passive house and later to more environmentally friendly buildings. The question is if these newer standards/targets are more sustainable than the older standards, if they do not perform as planned. This thesis shows that TEK 17 is more robust when it is compared to itself than passive house both in terms of overheating and heating energy demand. With regards to heating energy demand, when all designs are compared to each other, passive house is most robust due to its overall better performance in energy use.

The method employed in this research is a valuable tool for evaluating the robustness of different building designs together with performance. It is also a beneficial tool for many different stakeholders, as designers, homeowners and policymakers. This method may be included in the design phase to decide the most robust design, so it is more likely to perform as planned, and meet the stakeholders' desire. It is not only the factors mentioned in this thesis that can be considered in the robustness assessment. There are other factors in building operation and external conditions that are relevant regarding building's performance, e.g. heating setpoints or consumption of hot water.

6.1 Future Work

Thermal comfort can be measured in different ways. In future work, it is possible to base the overheating assessment on the adaptive model, e.g. how many degree hours that are outside category III. Thereby, it can be used in this robustness assessment and compared to other criteria, as cost or energy use.

Cost is a significant factor that is missing in this thesis. This factor is something almost every stakeholder think is important. Something interesting to investigate in the future would be TEK 17 and passive house in terms of energy use, thermal comfort and costs. Building a passive house might lead to cheaper electricity bills, but it often has higher investment costs due to the need for more materials. Terms that have become more frequently used in the building industry, are life cycle analysis (LCA) and life cycle costs (LCC), which considers the total costs and energy for the whole lifetime of a building. The materials needed to build a passive house often require more energy and costs to produce, transport and build than for a building based on TEK 17. Together with LCA, LCC and building performance simulations, robustness assessment is a good tool to support the choice of which design to be chosen for a building. The society is always focusing on implementing more energy-efficient buildings, but the question is if this is the correct focus based on the robustness assessment, the extra costs and energy it needs in production, transportation and construction.

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Appendices

Appendix A: Scenarios

Scenarios	Window Opening Strategy	Window Opening Schedules	Occupancy Schedules	Climate File
S1	Adaptive Model - Category I	NS 3031	NS 3031	**CURRENT**
S2	Adaptive Model - Category III	NS 3031	NS 3031	
S3	Multiconsult	Multiconsult	NS 3031	
S4	IDA ICE	NS 3031	NS 3031	
S5	Adaptive Model - Category I	IDA ICE - House living	IDA ICE - House living	
S6	Adaptive Model - Category III	IDA ICE - House living	IDA ICE - House living	
S7	Multiconsult	Multiconsult	IDA ICE - House living	
S8	IDA ICE	IDA ICE - House living	IDA ICE - House living	
S9	Adaptive Model - Category I	Paper	Paper	
S10	Adaptive Model - Category III	Paper	Paper	
S11	Multiconsult	Multiconsult	Paper	
S12	IDA ICE	Paper	Paper	
S13	Adaptive Model - Category I	NS 3031	NS 3031	**2050**
S14	Adaptive Model - Category III	NS 3031	NS 3031	
S15	Multiconsult	Multiconsult	NS 3031	
S16	IDA ICE	NS 3031	NS 3031	
S17	Adaptive Model - Category I	IDA ICE - House living	IDA ICE - House living	
S18	Adaptive Model - Category III	IDA ICE - House living	IDA ICE - House living	

S19	Multiconsult	Multiconsult	IDA ICE - House living	
S20	IDA ICE	IDA ICE - House living	IDA ICE - House living	
S21	Adaptive Model - Category I	Paper	Paper	
S22	Adaptive Model - Category III	Paper	Paper	
S23	Multiconsult	Multiconsult	Paper	
S24	IDA ICE	Paper	Paper	

Appendix B: Detailed Sample File

Simulation Number	Thickness, wall (insulation)	Thickness, roof (insulation)	Thermal bridge	g	t	u	Diffusion	Climate
C1	0.2	0.25	0.07	1	1	1	0	2018
C2	0.2	0.25	0.07	1	1	1	0	2050
C3	0.2	0.25	0.07	0.65	0.16	1	1	2018
C4	0.2	0.25	0.07	0.65	0.16	1	1	2050
C5	0.2	0.25	0.07	0.14	0.09	1	1	2018
C6	0.2	0.25	0.07	0.14	0.09	1	1	2050
C7	0.3	0.4	0.03	1	1	1	0	2018
C8	0.3	0.4	0.03	1	1	1	0	2050
C9	0.3	0.4	0.03	0.16	0.16	1	1	2018
C10	0.3	0.4	0.03	0.16	0.16	1	1	2050
C11	0.3	0.4	0.03	0.14	0.09	1	1	2018
C12	0.3	0.4	0.03	0.14	0.09	1	1	2050

Appendix C: Degree Hours and Unacceptable Hours

	X-axis			Y-axis		
Models/OB	**Degree hrs/yr**	**Total number of hrs/yr**	**Percentage (%)**	**Unacceptable hrs/yr**	**Total occupancy hrs/yr**	**Percentage**
OB1	218	8 760	2.49	121	8 760	1.38
OB2	606	8 760	6.92	793	8 760	9.05
OB3	48	8 760	0.55	58	8 760	0.66
OB4	9	8 760	0.11	25	8 760	0.29
OB5	232	8 760	2.64	123	6 933	1.77
OB6	521	8 760	5.95	638	6 933	9.2
OB7	40	8 760	0.46	27	6 933	0.39
OB8	53	8 760	0.61	24	6 933	0.35
OB9	274	8 760	3.13	87	5 995	1.45
OB10	547	8 760	6.24	424	5 995	7.10
OB11	40	8 760	0.45	15	5 995	0.25
OB12	97	8 760	1.10	10	5 995	0.17

Appendix D: Degree Hours

Window Shading – TEK 17

TEK 17	Current climate			2050		
Shading type	**No shading**	**Internal blinds**	**External blinds**	**No shading**	**Internal blinds**	**External blinds**
Median (Deg. Hrs/yr)	158	116	9	451	345	126
Mean (Deg. Hrs/yr)	224	147	14	575	446	161
Range (Deg. Hrs/yr)	597	404	50	1 342	1112	455

Window Shading – Passive House

Passive house	Current climate			2050		
Shading type	**No shading**	**Internal blinds**	**External blinds**	**No shading**	**Internal blinds**	**External blinds**
Median (Deg. Hrs/yr)	186	141	14	542	427	168
Mean (Deg. Hrs/yr)	285	196	26	694	563	235
Range (Deg. Hrs/yr)	816	581	106	1 649	1 392	749

Window Opening Strategies – TEK 17

TEK 17	**Current climate**				**2050**			
Window Strategy	**Category I**	**Categor y III**	**Multico nsult**	**IDA ICE**	**Category I**	**Categor y III**	**Mutlico nsult**	**IDA ICE**
Median (Deg. Hrs/yr)	163	321	27	9	584	942	72	76
Mean (Deg. Hrs/yr)	146	312	24	31	546	886	65	79
Range (Deg. Hrs/yr)	259	590	48	96	547	1 176	119	151

Window Opening Strategies – Passive House

Passive house	**Current climate**				**2050**			
Window Strategy	**Category I**	**Categor y III**	**Multico nsult**	**IDA ICE**	**Category I**	**Categor y III**	**Mutlico nsult**	**IDA ICE**
Median (Deg. Hrs/yr)	208	462	26	10	736	1 269	71	85
Mean (Deg. Hrs/yr)	185	434	24	33	688	1 149	66	85
Range (Deg. Hrs/yr)	304	798	49	103	632	1 378	122	167

Appendix E: Heating Energy Demand

Window Shading – TEK 17

TEK 17	Current climate			2050		
Shading type	**No shading**	**Internal blinds**	**External blinds**	**No shading**	**Internal blinds**	**External blinds**
Median ($kWh/m^2/yr$)	123	127	135	106	109	115
Mean ($kWh/m^2/yr$)	206	209	217	181	184	190
Range ($kWh/m^2/yr$)	345	344	344	314	314	315

Window Shading – Passive House

Passive house	Current climate			2050		
Shading type	**No shading**	**Internal blinds**	**External blinds**	**No shading**	**Internal blinds**	**External blinds**
Median ($kWh/m^2/yr$)	103	106	114	89	91	97
Mean ($kWh/m^2/yr$)	189	192	200	167	169	175
Range ($kWh/m^2/yr$)	357	357	358	325	325	327

Window Opening Strategies – TEK 17

TEK 17	**Current climate**				**2050**			
Window Strategy	**Category I**	**Category III**	**Multiconsult**	**IDA ICE**	**Category I**	**Category III**	**Mutliconsult**	**IDA ICE**
Median ($kWh/m^2/yr$)	126	125	464	127	108	108	417	109
Mean ($kWh/m^2/yr$)	126	126	464	127	108	108	417	109
Range ($kWh/m^2/yr$)	18	19	17	18	14	15	15	14

Window Opening Strategies – Passive House

Passive house	**Current climate**				**2050**			
Window Strategy	**Category I**	**Category III**	**Multiconsult**	**IDA ICE**	**Category I**	**Category III**	**Mutliconsult**	**IDA ICE**
Median ($kWh/m^2/yr$)	106	105	457	106	90	90	410	91
Mean ($kWh/m^2/yr$)	106	105	457	106	91	90	410	91
Range ($kWh/m^2/yr$)	16	18	16	17	11	14	15	13

Appendix F: Robustness Assessment

Degree Hours (deg. hrs/yr)

	Current												2050													
Design	OB1	OB2	OB3	OB4	OB5	OB6	OB7	OB8	OB9	OB10	OB11	OB12	OB1	OB2	OB3	OB4	OB5	OB6	OB7	OB8	OB9	OB10	OB11	OB12	Maximum performance	Minimum performance
TEK 17 - no shading	218	606	48	9	232	521	40	53	274	547	40	97	767	1419	126	76	732	1259	97	122	769	1264	93	170	1419	9
TEK 17 - internal blinds	163	411	32	7	162	321	27	37	185	321	25	70	644	1171	93	59	567	942	72	91	584	933	68	124	1171	7
TEK 17 - external blinds	44	50	1	1	19	19	1	2	16	16	0	2	378	463	20	30	248	277	10	19	222	243	8	19	463	0
Passive house - no shading	268	826	49	10	287	686	42	57	331	720	41	104	914	1734	130	85	898	1553	99	131	934	1566	94	185	1734	10
Passive house - internal blinds	208	588	32	7	206	459	26	40	229	462	25	76	796	1456	96	64	722	1269	71	98	736	1244	68	132	1456	7
Passive house - external blinds	78	106	1	1	34	36	0	2	27	28	0	2	548	757	21	33	343	406	10	21	302	356	8	18	757	0
Minimum performance	44	50	1	1	19	19	0	2	16	16	0	2	378	463	20	30	248	277	10	19	222	243	8	18		

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Performance Regrets

Design	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24
TEK 17 - no shading	174	556	47	8	212	502	40	51	259	531	39	95	388	956	107	47	485	982	87	103	547	1022	85	152
TEK 17 - internal blinds	119	361	31	6	143	302	26	36	169	305	25	68	266	708	73	29	319	665	61	71	362	691	60	106
TEK 17 - external blinds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Passive house - no shading	224	776	49	9	267	667	42	56	315	704	41	102	536	1271	111	56	650	1277	89	112	712	1324	86	167
Passive house - internal blinds	164	538	31	6	186	440	26	39	213	446	25	74	418	993	76	34	474	992	61	79	514	1001	60	113
Passive house - external blinds	34	56	0	0	15	17	0	0	11	12	0	0	169	294	1	3	95	129	0	2	80	113	0	0

Performance robustness	Performance spread	Performance deviation	Maximum performance regret
TEK 17 - no shading	1409	1418	1022
TEK 17 - internal blinds	1164	1170	708
TEK 17 - external blinds	462	462	1
Passive house - no shading	1724	1734	1324
Passive house - internal blinds	1449	1456	1001
Passive house - external blinds	757	757	294
Robust design	462	462	1

Heating Energy Demand (kWh/m2/yr)

	Current												2050													
Design	OB1	OB2	OB3	OB4	OB5	OB6	OB7	OB8	OB9	OB10	OB11	OB12	OB1	OB2	OB3	OB4	OB5	OB6	OB7	OB8	OB9	OB10	OB11	OB12	Maximum performance	Minimum performance
TEK 17 - no shading	118	117	456	118	123	121	461	123	124	123	461	124	102	101	409	102	106	105	414	106	107	106	414	107	461	101
TEK 17 - internal blinds	121	120	458	122	126	125	464	127	127	127	464	128	104	103	412	104	108	108	417	109	109	109	417	110	464	103
TEK 17 - external blinds	129	129	466	129	134	134	472	134	136	136	472	136	109	109	418	109	114	114	424	114	115	115	424	116	472	109
Passive house - no shading	99	97	449	98	103	101	454	103	104	103	455	104	86	84	403	84	88	88	408	88	89	89	408	90	455	84
Passive house - internal blinds	101	100	452	102	106	105	457	106	107	106	458	107	86	86	406	87	90	90	410	91	92	91	411	92	458	86
Passive house - external blinds	108	108	459	108	113	113	465	113	115	115	465	115	91	91	412	91	96	96	417	96	97	97	418	98	465	91
Minimum performance	99	97	449	98	103	101	454	103	104	103	455	104	86	84	403	84	88	88	408	88	89	89	408	90		

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Performance Regrets

Design	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24
TEK 17 - no shading	20	20	7	20	20	20	7	20	20	20	7	20	15	17	6	17	17	17	6	18	17	17	6	18
TEK 17 - internal blinds	23	23	10	23	23	24	10	24	23	24	10	24	17	20	9	20	20	20	9	20	20	20	9	20
TEK 17 - external blinds	30	32	17	30	31	33	18	32	32	33	18	32	23	25	15	25	26	26	16	26	26	27	16	26
Passive house - no shading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Passive house - internal blinds	3	3	3	3	3	3	3	3	3	4	3	4	0	2	3	2	2	2	3	2	2	3	3	3
Passive house - external blinds	9	11	10	10	10	12	11	11	11	12	11	11	5	8	9	7	8	8	9	8	8	8	10	8

Performance robustness	Performance spread	Performance deviation	Maximum performance regret
TEK 17 - no shading	361	378	20
TEK 17 - internal blinds	361	381	24
TEK 17 - external blinds	363	389	33
Passive house - no shading	371	371	0
Passive house - internal blinds	372	374	4
Passive house - external blinds	374	382	12
Robust design	361	371	0