Master's thesis

NTNU
Norwegian University of Science and Technology

Lars A. Justad

Potential for Heating Demand Reduction and Energy Flexibility by Improved Control and Automation of Heaters for Typical Norwegian Residential Buildings

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Preface

I would like to start off by thanking my supervisor Mohamed Hamdy for helping me with my thesis throughout this semester, both by answering my many questions and coming up with good ideas and constructive feedback. My cousin Eirik Magnussen has also helped me tremendously by providing thorough assistance during the writing of the Python script, in between his own hectic academic research. Lastly, I would like to express my gratitude towards Laurina Felius, as she lent me her well-executed building energy model.

Other very kind people that have helped me through this journey deserving of a thank you are Zac Mooney for helping proofread and Shabnam Homaei for providing me with a custom macro and guidance. Additionally, I want to thank my family for the support and even more proofreading. Lastly, my uncle Petter Grytten Almklov, a fellow NTNU person, providing me with both pointers for academic writing and nutrients via dinner invitations.

Lars A. Justad 18th June 2022

Abstract

The Norwegian residential building stock uses a substantial amount of energy on space heating during colder months. Reducing the heating demand would not only lead to cost savings but also be helpful in combating global warming by reducing CO_2 emissions. Another current issue is that many residential buildings have their peak load(s) during the same time of the day, putting pressure on the electrical grid. This is especially an issue, as we move towards more volatile and unpredictable energy sources (e.g., sun and wind). Since Norwegian households use a lot of energy on space heating, having the option to avoid heating during peak hours will be an important step towards demand-side energy flexibility. This will provide a potential for cost savings for the individual household due to the dynamic electricity prices (and presumably soon-to-be dynamic tariff pricing). Additionally, it may reduce the need to build new infrastructure to cover the ever-increasing energy consumption. This thesis thus has two main objectives, (1) to investigate how improved control and automation of heaters can reduce heating demand, and (2) to find the expected durations for ON/OFF-cycles and the changes in operative temperature whenever electrical heaters are turned off/on. These values may be used as a measure to hopefully achieve energy flexibility by programming the heaters to avoid peak hours, improving their smartness even further.

The building in this study was a detached single-family house of low thermal mass. The heaters were fully electric and requires no additional hardware, meaning the improved smartness comes from the software in the heater itself. To find the heating demand reduction by upgrading the smartness, control/automation functions from the standard NS-EN 15232-1 were modelled for four different efficiency classes in the simulation tool IDA ICE. The classes are used to classify the energy performance of the implemented functions. Four increasingly better envelopes were investigated, making a total of 16 cases. Additionally, to investigate the cycle durations and operative temperatures, eight new simulations were carried out, this time with a macro for the heating system based on adaptive thermal limits and optimal temperatures. The eight cases were the four envelopes, with all internal doors either closed or open. The cycle durations and relevant temperatures were logged and processed. Afterwards, linear regression was performed on the processed data, to find regression lines and their slopes (expected temperature drops/increases). Their reliability was measured with R^2.

The results show that there was a noticeable reduction in heating demand for all four envelopes (20-25%) when upgrading automation/control in line with NS-EN 15232-1. Regarding objective 2, the results show that cycle durations were longer for newer envelopes, and increased even further when the doors were open. Additionally, the OFF-cycles lasted longer than the ON-cycles. The slopes of the temperature changes were however smaller, meaning the temperature dropped/increased slower for newer buildings and when the doors were open. The R^2 was directly linked with the duration of the cycles, as it was worse when the durations were longer. To summarize the reliability: the regression lines were highly reliable for the ON-cycles with closed doors, and with open doors, only for the older buildings. Thus, results from cases such as these might be used. On the other hand, the regression lines were unreliable for all cases with open doors, during OFF-cycles. The results from the remaining cases (both ON and OFF-cycles) were only decently reliable, though they might prove useful to some extent. Suggestions for further work could be to find a way to use this kind of data and investigate how they might be utilized in conjunction with objective 1, to improve the control/automation functions even further.

Sammendrag

Den norske bygningsmassen har et særdeles høyt strømforbruk i kalde måneder grunnet romoppvarming. En reduksjon i oppvarmingsbehov vil både gi besparelser og bidra i kampen mot global oppvarming ved å redusere CO_2-utslipp. En annen utfordring er at mange boligbygg gjerne har sitt høyeste energiforbruk på like tider av døgnet, noe som øker presset på strømnettet. Dette er spesielt viktig nå som vi har begynt med mer uforutsigbare energikilder som sol- og vindenergi. Siden norske husholdninger bruker så mye energi på romoppvarming, er det å kunne unngå oppvarming i tidspunkter med høyt strømforbruk i landet et viktig steg mot energifleksibilitet for forbrukere. Dette vil gi et potensial for besparelser for hver husholdning på grunn av de dynamiske strømprisene (og trolig kommende dynamisk nettleie). I tillegg vil en slik energifleksibilitet kunne redusere behovet for å utvide infrastrukturen for det økende strømforbruket. Basert på dette har denne oppgaven to hovedmål (1) å undersøke hvordan forbedring av kontroll og automasjon av varmeovner kan redusere oppvarmingsbehov, og (2) å finne de forventede varighetene av PÅ/AV-sykluser samt endringer i operativ temperatur når varmeovner skrus på/av. Disse verdiene vil forhåpentligvis kunne bli brukt for å oppnå energifleksibilitet ved å programmere varmeovnene slik at de unngår tidene på døgnet med høyt strømforbruk, noe som vil gjøre varmeovnene enda smartere.

Bygget i dette studiet var en frittstående enebolig med lav termisk masse. Varmeovnene var 100% elektriske og krever ingen ny hardware, noe som tilsier at den økte smartheten heller kommer fra software i varmeovnen. For å finne reduksjonen i oppvarmingsbehov ved en økt smarthet, ble kontroll/automasjonsfunksjoner fra standarden NS-EN 15232-1 modellert for fire forskjellige energiklassifiseringer i simuleringsprogrammet IDA ICE. Disse klassene ble brukt for å klassifisere den energimessige yteevnen til funksjonene. Det ble undersøkt fire bygningskropper med økende kvalitet, noe som ga totalt 16 simuleringer. For å undersøke varigheten av sykluser og endring i operativ temperatur ble 8 nye simuleringer utført, med en ny makro som baserer seg på temperaturgrenser og optimaltemperaturer som endrer seg basert på temperaturen utendørs. De åtte simuleringene var delt opp i to set. Det første var for de fire bygningskroppene med åpne innvendige dører. Det andre settet var identisk, utenom at dørene heller var lukket. Varigheten på syklusene og de relevante temperaturene ble loggført og prosessert. Etter dette ble en lineær regresjonsanalyse utført for de prosesserte dataene, for å finne trendlinjer og deres stigningstall (forventet temperaturnedgang/-økning). Trendlinjenes pålitelighet ble målt med R^2.

Resultatene viser at det var merkbar reduksjon i oppvarmingsbehov når automasjon/kontroll ble oppgradert for alle fire bygningskroppene (20-25%) basert på NS-EN 15232-1. Når det gjelder mål 2 viser resultatene at syklusene var lengre for casene med nyere bygningskropper og de økte ytterligere når dørene var åpne. I tillegg varte AV-syklusene lengre enn PÅ-syklusene. Stigningstallene derimot var lavere, noe som betyr at temperaturen sank/økte tregere for bedre bygningskropper og når dørene var åpne. R^2 var direkte knyttet varigheten av syklusene, da den ble dårligere ved lengre sykluser. For å oppsummere trendlinjenes pålitelighet: de var svært pålitelige for PÅ-sykluser med lukkede dører, men for åpne dører gjaldt dette kun for de to eldste bygningene. Derfor er det mulig å bruke resultatene for slike caser. På den annen side var trendlinjene ikke pålitelige for casene med åpne dører, for AV-syklusene. Resultatene fra de resterende casene (både AV- og PÅ-sykluser) var kun delvis pålitelig, men kan fortsatt vise seg nyttige. Anbefalinger for videre forskning kan være å finne en måte å bruke denne typen data på, og å undersøke hvordan disse kan bli benyttet i sammenheng med det første målet, for ytterligere å forbedre kontroll/automasjon.

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Acronyms

AHU Air Handling Unit. 5, 8, 15, 35

BAC Building Automation Control. 1, 6, 10

BEM Building Energy Model. 9, 32

BPS Building Performance Simulation. 2, 8, 10, 11

CAV Constant Air Volume. 4, 15, 35

IAQ Indoor Air Quality. 2, 4

IoT Internet of Things. 1

NTBV Normalized Thermal Bridge Value. 5, 6, 11, 13

PH Passive House. 5, 10, 11, 13, 20, 23–25, 29

SFP Specific Fan Power. 5, 6, 15

TBM Technical Building Management. 6

Chapter 1

Introduction

1.1 Continuance from the specialization project

It is common practice for master students at NTNU to write a specialization project the semester prior to the master thesis. I wrote a report named “Impact of Operable Window Control Strategy on Energy Consumption of Buildings: A Narrative Review” (Justad, 2021). The project is not published. It is also common for students that the project is done as a preparation for the master thesis. This was not the case for this thesis, although the projects have similar themes, almost none of the gathered information from the literature review is used in this thesis. It did however prove useful as a practice in academic writing of longer texts.

1.2 Background

There is an increasing focus on reducing CO_2 emissions, as it is an important part of fighting global warming. The building industry is a large contributor to the emissions, and residential buildings play a big part in this (IEA, 2020). Colder countries use a lot of energy on space heating. In Norway, 66.2% of the residential energy consumption stems from space heating, and over half of this (63.9%) is from electrical heating (eurostat, 2022). This leaves a large potential for energy savings by lowering the energy used by electrical heaters, and is even more beneficial due to the recent spike in electricity prices in 2021/22.

One way of reducing energy consumption is to upgrade the smartness of the heating system, for instance, using the standard NS-EN 15232-1 which encompasses Building Automation Control (BAC) and building management. The investigating of how heating controls can be improved is not a new concept by any means, however, a lot of the studies doing so, contain the installation of additional hardware. With Internet of Things (IoT) heaters, upgrading the smartness of heaters can be achieved only with a software update (Danfoss, n.d.). Additionally, with the varying electricity prices, and presumably soon-to-be varying tariff prices (Eriksen et al., 2020), a large potential cost saving from demand-side energy flexibility is possible. For instance, if the heater could predict the time it takes for a room to reach undesired temperatures, it could also predict when it should be on/off to prevent heating when electricity prices are high. Furthermore, said energy flexibility, if utilized by many residential buildings, will have the possibility of removing the need for new infrastructure to support the ever-increasing energy usage. Both the reduction in heating demand from increased automation/control and the possibility of energy flexibility gives an overall positive potential for energy cost savings.

1.3 Objectives and research questions

Given the large spike in electricity prices, especially during peak hours, combined with the already high percentage of Norwegian residents using electrical heaters for space heating, this study will have two main objectives. The first main objective is to investigate how improved control and automation of heaters can reduce heating demand. The second objective is to find the expected cycle duration and temperature changes whenever electrical heaters are turned off/on. These values may be used as a measure to hopefully achieve demand-side energy flexibility by programming the heaters to avoid peak hours, improving their smartness even further. Based on this, four research questions have been formulated, two per objective. The questions are as follows:

1. How can the control/automation of electrical heaters be improved without installing additional hardware?
2. What are the potential energy savings for the different efficiency classes in NS-EN 15232-1, and does this vary between building envelopes?
3. How does the operative temperature respond to turning off and on heaters, and how does this change based on parameters such as the status of the internal doors, ON vs OFF-cycle, and envelope characteristics?
4. Are the results applicable/reliable, and does this differ for the previously mentioned parameters?

1.4 Prerequisites

To narrow down the scope of the study, some prerequisites have to be named. The results will, if not, be too general, and therefore not applicable to any significant extent.

The Prerequisites:

- The building is a detached single-family house.
- No additional hardware will be installed (such as occupancy detectors). All automation/control will come from software in the heater itself, as well as applications on smartphones.
- The building is of low thermal mass (e.g., wood and glass wool), which prevents any effective storage of heat.
- The heaters are fully electric, meaning they have lower thermal inertia compared to other heating systems, such as water-based heaters, and thus considered fast reacting.
- All buildings are mechanically ventilated, and the only time the windows are opened is if the Indoor Air Quality (IAQ) or temperature exceeds preferred levels.
- When investigating how the operative temperature changes when the heaters are turned off/on, the indoor temperature is assumed to be adjusted purely by the thermostat, and thus it is presumed that the windows are always closed.

1.5 Limitations

Some limitations should be mentioned to make it easier to place the findings into context (Ioannidis, 2007). There are limitations in terms of generalizability. The study only involves one kind of building (with four envelopes). The results will be less applicable for other types of buildings. Additionally, the author's knowledge of the Building Performance Simulation (BPS) program is limited. The custom macros are thus for the most part either simplified or borrowed from others.

1.6 Thesis structure

The structure of the thesis is built upon the classical term IMRAD (Introduction, Methodology, Result, Discussion), however, a theoretical framework is included before the methodology, to give a basis of knowledge to the reader and give a tie-in in which the discussion chapter will be based on. Furthermore, the conclusion is a separate chapter. The following is a brief explanation of the contents of each chapter:

Chapter 2: *Theoretical framework* provides fundamental information and some previous research.

Chapter 3: *Methodology* contains the methods used to get the results.

Chapter 4: *Results* contains the processed data from the simulations, presented in text and figures.

Chapter 5: *Discussion* reviews the main results and limitations.

Chapter 6: *Conclusion* contains the key findings and suggestions for applications/further work.

Chapter 2

Theoretical framework

This chapter explains the regulations and standards utilized when modelling. It also contains some fundamental information to help the reader gain a better understanding of the topics in this study. Lastly, some previous research from a brief literature review is presented.

2.1 Regulations and standards

The current Norwegian building regulations, TEK17 (DiBK, 2017), states all minimum technical requirements for construction works needed to erect a building. There is also made a guidance for TEK17 that provides pre-accepted solutions, which can be used to satisfy the requirements, without the need for a comprehensive documentation process. Furthermore, there is an organization called Standard Norge that produces standards that can be used as a common "recipe" for how something should be made or executed (Hofstad, 2018). These are, unlike TEK17, not mandatory to follow. They can however be used to fulfil requirements in TEK17.

2.1.1 Ventilation

Ventilation is important to maintain a good indoor environment. It works by replacing old indoor air with outside air to improve the IAQ and remove excess moisture. There are, according to Byggforskserien 552.301 (2017), three main principles of ventilation: mechanical exhaust ventilation, balanced ventilation, and natural ventilation. A balanced ventilation system should replace the old air with an equal amount of fresh air from the outside (Byggforskserien 552.301, 2017). An advantage of this type of ventilation is that it enables heat recovery from the warm exhaust air. This is done by the use of a heat exchanger, which can have an efficiency of up to 90%. This provides large energy savings during the heating seasons. Balanced ventilation can be divided into two subcategories. The first is Constant Air Volume (CAV), where the amount of air is either timed or constant. The second is variable air volume, where the air volume is varied based on different parameters.

It is not necessary to have both supply and exhaust air in all rooms (Byggforskserien 552.301, 2017). A more efficient distribution would be to supply fresh air where it is more needed, such as in bedrooms where occupants are sleeping many hours at a time. On the other hand, the exhaust vents can rather be placed in rooms where there is more air pollution and moisture production (e.g., kitchens, bathrooms). TEK17 contains several requirements for ventilation rates, based on the intended function of the room (DiBK, 2017). In general, when in use all rooms intended for continuous occupancy shall have a supply of fresh air at a rate of 1.2 m^3/h per m^2, and while not in use, a rate of 0.7. TEK17 states that rooms intended for continuous use are living rooms or similar, kitchens, and bedrooms. Rooms not intended for continuous occupancy, such as storages, are required to have a rate of 0.7 m^3/h per m^2. Additionally, bedrooms should have a supply rate of 26 m^3 per hour for each person sleeping. Lastly, wet rooms, toilets, and kitchens are required to have “satisfactorily effective vents” for the removal of old air. The ventilation rates are not specified, however, the pre-accepted solutions in the guidance can be utilized; these are shown in Table 2.1. Forced ventilation rates are the highest amount of air the vents need to be able to remove (Byggforskserien 552.301, 2017).

Table 2.1: Minimum ventilation rates for return air in wet rooms, toilets, and kitchens (DiBK, 2017).

Type of room	**Minimum ventilation rates**	**Forced ventilation rates**
Kitchen	36 m^3/h	108 m^3/h
Bathroom	54 m^3/h	108 m^3/h
Toilet	36 m^3/h	36 m^3/h
Laundry room	36 m^3/h	72 m^3/h

2.1.2 Energy efficiency requirements

The requirements for energy efficiency in building envelopes get stricter with every regulation that gets published (Felius, 2021). TEK17 states two ways of fulfilling the requirement for energy efficiency for residential buildings (DiBK, 2017). They are described in § 14-2-1 and § 14-2-2. The former works by keeping the annual heating demand below a certain threshold. For detached residential buildings, the threshold is $100 + 1600/m^2$ heated gross area, with the unit kWh/m^2a. This requirement has to be met in conjunction with a set of minimum requirements for the building envelope and a requirement regarding insulating the building’s heating system’s pipes, equipment, and ducts. The second way of fulfilling the requirement is the one used further in this thesis. It works by implementing nine energy-related measures for the building envelope and Air Handling Unit (AHU). These are listed in Table 2.2.

Table 2.2: The nine energy-saving measures connected to the requirement for energy efficiency (DiBK, 2017).

Energy-saving measure	**Value**	**Unit**
U-value walls	≤ 0.18	$[W/m^2K]$
U-value roof	≤ 0.13	$[W/m^2K]$
U-value floor	≤ 0.10	$[W/m^2K]$
U-value windows and doors	≤ 0.80	$[W/m^2K]$
Window + door area compared to heated gross area	$\leq 25\%$	[-]
Temperature efficiency ratio of heat exchanger	$\geq 80\%$	[-]
Specific Fan Power (SFP) in the AHU	≤ 1.5	$[kW/(m^3/s)]$
Infiltration at 50 Pa pressure difference	≤ 0.6	$[h^{-1}]$
Normalized thermal bridge value (NTBV)	≤ 0.05	$[W/m^2K]$

In 2013, the standard NS 3700 was published, with criteria and recommendations for achieving the status of a low-energy building, or the even stricter status of Passive House (PH) (Norsk Standard, 2013). The criteria for low-energy buildings are for the most part surpassed by TEK, however, the PH is still stricter. NS 3700:2013 defines a PH as a building of high quality with a good indoor climate and low energy consumption. Thus, a PH is a good milestone if a building of a higher quality than a TEK17-house is desired. The criteria and recommendations for achieving a PH are presented in Table 2.3. The standard also states two additional criteria not included in this thesis. These are maximum heat loss (by transmission- and infiltration) and, like TEK17, an annual net heating demand threshold (including heat supplied in the AHU).

Table 2.3: Criteria and recommended values for a residential building to receive the status as a passive house (Norsk Standard, 2013).

Criterion/recommendation	Value	Unit
Average U-value of windows and doors	≤ 0.80	[W/m^{2}K]
NTBV	≤ 0.03	[W/m^{2}K]
Heat exchanger efficiency	$\geq 80\%$	[-]
SFP in the AHU	≤ 1.5	[kW/(m^3/s)]
Infiltration at 50 Pa pressure difference	≤ 0.6	[h^{-1}]
U-value walls (recommended)	$\leq$ 0.10—0.12	[W/m^{2}K]
U-value roof (recommended)	$\leq$ 0.08—0.09	[W/m^{2}K]
U-value floor (recommended)	≤ 0.08	[W/m^{2}K]

2.1.3 Adaptive thermal comfort

The Health and Safety Executive (n.d.) defines thermal comfort as a term that, "describes a person's state of mind in terms of whether they feel too hot or too cold". The requirement § 13-4-1 in TEK17 states that rooms intended for continuous use shall have a satisfactory thermal environment (DiBK, 2017). NS-EN 16798-1 (Norsk Standard, 2019) mentions that the criteria for the thermal environment should be based on the PPD-PMV indices presented in NS-EN ISO 7730, which was originally produced by Fanger (1970). NS-EN 16798-1 does however state that an adaptive alternative can be chosen for buildings without active cooling. This requires that the occupants only perform sedentary activities and have easy access to operable windows, such as in offices or residential buildings. In addition, this only applies during spring, summer, and autumn, whenever the outdoor temperature is above 10 °C. The optimal operative temperature is a proportional function of the outdoor temperature. Operative temperature is the average of the indoor air temperature and the mean radiant temperature. As the outdoor temperature increases, it is assumed that the occupants tolerate higher indoor temperatures, as well as dress more lightly. Figure 2.1 shows this function (the middle line). The other lines, represent the upper and lower limits, depending on which comfort category is chosen. Category II is named the "normal" category. Thermal comfort is not within the scope of this thesis, however, the adaptive comfort model was used as a tool when modelling.

2.1.4 Automation

In this thesis, the BAC efficiency classes of NS-EN 15232 (Norsk Standard, 2017) are used to define the different levels of smartness for the heating system. The standard is part of a set of standards that are supposed to give a "harmonized" ground for assessing the energy performance of buildings. It encompasses the effect of BAC and Technical Building Management (TBM) functions. The functions are sorted by building discipline and BAC (heating control, domestic hot water supply control etc.). The BAC efficiency classes describe the energy performance of the different functions. The classes range from D to A. Class D corresponds to an inefficient BAC; class C is the minimum BAC for new buildings; class B corresponds to advanced BAC with certain TBM functions; and lastly, class A corresponds to high-performing BAC and TBM functions. Out of all the functions listed in the standard, only three functions are selected, as they are the only ones seemingly applicable to electrical heaters. The other functions related to heating control and automation are designed for other types of systems, such as heat pumps.

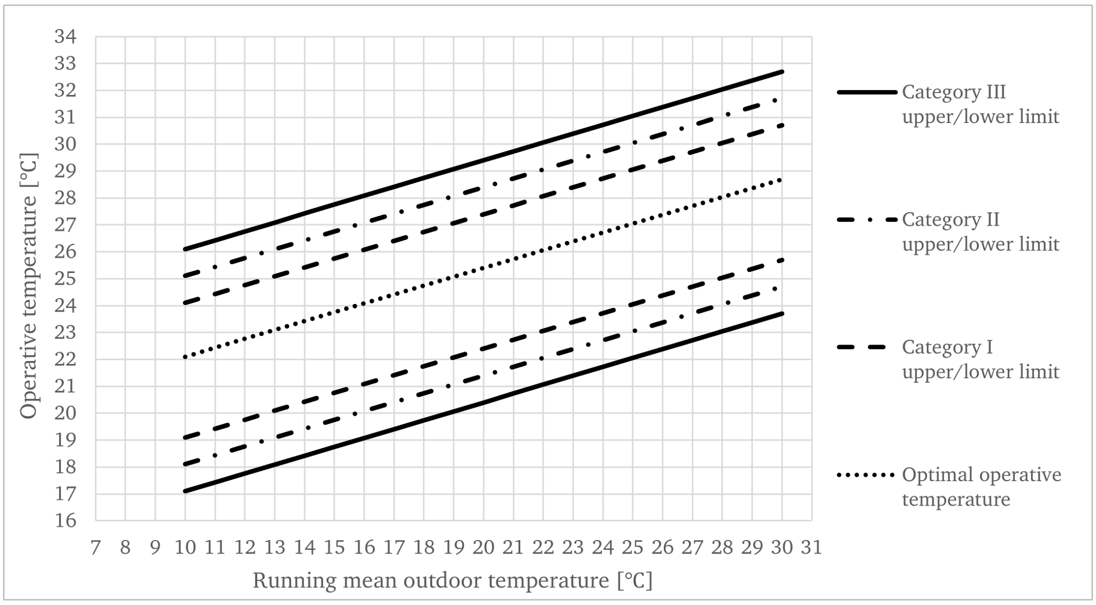

Figure 2.1: The adaptive comfort model from NS-EN 16798-1 (Norsk Standard, 2019). The middle line shows the preferred temperature, and the others are the upper and lower limits depending on the comfort category.

2.2 Box plot

A box plot, also termed as a box and whisker plot, is a diagram that is used in statistics to display multiple parameters and is often used to compare the contrast of two or more groups (Khan Academy, n.d.). It has the ability to show the interquartile range, median, mean etc. Figure 2.2 shows a series of values (left) and its box plot (right). The interquartile range is where 50% of the values reside. This means that the lowest 25% of the values are below the box and the remaining top 25% values are above. The values that are far away from the majority of the other values are represented with outliers.

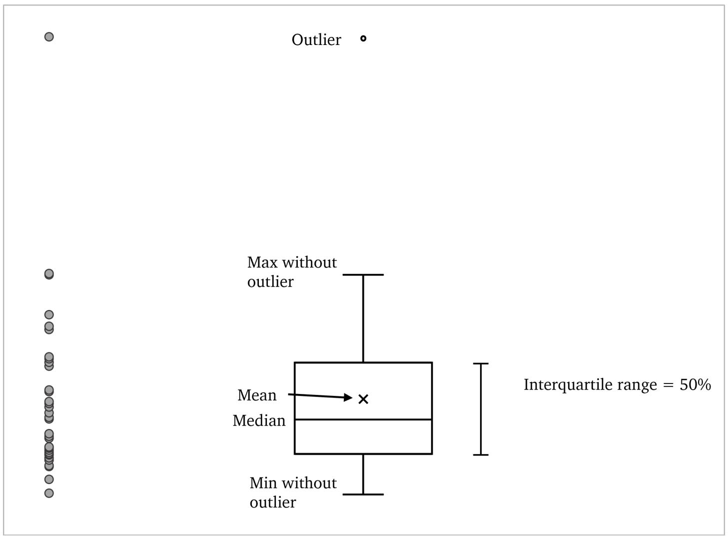

Figure 2.2: A set of values (left) and its box plot (right).

2.3 Linear regression

Linear regression is the most common type of regression analysis (Braut & Dahlum, 2021). It is the act of describing the relationship between dependent and independent variables by using a straight line. The way it is done is by finding the line which best fits the values. This line is called the regression line. To identify how well the regression line represents the actual values, a coefficient called R^2 can be calculated. This coefficient ranges from 0 to 1, where the closer to 1 the coefficient is, the more accurately the line predicts. Figure 2.3 shows two different scatter plots' regression lines, and the R^2 is calculated for both. The figure illustrates how the first regression line better represents the values and thus has a higher R^2 than the second line.

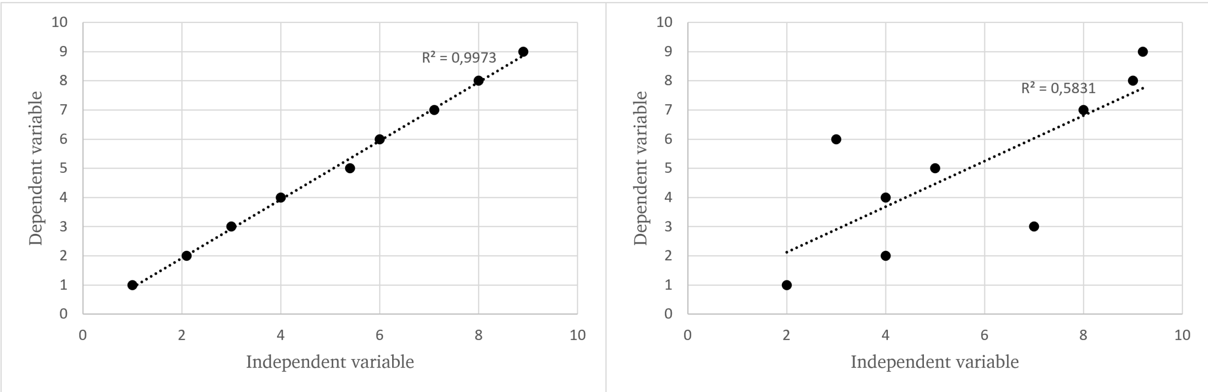

Figure 2.3: Linear regression of two different scatter plots, illustrating how the coefficient of R^2 works.

2.4 IDA ICE

IDA ICE is a BPS software and works by creating a model of a building, implementing the systems and controls, and then looking at the energy consumption and thermal indoor climate (EQUA, n.d.). An advantage of utilizing BPS is that it can be more cost-efficient than field studies that often require in situ measurements. Additionally, it can be done for a theoretical building which is not yet built.

2.5 Energy consumption vs. peak load

Energy consumption is often measured in kWh/a or kWh/m^{2}a. It describes how much energy is used annually. Heating demand is the part of this that is used for space heating, often including the heat used in the AHU. To reduce heating demand, one only needs to use less energy, e.g., by improving the building envelope, which reduces heat loss to the surroundings. Other ways could be, as this thesis is based around, reducing unnecessary energy usage, for instance by occupancy detection. When no occupants are present, there is a lot of wasted energy. Heating load on the other hand is the highest amount of energy used during a set period. As the world is shifting towards more volatile and less predictable (but more environmentally friendly) energy sources, it is important as a society not to use a lot of energy at the same time, as this puts pressure on the electrical grid (Johnsen et al., 2019). This is why energy flexibility is important and also why the electricity prices are higher during peak hours. The main objective of reducing peak load is not necessarily to reduce the amount of energy used, but rather to spread out the energy usage in a way that puts less pressure on the grid. This is rewarded by the lower electricity prices during off-peak hours. Today, only the price of electricity is dependent on the time of the day. Further down the line, a dynamic tariff is likely to be implemented

(Eriksen et al., 2020), making it even more beneficial for residents to load shift to a cheaper time of the day.

2.6 Previous work

There are many studies investigating how improved control/automation of the heating system will reduce the building's heating demand (e.g., Ben and Steemers, 2014; Cosar-Jorda et al., 2018; Kaminska, 2019; Moon and Han, 2011; van Moeseke et al., 2007). The first two research questions are designed to address this topic. Two noteworthy contributors to a high heating demand in residential buildings are overcooling by window opening and unnecessary high set-point temperatures for the heating system. For instance, Cosar-Jorda et al. (2018) showed a possible reduction in heating demand of 32% by controlling the window opening. Whilst Moon and Han (2011) showed a prominent reduction in heating demand from lowering set-point temperatures, both by the use of occupancy detection and night setback. Felius (2021), which this thesis somewhat builds upon, investigated how different renovation packages and building automation control system[1] efficiency classes affect the energy consumption of residential buildings. Although she concludes that renovation gives the largest energy savings, she also mentions that a building automation control system is a good alternative or addition. Especially upgrading of the heating system, which lead to a decrease of 22-28% of the heating demand (going from class D to C–A), for a detached single-family house with direct electrical heating and a typical 1969s envelope. These results are also a good way to validate the results from this thesis, as the same Building Energy Model (BEM) was used, only with a few alterations.

There are multiple studies that investigate how to achieve demand-side energy flexibility, though there is a lack of studies looking at direct electrical heating (especially for envelopes with a light thermal mass). After a brief literature review, there appears to be (to the author's knowledge) no studies that look at the OFF/ON-cycles of electrical heaters to provide demand-side flexibility similar to this thesis. The studies that do in fact investigate energy flexibility for direct electrical heating appears to rather be parametric studies, that look at what type of building, control etc. that gives the largest potential, such as Johnsen et al. (2019).

[1]Building automation control system is the system consisting of all the products, software etc. that provides an economical, energy-efficient, and safe operation of building services.

Chapter 3

Methodology

As the objectives of this study were to (1) investigate how improved control and automation of heaters can reduce heating demand and (2) look at the expected temperature drop/increase whenever electrical heaters are turned off/on, a type of measurement was required. Two common methods for acquiring such data are either in situ measurements or BPS. The resources for a master student are somewhat limited. Hence, why the BPS software IDA ICE was chosen to collect the needed data. Additionally, Python 3 and Excel were used to process the data and make it presentable. The BAC efficiency classes from NS-EN 15232:2017 were used to select the functions for control/automation of the heaters (Norsk Standard, 2017). Chapters 3.1–3.3 describes the methods that were used for answering the first two research questions, whilst Chapter 3.4 describes the methods used to answer the last two questions.

3.1 Benchmark model/class D

This chapter explains how the benchmark model was made. The heating system for this model was based on the efficiency class D, introduced in Chapter 2.1.4.

3.1.1 General information

For this study, one building with four increasingly better envelopes was used. Felius (2021) did a thorough literature review, investigating the Norwegian building stock. She concluded that the two most typical residential building types in the 1960s to the 1990s were detached single-family houses and apartment blocks, and made a model for each type based on the findings. The model of the detached single-family house was used in this study. The inputs were for the most part kept the same, however, some alterations had to be done so that the model better fits the objectives of this thesis. Additionally, some simplifications were done to reduce the complexity of the model and reduce computation time. The first envelope was for a 1969s house, which is fitting, as the model is of a typical house from the 1960s to 1990s. The other three envelopes were based on TEK97, TEK17, and the PH standard NS 3700:2013. The building was located in Trondheim, Værnes. There are no nearby objects that cause shading, however, the building was in a sloped terrain and is therefore partly submerged in the ground. The wind was defined as semi-exposed in IDA ICE, assuming it still does have some surrounding landscape and is not entirely in the open.

3.1.2 The building

The building had a total area of 173 m^2. Figure 3.1 shows the building, taken from IDA ICE. The black area on the walls represents the part that is submerged in the ground, which is from now on referred to as the basement walls. The floor plans, by courtesy of Felius (2021), are shown in Figure 3.2. All doors were closed, except for the one between the kitchen and the living room, which was modelled as a large opening. Furthermore, Table 3.1 shows the area, heating power, and internal gains for all the zones. The heating power differs for each of the four model variations and was found by performing heating load simulations (with closed internal doors). It works by simulating a cold wave for a short period of time and looking at the required power for the heating system. The simulation period was during a week in January, with a constant -19 °C, no internal gains, and unlimited power for the heating units. The internal gains from the equipment and lighting are the standardized values from the standard NS 3031:2014 (Norsk Standard, 2014). This means that in total, they give a heat gain of 10.5 and 17.5 kWh/m^{2}a, for all heated zones (i.e., not the attic). The schedules for equipment were defined as "always on", while the schedules for lighting and occupancy are shown in Appendix B. The domestic hot water was disregarded in all cases. Although it might affect the heating to some degree, it was deemed insignificant for this thesis.

Table 3.1: Area, heating power, and internal gains for each zone. The heating was found from heating load simulations and the internal gains are from NS 3031:2014 (Norsk Standard, 2014).

Zone	**Area [m^2]**	**Heating [W]**				**Internal gains [W/m^2]**	
		1969	TEK97	TEK17	PH	Equipment	Lighting
Attic	95.7	-	-	-	-	-	-
Bath	1.9	100	100	100	100	2.212	2.733
Bathroom	3.5	200	200	100	100	2.212	2.733
Bedroom	9.1	900	700	500	500	2.212	2.733
Bedroom-1	11.2	700	500	400	400	2.212	2.733
Bedroom-2	9.1	800	600	500	500	2.212	2.733
Bedroom-3	11.2	700	500	400	400	2.212	2.733
Hall	5.3	100	100	100	100	-	2.733
Hall-1	2.0	100	100	100	100	-	2.733
Hall-2	2.3	200	200	100	100	-	2.733
Hall-3	3.6	100	100	100	100	-	2.733
Kitchen	8.5	500	300	200	200	2.212	2.733
Laundry	6.4	400	300	100	100	2.212	2.733
Living room	35.1	1200	1000	600	600	2.212	2.733
Living room-1	21.0	1200	1000	600	600	2.212	2.733
Living room-2	26.4	2300	1500	1000	1000	2.212	2.733
Stairs	2.5	-	-	-	-	2.212	2.733
Storage-1	11.7	600	500	200	200	-	-
Storage-2	1.1	-	-	-	-	-	-
WC	1.6	200	100	100	100	2.212	2.733

3.1.3 The building envelope

All envelopes had the same structure, but a varying thickness of the insulation. Table 3.2 shows the U-values, infiltration and NTBV of the four envelopes. The external doors had the same U-value as the walls, as a simplification. The values for the 1969s house were the same as in Felius (2021) and are as follows: the U-values for the walls, floor, and roof are typical values for the Norwegian building stock during this period (Thyholt et al., 2009, as cited in Felius, 2021). The NTBV, infiltration, and the U-value for the windows are recommended input values when performing BPS, taken

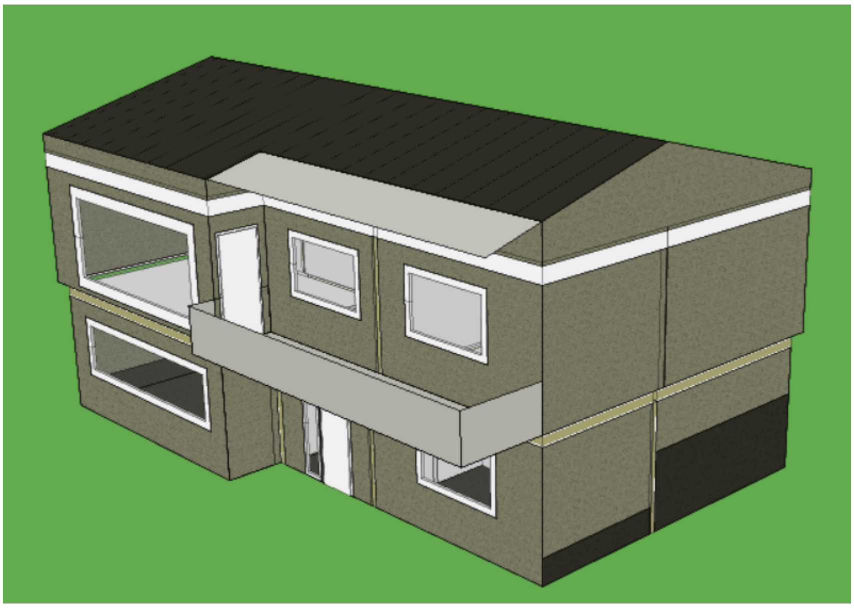

Figure 3.1: A 3d-model of the building.

Figure 3.2: The floor plans of both floors, courtesy of Felius (2021).

from NS 3031:2014 (Norsk Standard, 2014). Lastly, the U-value for the wall below the ground is a requirement stated in the building regulations of 1969 (DiBK, 1969). The U-values for the TEK97 building were all from TEK97 (DiBK, 1997). The infiltration was taken from the guidance, published two years later (DiBK, 1999). Lastly, the NTBV was from a guidance for energy classifications of houses produced by NVE (Norconsult, 2013). The values for both the TEK17 building and PH are from their respective requirements/criteria (DiBK, 2017) and (Norsk Standard, 2013). The U-values for the wall, floor and roof for the PH are however only recommendations. The window structure for all envelopes were modified versions of the already defined windows in IDA ICE.

Table 3.2: Requirements, criteria, recommendations, and assumed values for the different envelopes. Parenthesis represents a different value for the walls below ground.

Envelope characteristics	1969	TEK97	TEK17	PH
U-value wall [W/m^{2}K]	0.38 (0.80)	0.22	0.18	0.10
U-value floor [W/m^{2}K]	0.36	0.15	0.10	0.08
U-value roof [W/m^{2}K]	0.20	0.15	0.13	0.08
U-value window [W/m^{2}K]	2.80	1.60	0.80	0.80
Infiltration Pa [h^{-1}]	4.0	4.0	0.6	0.6
NTBV [W/m^{2}K]	0.07	0.05	0.05	0.03
Window type	2 panes w/air	3 panes w/air	3 panes w/Ar	3 panes w/Ar

3.1.4 Heating and cooling

The heating was modelled by making a custom macro replica of the PI-controller already in IDA ICE. This was done to log the heaters' output for every zone. Figure 3.3 shows this macro.

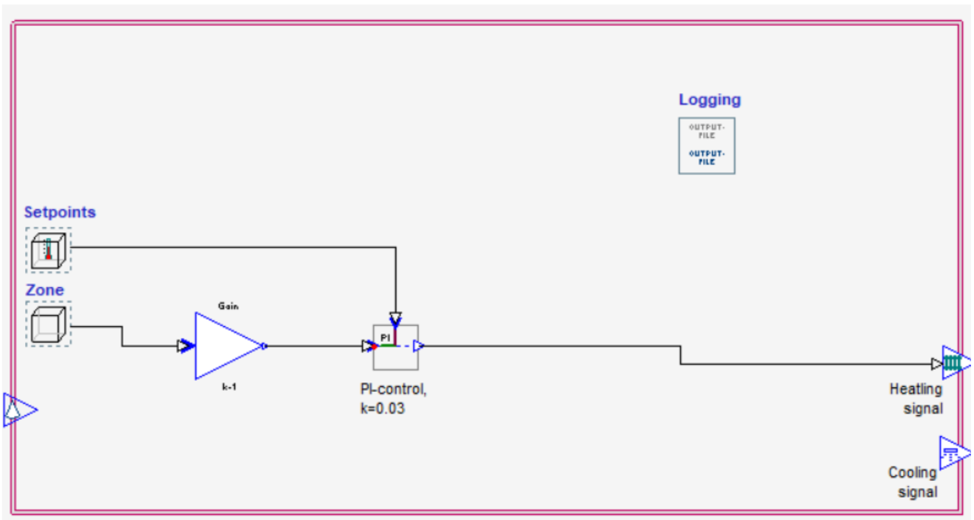

Figure 3.3: Custom macro for the heater. A replica of the built-in PI-controller.

For cooling, both window opening and blinds were used. For the window opening, the custom macro from Felius (2021) was used (see Figure 3.4), with some minor adjustments. This macro was supposed to emulate a realistic window opening behaviour in a residential building. The window opening was either triggered by a temperature threshold or a CO_2 limit of 1000 ppm. This only applied whenever the zone was occupied, and after the window was opened, a delay of 30 minutes was added, because it was assumed that occupants do not close the window at once. There was a

1 °C deadband for the temperature and a 100 ppm deadband for the CO_2. The temperature threshold was based on the adaptive comfort model's upper limit (mentioned in Chapter 2.1.3). Figure 3.5 shows the temperature set-point as a graph. The set-point was 2 °C above the optimal temperature. Originally, there was supposed to be a deadband of 2 °C, as this would make the window open at the upper limit of category II. This was changed last minute due to an unrealistic high heat loss. Thus, the window opens 0.5 °C below the upper limit of category II (because of the 1 °C deadband). As the adaptive thermal comfort model only applies whenever the outdoor temperature is above 10 °C, the set-point for window opening was constant when the temperature was below.

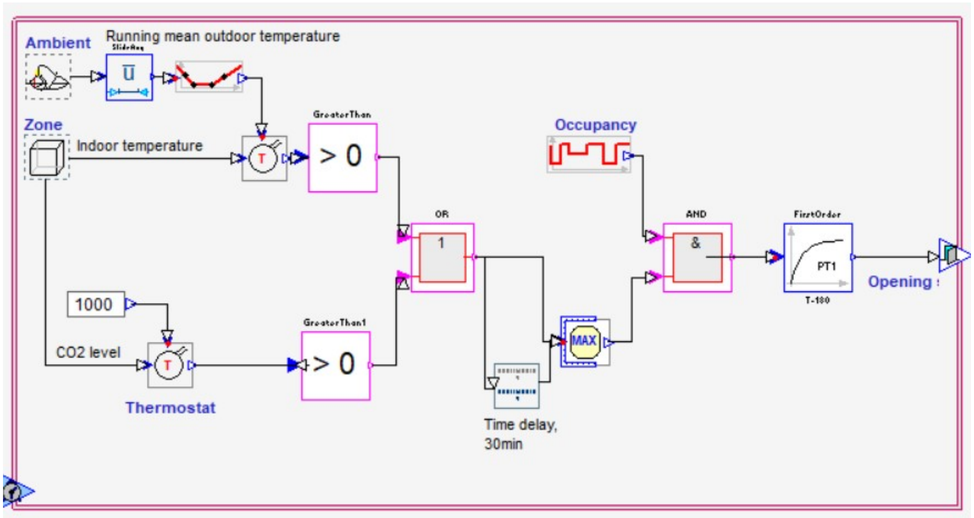

Figure 3.4: The macro for window opening, that emulates a realistic occupant behaviour (Felius, 2021).

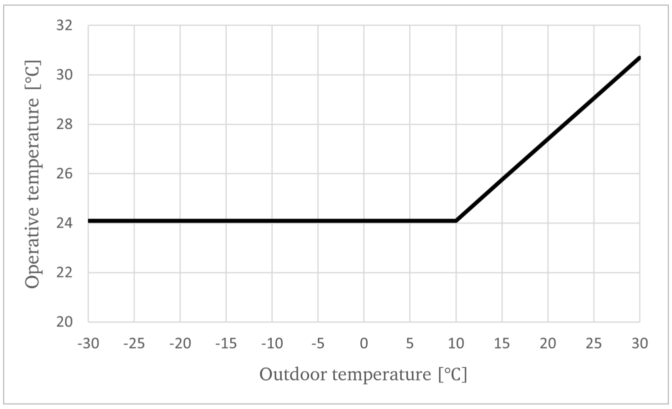

Figure 3.5: Set-point temperature for window opening, based on the adaptive thermal comfort model's upper limit (Norsk Standard, 2019).

The windows had varying degrees of shading. The three largest windows, which stand for approximately half of the total window area, had external blinds and therefore the most shading (when the blinds were down). The four smallest windows did not have any shading at all, and the remaining ones had internal blinds. The blind control was similarly to the window control, a custom-made macro from Felius (2021) that was supposed to emulate a realistic occupancy behaviour. It was however simpler than the window macro, using a constant set-point temperature of 23.5 °C. The shading only gets opened/closed when there were occupants present, and there was an added 30-minute delay. The control is shown in Figure 3.6.

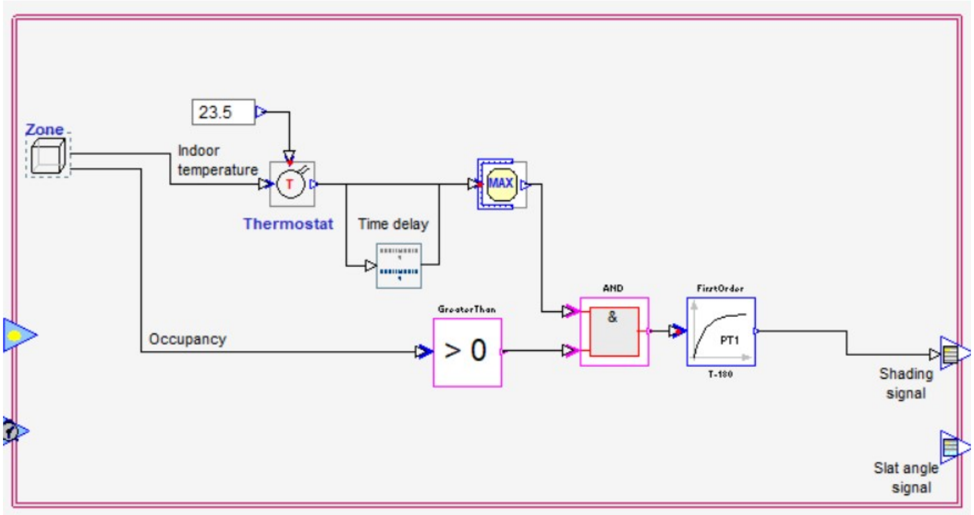

Figure 3.6: The macro for blind control, that emulates a realistic occupant behaviour (Felius, 2021).

3.1.5 Ventilation

The building was mechanically ventilated (balanced ventilation). The ventilation system was based on the principle of CAV. All bedrooms and living rooms had a supply of fresh air, whilst the wet rooms, kitchen, and the toilets had exhaust vents. All models were equipped with a TEK17-based ventilation system, with the exception of a deviation from § 13-2-3, which states that rooms not intended for continuous use shall have a supply of fresh air at the rate of 0.7 m^3/h per m^2; the halls and storages did not have any ventilation. The ventilation rates for all zones are summarized in Table 3.3. The supply of air for the living rooms equals to 1.2 m^3/h per m^2. Bedrooms 1 and 3 had a higher rate than required (26 m^3/h) due to the total supply and return air needing to be the same amount. The air was supplied at a constant 18 ℃, and the cooling coil was turned off. Lastly, the heat exchanger had an efficiency of 80%, and the SFP of the fans in the AHU were 1.5.

Table 3.3: Ventilation rates for the supply and return air for all ventilated zones.

Zone	Supply [m^3/h]	Return [m^3/h]
Bath	-	54
Bathroom	-	54
Bedroom	26	-
Bedroom-1	34	-
Bedroom-2	26	-
Bedroom-3	32	-
Kitchen	-	36
Laundry	-	36
Living room	41.7	-
Living room-1	25	-
Living room-2	31.3	-
WC	-	36
Total	216	216

3.2 Upgrading automation/control

The heating system of the building presented in the previous chapter is, as stated, based on efficiency class D. The following three chapters (Chapter 3.2.1–3.2.3) show how the three selected functions from NS-EN 15232-1 were implemented for each of the four classes (D–A). This is also the answer to research question 1, as it is suggestions on how improved control/automation could be implemented for heaters without additional hardware. The three functions are emission control, intermittent control of emission, and interlock between heating and cooling control of emission. Emission in this context refers to the release/removal of heat from the heating/cooling system. New classes contain all previous changes, meaning, for instance, the night setback implemented for class C, remains for classes B and A as well.

3.2.1 Heating control

The first function was emission control (i.e., control of heating at room level). For class D, a constant set-point temperature of 22 °C was set for all heated zones. This is a standardized value from NS 3031:2014 (Norsk Standard, 2014). For the other three efficiency classes, set-point temperatures depending on the room function were used, see Table 3.4. These are based on a survey of preferred room temperatures in Norwegian households (Halvorsen & Dalen, 2013). The function for class B was not implemented for emission control. For class A, occupancy detection was used. Since one of the prerequisites stated in Chapter 1 is that there will not be any need for additional hardware, two methods of occupancy detection were suggested; if none of the usual residents has been connected to the Wi-Fi for 30 minutes, the occupants will receive a push notification which asks if they want to lower the set-point temperature for a certain amount of time. The other suggestion works the same way, but is proximity-based, meaning if none of the occupants is within a certain radius, measured with their phone's GPS, the set-point gets lowered.

Table 3.4: The function "emission control" from NS-EN 15232-1.

Efficiency class	Description of function for given class, from NS-EN 15232-1	Implemented solution(s)
D	No automatic control or only central automatic control	Constant 22 °C in all rooms.
C	Individual room control	Different depending on room function. • 19 °C in the bedrooms • 23 °C in the bathrooms • 21.5 °C in the remaining zones
B	Individual room control with communication (not implemented)	Same as class C
A	Individual room control with communication and occupancy detection	Same as class C, plus: Occupancy detection, which lowers the set-point temperature to 18 °C when the house is empty.

3.2.2 Intermittent control of heating

The second function from NS-EN 15232-1 is an intermittent control of the emission (heating). This means that for class D, there are none, and the set-point temperatures never change. For the other three, a nigh setback was implemented. Table 3.5 summarizes the efficiency classes.

Table 3.5: The function "intermittent control of Emission" from NS-EN 15232-1.

Efficiency class	Description of function for given class, from NS-EN 15232-1	Implemented solution(s)
D	No automatic control	None
C	Automatic control with fixed time program	An 18 °C night setback. The heating goes back to normal 1 hour before the occupants wake up.
B	Automatic control with optimum start/stop (not implemented)	Same as class C
A	Automatic control with demand evaluation (not implemented)	Same as class C

3.2.3 Interlock between heating and cooling control

The last function was an interlock between the heating and cooling control of emission, i.e., the heaters and windows for this thesis. As it is unrealistic to achieve a total interlock without installing detectors, only a partial interlock was implemented (Table 3.6).

Table 3.6: The function "interlock between heating and cooling control of emission" from NS-EN 15232-1.

Efficiency class	Description of function for given class, from NS-EN 15232-1	Implemented solution(s)
D	No interlock	None
C	No interlock	None
B	Partial interlock (Dependent on the HVAC system)	When a heater registers a sudden temperature drop due to an open window, it turns off.
A	Total interlock (not implemented)	Same as class B

3.3 Modelling of the efficiency classes

This chapter shows how functions for the efficiency classes were modelled in IDA ICE. Class D was as stated the benchmark model, hence why this section only contains classes C, B, and A.

3.3.1 Class C

For efficiency class C, the three types of zones had the set-point temperatures mentioned in Chapter 3.2.1. Additionally, the night setback was scheduled as shown in Figure 3.7, which shows the schedules for the three different zone types. Although occupants are present during the night in the bedrooms, it is assumed 1 °C lower is acceptable (and maybe even preferable).

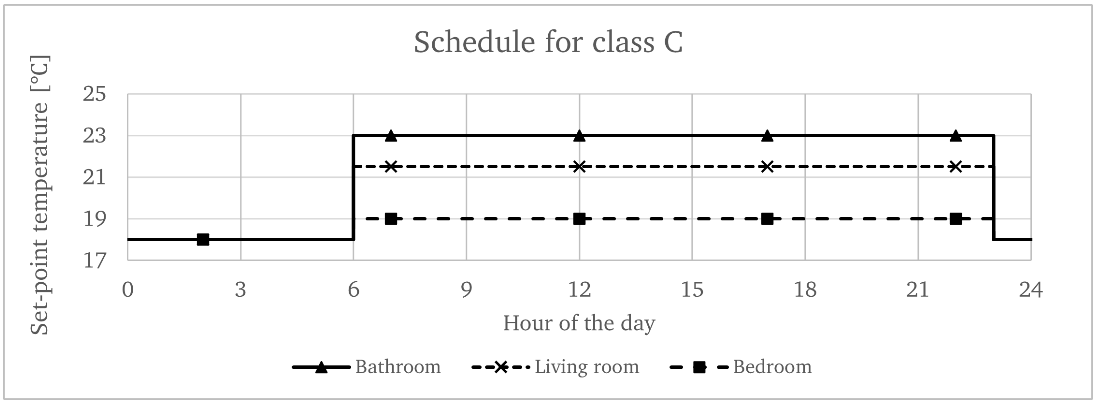

Figure 3.7: Schedule for the set-point temperature, showing the night setback for efficiency class C.

3.3.2 Class B

The set-point temperatures and night setback were modelled identically to class C. The macro for the heating units was however replaced with a macro that turns off the heater whenever the window was opened (Figure 3.8). The way the macro works is by replicating the macro for window opening but inverting the signal and multiplying it with the heater's signal. The heater partly overlaps with the window opening, due to an unknown error. Still, it acts as a partial interlock, which is fitting.

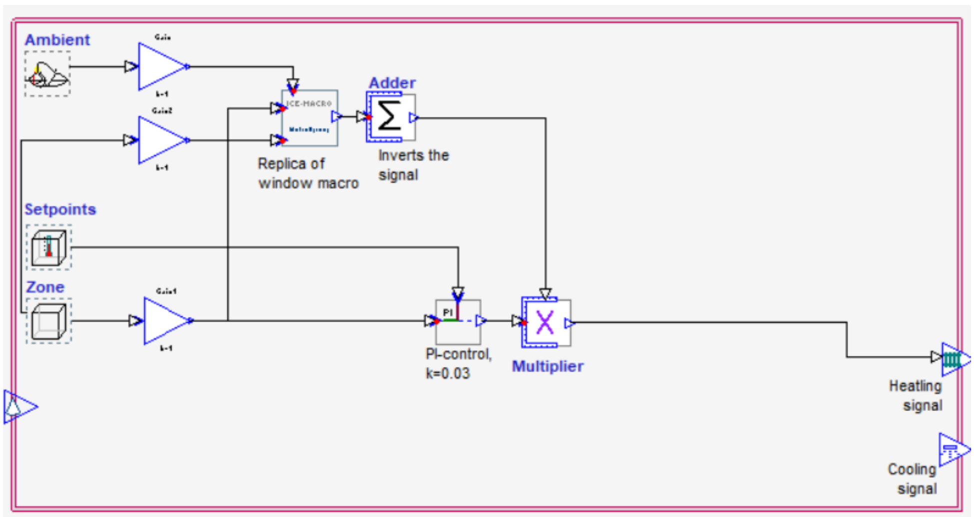

Figure 3.8: The new custom macro for the heaters, with an added window/heater interlock.

3.3.3 Class A

The set-point temperatures and night setback were modelled similar to class C and B, however, an alteration was done to the scheduled set-point temperature, to replicate the occupancy detection. This way, the house is assumed empty every weekday between 9 and 16, except for holidays. Figure 3.9 shows the new schedule.

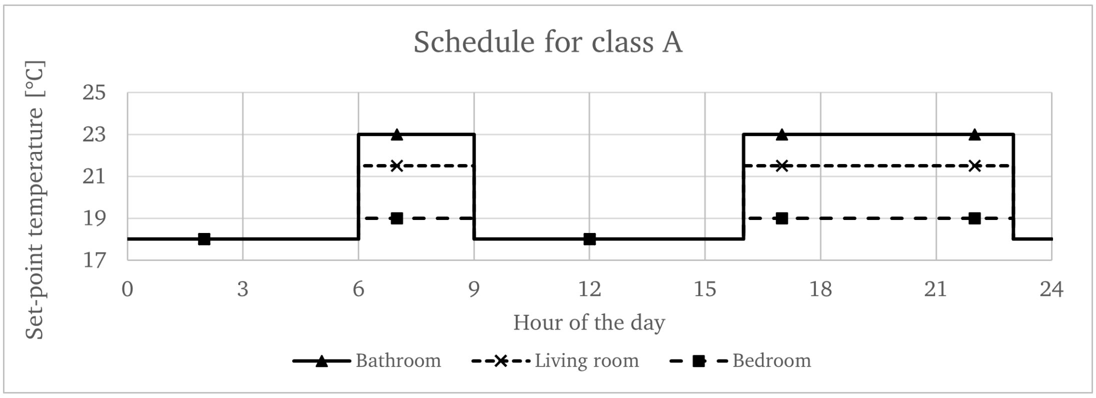

Figure 3.9: Schedule for set-point temperature, modified for efficiency class A. This change does only apply to weekdays (excluding holidays).

3.4 Investigating the possibility of energy flexibility

This chapter is, as mentioned, dedicated to the last two research questions. Eight new simulations were carried out, divided into two sets of four simulations. A time step of 15 minutes was chosen as common ground between computing time and accuracy. The benchmark model presented in Chapter 3.1 was again used, only with a few changes. This chapter contains what inputs were changed from the original model, as well as how the logged data were used.

3.4.1 Input changes

Firstly, all windows were modelled as “always” closed, as window opening would interrupt the logging of the operative temperature. Another change was the modification to the heaters and their placements. For the previous cases, the heaters were placed without any thought as to what would be practical in real-life situations, as only the change in heating demand was of interest. In total, 17 of the 20 zones had heating units. This seemed somewhat unrealistic and would give 17 sets of results. Thus, the number of heaters was reduced and only placed in the zones deemed the most important, i.e., all zones intended for continuous use and all bathrooms with external walls. This leaves the laundry, storages, halls, and the bathrooms with only internal walls. Additionally, the kitchen is connected to the zone “Living room” hence why it does not have its own heater. Figure 3.10 shows which of the zones had heating. Additionally, a new custom macro for the heaters was used (explanation in Chapter 3.4.2). The first set of simulations was one simulation for each of the four envelopes, with the aforementioned changes. Then, a new set of four identical simulations were carried out, only changing the internal doors; all but two of the internal doors were changed to “always open”. Figure 3.10 also shows the two doors (in red) that were kept as “always closed”.

The heating system needed to be sized again, since there now were fewer heaters in the building. The process was the same as described in Chapter 3.1.2. The new heaters’ power is shown in Table 3.7.

Figure 3.10: The floor plans of both floors, now showing which zones had heating units. The red doors are the only two doors kept closed during the second set of simulations.

Table 3.7: The heating power for the new heaters. The required power was found from heating load simulations.

Zone	**Heating [W]**			
	1969	TEK97	TEK17	PH
Bathroom	300	200	100	100
Bedroom	900	700	500	500
Bedroom-1	800	600	500	400
Bedroom-2	800	700	500	500
Bedroom-3	700	600	500	400
Living room	1300	1000	600	600
Living room-1	1500	1400	700	700
Living room-2	3000	2000	1300	1200
WC	200	100	100	100

3.4.2 New heating strategy

The new heating strategy uses a custom macro for the heating units instead of the standard PI-control. The macro was received from a PhD-student at NTNU. It works by using adaptive thermal limits (similar to the ones mentioned in Chapter 2.1.3) to determine when it should turn on and off. This is illustrated in Figure 3.11, showing one OFF-cycle and one ON-cycle. It also shows the regression line and its slope for each cycle, which illustrates how many degrees Celsius are dropping/increasing per hour. Additionally, Figure 3.12 shows how the upper and lower limits change during the year, with the operative temperature in between the limits. The limits follow the outdoor temperature, hence the name adaptive thermal limits.

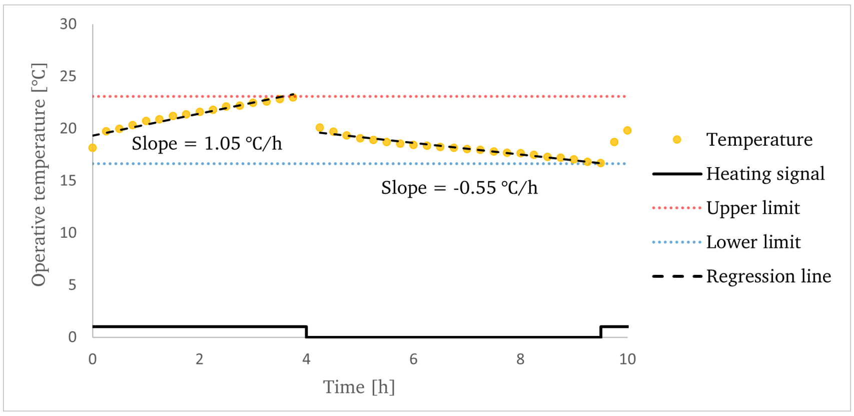

Figure 3.11: Example of two cycles, one ON-cycle and one OFF-cycle.

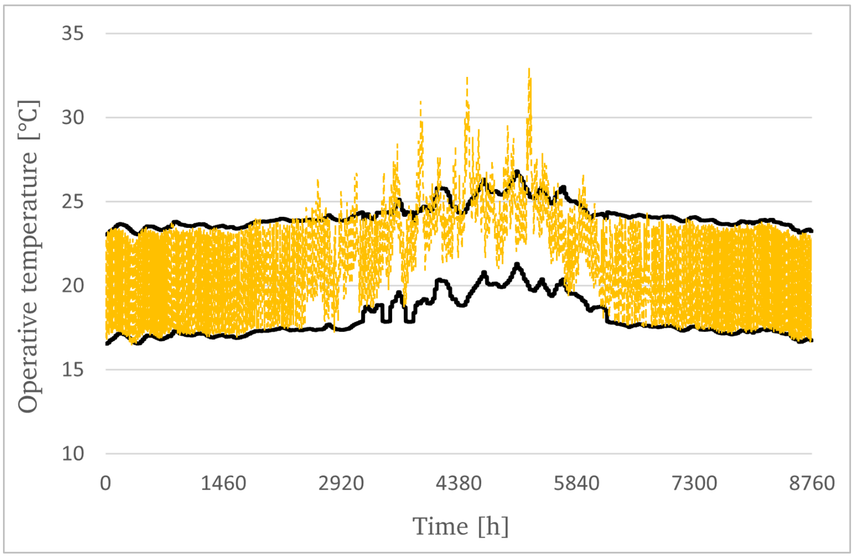

Figure 3.12: Operative temperature of a whole-year simulations, with the adaptive thermal limits that decided when the heater was turned on/off.

The custom macro is shown in Figure 3.13. It is based on a comfort temperature curve produced in a study by Peeters et al. (2009). In total, three curves were made, one for bedrooms, one for bathrooms, and one for the "remaining zones" (e.g., living room). The macro reproduces the curve for the remaining zones. This is the most fitting curve, as it is in the middle in regard to temperature, and four of the eight cases in this thesis are with open internal doors, so it acts as a sort of "middle ground" for the preferred cool bedrooms, and warm bathrooms. The macro works by having two functions, both using the outdoor temperature as an input. The outdoor temperature, more specifically, the daily running mean temperature, is an approximate calculation based on Equation 3.1 taken from NS-EN 16798-1 (Norsk Standard, 2019) (taking the temperatures of the previous 7 days as input). The first function is used whenever the daily running mean temperature is below 12.5 °C and the other is used when the temperature is above. The upper and lower limits are made by the use of the deadband of the thermostat. Function number 1 uses a deadband of 5.5 °C and the second one uses a deadband of 6.5 °C.

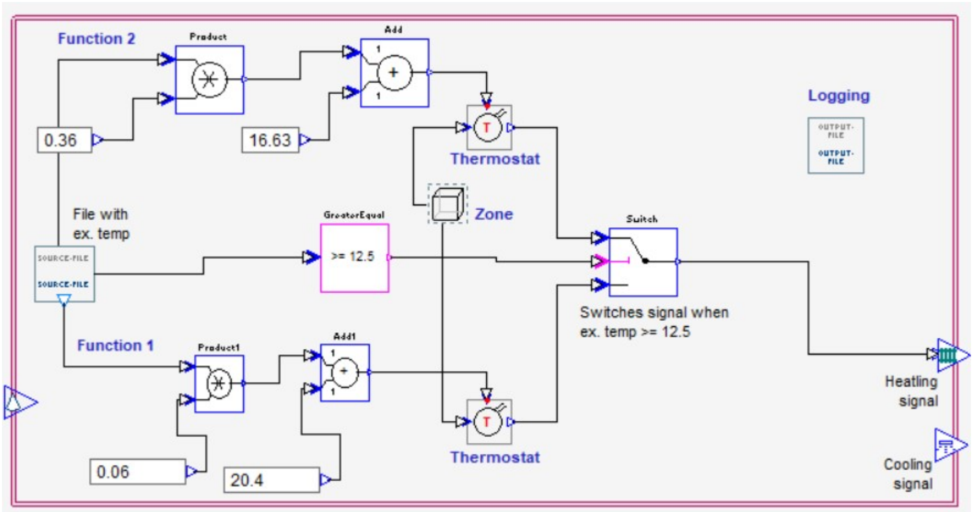

Figure 3.13: A custom macro for the heater received from a PhD-student at NTNU. It is based on a comfort temperature curve and uses adaptive thermal limits to determine when to turn off/on.

$$\Theta_m = (\Theta_{ed-1} + 0.8\,\Theta_{ed-2} + 0.6\,\Theta_{ed-3} + 0.5\,\Theta_{ed-4} + 0.4\,\Theta_{ed-5} + 0.3\,\Theta_{ed-6} + 0.2\,\Theta_{ed-7})/3.8 \quad (3.1)$$

3.4.3 Processing the data

The data from the new simulations were logged and exported to Excel. Using the Python script in Appendix A, all relevant information was extracted, such as cycle duration and the temperatures at the start and end of all cycles. Furthermore, the script performed linear regression for all cycles, with the intent to identify the slopes of all regression lines and their respective R^2. All these data were then exported to one common Excel file, which was then used manually to make the result presentable.

Chapter 4

Results

The result chapter is split into two parts, one for each of the main objectives. The chapter for objective 2 is further divided into three parts, showing cycle durations, slopes of the regression lines, and lastly R^2.

4.1 Upgrading the automation/control

All four building types had a noticeable reduction in heating demand from upgrading the automation/control. The older the house, the larger the savings. Figure 4.1 shows the reduction for all automation levels and building envelopes. There was a significant improvement from efficiency class D to C and class B to A. However, the improvement from class C to B was minimal compared to the others. Looking at the total reduction, starting with class D through A, shows that the biggest difference was for the 1969s house, and it gave a reduction of 27.76 kWh/m^{2}a (25%). The smallest difference was for the PH, with a reduction of 7.31 kWh/m^{2}a (20%).

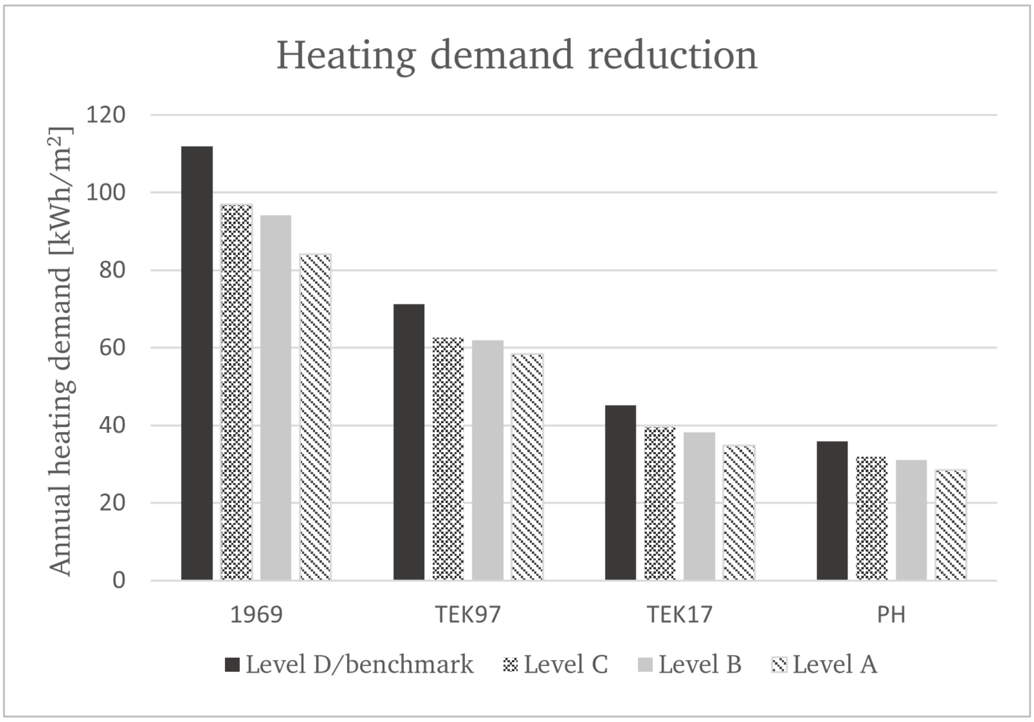

Figure 4.1: The annual heating demand for all automation levels and building envelopes.

4.2 Investigating the OFF/ON-cycles

Although the variables for all zones with a heater were logged and all the data were processed, only the results for one zone are presented. The selected zone is “Living room”. It is connected with the kitchen (sharing one heater) as stated earlier, technically making it the largest zone. It was assumed that the largest zone should be representative enough. The results from all eight cases are presented. The number of cycles for these is shown in Figure 4.2. The older the house, the more cycles. Additionally, cases with closed doors had more cycles as opposed to cases with open doors.

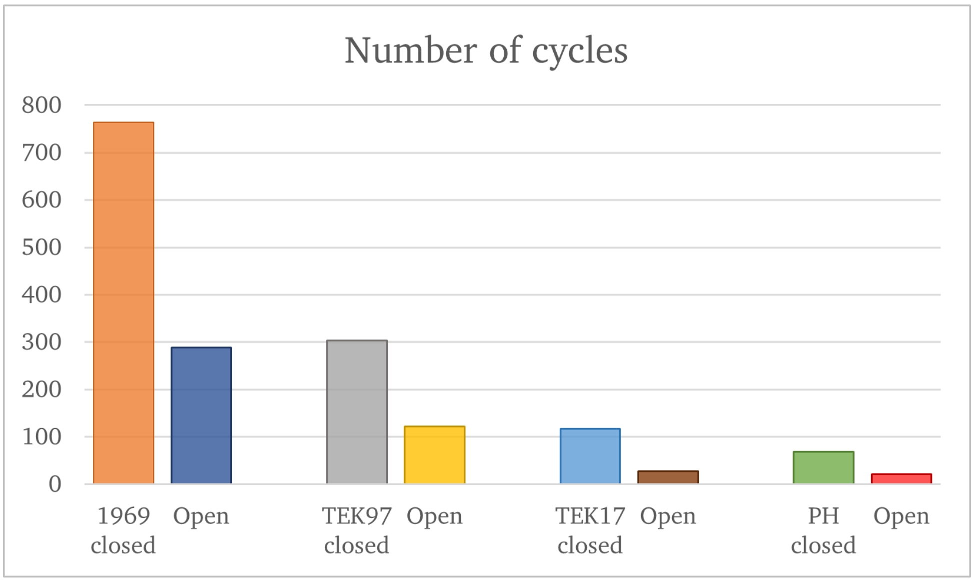

Figure 4.2: Number of cycles for each of the eight cases. Open/closed refers to the internal doors.

4.2.1 Cycle duration

Figure 4.3 shows the durations of all OFF-cycles (left). All cases had one OFF-cycle that was substantially long, due to the heater being turned off during the warmer months. Thus, this cycle is removed for all cases. The right box plot shows the durations after removing said cycle. The cases with open doors and a TEK17/PH envelope show a more significant spread than the others. Additionally, based on Figure 4.3, a duration cap of 400 hours is implemented for some of the subsequent figures.

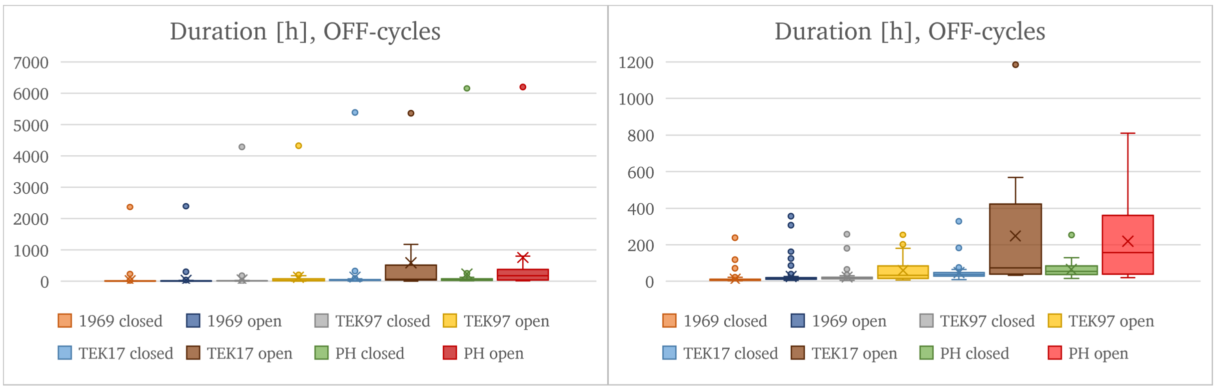

Figure 4.3: Duration of the OFF-cycles, with and without the cycle during summer (left and right, respectively).

Figure 4.4 (left) shows the duration of the ON-cycles, and it shows that the better-insulated buildings had longer ON-cycles. Similarly to the OFF-cycles, the ON-cycles for the TEK17-building and the PH with open doors had a larger spread. The figure also displays the power of the heating unit in the zone for the four building envelopes. To compare, a new set of simulations were performed (right); now all heaters had the same power output (the 1969s). This shows the opposite pattern, i.e., better envelopes give shorter ON-cycles. On the other, both sets of simulations show that when the doors were open, the ON-cycles were longer than when the doors were closed.

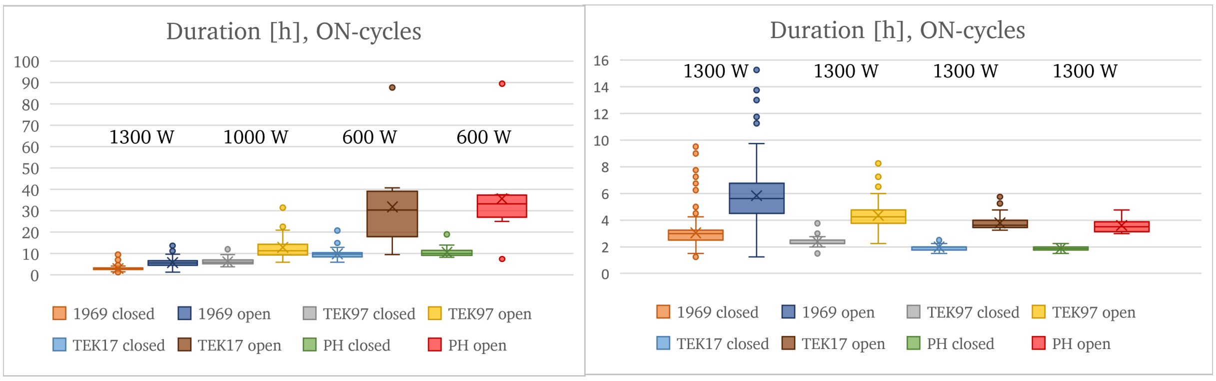

Figure 4.4: Duration of the ON-cycles. The left figure shows the duration with the original heating power, and the right figure shows the duration with equal heating power.

Figure 4.5 displays how the outdoor temperature affects cycle durations. The duration of the OFF-cycles (left) increases with the outdoor temperature, while the opposite applies to the ON-cycles (right). The patterns mentioned in the previous two paragraphs are also present in this figure; the duration of the OFF-cycles was longer than for the ON-cycles, and the duration of the cycles was longer when the doors were open. To compare, the building with the worst and best envelope characteristics are presented in Figure 4.6, showing again that the cycles for the PH are longer. The duration in the figure is capped at 400 hours.

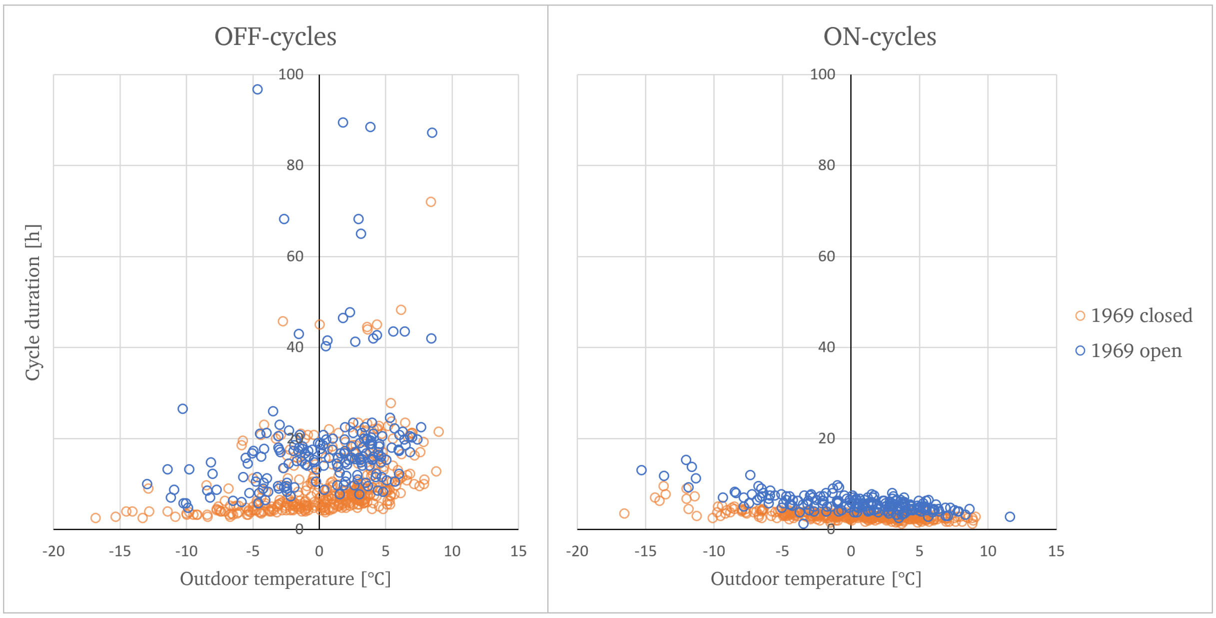

Figure 4.5: Cycle duration as a function of outdoor temperature for the 1969 envelope.

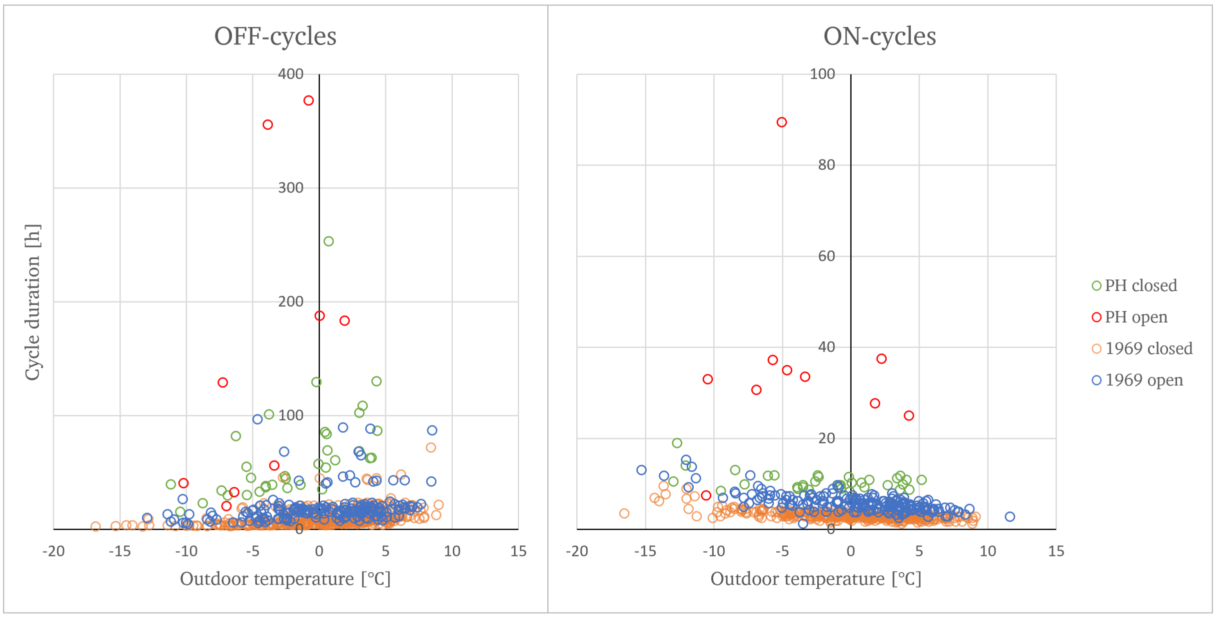

Figure 4.6: Cycle duration as a function of outdoor temperature for the 1969 envelope, with PH as a comparison. The cycle duration is capped at 400 hours.

Lastly, to summarize the results, Figure 4.7 shows the mean duration for all eight cases (excluding cycles over 400 hours).

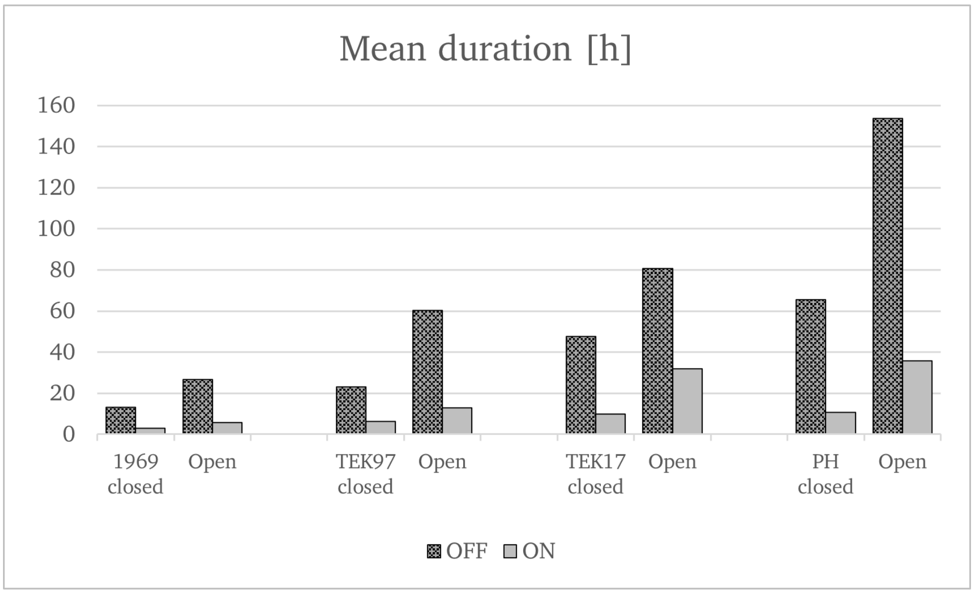

Figure 4.7: Mean duration of the cycles below 400 hours.

4.2.2 Slopes of the regression lines

Figure 4.8 shows the decrease in operative temperature whenever the heaters were turned off. The decreases were faster when the buildings were less insulated, and when the doors were closed. Figure 4.9 shows the increase when the heaters were turned on. The zone heated up faster when the internal doors were closed. Additionally, the less insulated the building was, the quicker it heated up. This is, again, because of the difference in heating power, as mentioned in Chapter 4.2.1.

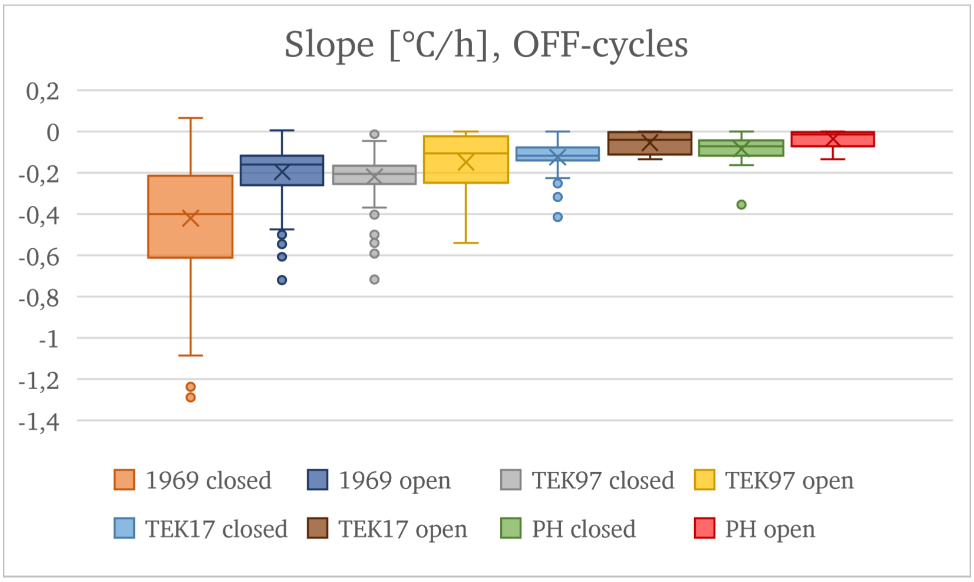

Figure 4.8: Slopes of the regression lines for the OFF-cycles.

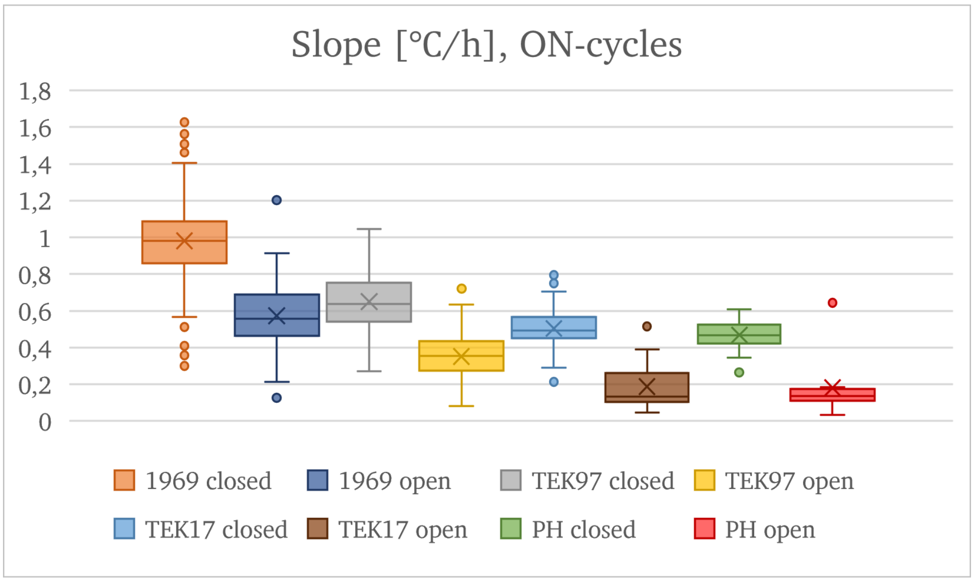

Figure 4.9: Slopes of the regression lines for the ON-cycles.

The slopes of the regression lines increased with the outdoor temperature for all simulations (Figure 4.10). In other words, when the outdoor air was warmer, the buildings cooled down slower during OFF-cycles, and the buildings heated up faster during ON-cycles. Figure 4.11 summarizes the results. It shows the mean for all cases (excluding cycles over 400 hours), with closed and open doors. The slopes for the OFF-cycles are however the absolute values, and they were originally negative.

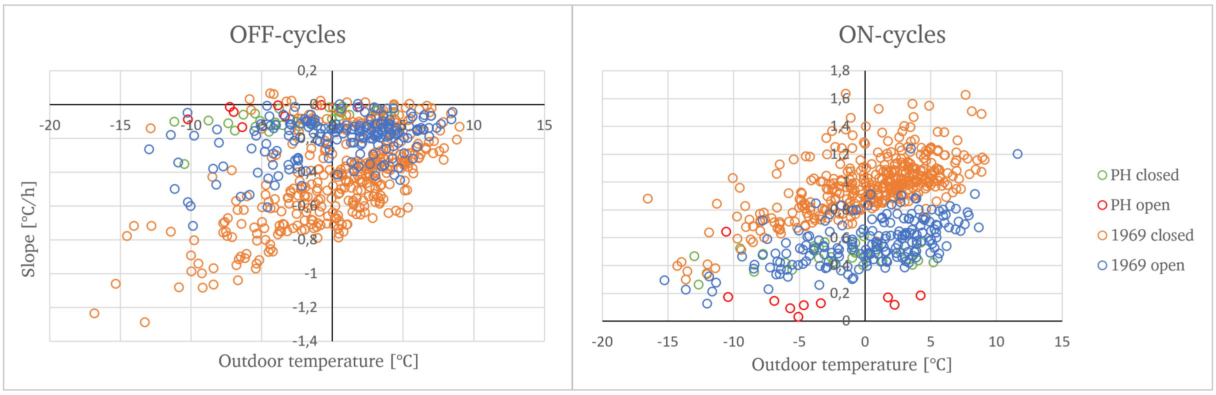

Figure 4.10: Scatter plot of the slopes of the regression lines as a function of the outdoor temperature, for the 1969 and PH envelopes.

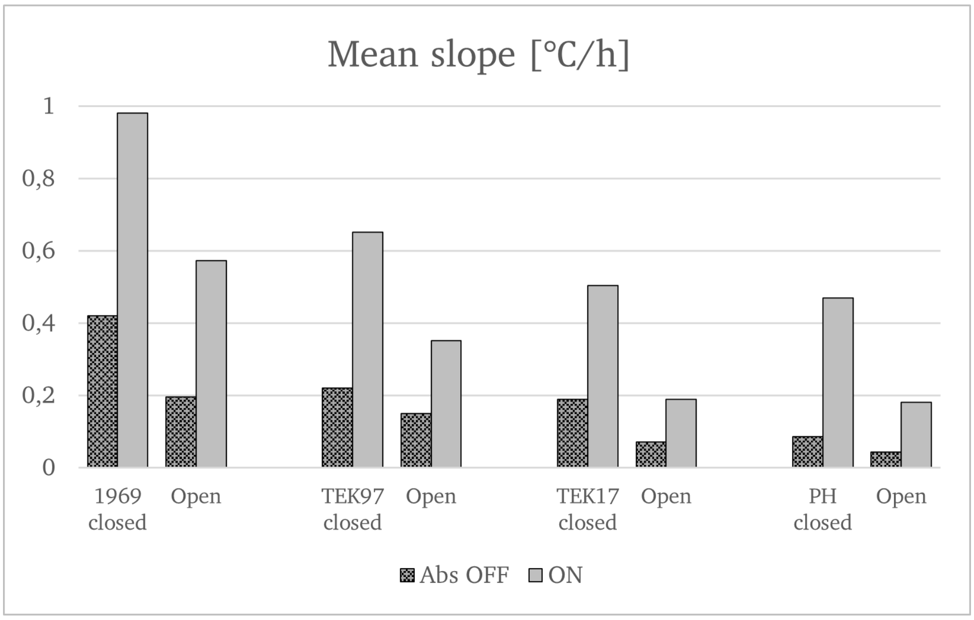

Figure 4.11: Mean of the regression lines' slopes, for all the cycles under 400 hours.

4.2.3 R-squared

Figure 4.12 shows the R^2 of the regression lines for the OFF-cycles. The R^2 was on average lower/-worse and more varying for the cases with open internal doors. It decreases even further when the envelope characteristics were better.

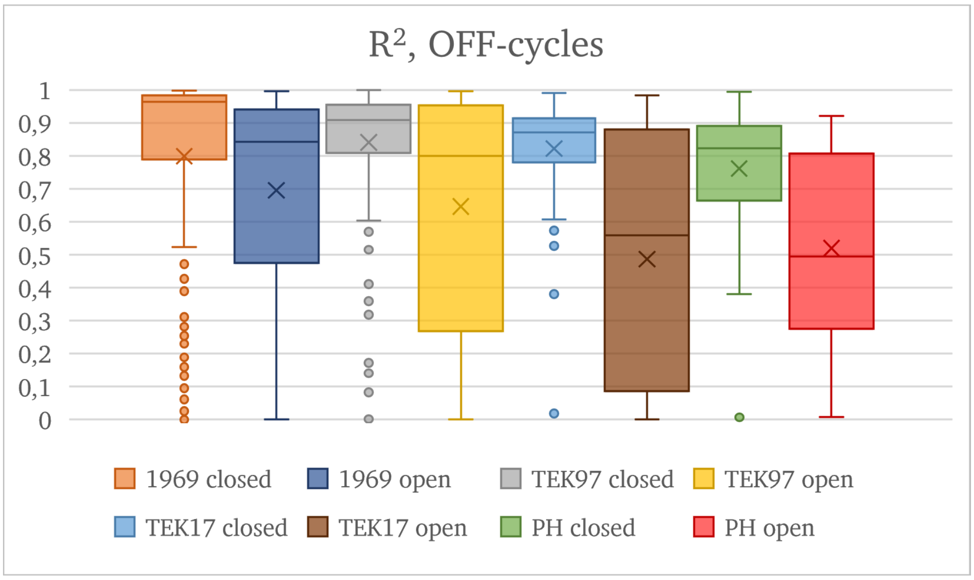

Figure 4.12: The R^2 of the regression lines, for the OFF-cycles.

Figure 4.13 shows the R^2 of the regression lines for the ON-cycles. These were higher and more consistent than for the OFF-cycles (note the different y-axes values). The other trends are however the same; R^2 was worse and more varying when the doors were open, and it decreases when the envelope characteristics were better.

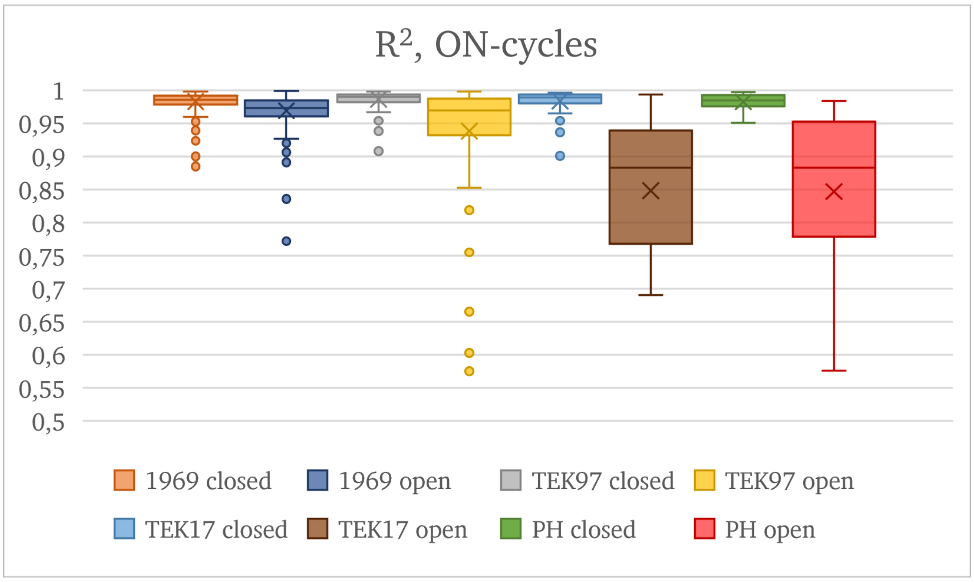

Figure 4.13: The R^2 of the regression lines, for the ON-cycles.

The R^2 was lower for longer cycles, both for OFF and ON-cycles (Figure 4.14). Figure 4.14 is the same as Figure 4.15, but with PH included. The duration is again capped at 400 hours. The R^2 decreased faster for the 1969 envelope when the durations got longer, compared to the PH envelope.

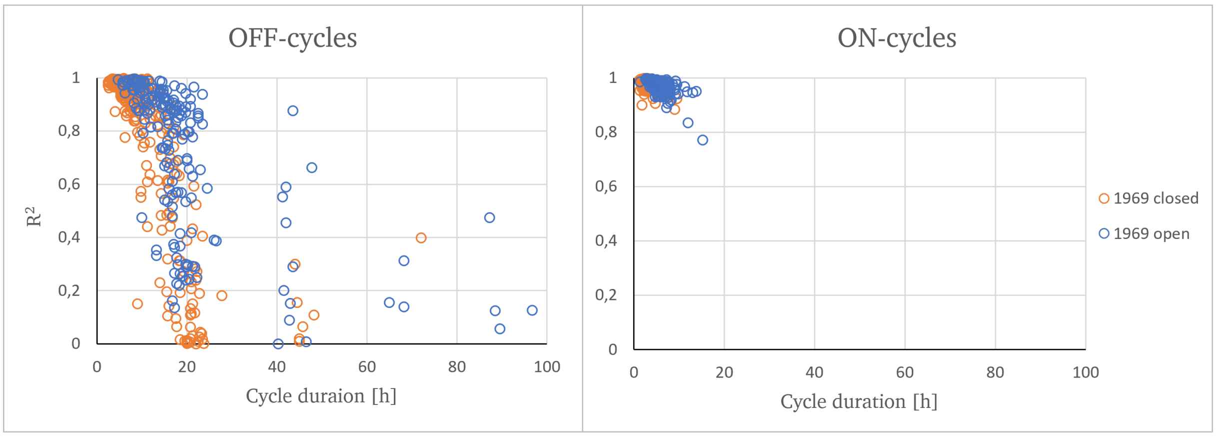

Figure 4.14: Scatter plot of R^2 as a function of the cycle duration, for the 1969 envelope.

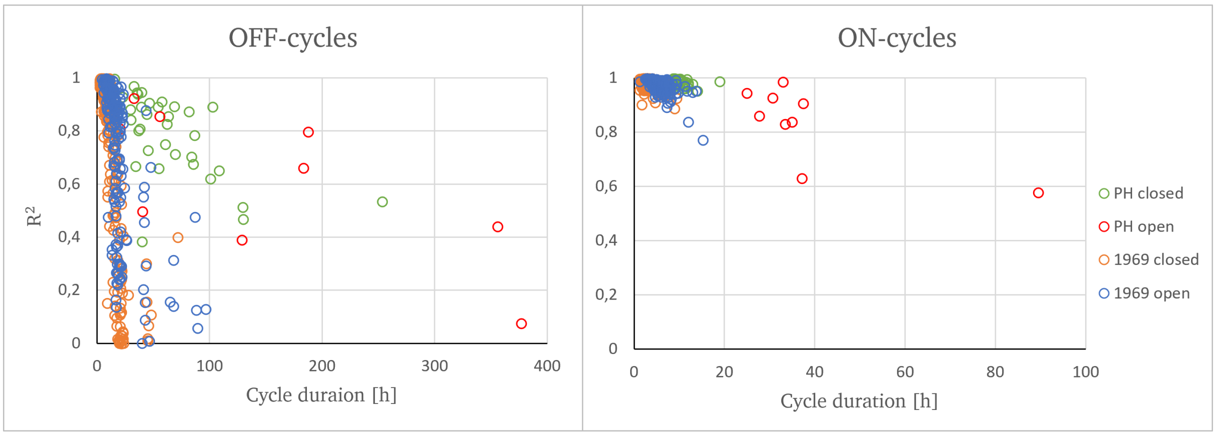

Figure 4.15: Scatter plot of R^2 as a function of the cycle duration, for the 1969 and PH envelopes. The durations are capped at 400 hours.

Figure 4.16 summarized the results, by showing the mean R^2 for all envelopes, both when the internal doors were closed and open. An interesting observation is that for all the previous figures, the values always decreased/increased with better envelopes. Yet, R^2 remains the approximately same for all four envelopes during ON-cycles, with closed internal doors. Additionally, for OFF-cycles with closed doors, the R^2 does not have a clear pattern, as TEK97 in fact has the best R^2.

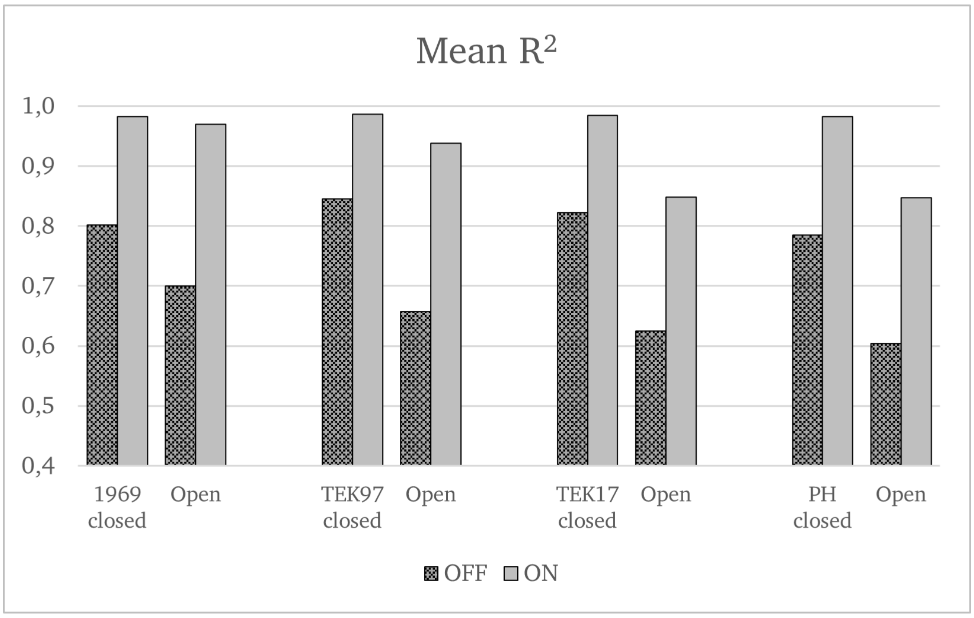

Figure 4.16: The mean R^2 of the regression lines, for all cycles under 400 hours.

Chapter 5

Discussion

The discussion chapter is, similarly to results, split into two parts, one for each of the main objectives. The chapter for objective 2 is further divided into three parts, showing cycle durations, slopes of the regression lines, and lastly R^2. Additionally, a chapter discussion the limitations of this study is included.

5.1 Objective 1: Upgrading the automation/control

The first objective was to investigate how improved control and automation of electrical heaters can reduce heating demand. The first research question related to this objective was how control and automation could be improved with no additional hardware installed. This is partly answered in Tables 3.4, 3.5, and 3.6 presented in Chapter 3.2, where suggested solutions for each of the efficiency levels are presented. The remaining is answered in Chapter (XX) (called Applications). Regarding research question 2, the energy-saving potential was presented in Figure 4.1. These results showed that a heating demand reduction was achievable for the four different envelopes, albeit to a varying degree (7.31–27.76 kWh/m^{2}a or 20–25%).

The results suggest that upgrading from class D to C and B to A gives a more significant reduction than going from class C to B. This, however, might stem from the fact that the macro for the interlock did not fully work as intended, as the heater was sometimes active when the windows were opened. If it had worked as intended, a larger reduction would be achievable, as window opening presumably causes a lot of heat loss during the colder months. Interestingly, the heating demand reduction was relatively similar for all four envelopes percentage-wise, which indicates that improving BAC functions is always somewhat effective, regardless of the envelope characteristics. Felius (2021) found that a heating demand reduction of 28% (AHU heating excluded) was possible, for a building like the 1969s house in this thesis, when going from class D to A, which is similar to the findings in this study (25%). This is for the same BEM, only with a few changes, and additionally, some different solutions for the control and automation functions implemented for the heaters.

5.2 Objective 2: Possibility of energy flexibility

The second objective of this thesis was to analyse the expected duration and temperature drop/increase whenever electrical heaters were turned off/on, as the results may be used as a measure to hopefully achieve demand-side flexibility by avoiding heating during peak hours. And lastly, check the predictability of the slopes and thus also the reliability, by calculating R^2.

5.2.1 Cycle durations

The duration of the cycles was on average longer for buildings with better envelope characteristics and whenever the internal doors were open. Additionally, the OFF-cycles were longer than the ON-cycles. The comparison between closed and open doors, and the discussion of the change based on outdoor temperature, is rather discussed in the next chapter, as these factors closely relate to the slopes.

The fact that the OFF-cycles for better-insulated buildings were longer than for poorly insulated buildings came as no surprise, as there is less heat loss through the envelope. On the other hand, quite surprisingly, the ON-cycles were longer as well, meaning it takes longer to heat up the zones, even though the heat loss is smaller. Most likely, this is a result of the lower power of the heating units, as supported by Figure 4.4, where all heating units were changed to having the same power, and after that, better-insulated buildings heated up faster than the less insulated ones. Another surprising observation is that the mean duration of the OFF-cycles is longer for the TEK17-house compared to the PH (looking at the right figure). This might be a consequence of the outlier, as the median is way lower.

5.2.2 Slopes and the influence of cycle curation

For the regression line of the logged temperatures, a better-insulated building gave a smaller slope for both OFF and ON-cycles. This means that for the PH, the temperature dropped slower when the heater was turned off, and it increased slower when the heater was turned on, compared to the older houses such as the 1969-house. The same applied to the cases with internal doors, i.e., slower temperature changes compared to when the doors were closed.

As mentioned in the previous chapter, the cycles were longer for the better-insulated buildings, which is why the slopes are smaller (the temperature changes slower per hour). And the same applies when comparing closed vs open internal doors: longer cycles when the doors were open, hence why the slopes are smaller. The reason for this might be because when the doors are closed, the heaters are for the most part heating their individual zone, whereas when the doors to the living room are open, the heat is traded to the other zones; the nearby heaters give the living room heat during its OFF-cycle. On the other hand, when the heater in the living room is on, adjacent zones might not have their heater on, and “steal” heat from the living room. When looking at the outdoor temperature, the temperature decreased faster, when it was colder outside (for the OFF-cycles). For the ON-cycles, the zones heated up slower when it was colder outside. Both are unsurprising, as the heat loss is larger when it is colder outside.

5.2.3 R-squared

The R^2 was significantly higher (and thus better) for the ON-cycles compared to the OFF-cycles, especially for the cases with closed doors. When the internal doors were closed, the R^2 was almost 1, regardless of the envelope. The remaining results (all OFF-cycles and the ON-cycles with open doors) showed a pronounced trend where the R^2 got worse when the building envelope was better.

There seems to be a reoccurring pattern, in that longer cycles always resulted in a worse R^2. It appears to be (at least) four parameters that affect the duration, i.e., building envelope characteristics, ON vs OFF-cycles, open vs closed internal doors, and outdoor temperature. Open doors, OFF-cycles, and a good building envelope for the most part result in a longer cycle, and it is reflected in the worse R^2. Interestingly, the envelope characteristics did not matter for ON-cycles as long as the internal doors were closed, which indicates good applicability, while if the doors are kept open, only the TEK97 and 1969s buildings retain this level of applicability. For OFF-cycles, the regression lines for the cases with open doors do not seem to be able to accurately predict the temperature drop, as the R^2 is approximately <0.7 for all cases. The R^2 for the OFF-cycles when the doors were closed was around 0.8 for all four envelopes. This means that the regression lines are nowhere near as reliable as for many of the ON-cycles with an R^2 close to 1. Still, the regression lines can predict reasonably well, and one has to decide what classifies as a good enough R^2. Figure 5.1 is a suggestion on how this can be decided. The green area is for the R^2 over 0.9; the yellow covers the area of 0.9–0.75, and can be interpreted as the area that covers the cases with a sufficient R^2; and the red area is for cases with an R^2 lower than 0.75, which should not be used as it is not reliable enough. Though, this is just a suggestion and has to be judged for each individual case.

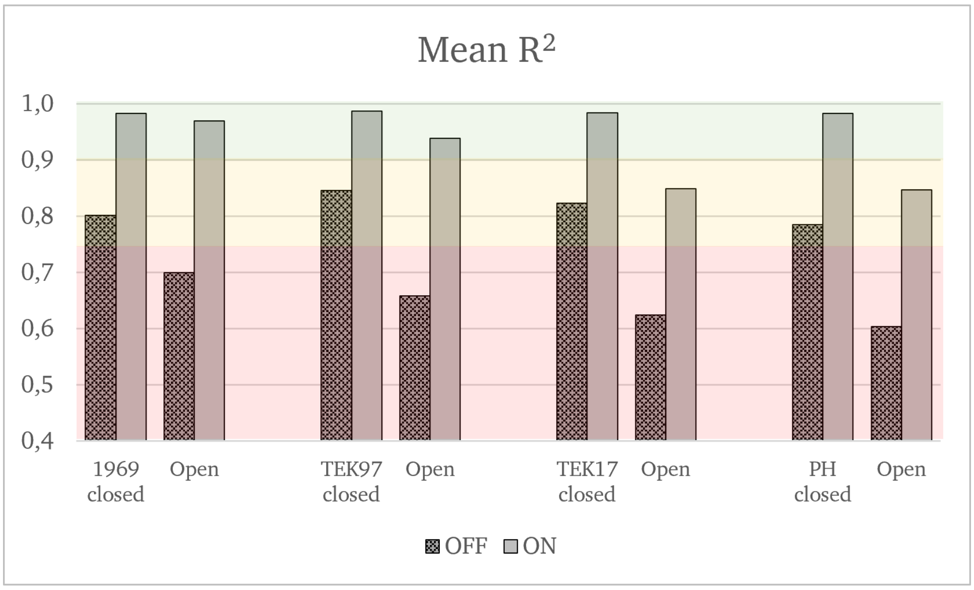

Figure 5.1: The mean R^2 of the regression lines, for all cycles under 400 hours. With suggested classifications of reliability (the green, yellow, and red area).

One interesting observation is for the mean R^2 for OFF-cycles when the doors are closed. It is expected that the 1969 building should have the highest R^2, as that seems to be the pattern. Yet that was not the case, as it in fact had the second-lowest mean. A reason for this might stem from the "older" windows of the 1969s building. It was the only building with two-paned windows, and it had no low-emission coating like the TEK17 and PH windows. This makes the solar gain higher. This extra heat gain might be enough to counteract the heat loss. Figure 5.2 shows a typical OFF-cycle for winter (top) and spring (bottom) for the 1969s building, which supports this theory, as there is a temperature increase even when the heater is OFF during the spring (when there is a higher solar gain). As a result, the R^2 is only 0.23 compared to the winter cycle with an R^2 of 0.975. This might also be why the R^2 for the 1969 building drops faster when the cycles get longer, compared to the PH (because the longer OFF-cycles are during spring/autumn), as shown in Figure 4.15.

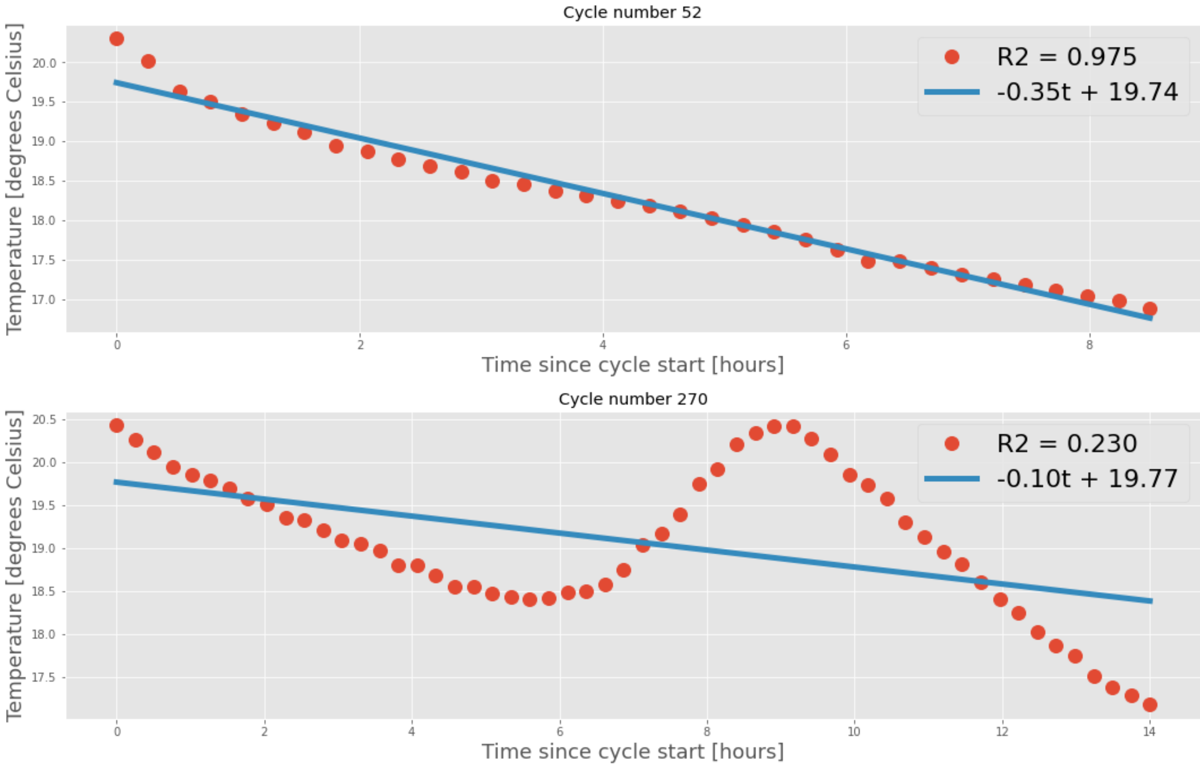

Figure 5.2: Typical temperature drop during OFF-cycles for winter (top) and spring (bottom). Taken from the Python script's plotting.

5.3 Limitations of the study

There are some limitations of this study; for instance, as previously mentioned, in terms of generalizability. This is especially prevalent for some of the cases where the reliability (identified by R^2) was not that great, and will then be even less reliable for other types of buildings not included in this study (e.g., apartment blocks). Still, the Python script is a very general script that can be used for any building type. So, for any building where the results from this thesis cannot directly be used, one may carry out their own simulations and use the script. The fact that the author had limited knowledge of the BPS program presented some problems, but proved to be manageable. The heater/window interlock did however not work fully as intended, and this affected the results to some degree (as discussed in 5.1). Due to time restraints, some factors that most likely will affect the result were not considered. These are as follows:

- How the AHU heating coil affects the slopes (i.e., if it is on vs off).
- Ventilation rates and whether the zones had supply or return air.
- The type of ventilation system. All cases had a TEK17-based system, with CAV. Older houses might not even have balanced ventilation, for instance. On the other hand, newer buildings might have variable air volume instead of CAV.

Chapter 6

Conclusion

This chapter concludes this thesis by summarizing the key findings in relation to the main objectives and research questions. Furthermore, practical applications and suggestions for what further work could be carried out are presented.

6.1 Key findings

The first main objective of this study was to look at how improved control/automation of electrical heaters could reduce the heating demand, without the need for additional hardware. NS-EN 15232 proved useful for identifying relevant functions that could be used to upgrade the smartness of the heaters. Based on these functions, some suggestions on how these could be implemented were suggested. For instance, night setback; occupancy detection based on Wi-Fi or GPS on residents' phones, rather than using detectors; and window/heater interlock based on the detection of a sudden temperature drop. Implementing such functions gave an overall good reduction in heating demand percentage-wise, regardless of the building envelope (20–25%).

This study also aimed to investigate the possibility of demand-side energy flexibility by analysing the expected cycle durations and temperature changes when the heaters are turned off/on. The data from the analysis can hopefully be used in further work to help the heater to predict when to heat, to avoid peak hours. The results show that there is a varying potential for energy flexibility, based on the parameters of the building envelope characteristics, ON vs OFF-cycle, and the status of the internal doors. The reliability, measured with R^2, was worse for longer cycles. Every parameter that increased cycle duration, would then, also worsen the R^2. The suggested three-part classification system, presented in Chapter 5.2.3, shows that for ON-cycles, the regression lines are highly reliable for all cases with closed doors, and cases with open doors and poorly insulated envelopes (1969s and TEK97). The regression lines for the ON-cycles for the better-insulated buildings (TEK17 and PH), were however, only decently reliable. The same applies to the OFF-cycles, for all cases with closed doors. Lastly, none of the regression lines were reliable for OFF-cycles when the doors were open. There were also external factors affecting the reliability, i.e., outdoor temperature (worse with higher temperatures) and presumably solar gain for older windows. Thus, there seems to be a varying potential of energy flexibility, depending on the aforementioned parameters.

6.2 Recommendations

6.2.1 Practical applications

The findings for objective 1 can be useful for deciding if upgrading the heater's smartness is worth it (or alternately, upgrading from a standard heater to a smart heater). It can also, at least to some degree, help serve as inspiration for manufacturers when designing IoT heaters.

The results from objective 2 could be used as a tool for AI learning to improve the heater's smartness even further, and it can serve as a "stepping-stone" to achieving demand-side flexibility. An example of how this could work is: the outdoor temperature is 10 ℃ and according to the thermal adaptive comfort model, a temperature below 18.1 ℃ is undesired. It is not that cold yet, but based on the expected temperature drop for the building type, the temperature will reach 18.1 ℃ in, for instance, two hours. The heater can then check if this is by chance also during peak hours, and it will be able to know if it is more cost-effective to heat before the building reaches the undesired temperature, and rather stop before the electricity price increases (due to peak hours). Additionally, apart from avoiding peak hours, this prediction of temperature drop can also help improve thermal comfort. If the heater knows that the temperature hits undesired temperatures in two hours, it could start heating after 1 hour and 45 minutes. The same applies to heating, in that the heater could turn off 15 minutes before the zone gets too hot. Other ways the results might be utilized, could for instance be for the heaters to better predict whenever a window is opened. It already knows what a common temperature drop is (based on the envelope, outdoor temperature etc.), and if it is faster, a window is most likely open. There is also a possibility of that this information can be used for the heaters to predict if the internal doors are open, and maybe improve communication between heaters in different zones. Though this is just speculation, and it is unclear of how this might be done. (might be difficult in practise)

6.2.2 Further work

Any further work should expand on what was previously mentioned in Chapter 6.2.1, or investigate the impact of some of the limitations discussed in 5.3. Suggestions for further research that would help build upon this study are as follows:

- Investigate if/how the results related to objective 2, can be used in conjunction with objective 1; an improved window/heater interlock, better communication between zones etc.
- A parametric study, analysing how the AHU heating coil, ventilation system/rates, and adjacent zones affect the slopes of the regression lines, and its R^2.

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Appendix A

Python script

The following Python 3 script was used to process the data exported from IDA ICE via Excel files. It takes four Excel files as an input, using the default names IDA ICE gives the file when exporting. The script processes the data; plots it, so it is easy to spot errors; and lastly exports all the results to one common Excel file.

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from sklearn.linear_model import LinearRegression
from sklearn.metrics import r2_score

plt.style.use("ggplot")
```

Code listing A.1: Imports Python libraries etc.

```
envelope = str(input("What envelope? (1969, TEK97, TEK17 or PH) ")).upper()
doors = str(input("The internal doors are? (open/closed) ")).lower()
```

Code listing A.2: Defines the building.

```
print("Zones: bedroom, bedroom-1, bedroom-2, bedroom-3, living room, living room-1, living room-2,
    bathroom, wc")
zone = str(input("What zone? ")).lower()

heater = zone + ".ElRad.El_Radctrl.OUTPUT-FILE.prn.xlsx"
temp = zone + ".TEMPERATURES.prn.xlsx"
outdoor_temp = "External_temperature.xlsx"
date_excel = "Date.xlsx"

df_heater = pd.read_excel(heater, engine="openpyxl")
df_temp = pd.read_excel(temp, engine="openpyxl")
df_outdoor_temp = pd.read_excel(outdoor_temp, engine="openpyxl")
df_date = pd.read_excel(date_excel, engine="openpyxl")

df_combine = df_outdoor_temp.merge(df_temp, on = "Time", how = "left")
df_combine = df_combine.merge(df_heater, on = "Time", how = "left")
df_combine = df_combine.merge(df_date, on = "Time", how = "left")

df_combine  # Displays the first and last five rows
```

Code listing A.3: Defines the zone, then extracts data from Excel output files from IDA ICE, and merges everything into one DataFrame.

```
cycle = df_combine["y_var"]
temp = df_combine["Operative temperature, Deg-C"]
time = df_combine["Time"]
ex_temp = df_combine["MEASURE"]

segm_time, segm_temp, segm_ex_temp, cycle_list = [], [], [], []

aux_t, aux_temp, aux_ex_temp = [], [], []

aux_t.append(time[0])
aux_temp.append(temp[0])
aux_ex_temp.append(ex_temp[0])

heating_onoff = [cycle[0]]
for i in range(1, len(cycle)):
    if abs(cycle[i] - cycle[i-1]) == 0:
        aux_t.append(time[i])
        aux_temp.append(temp[i])
        aux_ex_temp.append(ex_temp[i])
    if (len(aux_t) > 0 and abs(cycle[i] - cycle[i-1]) == 1) or i == len(cycle)-1:
        heating_onoff.append(cycle[i])
        segm_time.append(aux_t)
        segm_temp.append(aux_temp)
        segm_ex_temp.append(aux_ex_temp)
        aux_t = []
        aux_temp = []
        aux_ex_temp = []
        aux_date = []
        cycle_list.append(len(segm_time))

heating_onoff = ["On" if h == 1 else "Off" for h in heating_onoff[:-1]]
```

Code listing A.4: Makes three lists for each cycle (outdoor temperature, operative temperature, and duration).

```
cycle_duration, a_list, R2_list = [], [], []

T_list, end_T, ex_T_list, ex_end_T = [], [], [], []

for t, T, ex_T, c in zip(segm_time, segm_temp, segm_ex_temp, cycle_list):
    t = np.linspace(0, 0.25*len(T), len(T))
    T = np.array(T)
    ex_T = np.array(ex_T)

    model = LinearRegression()
    model.fit(t[:, None], T)

    T_pred = model.predict(t[:, None])

    cycle_duration.append(abs(t[0] - t[-1]))
    a_list.append(model.coef_[0])
    R2_list.append(model.score(t[:, None], T))
    T_list.append(T[0])
    end_T.append(T[-1])
    ex_T_list.append(ex_T[0])
    ex_end_T.append(ex_T[-1])

    plt.figure(figsize=(18,5))
    plt.plot(t, T, "o", markersize=12, label = f"R2 = {r2_score(T, T_pred):.3f}")
    plt.plot(t, T_pred, lw=5, label = f"{model.coef_[0]:.2f}t + {model.intercept_:.2f}")
```

```python

    plt.title(f"Cycle number {c}")
    plt.xlabel("Time since cycle start [hours]", fontsize=18)
    plt.ylabel("Temperature [degrees Celsius]", fontsize=18)
    plt.legend(fontsize=22)
    plt.show()
```

Code listing A.5: Performs a linear regression analysis of every cycle, and appends the start/end temperature for each cycle. If using different time steps than 15 minutes, the 0.25 has to be changed.

```python
df_output = pd.DataFrame({
    "Cycle number": cycle_list,
    "Heating [On/Off]": heating_onoff,
    "Cycle duration [h]": cycle_duration,
    "Outdoor start temp": ex_T_list,
    "Outdoor end temp": ex_end_T,
    "Operative start temp" : T_list,
    "Operative end temp" : end_T,
    "Slope" : a_list,
    "R^2" : R2_list
})

df_output.to_excel(envelope + "_" + zone + "_" + doors + "_doors_output.xlsx", index=False)
```

Code listing A.6: Exporting the processed data to Excel. The output file's name depends on the previous inputs (envelope, zone and if internal doors are open/closed).

Appendix B

Schedules

This appendix contains the schedules not shown in the main text. Equipment is, as previously mentioned, modelled as “always on”.

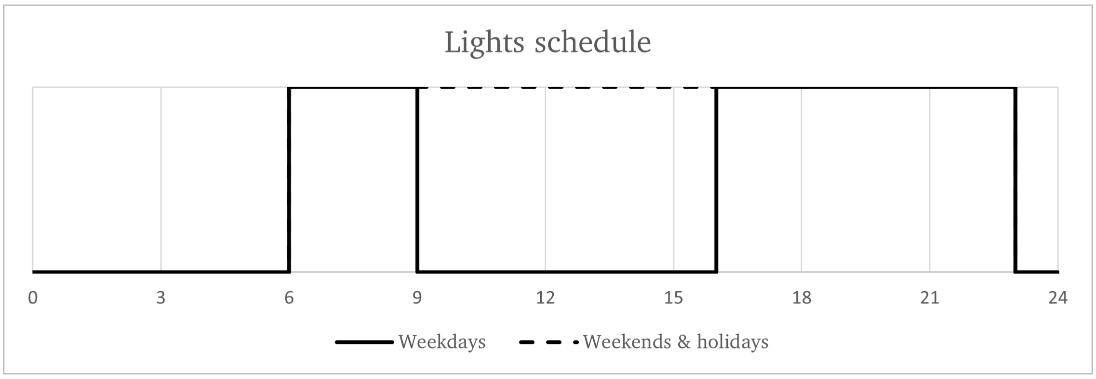

Figure B.1: Schedule for lights in all zones.

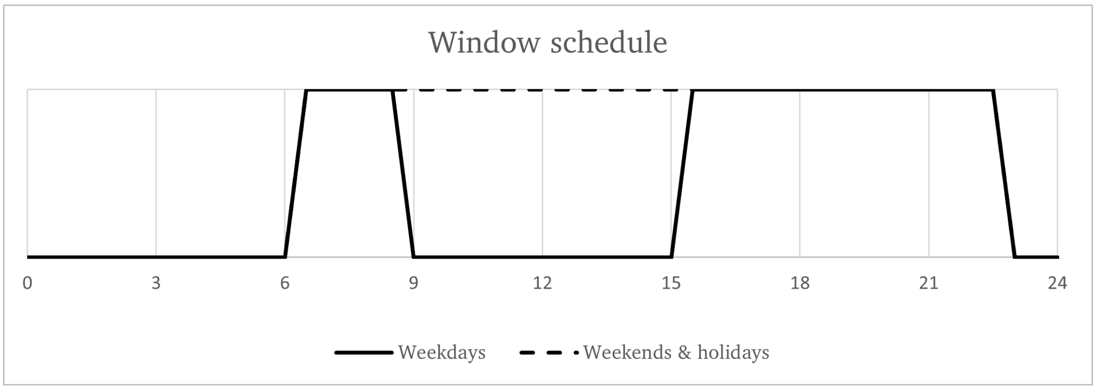

Figure B.2: Schedule for windows, used in the custom window macro. The windows were only able to open based on this schedule.

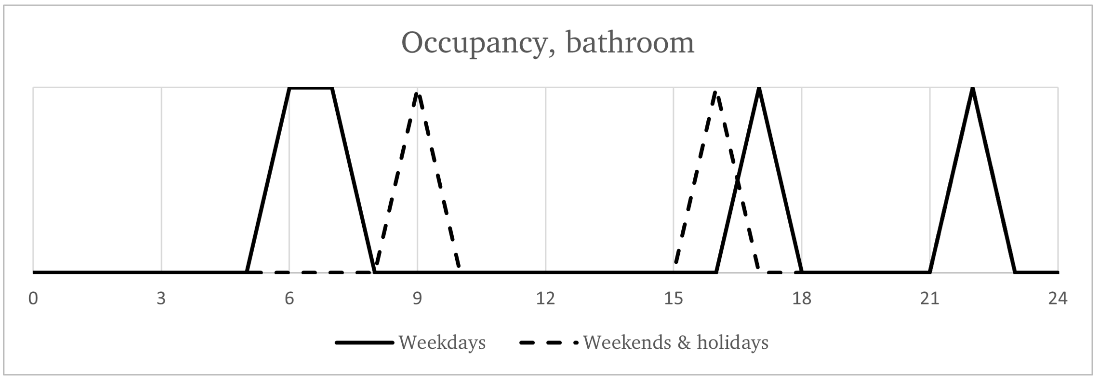

Figure B.3: Occupancy schedule bathrooms.

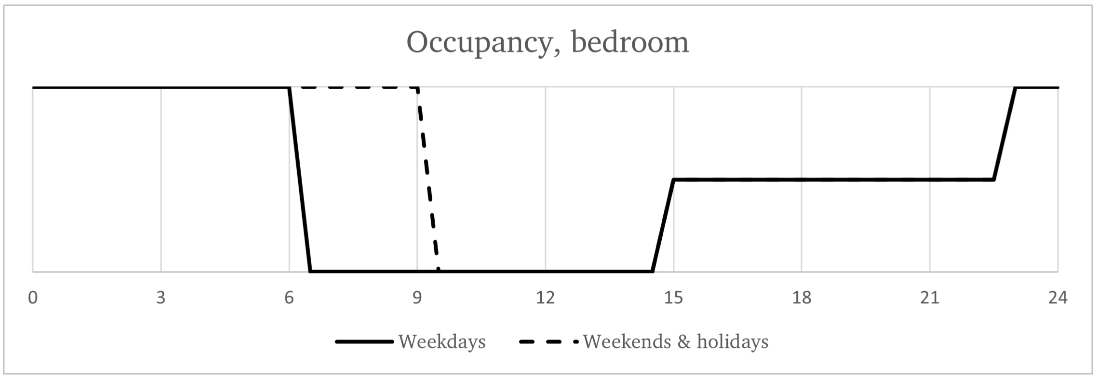

Figure B.4: Occupancy schedule bedrooms.

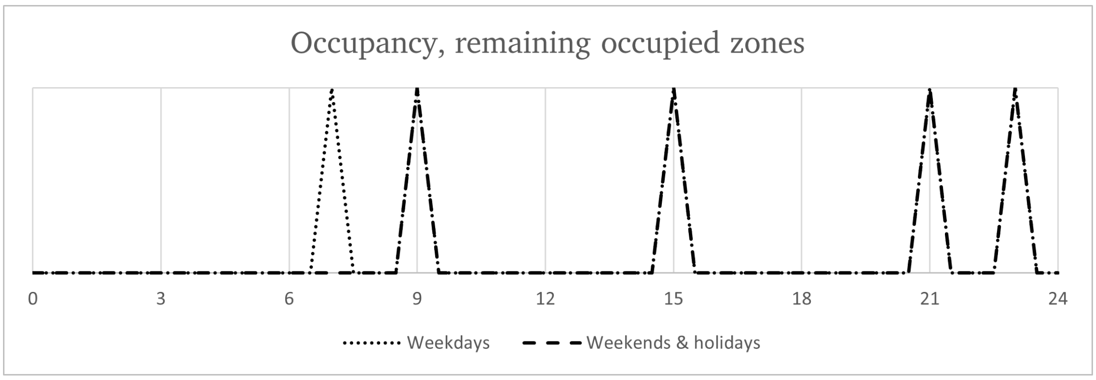

Figure B.5: Occupancy schedule for the remaining occupied zones, which is the living rooms, kitchen, laundry, and halls.

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