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Simplified space-heating distribution in highly-insulated residential buildings

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MASTER THESIS

for

Fredrik Håheim

Spring 2016

Simplified space-heating distribution in highly-insulated residential buildings:

Forenklet anlegg for oppvarming i super-insolerte byggninger:

Background and objective

Many of the building concepts for current and future energy-efficient buildings are based on highly-insulated building envelopes, such passive houses, zero emission buildings or nearly-zero energy buildings (nZEB). As the building is highly-insulated, it is possible to simplify the space-heating distribution subsystem and reduce the number of heat emitters to a few elements. One solution is to use a hydronic distribution equipped with few low-temperature radiators, for instance, one in each floor as well as one in the bathroom. This solution reduces thermal losses from the pipes and the investment, but theoretically provides for less thermal comfort than a complete/standard loop. This Master thesis investigates the *trade-off between energy efficiency, flexibility to users and the thermal comfort* when using a simplified radiator network as space-heating distribution subsystem in highly-insulated residential buildings. This work is performed within the framework of a competence project supported by Husbanken and in collaboration with the ZEB centre and the EBLE project.

This Master thesis is the follow-up of a specialization project where two similar passive houses of the MiljøGrånåsen project developed by Heimdal Bolig were investigated. Cross-comparison between measurements and thermal dynamic simulations (here using IDA-ICE) will be improved as well as user surveys. At the end of the thesis, the performance of the simplified space-heating distribution should then be discussed and compared to standard distribution approaches.

The following tasks are to be considered:

1. Further analysis of the results from the first measurement and interview campaign
2. Determine what should be improved to calibrate building simulations
3. Plan the second measurement campaign and perform it
4. Calibrate simulations using measurements and interview answers, discuss results and their limitations
5. Discuss the performance of simplified heat distribution in passive houses and, propose optimal way to design the heat distribution and to operate it and the building to improve performance

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering
☐ Field work

Department of Energy and Process Engineering, 13. January 2016

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PREFACE

This Master's thesis is written by a student at the Departement of Energy and Process Engineering at NTNU. The thesis is a part of bigger competence project funded by Husbanken investigating the trade-off between cost reduction, energy performance and loss of flexibility for users in passive houses with a simplified heat distribution loop.

I would especially like to thank my main supervisor Associate Professor Laurent Georges, and also co-supervisors Maria Justo Alonso and Judith Thomsen for their great support during the project. Whenever I had questions, they were always helpful and willing to answer. I would also like to thank Heimdal Bolig and Kristian Stensrud for helping to find occupants willing to participate in the study. I also thank the occupants participating in the project who were willing to let us install sensors in their houses and perform interviews.

Lastly, I will thank my computer for surviving when running endless amounts of simulations and scripts. I know you will appreciate the upcoming vacation as much as myself.

ABSTRACT

With the world facing climate changes there is a need for drastically reducing the energy consumption. In the building sector this can be effectively done be introducing super-insulated buildings, such as passive houses, in cold climate countries. The super-insulated building envelope enables for introducing a simplified space heating distribution system, with few heat emitters. This Master's thesis investigates the trade-off between thermal comfort and energy efficiency in two Norwegian row houses with a simplified hydronic heating distribution system, built according to the Norwegian passive house standard.

It was performed temperature measurements during two separate two-week periods in March and April in the dwellings, along with detailed user interviews. The thermal comfort and energy efficiency was investigated using detailed dynamic building simulations (IDA-ICE).

The calibration of the IDA ICE-model with the measurements reproduced satisfactory temperature levels in most rooms, although not perfect. It was performed yearly simulations with different control strategies to lower the bedroom temperature to a satisfactory level. Control strategies with window openings was able to introduce the lowest bedroom temperatures. Without door and window openings, supplying air with 16 °C appeared to be the best solution if the bedroom temperature wanted by the occupants is 14-16 °C. This strategy resulted in a heating demand of 37.7 kWh/m^{2}year with space-heating set point of 21 °C. However, this strategy could possibly cause discomfort with the living room temperature mostly between 20-22 °C, compared to the desired temperature of 22-23 °C. If desired bedroom and living room temperature is 20 °C and 22 °C respectively, supplying air with 21 °C appeared the most suitable option, with a resulting heating demand of 34.1 kWh/m^{2}year.

Based on the building simulations performed and with the given conditions, it might be difficult to introduce substantial temperature zoning within this kind of building typology. If desiring 14-16 °C in the bedroom and 22-23 °C in the living room, occupants would have to enter some kind of compromise, and accept deviations from their desired temperature level.

The possibilities for introducing such drastic temperature zoning inside dwellings with large temperature differences (5-10 °C) between rooms, should be investigated further.

SAMMENDRAG

Ettersom verden utsettes for klimaendringer er det blitt et behov for å redusere energibruken. I byggesektoren kan dette effektivt gjøres ved å introdusere superisolerte bygninger, som passivhus, i land med kaldt klima. Den superisolerte bygningskroppen åpner for å introdusere et forenklet romoppvarmingssystem, med få varmeavgivere. Denne masteroppgaven undersøker avveiningen mellom termisk komfort og energieffektivitet i to norske rekkehus med forenklet vannbårent romoppvarmingssystem, bygget etter den norske passivhusstandarden.

Det har blitt foretatt temperaturmålinger gjennom to separate to-ukers perioder i mars og april i husene, samt detaljerte intervjuer av beboerne. Ved hjelp av måleresultatene ble den termiske komforten og energieffektiveten undersøkt ved bruk av detaljerte dynamiske bygningssimuleringer (IDA-ICE).

Kalibreringen av IDA ICE-modellen med målingene førte til relativt tilfredsstillende temperaturnivå i de fleste rom. Det ble utført årlige simulering med ulike kontrollstrategier for å senke temperaturen i soverom til et tilfredsstillende nivå. Kontrollstrategier ved bruk av vindusåpninger førte til de laveste temperaturene i soverom. Uten å åpne dører og vinduer, viste det seg at å tilføre luft med 16 °C var den beste løsningen hvis ønsket temperatur av beboerne er 14-16 °C. Denne strategien resulterte i et oppvarmingsbehov på 37.7 kWh/m^{2}år, med settpunkt for romoppvarming på 21 °C. Ettersom beboerne ønsket 22-23 °C i stua, vil denne strategien kunne føre til diskomfort i stua grunnet temperaturer på 20-22 °C mesteparten av tiden. Om ønsket temperatur er 20 °C i soverom og 22 °C i stua, vil det å tilføre luft med 21 °C være den beste løsningen, med et resulterende årlig oppvarmingsbehov på 34.1 kWh/m^{2}år.

Basert på bygningssimuleringene og med de gitte betingelsene, vil det muligens være vanskelig å innføre betydelige temperaturedifferanser mellom ulike rom i denne bygningstypologien. Hvis det ønskes 14-16 °C i soverommet og 22-23 °C i stua, er beboerne nødt til å inngå et form for kompromiss, og akseptere avvik fra det ønskede temperaturnivået.

Mulighetene for å introdusere slike drastiske og store temperaturdifferanser (5-10 °C) mellom rom i boliger, bør utforskes ytterligere.

NOMENCLATURE

$T_{S,HB}$ – supply air temperature after the heating battery.

$T_{SET,HB}$ – set point temperature for supply air after the heating battery.

$T_{S,HR}$ – supply air temperature after the heat recovery wheel, before the heating battery.

$T_{SET,HR}$ – set point temperature after the heat recovery wheel, before the heating battery.

T_A – air temperature.

$T_{MAX,AVG}$ - the maximum measured temperature during one day. The average then calculated from all the days during the period.

$T_{MIN,AVG}$ - the minimum measured temperature during one day. The average then calculated from all the days during the period.

$T_{SET,SH}$ – set point temperature for space-heating.

T_{HRP}– potential temperature after the heat recovery wheel.

T_{BHR}– temperature before the heat recovery wheel.

T_{EXT}– temperature of the extract air in the air handling unit.

T_{EXH} – temperature of the exhaust air leaving the air handling unit to the outside.

η_{HR}- temperature efficiency of the heat recovery wheel.

T_{avg} – average temperature for a given period.

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1 INTRODUCTION

By the end of 2020, all new buildings in the European Union should be nearly zero-energy buildings, thus will all new buildings need to have very high energy performance. The low amount of energy used in these buildings should primarily come from renewable energy sources (Council of the European Union, 2010). The EU countries must set minimum energy performance requirements for all new buildings, along with a national plan to help achieve this. The passive house concept has emerged as a possible solution for reaching this target, leading to an increased construction of passive houses in Norway the recent years. By introducing super-insulated building envelopes in Nordic climates, the space-heating demand can be drastically reduced.

Passive houses are highly insulated, and it is therefore possible to introduce a simplified space-heating distribution subsystem and keep the number of heat emitters to a minimum. In this Master's thesis, two row houses located at Miljøbyen Granåsen in Trondheim have been studied. Both houses are built in accordance with Norwegian passive house standard and the simplified heat distribution concept, and have only two radiators for space-heating installed. This simplification leads to reduced thermal losses and reduced investment cost, but theoretically provides for less thermal comfort than a standard heat loop with a higher number of heat emitters. This thesis has investigated the trade-off between energy efficiency, user flexibility and thermal comfort when using a simplified heat distribution subsystem in Norwegian passive houses. The investigations were a continuation of a specialization project performed during the autumn 2015. The work was carried on using qualitative user interviews, detailed temperature measurements along with recording of door and window openings, as well as detailed dynamic building simulations in IDA ICE. Control strategies to achieve the desired temperature level in different rooms were proposed, and discussed as regards thermal comfort and energy efficiency. Lastly, conclusions based on the discussion was made, and suggestions for future work was proposed.

1.1 PASSIVE HOUSES

The term passive house is a concept developed by several people and institutions. According to the Passive House Institute in Germany, the exact definition of a passive house is: "a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air (Passipedia, 2015)." The definition is valid for all climates and does not quantify any numerical requirements needed to be fulfilled. There is therefore no universal standard that applies for every country, the countries themselves will make the requirements needed to fulfil the passive house definition.

1.2 CURRENT REGULATIONS

Today, all new Norwegian buildings have to comply with TEK10, the current building regulation (DIBK, 2011). This regulation sets minimum requirements for the energy performance of the buildings, including minimum requirements of different building parts, the fan energy used for ventilation and heat recovery efficiency of the ventilation system. As of

01.01.16, the requirements for energy performance in TEK10 have been revised and improved. During a transition period until 01.01.17 it is optional to use either the revised or the old requirements. The revised building regulation, not yet officially named, have stricter requirements than TEK10. The requirements regarding heat loss are at level with the Norwegian passive house standard.

1.3 The Norwegian passive house standards

NS 3700:2013 and NS 3701:2012 are the Norwegian passive house standards developed for the Norwegian climate and conditions. NS 3700:2013 – criteria for passive houses and low-energy building, applies for residential dwellings. This standard contains definitions of passive houses and low-energy buildings, with requirements for energy demand, design criteria, criteria used for certification, and requirements for documentation of dwellings that can be classified as passive houses or low-energy buildings (Standard Norge, 2013).

1.4 Other studies

There have been studies investigating the space heating in highly-insulated buildings in Nordic countries. So far there is a no other studies in Norway investigating the thermal comfort and user satisfaction in super-insulated residential buildings by using interviews, building simulations and detailed measurements. The other studies have been limited to focusing on other aspects, and selection of the studies will be presented in chapters 1.4.1-1.4.3.

1.4.1 Evaluation of nine passive house dwelling in Sandnes

SINTEF Byggforsk performed a case study as a part of the EBLE-project (evaluation of residential buildings with low energy demand), evaluating nine passive houses in Sandnes (Thomsen, et al., 2014). Measurements of indoor and outdoor temperature, energy and relative humidity were performed from 01.06.2012 to 01.06.2013. One condition separating this thesis with the case in Sandnes is the geographical location. Sandnes is in the west of Norway, known for its relatively humid and mild climate. The mean temperature during a year in Sandnes is 7.6 °C and DOT is -9 °C (DOT for Stavanger is used). In Trondheim this is 5.8 °C and -19 °C respectively (SINTEF Byggforsk, 2012). In addition, the houses in Sandnes are single houses. This results in a larger part of the house being in contact with outdoor air, compared to a row house.

The study reported that people in general are happy with their passive houses. However, there are also some issues regarding the thermal environment. Some occupants reported the indoor air temperature as too cold during the winter, even though measurements showed that the temperature was relatively high during the same period. There was no clear reason for this negative experience of the indoor temperature. There was only one measuring point in each house placed in the extract duct in the kitchen, and this could be a possible explanation for the experience. The one measuring point will not give a clear indication of the temperature distribution inside the building. It could also be because people will experience the thermal environment differently.

The study reported that some people felt there was dry air during the winter, which was supported by the measurement of relative humidity under 20 %. Also people wanted to be able to adjust the temperature in different rooms in the Sandnes study. The study reported that people especially want lower temperature in the bedroom.

1.4.2 Cost study electric and waterborne space-heating

Smedegård et al. performed a cost study to investigate the cost difference between installing a hydronic heating system and an electric heating system, in passive house standard and TEK10 buildings. The buildings studied were one single house, one block, one kindergarten and two different sized office buildings (3600 m^2 and 7200 m^2). The interface of the hydronic heating system consists of the heat distribution system (pipes, valves, heat emitters), the pump, security and cleaning central. This excludes the heat source, peak and base load, and all equipment associated with hot water heating.

The passive house hydronic heating loop in the study is a simplified loop with one centrally placed radiator in each floor (two floors), along with floor heating in the bathroom. In the study it is suggested that the specific cost of a waterborne heating system will vary between 351 to 423 NOK/m^2 for a passive house single family housing, while the cost for an electronic heating system for the same housing will be 102-124 NOK/m^2. When comparing the waterborne heating system with the electric heating system, the cost is 183 % to 314 % higher for the waterborne system. The specific cost of a passive house block with a waterborne heating system is 261-316 NOK/m^2, while for an electric heating system the specific cost is 101-123 NOK/m^2 (Smedegård, et al., 2012).

The study clearly shows that the cost of installing an electric heating system is much lower compared to a hydronic heating system. The new requirements in the revised TEK allows for using direct acting electricity for heating of buildings under 1000 m^2 (Lavenergiprogrammet, 2016). If only looking at the costs of installing a heating system, this change in the regulations will not stimulate to increased use of waterborne heating systems.

1.4.3 The need for temperature zoning in high-performance residential buildings

M. Berge et al. performed a case project regarding the thermal comfort of inhabitants for terraced and detached houses at Miljøbyen Granåsen. The study was based on a questionnaire, in which 28 of 62 households responded (Berge, et al., 2016).

The thermal comfort during were accessed using the 7-point scale in accordance with EN 15251 (European Commitee for Standardization, 2007) and ASHRAE standard 55 (ASHRAE, 2013), in which -3 corresponds to cold, 0 to appropriate and +3 to hot. For thermal comfort during the last winter, 89 %, 96 % and 46 % considered the room temperature to be appropriate for the living room, bathroom and bedroom respectively. For the bedroom, 50 % experienced the temperature as too warm.

Regarding the thermal comfort during summer, 50 % considered the living room temperature to be appropriate and 25 % slightly warm, 21 % warm and 4 % hot. For the bedroom only 11 % considered temperature appropriate, 29 % slightly warm, 45 % warm and 14 % hot.

The questionnaire found that during the summer, nearly all occupants kept the bedroom window open for at least a few hours throughout the day. Regarding the winter situation, half of the occupants kept the window open for at least some hours. The findings supported that main reason for window ventilation behaviour was to control the temperature.

1.5 Miljøbyen Granåsen

Miljøbyen Granåsen is the largest passive house project in the Nordic region. Granåsen is located east from Trondheim centrum, close to Dragvoll. The plot of land is slightly sloping down towards north. It is planned to build in total 455 units, in which 17 is detached houses, 67 is row houses and 371 is apartment blocks. 206 apartments are still under construction, while the construction of 68 apartments has not started yet (Stensrud, 2015).

All units fulfil the requirements in NS 3700. The heating system used is a waterborne system, using approximately 60 % district heating and 40 % electric heating. The passive house project won Energispareprisen 2014, an award for projects that have completed provident energy saving measurements in buildings, construction or industry in Trondheim municipality (Trondheim kommune, 2015).

The climate in Trondheim is mild and humid. Trondheim is located inside the zone for temperate climate, but close to the polar circle (Bratberg, 2008). In the north lays the cold polar air, while in south there are warmer air masses. This contributes to a highly unstable climate, as Trondheim alternates between the cold and warmer air zones.

1.5.1 The row houses

The units studied in the thesis are three row houses at Miljøbyen Granåsen. They are referred to as house 1, house 2 and house 3. House 1 was used as a test house during a specilization project the autumn 2015, performing preliminary investigation. The experience from this specialization project was used to perform enhanced investigations for this Master's thesis. It was initially planned to perform a second set of measurements in house 1, but the occupants was not able to participate for a second time. Therefore a new house to investigate had to be obtained, in this case house 3. House 1 is not further investigated in this thesis, but the houses investigated are named house 2 and house 3 to avoid confusion.

The houses are identical in terms of area, but have slightly different layout. The row houses consist of 3 floors, with 3 or 4 sleeping rooms. House 2 have the entrance in the first floor, while house 3 have the entrance in the basement. Therefore, the layout will differ for the two row houses at B7.

The occupants in house 2 have chosen to have three rooms in the basement. The basement consists of a technical room, a storage room and a living room. It is installed electrical floor heating all over this basement. The layout of house 2 is shown in Figure 1.1.

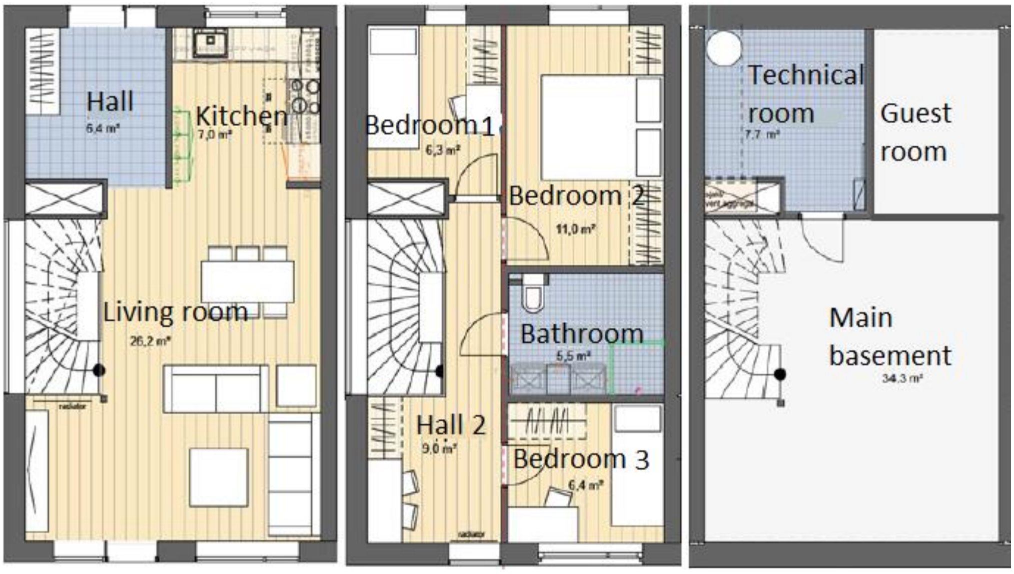

Figure 1.1: layout of house 2, from left to right: first floor, second floor and basement.

The layout of house 3 is slightly different from house 2. The entrance is here in the basement, with living room and kitchen in the first floor. The second floor conist of two bedrooms, a bathroom and a bedroom/office. The radiators are here placed in the basement and the second floor, and the layout can be seen in Figure 1.2.

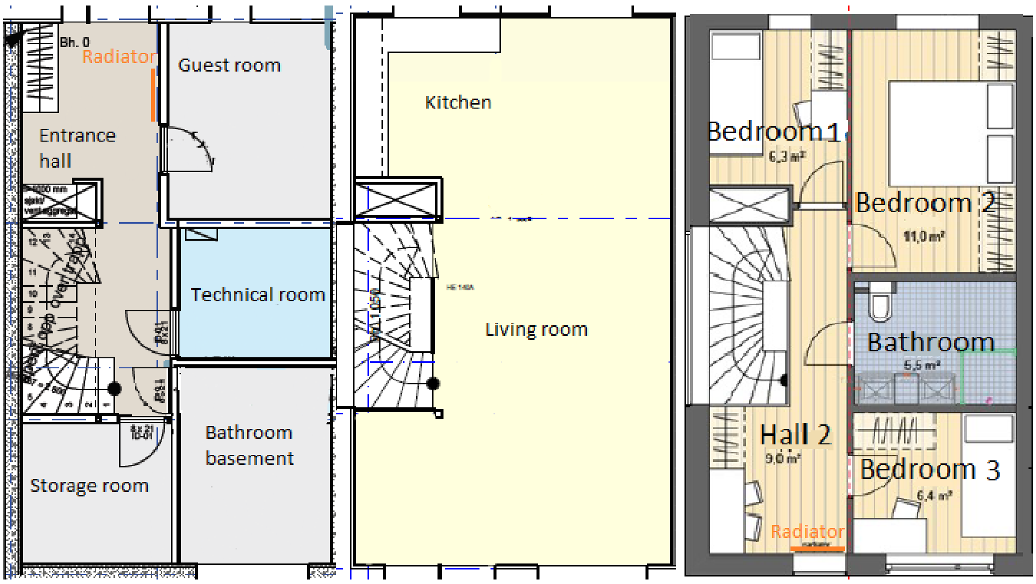

Figure 1.2: layout of house 3, from left to right: basement, first floor and second floor.

1.5.2 Energy efficiency specifications for the row houses

The data for the specifications regarding the row houses, was obtained from a Simien file used by SINTEF for energy evaluation of the building. This evaluation considered all the row houses as one envelope, but the input is still valid for each row house. One difference for the specifications is that it might be less thermal bridges in the middle row houses than the end row houses.

Table 1: *energy efficiency specifications for the row houses in B7, compared with regulations and passive house standard.*

Requirement	Passive house standard	Revised TEK10	Row houses
U-value window/door	≤ 0.80 W/(m^{2}K)	≤ 0.80 W/(m^{2}K)	Windows:0.79 W/(m^{2}K) Doors: 0.66 W/(m^{2}K)
Normalized thermal bridge value	≤ 0.03 W/(K/m^2 GIA)	≤ 0.05 W/(m^{2}K)	0.03 W/(K/m^2 GIA)
Mean temperature heat recovery efficiency	≥ 80 %	≥ 80 %	88 %
SFP-factor	≤ 1.5 kW/(m^3/s)	≤ 1.5 kW/(m^3/s)	1.2 kW/(m^3/s)
Leakage number by 50 Pa	≤ 0.60 h^{-1}	≤ 0.60 h^{-1}	0.60 h^{-1}
U-value external wall	0.10-0.12 W/(m^{2}K) ^{a}	≤ 0.18 W/(m^{2}K)	0.16 W/(m^{2}K)
U-value roof	0.08-0.09 W/(m^{2}K) ^{a}	≤ 0.13 W/(m^{2}K)	0.06 W/(m^{2}K)
U-value floor	0.08 W/(m^{2}K) ^{a}	≤ 0.10 W/(m^{2}K)	0.10 W/(m^{2}K)
	a: these values are not requirements, but typical values for a passive house building. GIA: gross internal area.		

1.5.3 Ventilation system

Each dwelling has a decentralized air handling unit, Flexit UNI 4, with a rotary heat exchanger with temperature efficiency of 88 % and SFP= 1.2 kW/(m^3/s). The maximum heating power from the electric heating battery is 1.3 kW. The supply air flow rate and temperature can be controlled by a control panel placed in the hall in the second floor, and can only be controlled by the unit as a whole, not separately for each room.

The ventilation principle applied in the dwellings is a cascade-flow ventilation. As can be seen in Figure 1.3, the fresh air is supplied in the rooms with the highest occupation time, as living rooms and bedrooms. The air is then extracted from the rooms with lower occupation time, as the kitchen and bathrooms. This ensures a lower concentration of pollutants in rooms with higher occupancy (Rojas, et al., 2015).

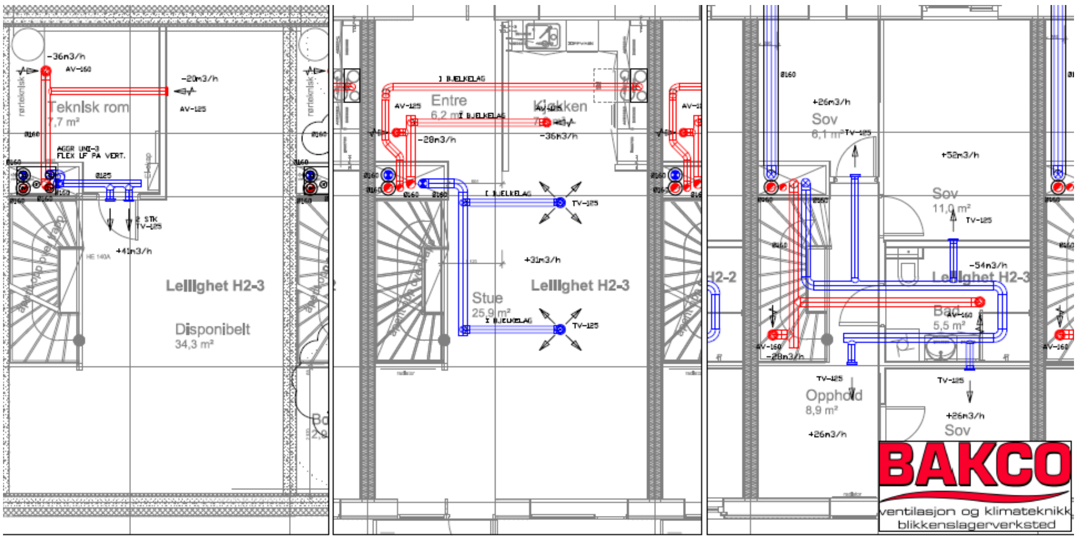

Figure 1.3: *Technical drawing of the ventilation loop in which blue ducting represents supply air and red ducting represents extract air.*

The ventilation system in the basement of House 3 is not completely known, as there are added additional rooms to the basis layout. The ventilation system of House 2 is shown in Figure 1.3.

House 3 have the CI 60 control panel, while house 2 have the more advanced control panel CI 600, both shown in Figure 1.4. The main difference between the two panels is that CI 600 have the ability to automatically control the supply air temperature with predefined or custom control schedules. This allows for e.g. night setback. When adjusting the CI 60 one cannot see the supply air temperature, while this can be seen on the screen for the CI 600.

Figure 1.4: *control panel CI 60 and more advanced CI 600*

1.5.4 Heating system

The heating system in the dwellings consists of a simplified hydronic system using district heating as heat source. There are two radiators in each house. In house 2 the radiators are installed in the living room in the first floor, and in hall 2 in the second floor. House 3 have the radiators in the entrance hall in the basement and in hall 2 in the second floor. The radiators are controlled by a thermostatic valve from TA Hydronic, see Figure 1.5. The thermostatic valve have settings ranging from 1 to 5, in which 1 is equivalent to an air temperature (T_A) of 12 °C and 5 is equivalent to T_A=28 °C.

Figure 1.5: *thermostatic radiator valve from TA Hydronics, model TRV Nordic.*

The hydronic heating system for house 2 is shown in Figure 1.6. Due to lack of drawings for house 3, one could assume a similar piping for this dwelling. Both dwellings have installed electrical floor heating in the bathrooms and technical room. In addition, house 2 has electric floor heating all over the basement. The floor heating is controlled by a thermostat with a temperature sensor in the floor.

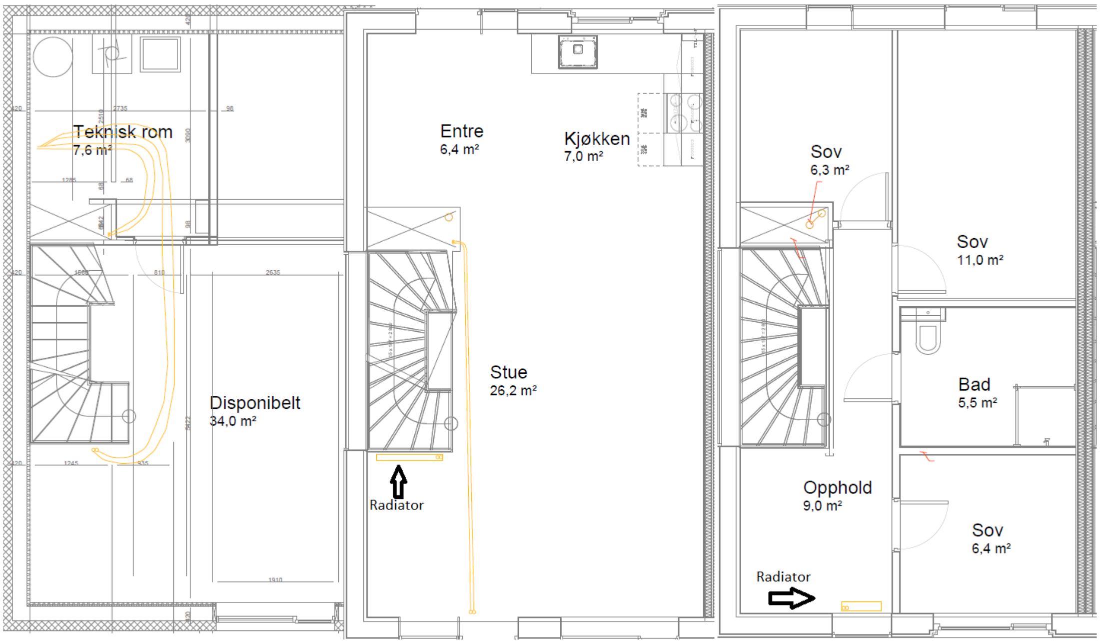

Figure 1.6: *Technical drawing of the heating system, the pathways of the piping drawn in yellow along with radiators, also marked with an arrow.*

2 FIELD RESEARCH

2.1 INTERVIEW METHOD

The goal of the interviews was to identify the occupants' satisfaction with the dwelling, along with the user habits and how the user behaviour is influenced by living in a passive house contrary to not as energy efficient dwellings. It was especially investigated how and why occupants regulate the thermal comfort by the use of door- and window openings, the use of radiators and other heat sources, and the use of ventilation by regulating supply air temperature and/or supply air flow rate. It was investigated the users desired temperature level in different rooms during daytime and night time, and the difference between the desired indoor temperature during winter and summer was also investigated.

The interviews and measurements are a good basis when evaluating building energy simulations, as to what kind of measures that could be implemented to increase user satisfaction in a passive house.

The results from the interviews will be compared and discussed with the findings from other literature.

2.2 MEASUREMENTS METHOD

2.2.1 Second measurement campaign

For the second measurement campaign 40 iButton DS1922L-F5 newly acquired temperature sensors were used. Experiences from the first campaign made it necessary to modify the placement of some sensors, which led to five additional temperature sensors being added for this campaign.

2.2.2 Placement of temperature sensors

For the first campaign (autumn 2015), the temperature stratification in the living room was measured in five heights, from 0.1 m to 2.4 m with equal length between each sensor. As the temperature stratification in the living room was minor in the first campaign, for the second campaign only three sensors were placed in a vertical line at 0.1 m, 1.5 m and 2.4 m height.

To further investigate the thermal losses in the ventilation ducts discovered after the first measurement campaign, temperature sensors were placed at the supply air diffusers in the basement hall, in the living room, in the hall 2 and the three different bedrooms.

An extra temperature sensor was placed on the north exterior wall in case of an error. All other sensors were placed as in the first campaign. The placement of the temperature sensors in the houses is shown in Figure 2.1 and Figure 2.2.

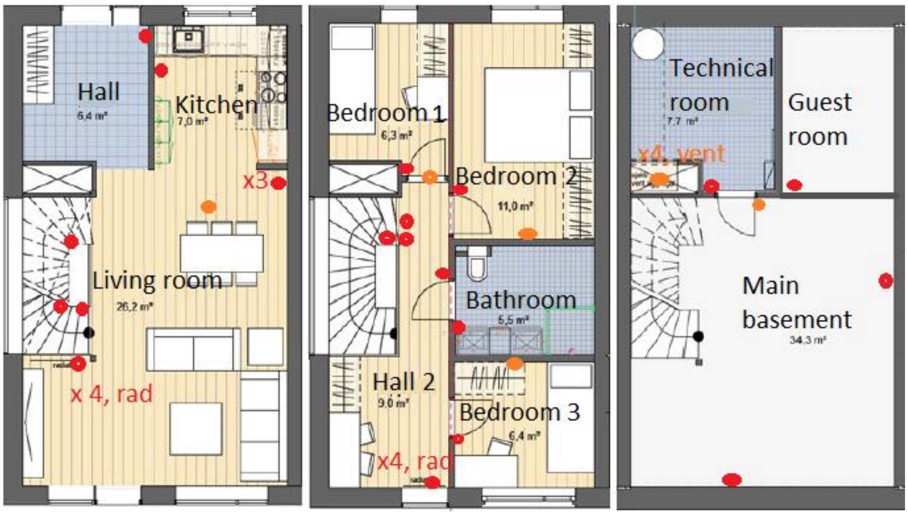

Figure 2.1: *placement of temperature sensors in house 2, orange colour indicates sensors measuring the ventilation air while the red dots represents the remaining sensors.*

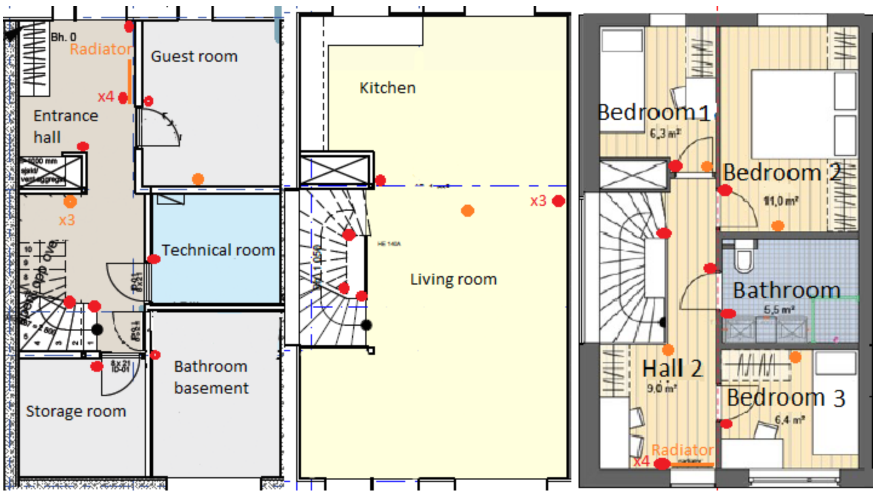

Figure 2.2: *placement of temperature sensors in house 3, orange colour indicates sensors measuring the ventilation air while the red dots represents the remaining sensors.*

2.2.3 Door/window sensor

In order to better understand the internal air- and heat flow inside the house, it was decided to register the opening and closing of internal and external doors, as well as windows. This was done by using battery powered reed sensors from Fibaro. The sensors consist of two parts. The first part is the main component, which registers and sends the signals. This part was installed at the door moulding. The second part is a small magnet, which was installed at the movable part of the door or window. When the two parts have a distance between them longer than 5 mm, the door/window is registered as open. When the distance is 5 mm or less, the door/window is registered as closed. The signal is then sent to a central device that is connected to WIFI, where the results are uploaded to an internet server. The results can then be found by logging in to an internet site, where the whole system can be monitored. The exact time of the door/window being closed or opened can be seen here.

The door/window sensors were placed on every internal door and balcony door. The sensors were also placed on the windows the occupants told were usually opened and closed.

2.2.4 Schedule of ventilation, radiators and solar shading

To determine the manual operation of the ventilation system, the occupants were asked to fill a scheme of when they manually adjusted the ventilation, both in terms of capacity and temperature. The rest of the ventilation operation was found by reading the data from the ventilation control panel, which consists of a predefined program of the air flow rate and supply air temperature at different times during the day and the week.

The occupants were also asked to fill a scheme of when they manually adjusted the two installed radiators. They would fill in the time of the adjustment and the position of the radiator valve. The operation of the electric floor heating in the bathroom and in the basement, were assumed to be constant during the measurement campaign and read from the panel.

House 2 had manually controlled solar shading for two of four windows on the south facing façade. To monitor the solar shading strategy, the occupants were asked to fill a form of when the solar shading were applied. House 3 had automatic controlled solar shading on three of four windows facing south, while the last window was controlled manually. The automatic solar shading is activated when the solar radiation exceeds a given value, here assuming 100 W/m^2 on the inside surface of the window.

2.3 Interview results

The occupants in both dwellings moved in February 2014, and had been living there for roughly two years when the interviews were conducted. The inhabitants in house 2 listed the main motivation for moving due to the size of the dwelling, while house 3 occupants' main motivation was the location of the dwelling. Both housings considered the energy efficiency of the dwelling as a bonus, and both housings also have in general been very satisfied with their dwellings so far.

2.3.1 Summer thermal comfort

House 2 reported high temperatures for both the living room and bedrooms during summer, and therefore keep the bedroom windows open most of the summer days to cool the bedrooms. The bedroom doors are usually open when the windows are open during summer. To avoid high summer temperatures, the occupants use manually controlled external shading on the south façade. The desired bedroom and living room temperatures during summer are ~20 °C all day. House 3 did not feel that high bedroom temperatures occurred during summer. However, the occupants suggested that this could be explained by the fact that they were on vacation most of the summer 2014 and that the summer of 2015 was quite cold. They have automatic external shading in the form of solar screen, which contributes to avoid too high temperatures. They also open the windows during night and keep the bedroom door closed. They want approximately 14-16 °C in the bedrooms and 22-23 °C in the living room all year.

2.3.2 Winter thermal comfort

Both house 2 and 3 were satisfied with the indoor temperature in the living room during winter and did not feel that it was too cold. If the indoor temperature was too cold, they would adjust the radiator thermostat to get a satisfactory temperature. House 2 was satisfied with the temperature in the bedrooms during winter, and sometimes opened the bedroom windows before sleeping. They wanted 20 ℃ and 22 ℃, in the bedroom and living room respectively. If too cold in the bedroom, they would open the bedroom door and increase the radiator thermostat temperature. House 3 said that they were not satisfied with the bedroom temperatures if the window was not open during night. Therefore, they usually have the bedroom window open 6-7 hours every night, except for the coldest winter days. If it were to be too cold in the bedrooms during winter, which they have not yet experienced, they would close the window, open the bedroom door and adjust the radiator.

2.3.3 Window and door opening motivation

House 2 reported the motivation for opening the windows to be fresh air and lower temperatures, while the motivation for closing the window was due to noise outside. The motivation for opening the window in house 3 was to get lower bedroom temperatures and fresh air, and closing it due to pollen allergy. House 2 opens the bedroom door to get better ventilation. They close the door to heat the room, and due to privacy and old habits. House 3 usually have the bedroom door closed, and the motivation for this is privacy, keeping their dog out, old habit, to keep the bedroom temperature low and not cool down the other rooms.

2.3.4 Satisfaction with technical systems

House 2 are satisfied with the heating system, but suggested floor heating all over the dwelling would have been preferred to get more stable temperature distribution. They also felt that better information could have been provided after the house takeover, it was mostly referred to a provided information folder. House 3 are satisfied with the operation and information about the heating system and think it works fine. Both think the information about user instructions regarding the ventilation systems are ok, but could have been better. They both stressed that it also their responsibility to learn how to operate these systems, and that they have been provided with a detailed information folder regarding the technical systems. Both feel the controllability of the living room temperature is fine, while house 2 think it could have been better in the bedroom. House 3 reported that they have to open the window to get a satisfactory bedroom temperature, but they would consider using another solution (e.g. lower supply air temperature in bedrooms) if such a solution was available.

2.4 MEASUREMENT RESULTS

In this subchapter, the measurements are presented for house 2 and house 3. For house 2, measurements were performed for a first campaign in December and a second campaign in March. The results from the second campaign will be mostly used, due to purposeful justifications performed to enhance the measurements. The justifications performed were the introduction of door and window opening sensors, modified placement of temperature sensors and additional temperature sensors placed at supply air transfer devices. The justifications will make the results from house 2 and house 3 more comparable. They can still not be directly compared due to different boundary conditions, here the outdoor temperature, different layout and number of external facades. The only result presented from the first campaign in house 2, is the operation of the radiators.

2.4.1 Bedroom 1

From Figure 2.3 we can see that the bedroom window was opened once for a short period during the campaign, and the bedroom door was open the majority of the time. This room was occupied by a child, which can explain the infrequently opening of door and window. The average temperature is 21.65 °C, fluctuates between 19-24 °C and is lower than the adjacent rooms. There is a coinciding temperature rise in the bedroom when the temperature in hall 2 increases. This temperature rise is due to increasing solar gains in hall 2, and the reported open door will lead to a heat flow to the bedroom.

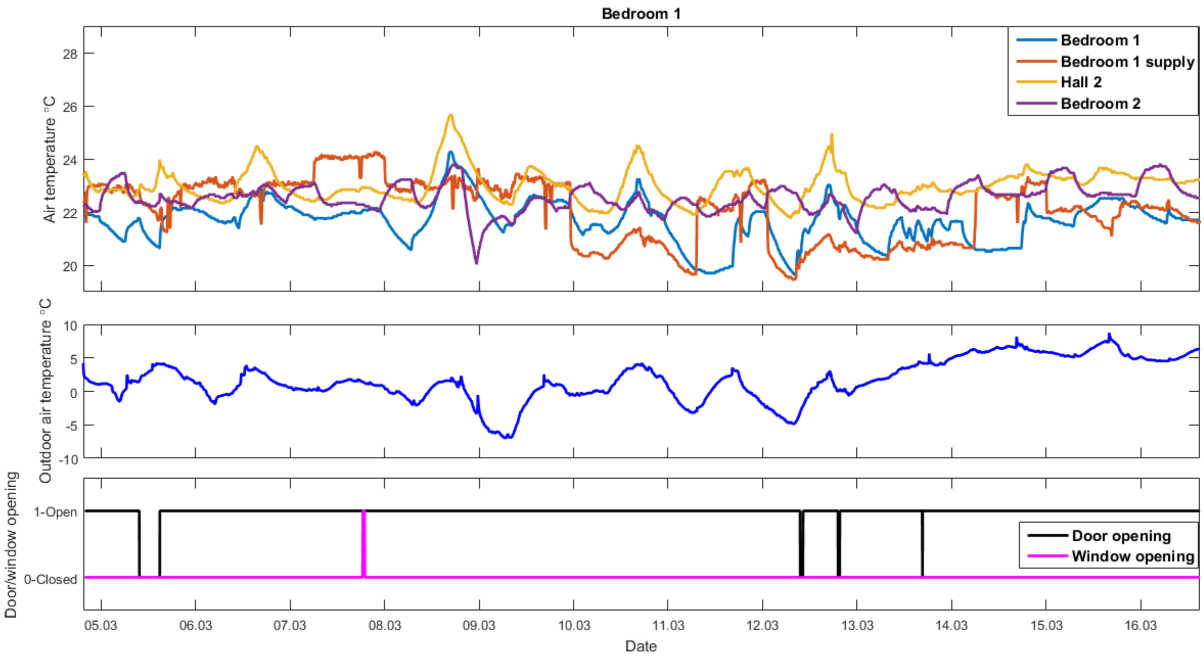

Figure 2.3: *temperature measurements in house 2 during a period in March, the upper graph shows the temperature in bedroom 1, supply air and adjacent rooms hall 2 and bedroom 2, and middle graph shows the outdoor temperature while lowest graph shows the door opening.*

In Figure 2.4 the temperature in bedroom 1 and adjacent rooms in house 3 are displayed. The occupants reported that there is no permanent occupant in this room, and it is therefore only used when they have visitors. From 14.04 to 24.04, the temperature in bedroom 1 fluctuates between 18.5 °C and 21 °C, while the next three days the fluctuations range from 21-23 °C. There is a clear correlation between the temperature increase 24.04 and the reported opening of the door the same period. This leads to a convective heat transfer from hall 2 to the bedroom, decreasing the temperature difference between the rooms from 4-5 °C to 2-3 °C. The last two days the door is again closed and the bedroom temperature decreases to around 20 °C, leading to an increasing temperature difference between the rooms.

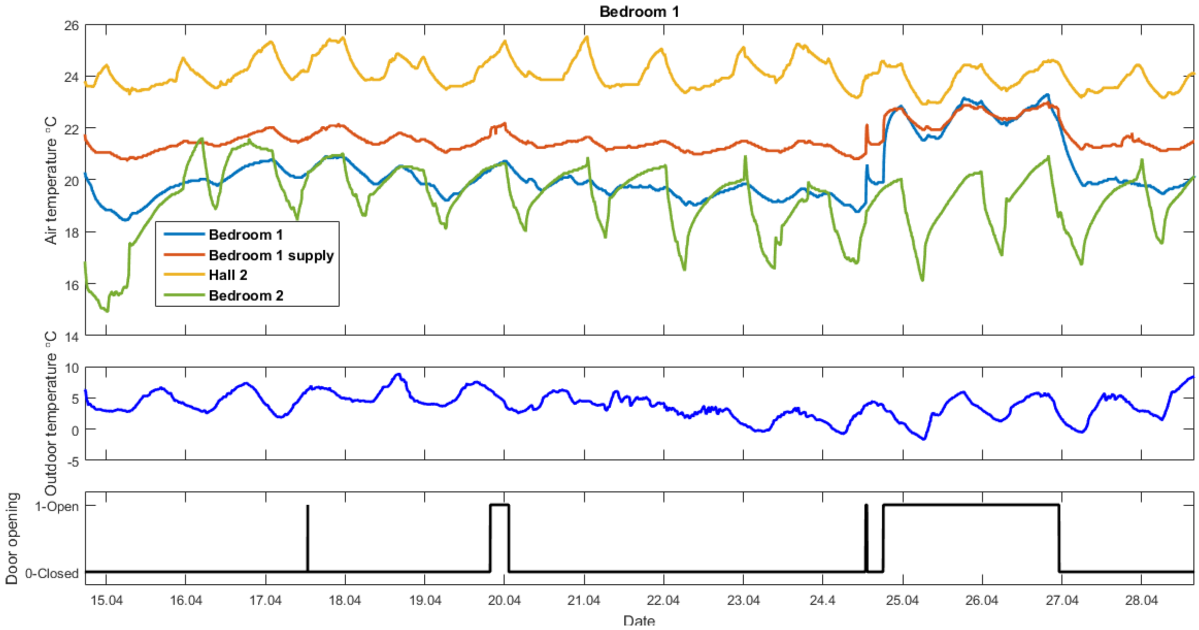

***Figure 2.4:** temperature distribution in bedroom 1, bedroom 2 and hall 2, along with the outdoor temperature, while the lower part shows the opening of the door in bedroom 1.*

2.4.2 Bedroom 2

Temperature measurements performed in house 2 are reported in Figure 2.5. We can see that the bedroom door is reported open most of the time, while the window is kept closed most of the time. The window opening leads to a temperature drop from 23.7 ℃ to 20.0 ℃. The already decreasing air temperature in hall 2 the same period is boosted by the opening of the bedroom window and the door between the rooms. The bathroom temperature is steady around 25 ℃ before the window opening in bedroom 2 leads to 1 ℃ drop, even with closed bathroom door. The temperature in bedroom 2 is relatively stable, ranging from 21-23 ℃. The supply air temperature is ranging from 20-24 ℃, and there is no clear relationship between the room temperature and the supply air temperature.

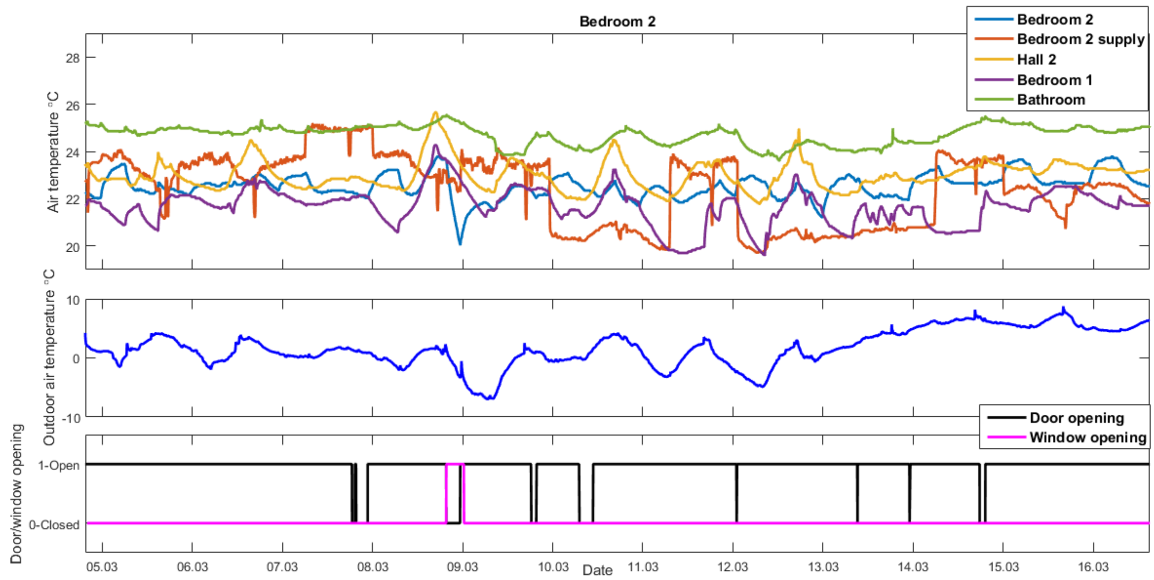

***Figure 2.5**: temperature measurements in house 2 performed during a period in March, the upper graph shows the temperature in bedroom 2, supply air and adjacent rooms hall 2 and bedroom 1, along with outdoor temperature in the middle part and door/window opening.*

Temperatures in second floor in house 3 are displayed in Figure 2.6. One can see that there is an almost oscillating pattern for the window opening in the bedroom. The window is opened everyday around midnight and is closed again around 06-07 the following morning. In the weekends, the closing is delayed to 09-10. In addition, the opening and closing of the bedroom door follows a pattern. The door is used before the occupants go to bed and when they wake up. Most of the time the door is kept closed during day and night time.

There is clear correlation between the opening of the bedroom window and the bedroom temperature. When the window is opened, the bedroom temperature smoothly decreases to the point where it is closed again. Then the bedroom temperature rapidly increases and flattens out when nearing the temperature in the adjacent bedroom. The bedroom temperature will reach minimum 15-19 °C during night ($\bar{T}_{min}$=17.2 °C, n=14) and maximum 20.1-21.5 °C during day ($\bar{T}_{max}$=20.7 °C, n=14). This corresponds quite well with the desired bedroom temperature reported in the interview, that was 14-16 °C during night, although the minimum temperature is higher than 17.0 °C half the days during the period.

The temperature in hall 2 is also affected when the window is open, typically dropping 1-2 °C. The door between the rooms is closed, so most of the heat transfer is likely in form of transmission. The bathroom has an adjacent wall with the bedroom, and the temperature here drops 0.1-0.5 °C during night when the bedroom window is open. The bathroom is controlled by a thermostat, with constant set point temperature of 25 °C, keeping the temperature relatively steady throughout the whole measurement period. The measurement of the supply air temperature shows that there is a small decrease when the bedroom temperature drops, so that the sensor may have been influenced by this drop as the air transfer device is inside the room.

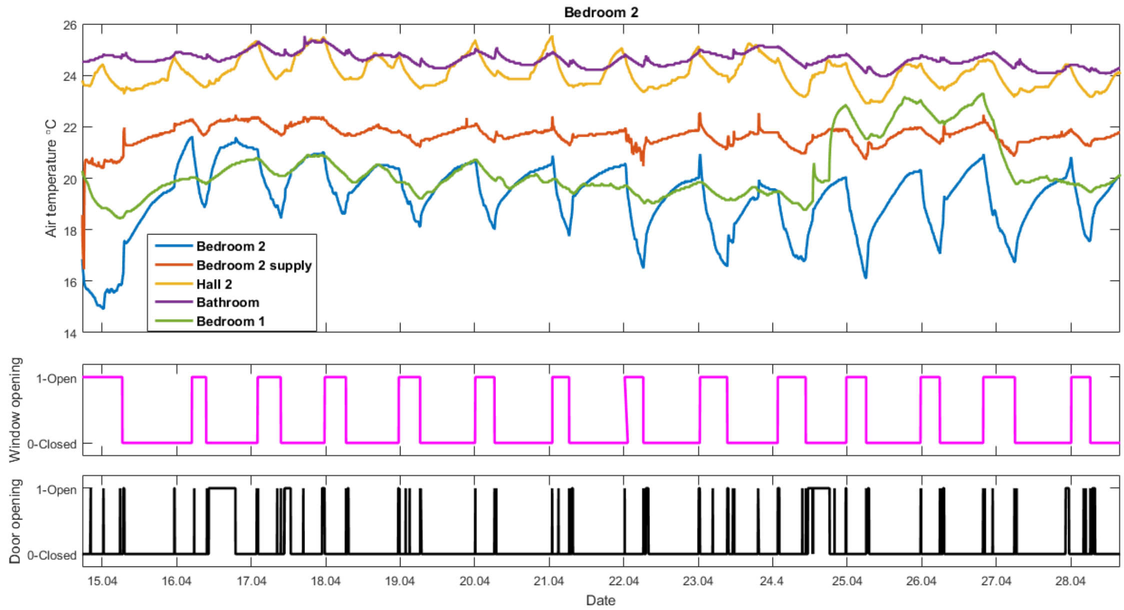

Figure 2.6: *temperature distribution in bedroom 1, bedroom 2, hall 2 and bathroom, and the supply air temperature in bedroom 2, while the middle plot shows the opening of the bedroom window and the lower part the opening of the bedroom door.*

2.4.3 Bedroom 3

Figure 2.7 reports the temperatures influencing bedroom 3 and the opening of both bedroom window and door. The bedroom door is open most of the time, while the window is opened once for one hour 12.03. While the window is open a temperature drop of 1 ℃ occur, dropping a further 3 ℃ after the window is closed and stabilizing around 22 ℃ during the night.

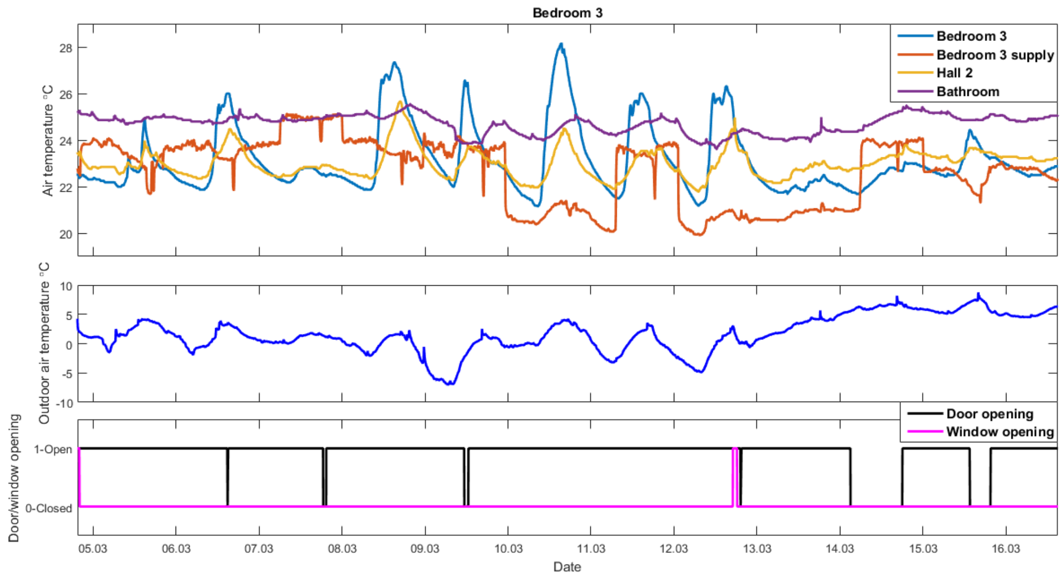

Figure 2.7: *temperature measurements in house 2 during a period in March, where the upper graph shows the temperature in bedroom 3, supply air and adjacent rooms hall 2 and bathroom, while the middle graph shows the outdoor temperature and the lowest graph shows the door/window opening.*

The bedroom is facing south, and therefore the temperature peaks in bedroom 3 corresponds well with measurements of increasing solar radiation at the time. We can see this effect by looking at Figure 2.8, where a temperature increase typically starts 09:00-10:00 and peaks around 15:00. The average solar energy on horizontal surface during the period was 1.67 kWh/m^{2}day.

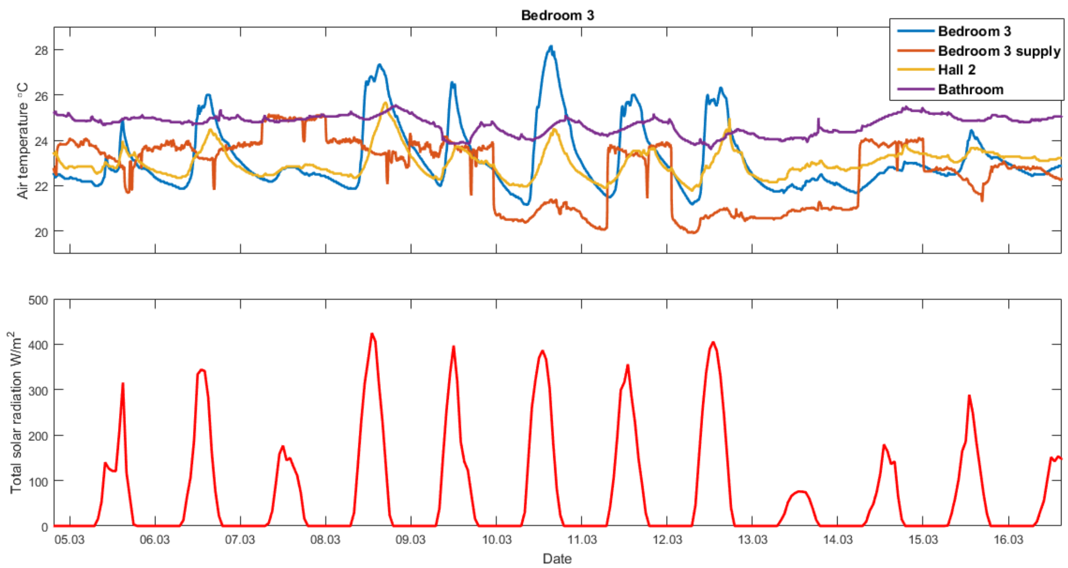

Figure 2.8: *temperature in rooms influencing bedroom 3 in house 2, the lower part shows the total solar radiation measured at a horizontal surface at Gløshaugen weather station 3 km away from the house.*

Let us take a closer look at bedroom 3 in house 3. It should be mentioned that this room was not actually used as bedroom, but as a rarely used office. It is still called bedroom 3 for the sake of comparison with house 2, as the room is identical in term of build-up and physical location inside the house. From Figure 2.9 we can see that the door is kept open most of the time, except for some small periods. There is no clear influence on the bedroom temperature when the door is closed. The window was closed during the whole period.

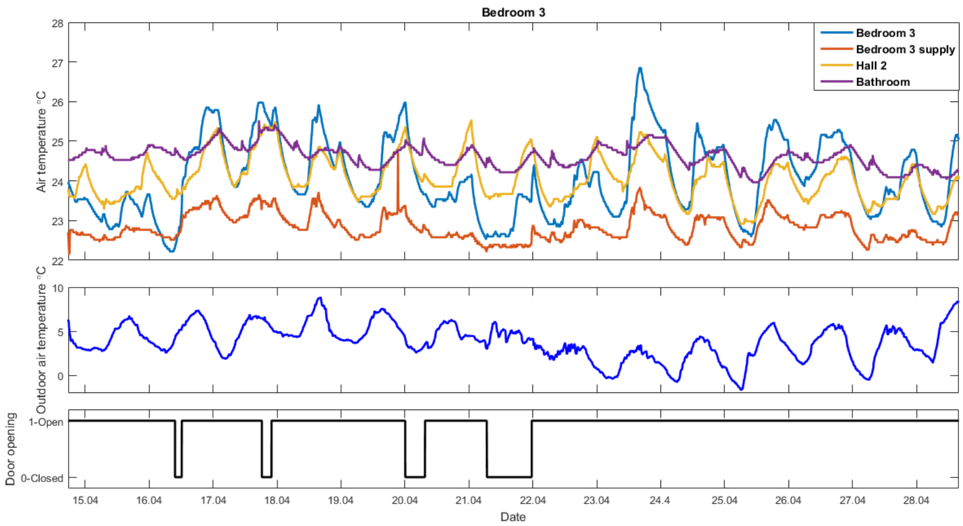

Figure 2.9: *temperature distribution in bedroom 3, hall 2 and bathroom and supply air temperature, in the middle part the outdoor temperature and in the lower part the opening/closing of bedroom 3 door.*

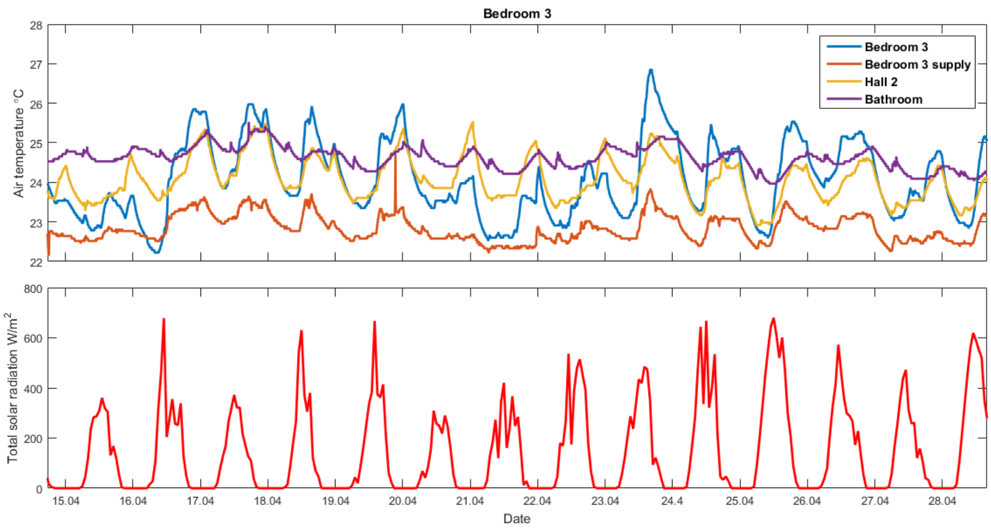

Figure 2.10: *temperature in rooms influencing bedroom 3 in house 2, the lower part shows the total solar radiation measured at a horizontal surface at Gløshaugen weather station 3 km away from the house.*

The bedroom temperature typically increases from 10:00-12:00 and reaching the peak 15:00-17:00. The peaks match well with the measured total solar radiation at the time, as the bedroom is facing south. The temperature in hall 2 is also influenced by the solar gains, because of one wall facing south. The impact is not as severe as in bedroom 3, but it has to be considered that the sensor is placed further away from the window than the sensor in bedroom 3. The temperature of the bedroom increases 1-4 °C when there are high solar gains measured. We can see the effect of the solar gains better by looking at Figure 2.10, where the hourly total solar radiation at a horizontal surface measured approximately 3 km away is also plotted. The average solar energy at a horizontal surface during the period is 3.54 kWh/m^{2}day.

2.4.4 Ventilation house 2

Temperature measurements performed inside the air handling unit are plotted in the upper part of Figure 2.11, along with the set point temperature of the air handling unit. It is clear that the supply air has a much higher temperature than the set point when leaving the air handling unit. From 04.03 to 10.03, the average temperature leaving the air handling unit is 26 °C, while the set point is ranging from 19 °C to 21 °C. From 10.03 to the morning of 11.03, the average measured temperature after the heating battery ($T_{S,HB}$=19 °C) is actually lower than before the heating battery ($T_{S,HR}$=19.66 °C), while the set point ($T_{SET,HB}$) is 21 °C. From the morning 11.03 to midday 12.03, $T_{S,HB}$ again increases to an average of 25.54 °C while $T_{S,HR}$ is somewhat constant around 19.62 °C. Then $T_{S,HB}$ stays around 0.6 °C below the temperature after the heat recovery unit. The remaining period the temperature after the heating battery is 2-5 °C higher than $T_{S,HR}$, aborted by temperature drops of the $T_{S,HB}$ for two minor periods.

There is a rapid increase in $T_{S,HB}$ to 29-30 °C (07.03) and 26-27 °C (14.03), at approximately the same time the set point temperature drops from 21 °C to 20 °C (07.03 and 14.03). This conflicts with the set point and contradicts the supposedly operation of the air handling unit. When the set point temperature drops from 21 °C to 19 °C (08.03 and 15.03), the heating battery seem to work more logically, $T_{S,HR}$ instantly drops 2-3 °C for both incidents. When the set point increases from 20 °C to 21 °C (07.03 and 14.03) there is no clear change and $T_{S,HB}$ stays constant. However, when the set point change from 19 °C to 21 °C (08.03 and 15.03) $T_{S,HB}$ slowly drops ~2 °C to approximately 2 °C higher than the set point. The temperature now corresponds better with the set point, but the action taken, an increase in set point temperature, do not correspond well with a temperature drop. From 08.03 to 15.03 the set point is constant at 21 °C, but $T_{S,HB}$ is not constant for that period.

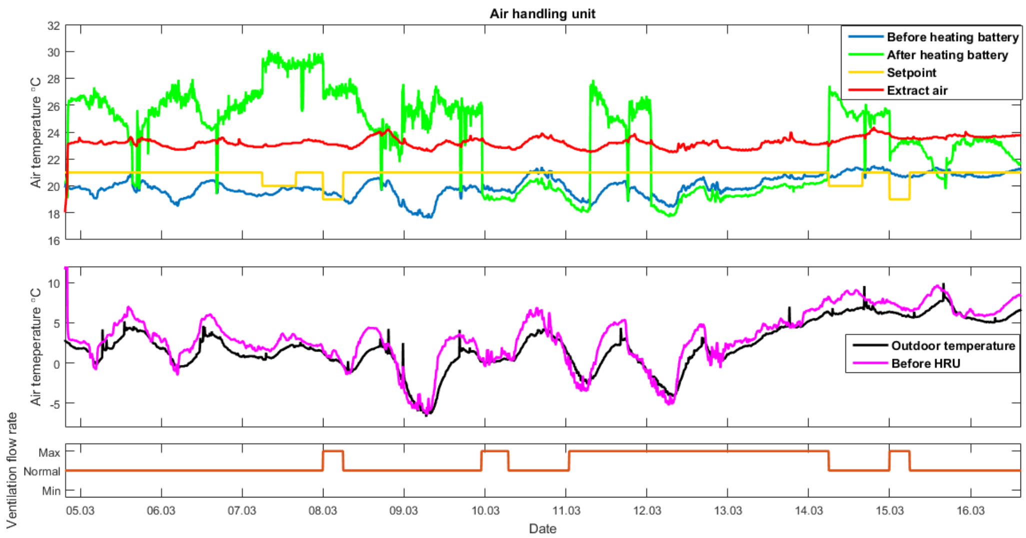

Figure 2.11: *temperature measurements inside the air handling unit in house 2 during a period in March, also showing outdoor temperature and flow rate of the ventilation.*

The temperature measured at the supply air terminals and after the heating battery in house 2 is plotted in Figure 2.12. One can see that there is 1-5 °C difference between the temperature measured after the heating battery and at the various supply air terminals.

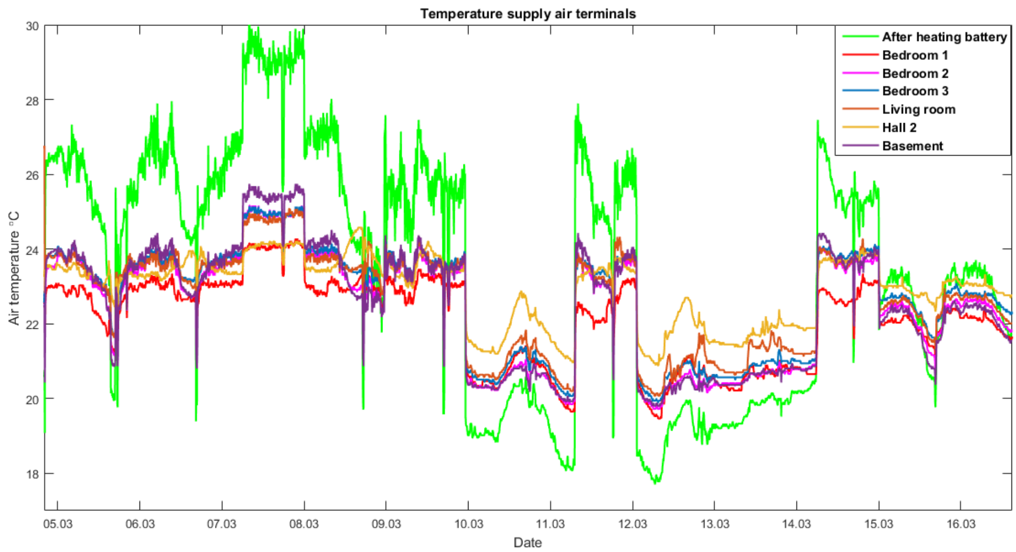

Figure 2.12: *temperatures measured at the supply air terminals at different spots in house 2.*

2.4.5 Ventilation house 3

For the ventilation system in house 3 it is important to have in mind that it was not possible to access the supply side of the air handling unit, which means the operation of the heating battery cannot be investigated for this house. As an approach, the mean average supply air temperature measured at the air transfer devices inside the house is used as the temperature after the heating battery. From house 2 it was observed that the air temperatures at the supply air terminals was lower than inside the air handling unit, and therefore are closer to the actual set point of the supply air. It cannot be concluded if that is also the case for house 3. There is a possibility that the air temperature after the heating battery is higher inside the air handling unit than the average of all the temperatures at the supply air terminals.

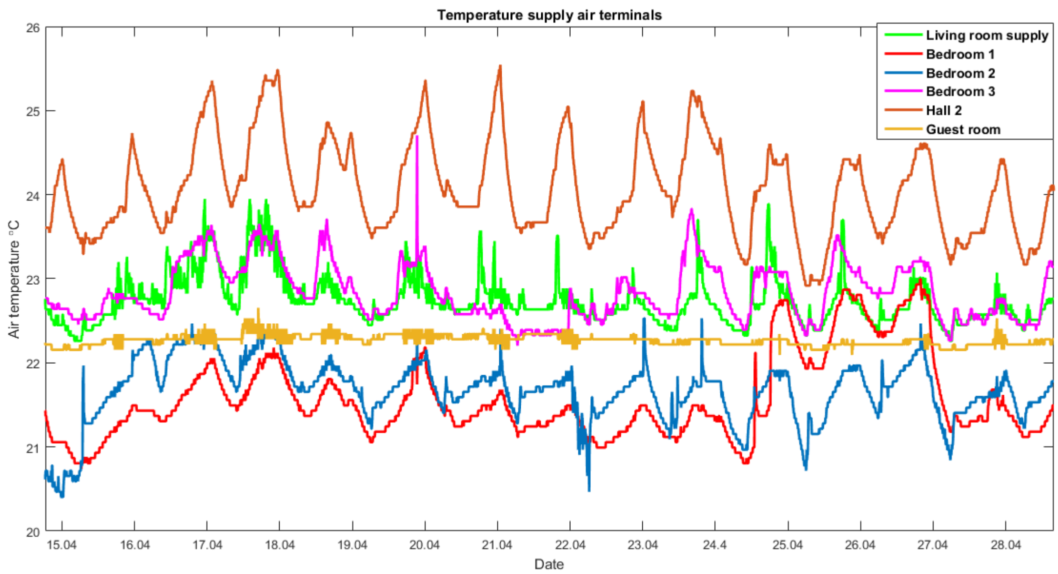

Figure 2.13: *temperature measured at the supply air terminals at different spots in house 3.*

The supply air temperature measured at the air terminals at different spots in the house is shown in Figure 2.13. One notices that the temperature in bedroom 1 and bedroom 2 is 3-4 °C lower than in hall 2. The temperature fluctuations and differences at the various air supply terminals indicates that the temperature sensors are influenced by the room temperature, and therefore cannot be applied as the exact supply air temperature.

In Figure 2.14, the performance of the air handling unit in house 3 is plotted. The heat recovery efficiency and the measurements inside the air handling unit are used to calculate the potential heat recovery with the following equation:

$$T_{HRP} = T_{BHR} + \eta_{HR} \cdot (T_{EXT} - T_{BHR}). \quad (1)$$

Where T_{HRP} is the potential temperature after heat recovery, T_{BHR} is the measured temperature before the heat recovery unit, T_{EXT} is the measured extract air temperature and η_{HR} is the heat recovery efficiency specified, in this case 88 %.

The extract air temperature is quite stable around 24 °C, which was also the case for house 2 (~23 °C). The supply air temperature is also almost constant, averaging 22.5 °C. This is 1.5 °C higher than the set point temperature, which was constant at 21 °C during the period. For house 2 the supply air temperature is 2.65 °C higher in average. The exhaust air temperature (T_{EXH}) is ranging from 15-22 °C and fluctuates accordingly to the outdoor temperature. When T_{BHR} increases, T_{EXH} also increases, and opposite when decreasing.

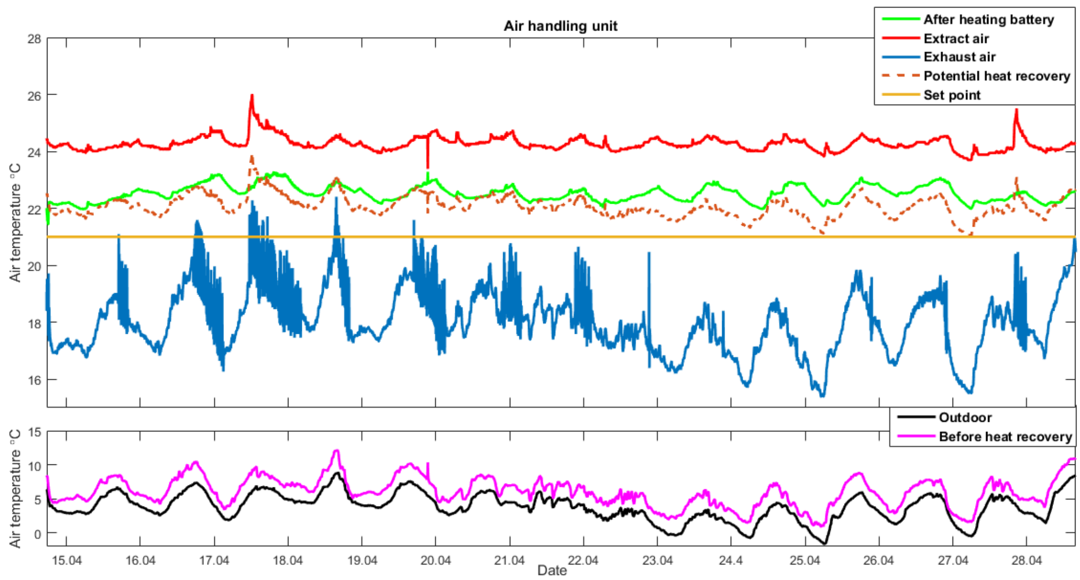

Figure 2.14: *the measured temperatures inside the AHU in house 3 and outdoor temperature during a period in April.*

The air entering the air handling unit is preheated in the intake ducts from outdoor to the air handling unit, which can be seen from the lower part of Figure 2.14. The average temperature difference is 2.20 °C, compared to 1.53 °C for house 2. This preheating of the air will increase the performance of the heat recovery and enable for a higher $T_{S,HRP}$.

2.4.6 Living room

When looking at Figure 2.15, the first thing one should notice is the large temperature drop 12.03, where the measured temperature near the thermostatic valve is dropping from 22 °C to 11 °C for a short period. The living room temperature measured further away from both the radiator and the balcony door is only dropping 1.5 °C. The living room temperature then increase to 24 °C throughout the day. At 06.03 and 09.03, the balcony door is reported open, but neither the thermostatic valve temperature or the living room temperature is particularly affected. This suggest that the door is barely open, as the open signal does not distinguish between 1 % or 100 % opening. The living room temperature is quite stable during the period, averaging 22.7 °C, which is close to the desired temperature reported in the interview, here ~22 °C.

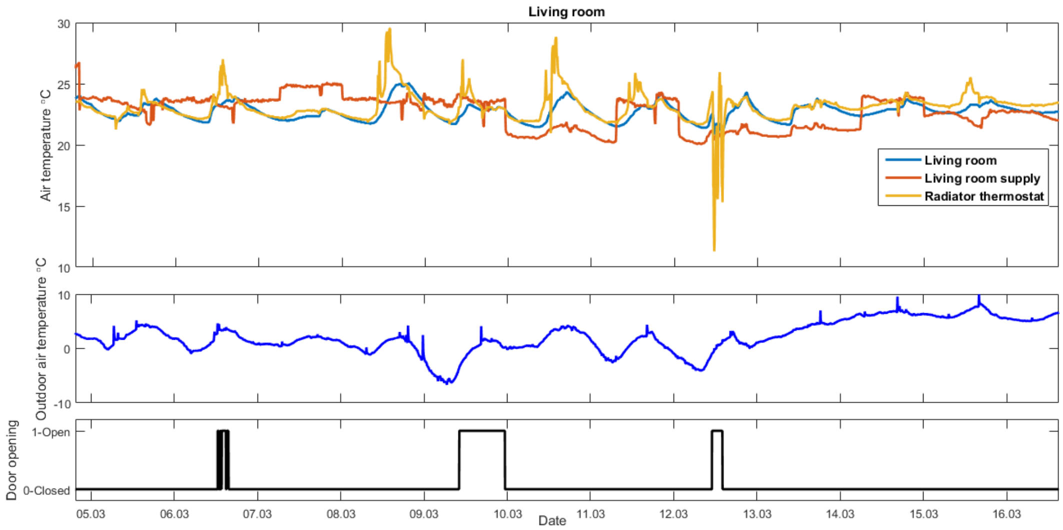

Figure 2.15: *measured temperature in the living room, radiator thermostat and supply air in house 2, while the middle part shows the outdoor temperature and the lower part shows the opening of the balcony door in the living room.*

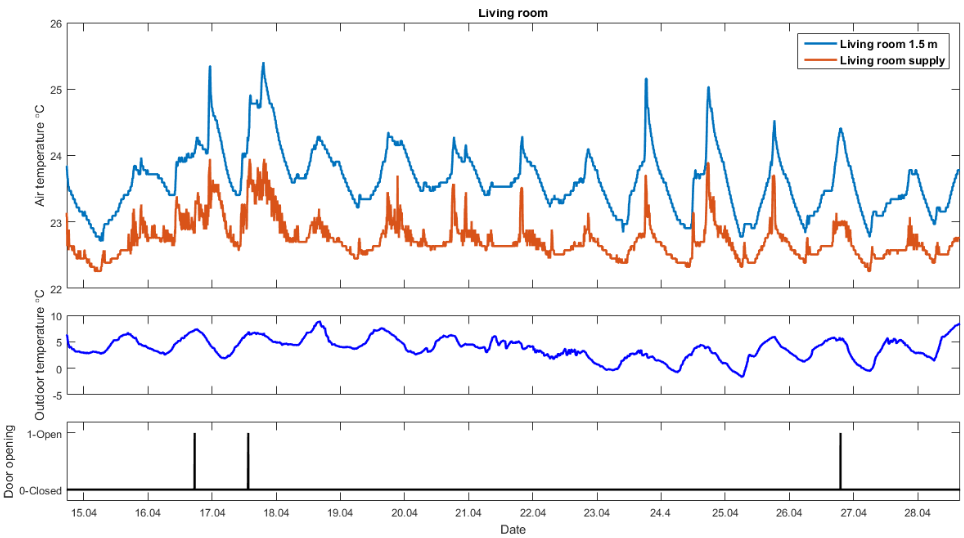

Figure 2.16: *measured temperature in the living room and supply air in house 3, and the outdoor temperature in the middle part while the lower part shows the opening of the balcony door placed in the living room.*

One dissimilarity between the living room in house 2 and house 3, is that house 3 does not have a radiator in the living room. The temperature in the living room is displayed in Figure

2.16, along with the outdoor temperature and the opening of the balcony door in the living room. The room temperature here fluctuates between 23-25 °C, and stays around 24 °C. The supply air temperature follows the same pattern as the temperature of the living room, ranging from 22.5-23.5 °C. The balcony door is opened three times but this does not impact the room temperature significantly.

2.4.7 Radiator 1 house 2

It was conducted measurements in house 2 for two periods, one in December and one in March. In Figure 2.17 the performance of the radiator in the living room are displayed for both periods. The set point temperature of 23.2 °C is the same for both periods. During the first campaign, the room temperature and the temperature measured at the thermostat position are slightly under the set point. The thermostat sensor is measuring the reference temperature that the thermostatic valve use to operate. This one is steadily higher than the room temperature measured further away from the radiator. The living room temperature is ranging from 21-24 °C, and the thermostat from 22-24 °C. The radiator is operating as expected.

During the second campaign, all measurements show larger and more frequent fluctuations. It is worth mentioning that the average outdoor temperature is 1.7 °C, 2 °C lower than during the first campaign. Here the radiator also operates as expected, with decreasing surface temperature when room temperature increases and vice versa. The room temperature exceeds the set point of 23.2 °C for longer separate periods than for the first campaign. The living room temperature is ranging from 22-25 °C when the balcony door is kept closed. The average measured temperature at the thermostat is 23.1 °C, which is very close to the set point (23.2 °C).

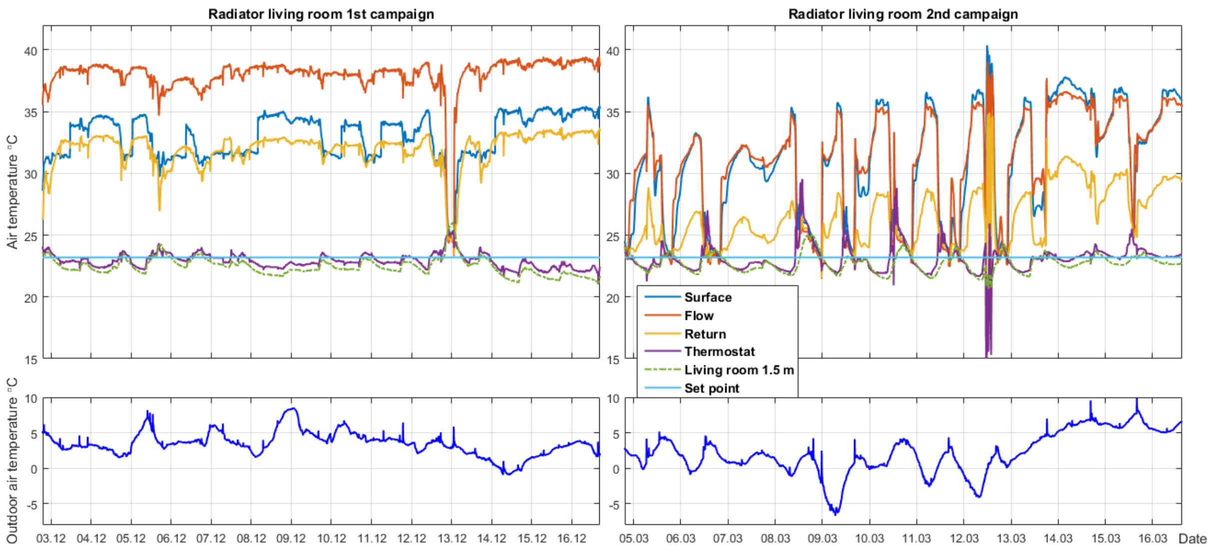

Figure 2.17: *the temperature distribution on radiator surfaces placed in the living room in house 2, for one period in December 2015 and one period in March 2016, while the temperature in the living room at 1.5 m is also plotted along with the outdoor temperature.*

2.4.8 Radiator 2 house 2

The operation of the radiator in the second floor follows the same pattern when comparing the two campaigns. For the first campaign all measurements show steadier radiator operation, and here the room temperature is higher than the set point. For the second campaign, there is larger temperature fluctuations measured at the different radiator surfaces. The room temperature is higher than the set point, ranging from 22-24 °C. As the room temperature is higher than the set point and there is heat emitted for both periods, there is a possible error in the measurements that will be further discussed in chapter 4.2.

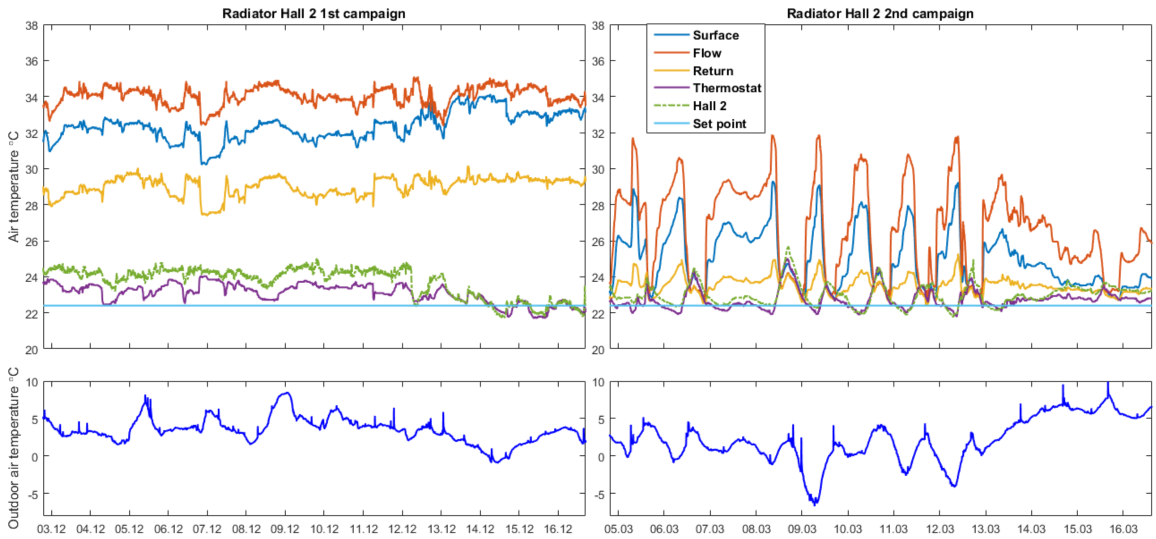

Figure 2.18: *the temperature distribution on radiator surfaces placed in hall 2, for one period in December 2015 and one period in March 2016, while the temperature in hall 2 is also plotted along with the outdoor temperature.*

2.4.9 Radiator 1 house 3

The operation of the radiator in the entrance hall in house 3 is very stable. Remember that this radiator is placed in the basement, and that there is no radiator in the living room of this house, as opposed to house 2. The temperature near the thermostatic valve is lower than the set point temperature during the period. It is 0.8 °C lower in average than the set point of 24 °C, while the temperature in the room is in average 22.4 °C.

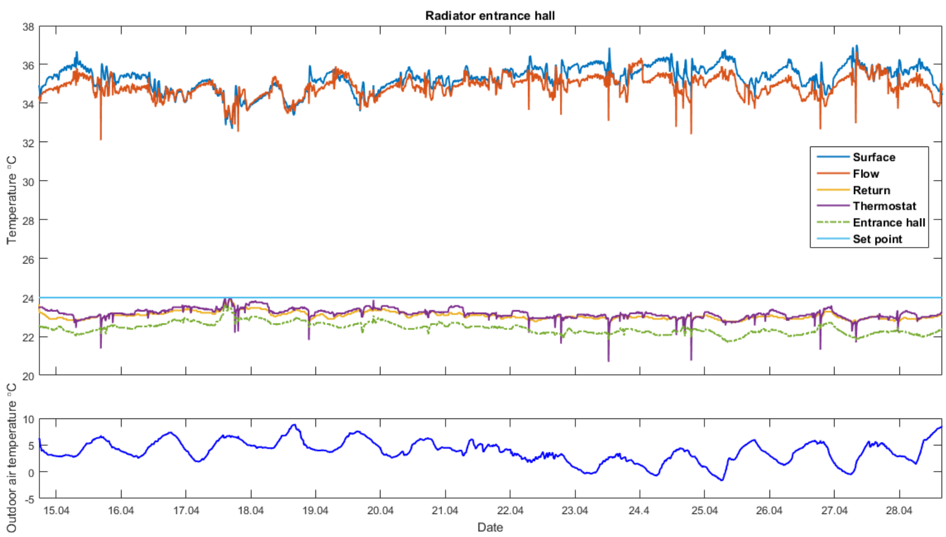

Figure 2.19: *temperature measurements on the surfaces of the radiator and room temperature in the entrance hall in house 3, with the lower part showing the outdoor air temperature.*

2.4.10 Radiator 2 house 3

Looking at Figure 2.20, one can see that it is difficult to distinguish between the different plots. This suggests a steady operation in which there is only a small or no flow through the radiator. The room temperature is also very similar to the temperature measured at the thermostatic valve.

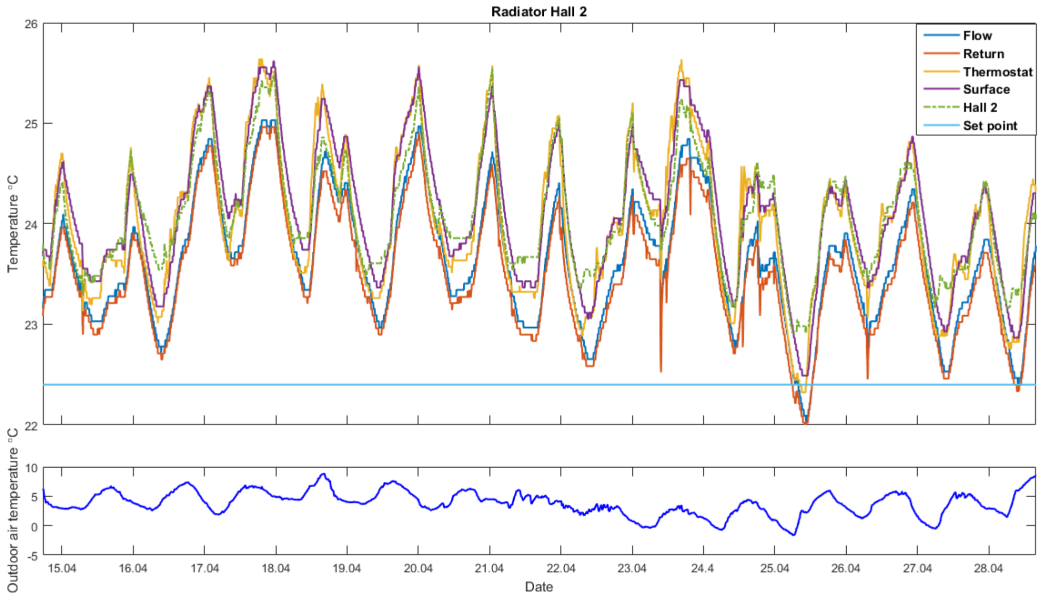

Figure 2.20: *temperature measurements performed on the surfaces of the radiator and the room air temperature in hall 2 in house 3, while the lower part shows the outdoor air temperature.*

3 SIMULATIONS

In this chapter, building simulations are calibrated and compared with the measurements performed. After the calibration, the thermal environment and energy efficiency is investigated using various simulations. Lastly the simulations are used to propose measures that can be applied to achieve high energy efficiency and thermal comfort.

3.1 METHOD

The row houses are modelled using the detailed dynamic simulation software IDA ICE 4.5. The dwellings are modelled according to given input data by the building contractors, and the basis of the model was obtained from a Master's thesis performed in 2015. Some adjustments of the model had to be made, and are explained in this chapter.

The row houses are divided into zones, where each zone represents a room. The placement of supply and extract air diffusers is found from drawings of the ventilation system by the building contractor, here using cascade flow ventilation with constant air volume (CAV) and temperature efficiency (η) of 88 %. The flow rates are also given in this drawing, and are calculated according to TEK10. The flow rates are added to the model along with the zone location of the supply and extract air. Note that the air transfer devices do not have any physical location in the simulation model, and that the ventilation is assumed fully-mixed along with uniform air temperature in each zone. SFP of 1.2 kW/(m^3/s) is added to the model and the efficiency of the electric heating battery is assumed 100 %.

The placement of the radiators in the row houses, as earlier mentioned in chapter 1.5.4, is found in drawings conducted by the building contractor, along with given nominal power for each radiator. Each row house has two radiators installed, and the placement varies for each house. In the simulation model, the radiators are added as the component *Water Radiator* with the given nominal power, and have a physical location and size.

As mentioned in chapter 1.5.4, both dwellings have electric floor heating installed in the bathrooms and technical room, while house 2 have electric floor heating all over the basement floor. The floor heating is added to the model by the component *Electric Floor Heating.* The actual installed power of the floor heating was not given, leading to an assumption of 100 W/m^2 in the bathrooms and 60 W/m^2 in the other rooms (Nexans, 2015). The floor heating in the model is controlled by a PI-regulator with air temperature sensor.

House 2 is an end row house with three facades towards the ambient air, while the east wall is connected to the neighbour row house. It is assumed the east wall is adjacent to a zone with the same temperature, the wall is therefore adiabatic in the model. House 3 is a middle row house and has two adiabatic walls and two walls facing the ambient air in the first and second floor. House 3 has the entrance in the basement, and the north basement wall is adjacent to the ambient air. The east and west wall in the basement is adiabatic, while the south basement wall is modelled as *connected to ground.* The basement in house 2 is under ground and is modelled as *connected to ground* for the south, west and north basement walls. The whole east wall is adiabatic.

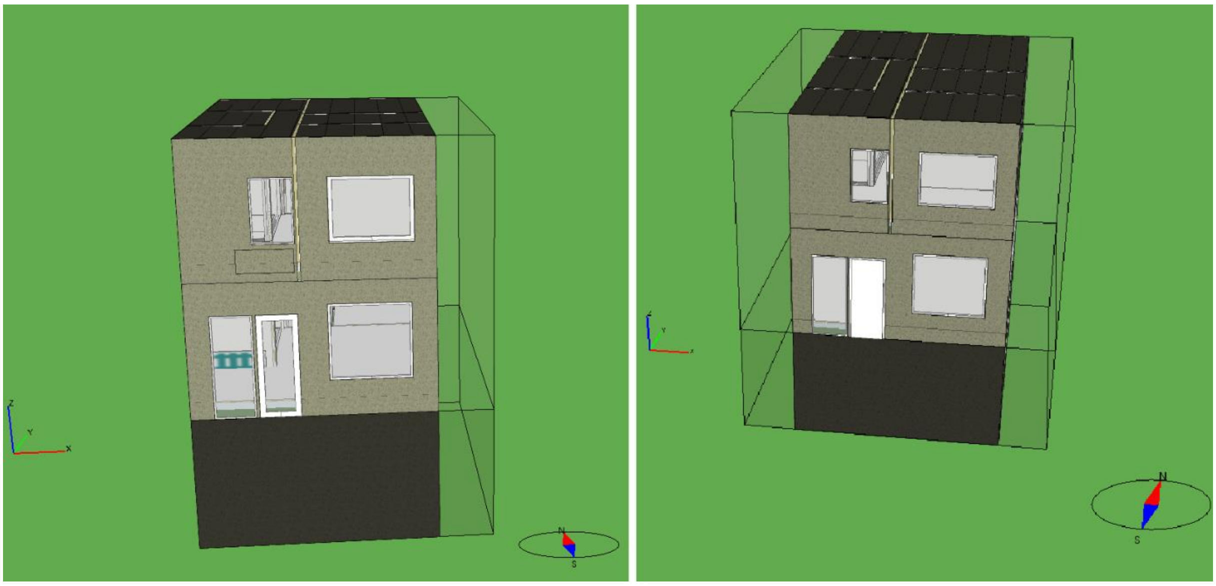

Figure 3.1: IDA ICE-model, house 2 on the left with adiabatic walls on the east side and house 3 on the right with adiabatic walls on the west and east.

NS 3700 internal gains are imposed to the model, and are uniformly distributed inside the building. The gains are 1.95 W/m^2 for lights, 1.8 W/m^2 for equipment and 1.5 W/m^2 for persons. Lights and equipment are scheduled to be on 07.00 to 23.00 every day, while person occupancy is set to always present (Standard Norge, 2013).

3.2 Model calibration

An important task for this thesis was to calibrate the simulations with the on-site measurements. When ensuring a good calibration of the simulation model, it is possible to take advantage of the software in order to represent the real case as accurate as possible (Cornaro, et al., 2016). This enables for altering the simulation model to run various scenarios and therefore predict the real performance of the building.

The first step is to make a weather file according to the weather during the period. The measured on-site outdoor air temperature is added, along with the measured total horizontal shortwave radiation at Gløshaugen approximately 3 km from the building. IDA ICE requires both diffuse and direct radiation, while only the total radiation is available. Therefore, the total radiation is assumed diffuse and the direct radiation is set to zero. The supply air temperature in the air handling unit during the measurement period is added to a file for the given time steps (every 6 minutes). This file is used as the schedule of the supply air temperature in the air handling unit in the IDA ICE simulations for the period 04.03-16.03 for house 2, and 14.04-28.04 for house 3. This is also done for the opening/closing of doors and windows, ensuring the opening schedules in the simulation are close to the reality. At last, the set point temperatures from the radiators and electric floor heating are added to the model. Manually controlled external shading is added according to diary written by occupants for house 2.

Results of the calibration of house 2 are shown in Figure 3.2, Figure 3.3, Figure 3.4 and Figure 3.5. It is chosen to focus on the bedrooms in the second floor, and the living room/kitchen in the first floor, as these are the rooms with highest occupation time.

Looking at Figure 3.2, we can see that for bedroom 1 the temperature in the simulations is around 2 ℃ higher than measured during the whole period. The bedroom door is open most of the time, which in theory would lead to a small temperature difference between bedroom 1 and hall 2. Here the temperature measurements show a difference of 1-2 ℃. For the simulation, the temperature difference is small between hall 2 and bedroom 1.

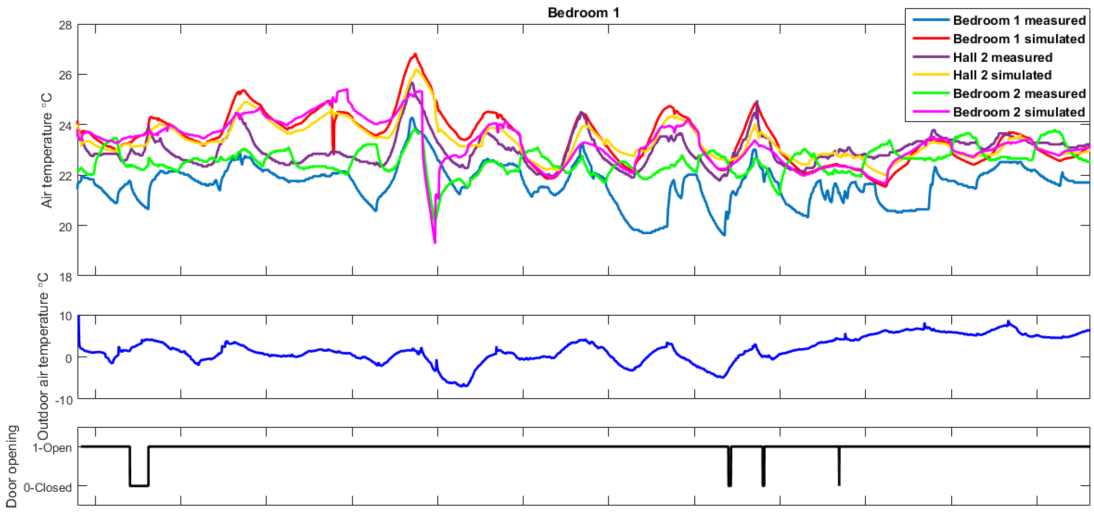

Figure 3.2: *Calibration of the model of house 2 shows the temperature in bedroom 1 and the temperatures influencing bedroom 1, with outdoor air temperature (middle part) and bedroom 1 door opening (lower part) also plotted.*

As displayed in Figure 3.3, the simulated temperature in bedroom 2 is ~2 ℃ higher than measured during the while period. The temperature in hall 2 and bedroom 1 is influenced by the window opening 08.03, which can be seen for both the simulation and measurements. From 09.03 to 16.03, the temperature in the simulation and measurements in hall 2 is close to equal.

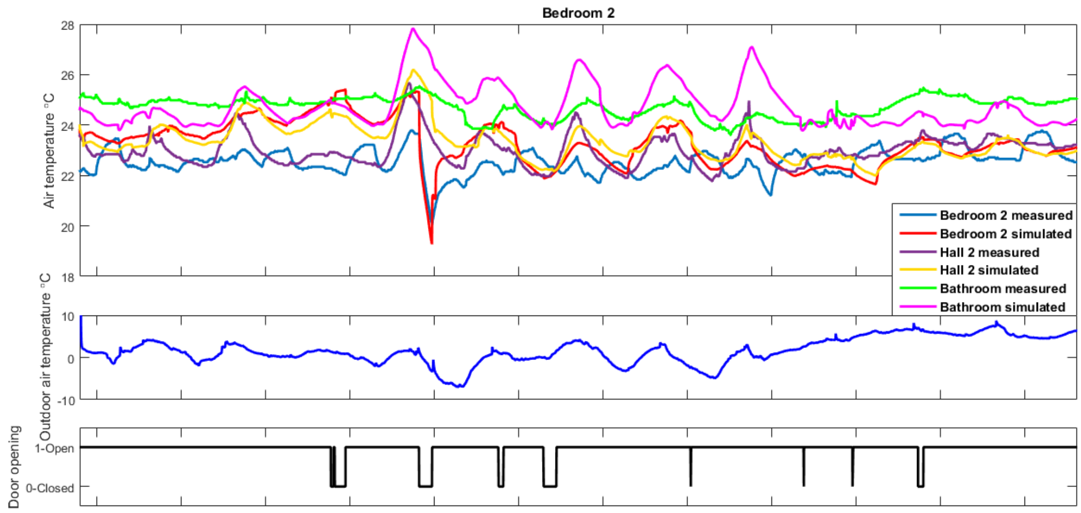

Figure 3.3: *Calibration of the model of house 2 shows the temperature in bedroom 2 and the temperatures influencing bedroom 2, while the outdoor air temperature is plotted in the middle graph and bedroom 2 door opening in the lower graph.*

Moving on to Figure 3.4, the measured bathroom temperature is stable around the set point of 24 °C, while the temperature in the simulation has larger fluctuations. For bedroom 3 the simulation is able to reproduce a relatively satisfactory temperature distribution, while the measurements are likely more affected by the increased solar gains than the simulation suggests. It is possible that the door is not fully open, which would lead to higher temperature in the bedroom in the simulation. The measurement shows that the bathroom temperature is slightly influenced by the temperature change in adjacent rooms.

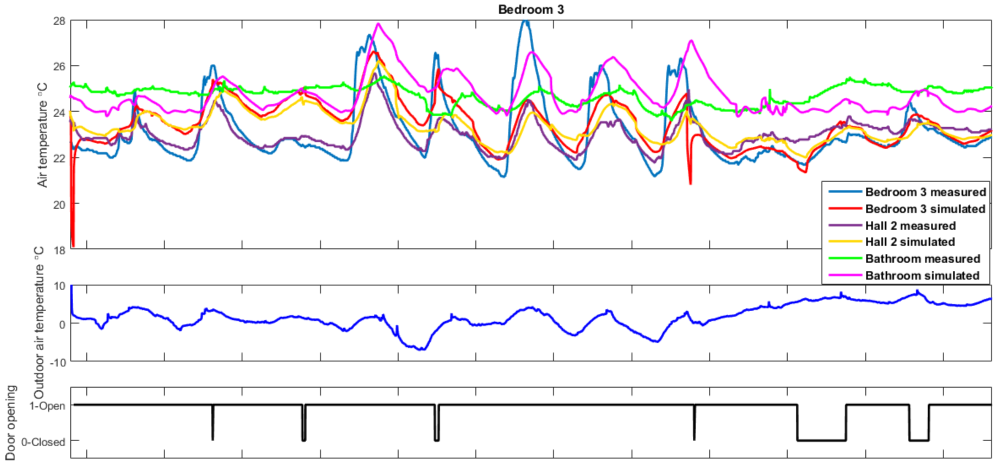

Figure 3.4: *Calibration of the model of house 2 shows temperature in bedroom 3 and the temperatures influencing bedroom 3, while the outdoor air temperature is plotted in the middle graph and bedroom 3 door opening in the lower graph.*

Figure 3.5 illustrates the temperature in the living room and entrance hall. The simulations are not able to perfectly reproduce the temperature distribution in the first floor, but the trends are well reconstructed. It is worth remembering that the living room temperature is uniform over a large area in simulations, while temperature sensors for the measurements are located at a single point. The measurements show that the temperature is ~1 °C lower in the hall than in the living room, while in the simulation the difference is minimal. The living room is more influenced by the balcony door opening in simulation, in which 10 % opening is assumed.

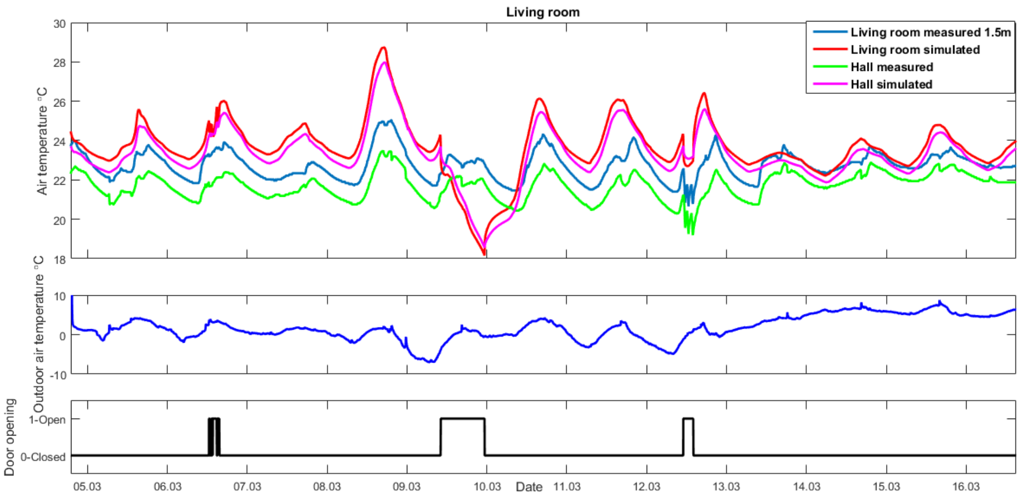

Figure 3.5: *Calibration of the model of house 2 shows the temperature in the living room and hall in the first floor, while the outdoor air temperature is plotted in the middle graph and the living room balcony door opening in the lower graph.*

For house 3 it is necessary to do further adjustments in order to ensure a better calibration. It was not possible to obtain information about the exact control of the automatically controlled screen, so an assumption is made. The assumption is that the window in bedroom 3 is set to draw the external screen when solar radiation on internal surface exceeds 100 W/m^2, the same is done with the most east window in the living room. The balcony door and nearby window only have manually controlled screen, and they are set to be drawn at after work hours from 16.00-20.00 on weekdays, and 10.00-20.00 on weekends and holidays. This was based on details from the user interview. It is introduced internal drapes, (light, tightly woven internal drape) in the windows in bedroom 1 and bedroom 2, and one window in the kitchen. It was not possible to link the north wall in the basement to the ambient air, as the wall is set from -3 m to 0 m, when using 0 m as reference point. A simplification is then introduced, assuming the wall is connected to a surface with a constant temperature, here using the average outdoor temperature of 2 °C during the period.

As the ventilation contractor went bankrupt, it was not possible to obtain drawings of the ventilation system. Therefore, the same air flow rates as in house 2 is used. In the basement, the air is supplied in the guest room, and extracted in the technical room and the basement bathroom. There was no display showing the set point for the floor heating in the basement bathroom, so the same set point temperature as in bathroom in the second floor is used (25 °C).

Figure 3.6 shows the measured and simulated temperature distribution for bedrooms in house 3. As can be seen from the figure, the simulations are not able to perfectly reproduce the temperature distribution. For bedroom 1 the simulations produce a temperature 2-3 °C higher than measured, while for bedroom 2 the minimum points are equal. The maximum points are 1-2 °C higher for the simulation. However, for bedroom 3 the simulation shows a lower temperature than for the measurements.

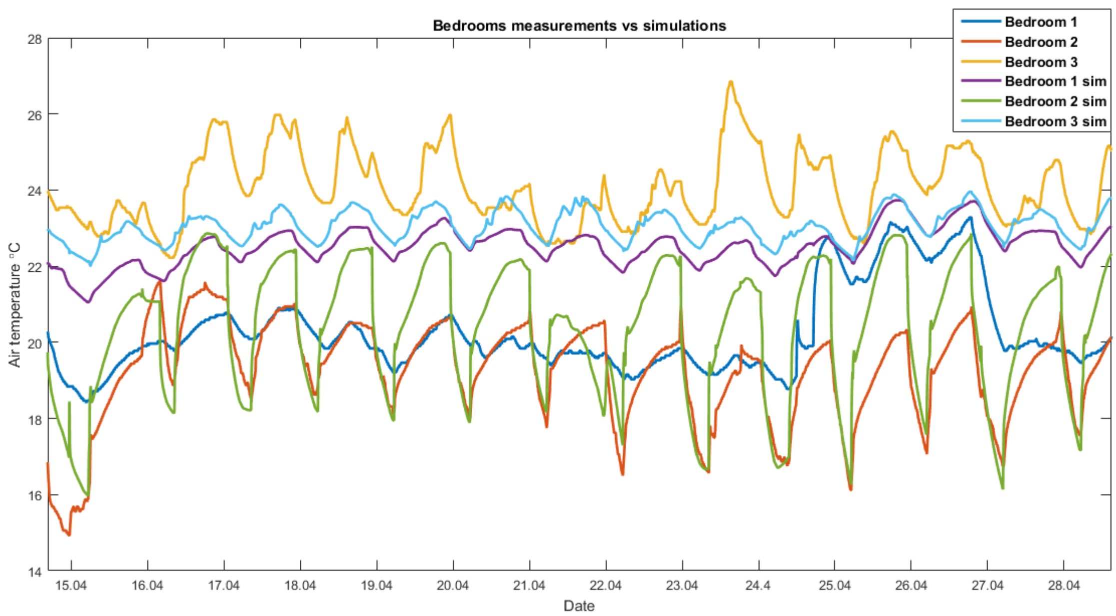

***Figure 3.6**: measured and simulated temperature distribution in bedrooms in house 3.*

As mentioned, the temperature in bedroom 1 is 2-3 ℃ higher in the simulation compared to measurements. As can be seen in Figure 3.7, the bedroom temperature is closer to the measurements when the door is opened. The temperature in bedroom 1 is influenced by the temperature drop in bedroom 2, and decreases around 0.5 ℃ for both simulation and measurements.

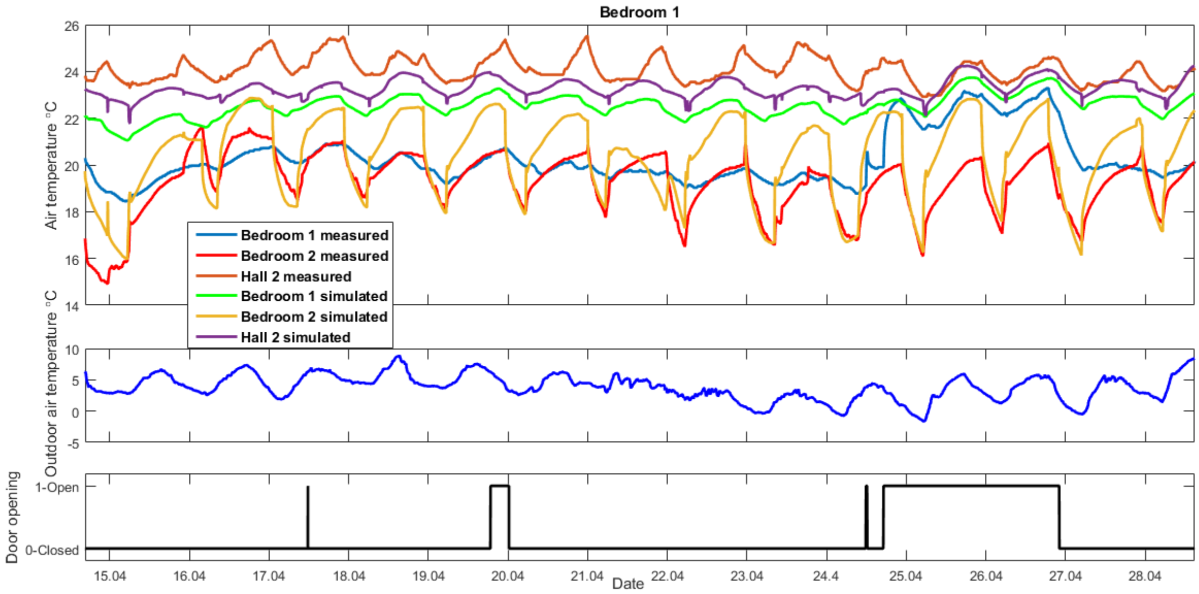

Figure 3.7: *temperature in bedroom 1 and temperature influencing bedroom 1 for both measurements and simulation, with the outdoor temperature in the middle graph and bedroom 1 door opening in the lower part.*

Measured and simulated temperature in bedroom 2 and adjacent rooms is displayed in Figure 3.8. The opening of the window in bedroom 2 follows a routine and the temperature is clearly influenced accordingly. The simulation produces an average temperature 1.3 ℃ higher than the measured. The simulation is able to reproduce satisfactory temperature in the bathroom, with a difference between measurements of 0.2 ℃ in average.

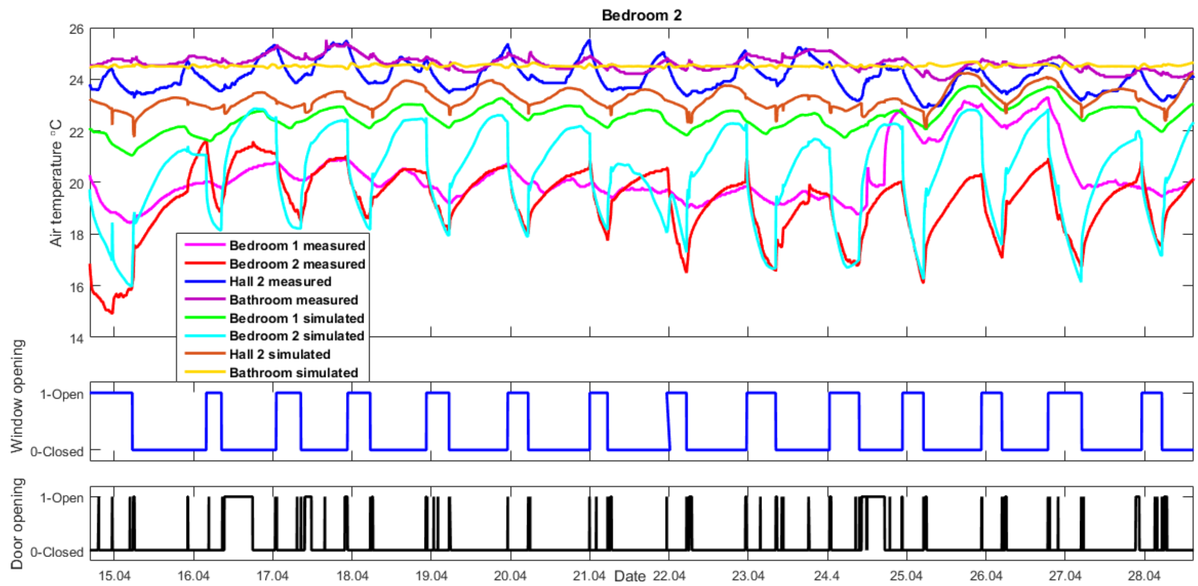

Figure 3.8: *temperature in bedroom 2 and temperatures influencing bedroom 2 for both simulation and measurements, with bedroom 2 window opening shown in the middle plot and door opening in the lower plot.*

Bedroom 3 is the only bedroom where the temperature is lower for the simulation, as can be seen in Figure 3.9. The measured bedroom temperature is here supposed to be influenced by a larger amount of solar gains. The automatically controlled external screen in the bedroom are set to draw when the solar radiation on the internal window surface exceeds 100 W/m^2, which might not be the case in reality. There could also be questions asked about the actual opening of the door, here using 100 % in the simulation model.

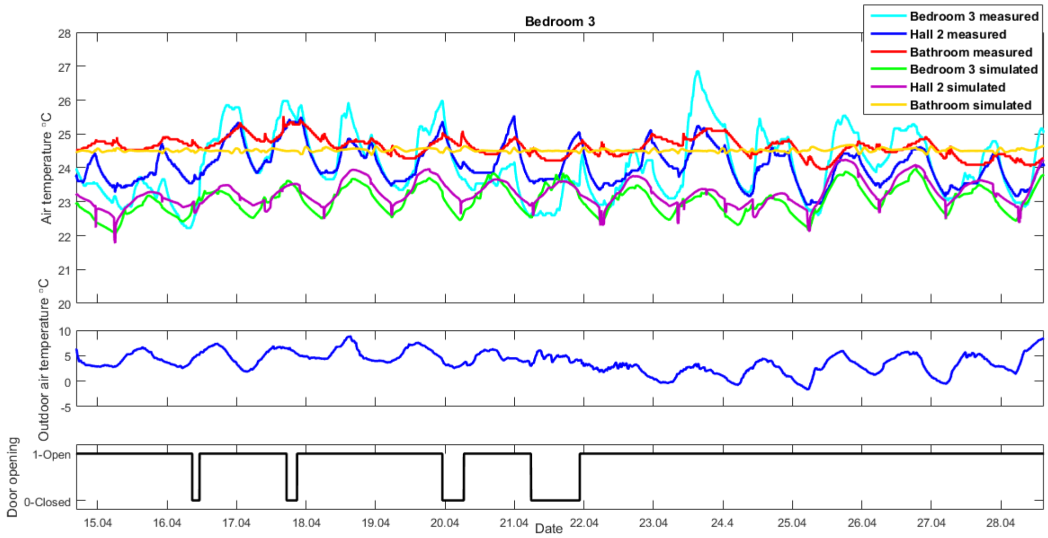

Figure 3.9: *temperature in bedroom 3 and temperatures influencing bedroom 3 for both measurements and simulation, while the outdoor temperature is plotted in the middle graph and bedroom 3 door opening in the lower part.*

Figure 3.10 displays the temperature in the living room and the kitchen. The simulation reproduces a satisfactory temperature in the living room, although not perfect. The simulation seems to be affected to a larger amount by the increased solar gains. In the kitchen, the difference is larger with higher temperature for the simulation. Right before the solar gains starts to influence the building, the temperature for the simulation and measurements is close to equal.

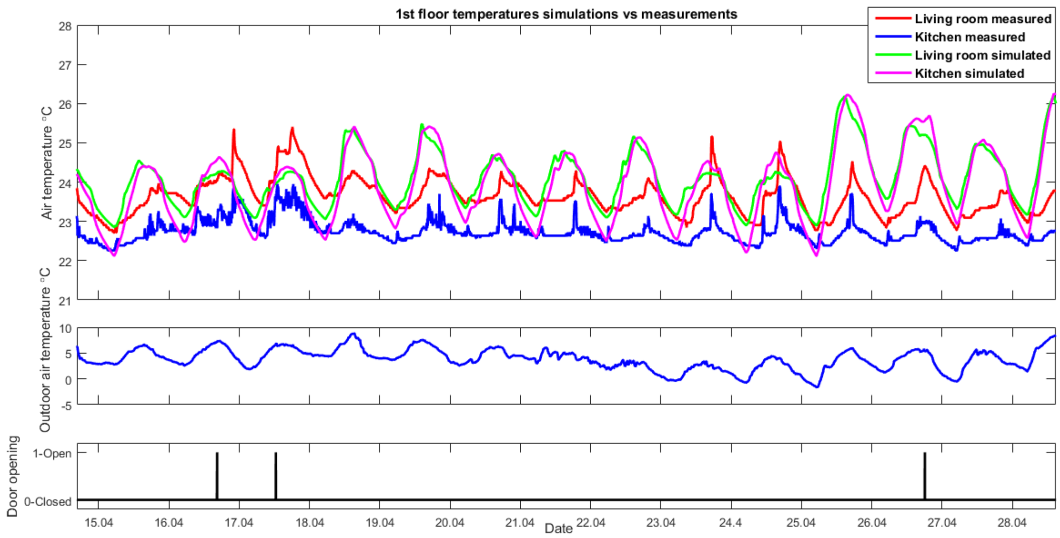

Figure 3.10: *temperature distribution in the first floor for both simulation and measurements, with the balcony door opening in the living room displayed in lower plot.*

The greatest contrasts between the simulation and measurements occur in the basement. This is also the floor where there are most uncertainties regarding the simulation model. From Figure 3.11, we can see that the measured bathroom temperature is around 1 °C higher than simulated, while the guest room have more stable measured temperature during the period compared to the simulation. The temperature in the simulation is higher in the entrance hall than for the measurement, here 2-3 °C higher.

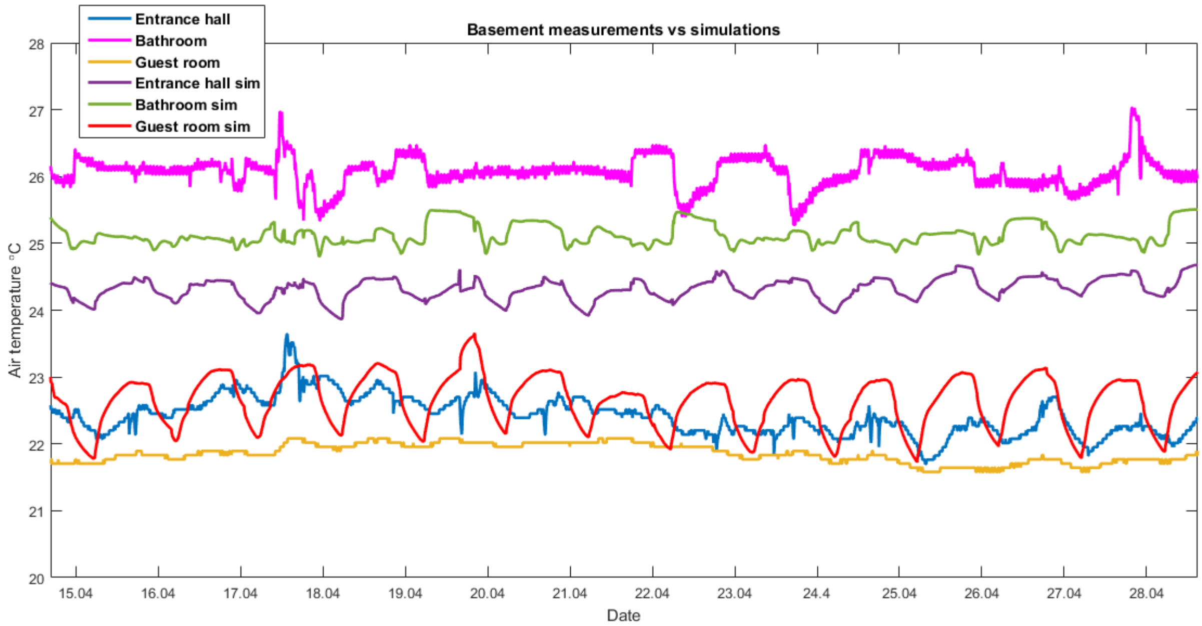

Figure 3.11: *temperature distribution in the basement in house 3 for both simulation and measurements.*

3.3 Investigation strategies

The underlying goal for the building simulations is to suggest possible control strategies for the ventilation and heating system, along with the opening/closing of windows and internal doors. When using balanced mechanical ventilation, it is desired to keep windows closed and use the technical systems to maintain a satisfying thermal comfort. To determine what control strategies that could be further assessed, several preliminary investigations are performed. The preliminary investigations chosen to examine are the effects of the following: internal door openings, supply air temperature set point, thickness of internal walls and radiator thermostat set point. It is not necessary to examine if it would be any effects of opening windows, as it obviously will affect the indoor temperature. For the investigations, only house 2 is used as the baseline, as the effects would be approximately the same for both houses when not considering the different boundary conditions.

3.3.1 Internal door opening effect

Demonstrated by Feis et al., with a temperature difference of 1 K between rooms approximately 10 W heat can be transferred through an air transfer device, for instance a small gap under the door, with a flow rate of 30 m/h^3 (Feist, et al., 2005). With 1 K temperature difference between rooms, a heat transmission of 10-20 W occurs through a 10 m^2 wall. For the same temperature difference between two rooms, multi zone air flow simulations and CFD calculations show that 100-200 W of heat can be transferred through an open door.

With this information in mind, investigations are carried on using simulations with various opening schedules for doors. The reference situation is the situation with the measured door openings and measured ventilation operation. Simulations with internal doors being kept closed all the time, are carried on to use as a comparison with the doors opened according to the schedule.

Displayed in Figure 3.12, from 04.03 to 10.03 the temperature in bedroom 1 will be around 1 °C lower when the internal doors are kept closed. The remaining period the temperature will be 1-2 °C lower, and 1.5 °C in average over the whole period. The temperature in hall 2 will be slightly higher most of the time when all doors are closed compared to open according to the schedule.

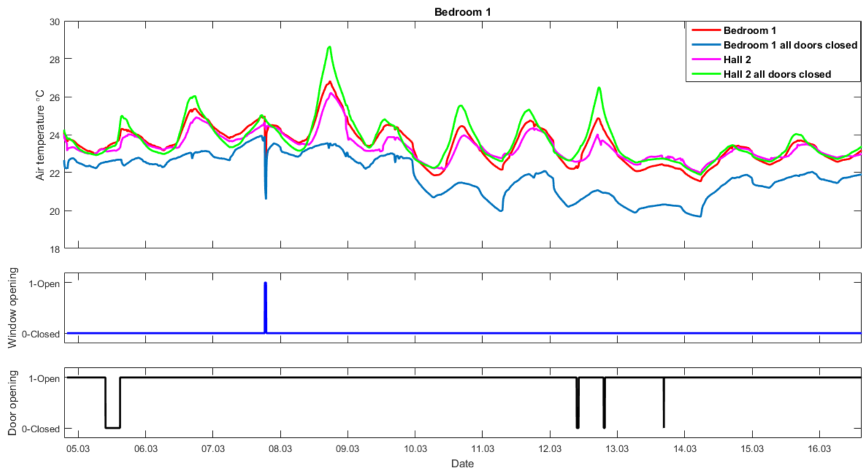

Figure 3.12: *showing the difference in bedroom 1 when doors open according to schedule and when closed all the time, while also showing the measured and simulated temperature in hall 2.*

In bedroom 2 the temperature when doors are closed and when opened according to the schedule, will be almost the same before the window is opened, which can be seen in Figure 3.13. After the window opening, the temperature will be ~1 °C lower when doors are kept closed.

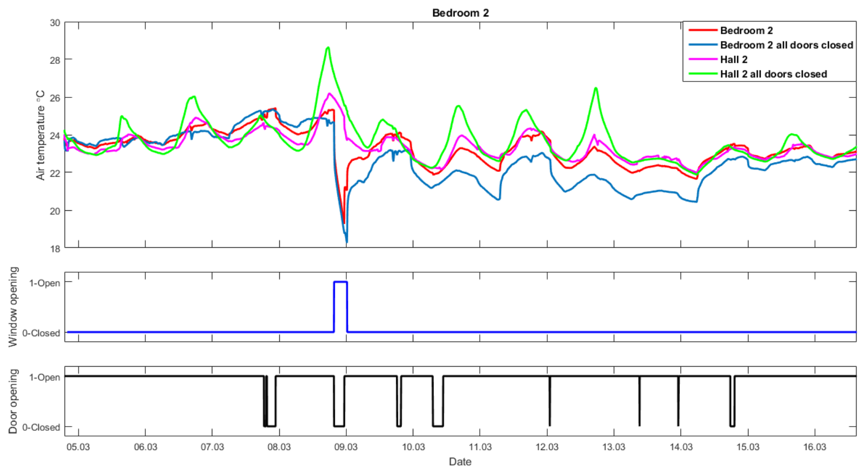

Figure 3.13: *bedroom 2 showing difference when doors open according to schedule and when closed all the time, also showing the measured and simulated temperature in hall 2.*

Almost the same can be seen in Figure 3.14, the all doors closed case will have a higher temperature most of the time in bedroom 3 before the window is opened. After the opening (12.03) the temperature will be lower.

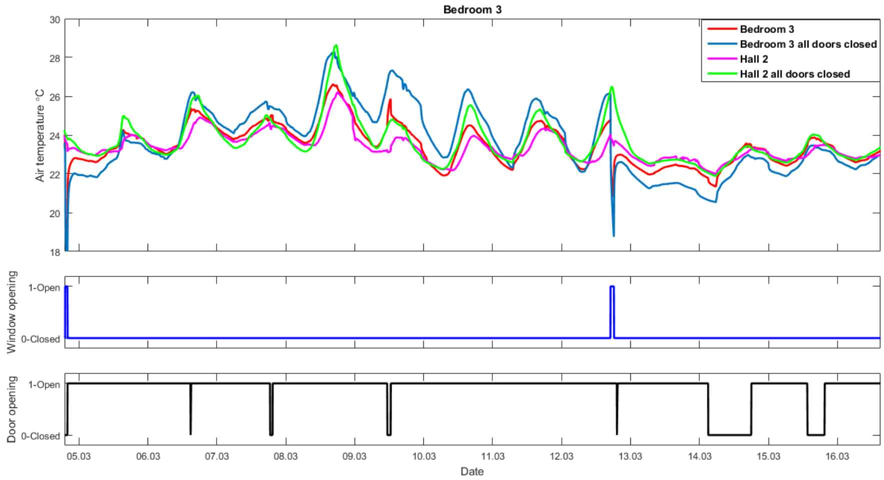

Figure 3.14: *showing temperature difference in bedroom 3 when doors and windows are open according to schedule and when doors are closed all the time, also showing the measured and simulated temperature in hall 2.*

3.3.2 Supply air temperature investigation

To investigate the supply air temperature influence on the room temperature, simulations with different supply air temperature are performed. It used constant supply air temperature in all rooms. Schedule for opening of doors and windows are kept unchanged, along with set points for thermostatic radiator valves. Internal gains from humans, equipment and lighting are uniformly distributed, using internal gains obtained from NS 3700.

3.3.2.1 Bedroom 1

We can see from Figure 3.15 that the measured temperature in bedroom 1 during the period is in good accordance with the building simulation, using the real set points for ventilation and radiators. The trends are quite similar, while the biggest differences occur during the peaks. The reduction in $T_{set,HB}$ shows that it is possible to reduce the bedroom temperature by only using the ventilation as a measure. The corresponding T_A in the zone will then be approximately 1 °C higher than the $T_{set,HB}$.

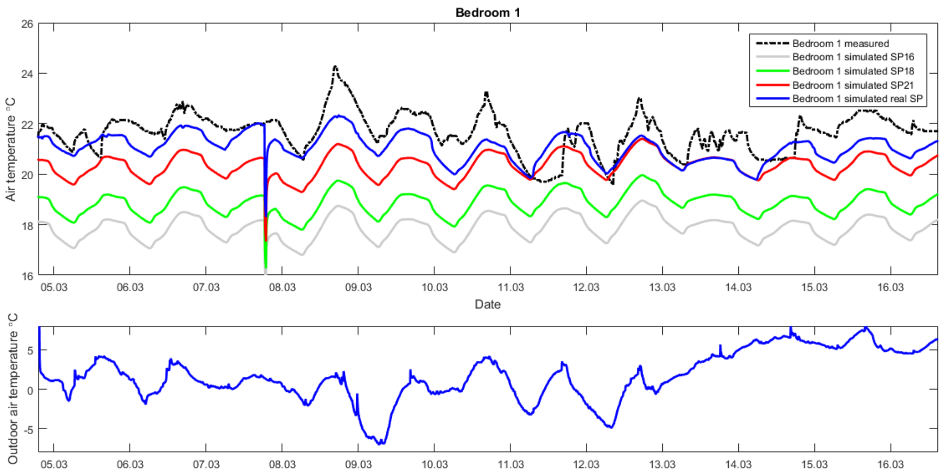

Figure 3.15: *comparison of different set point temperatures for the ventilation with all internal doors are kept closed.*

3.3.2.2 Bedroom 2

While the simulation with real set points showed lower temperature for bedroom 1 than measured, this is not the case for bedroom 2. Here the simulations show higher bedroom temperatures than measured, but is still within an acceptable difference. This hints to suspicions regarding the reliability of the measurements of door openings. As can be seen in Figure 3.16, the bedroom door are supposedly open most of the time, while the occupants stated that the door used to be closed at least during night. There is a good chance that the door is almost closed for some periods during the measurements, and not fully open as is the case in the simulations.

Simulations suggest that also for this bedroom the air temperature (T_a) will be reduced when reducing the supply air temperature. However, for bedroom 2 the T_A will not be as low as for bedroom 1. This is likely because this bedroom has an adjacent wall of about 8.5 m^2 to the bathroom, which has high temperatures, ~25 °C. When supplying air with $T_{S,HB}$ of 16 °C, the corresponding T_A will be around 20 °C.

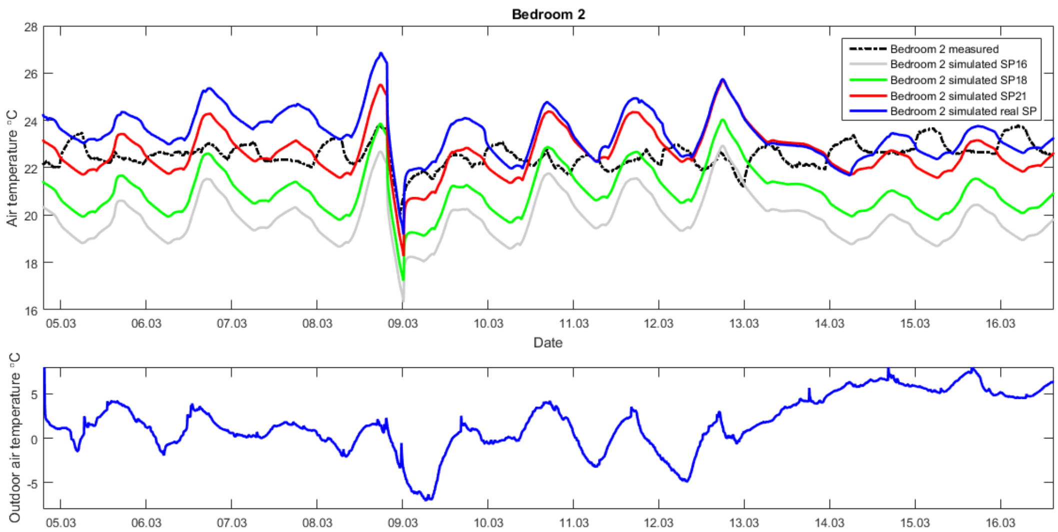

***Figure 3.16:** comparison of different set points temperature for ventilation in bedroom 2.*

3.3.2.3 Bedroom 3

This is the bedroom with the highest fluctuations and the highest mean temperature during the period. Both the fluctuations and the high temperatures can be explained by the fact that this bedroom is facing south, and is therefore more influenced by the solar radiation than other bedrooms. The measurements show that the temperature can be as high as 28 °C, even during winter when the outdoor temperature is about 2 °C. This bedroom is also influenced by having an adjacent wall to the bathroom, and having a radiator close in the nearby room.

Simulations points that the bedroom temperature while be quiet high (20-24 °C), even with low supply air temperature of 16 °C.

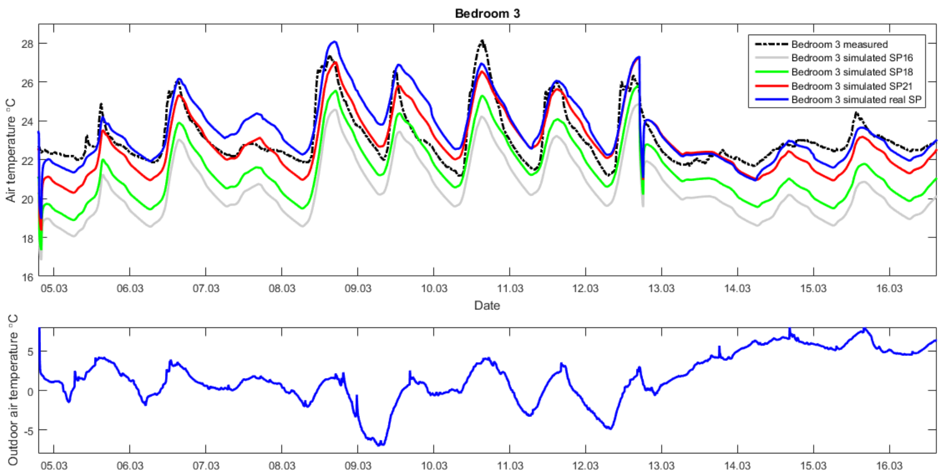

Figure 3.17: comparison of different set point temperatures in bedroom 3 and the measured temperature during the period.

3.3.3 Investigation of internal wall thickness effect on temperature

Simulations with different thickness of the internal walls in the second floor are performed. The U-value is adjusted from the original value of 0.40 W/m^{2}K to 0.15 W/m^{2}K, in order to investigate the effect of increased heat transfer coefficient between rooms.

The increase of the thickness of internal walls, hence the lowered U-value, showed minimal or no effect on the temperature distribution inside each room in the second floor, with internal doors kept closed. The results are not further reported for the sake of brevity.

3.3.4 Investigation of radiator thermostatic set point effect on temperature

Simulations with increased set point temperature to 24 °C for the radiators showed minimal effect on the bedrooms and bathroom, when internal doors are kept closed. The rooms where the radiators are placed, hall 2 and living room, showed a small increase in the temperature. The results are not reported for the sake of brevity. When introducing door openings, as shown in Figure 3.18, the bedrooms were more affected. It is chosen to only display the bedrooms, for the sake of simplicity. The living room and hall 2 will obviously be affected as the radiators are placed in these rooms. The temperature in all the bedrooms will increase ~1 °C when adjusting the set point to 24 °C.

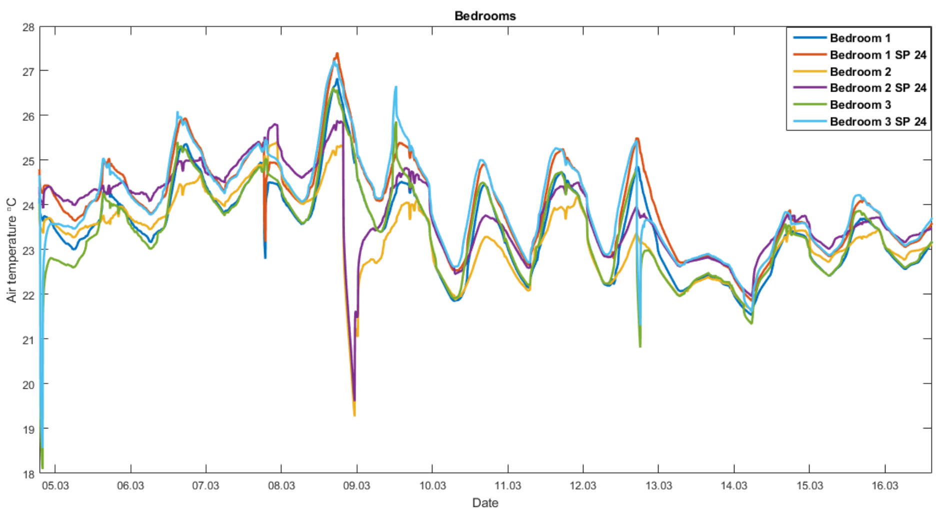

Figure 3.18: temperature in bedrooms with the real set points and set point of 24 °C for both radiators.

3.4 ALTERNATIVE CONTROL STRATEGIES

With the results in mind from of the possible measures applied to influence the temperature distribution, alternative scenarios were developed and investigated using systematic building simulations. For some strategies it has been chosen to open only the window for bedroom 2, where the adults live. For both house 2 and house 3, the windows in bedroom 1 and bedroom 3 were usually kept closed. The investigations are performed using the typology of house 2, with three facades facing the ambient air. It was chosen not to do the same kind of simulations with the models of both houses, as the results are assumed to produce no noteworthy differences. The different control strategies are listed under.

Control 0: the baseline control strategy corresponding to the real measurements.

Control 1: the set point of the ventilation is adjusted so that it corresponds to the supposedly values seen on the control panel. This control strategy corresponds to the set points that would have been used if no measurements had been performed.

Control 2: the set point of the heating battery is set to 16 °C, while the set point of the heat recovery wheel is according to the schedule. No further adjustments are applied.

Control 3: the set point for both the heat recovery wheel and the heating battery is set to 16 °C. No further adjustments are applied.

Control 3c: same as control 3 and adjusting the set point temperature for the radiator in hall 2 and living room to 16 °C during night (20.00-08.00).

Control 4: set point temperature of 14 °C for both heat recovery wheel and heating battery is applied.

Control 5: set point temperature of 16 °C for both heat recovery wheel and heating battery is applied. Window in bedroom 2 kept open all the time, bedroom door closed all the time.

Control 6: same as control 3, while window in bedroom 2 are kept open if the air temperature exceeds 16 °C.

Control 7: night setback for ventilation, using 16 °C supply air temperature 20.00-08.00 and 20 °C 08.00-20.00.

Control 8: separate supply air temperature for bedrooms. Using 16 °C supply air temperature for bedrooms and 21 °C for other rooms. Other conditions kept as in the baseline.

3.4.1 Simulations for the period

The reader is warned that it might be hard to distinguish between the different plots in the figures in this chapter. However, the figures are kept to display the effects, or the lack of it, when simulating different control strategies. The different control strategies are simulated for the measured period using the actual weather.

3.4.1.1 Bedroom 1

By looking at Figure 3.19, it is clear that the baseline strategy will keep the bedroom temperatures highest during the period when internal doors are constantly closed. Control 1 and control 2 reduce the average temperature by 2-3 °C. When adjusting the $T_{SET,HB}$ to 16 °C (control 3), separate bedroom supply temperature of 16 °C (control 8) and night-setback of $T_{SET,SH}$ to 16 °C (control 3c), the temperature will fluctuate around 17-18 °C. The ventilation night setback strategy (control 7) produces temperatures around 18 °C during the night and 19 °C during the day. The lowest temperatures occur with control 4 and control 5, here staying around 16-17 °C.

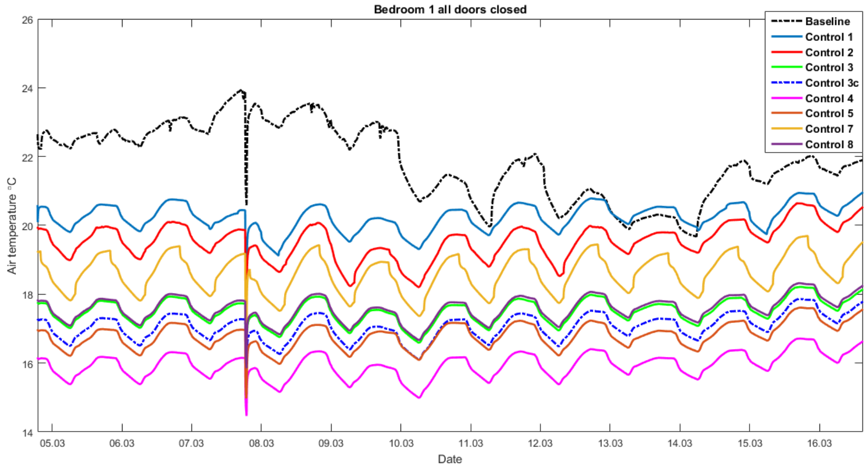

***Figure 3.19**: temperature in bedroom 1 for building simulations with different control strategies during the period a period in March, with all internal doors kept closed.*

When introducing door openings, the bedroom temperature will be different as can be seen in Figure 3.20. One clearly notices that control 5 will have distinctly lower temperatures than the rest of the strategies. Note also that the bedroom door is closed for control 5, as the opening would lead to drastically increased space-heating need. Here, control 7 will have the highest bedroom temperatures, while the highest average will still be for the baseline. The opening of the door produces higher temperatures for all strategies, because of the almost constant flushing of thermal mass in the bedroom. When internal doors are open most of the time, no control strategy would be able to keep the bedroom temperature as desired for occupants in house 3 (~16 °C), but control 3c and control 4 could satisfy the desired temperature for house 2 (~20 °C).

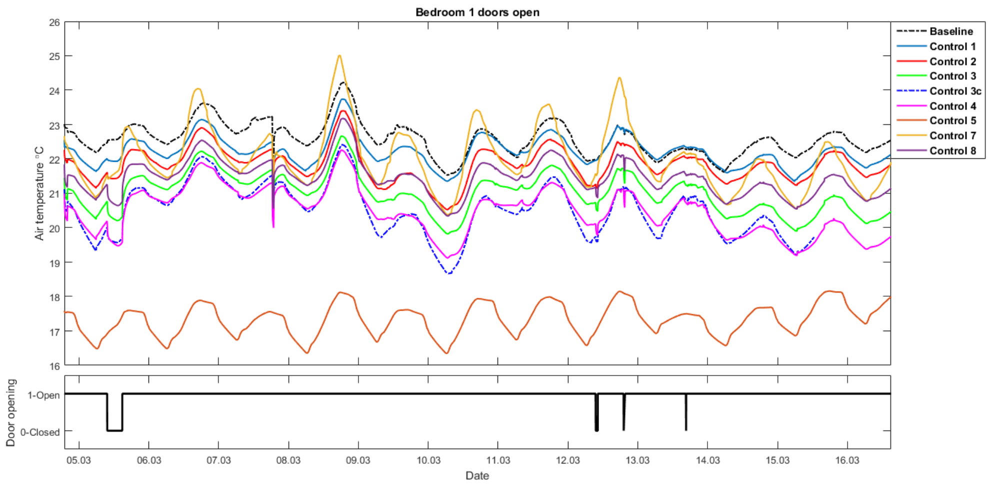

***Figure 3.20:** temperature in bedroom 1 for building simulations with different control strategies during one period in March, with all internal doors kept open according to schedule*

3.4.1.2 Bedroom 2

Figure 3.21 shows that the baseline strategy will have the highest bedroom temperatures during the period. With supply air temperature of 16 °C and windows open all the time (control 5), the lowest temperatures will occur, around 14-16 °C. When keeping windows open only when bedroom temperatures is lower than 16 °C (control 6), the temperature will range between 16-17 °C. This strategy also retains the most stable bedroom temperature for the period. The supposedly set points from the control panel (control 1), would have ensured a lower bedroom temperature than the baseline, but still higher than the rest of the strategies. When using the measured set point after the heat recovery and a heating battery set point of 16 °C (control 2), the average temperature is lowered 2.5 °C from the baseline. Applying 16 °C set point for heat recovery and heating battery (control 3), the temperature will stay around 18 °C. Control 8 will follow very much the same pattern as control 3. A small justification from control 3, when using night setback (16 °C) for radiators in hall 2 and living room (control 3c), the average temperature is lowered by 0.2 °C. Limiting the supply air temperature to 14 °C (control 4), temperatures will mostly range from 16-17 °C, with an average of 16.3 °C. This leaves control 7 with night setback not mentioned yet. Here the temperature fluctuates from 18-20 °C, gradually and simultaneously increasing and decreasing with the corresponding ventilation schedule.

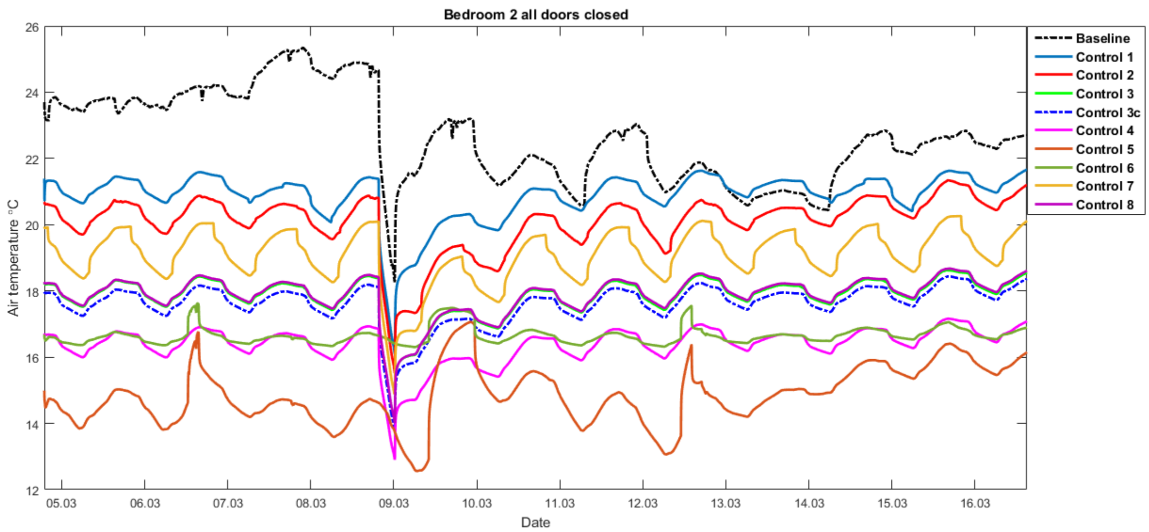

Figure 3.21: *building simulations with different control strategies during one period in March, with all internal doors kept closed.*

We can see that the opening of windows is an effective way of decreasing the bedroom temperature (control 5 and control 6). When the window is opened as function of the bedroom temperature (control 6) the temperature level will stay quite stable, while when windows kept open all the time (control 5) it will accordingly fluctuate with the outdoor temperature. One interesting result is seeing the reduction in the bedroom temperature that occur when applying the supposedly set points for the ventilation (control 1), compared to the baseline. Control 4 would be able to maintain temperatures right under 20 °C, with low supply air temperature of 14 °C.

Now moving on to the same control strategies, while also applying the door opening schedule according to the measurements.

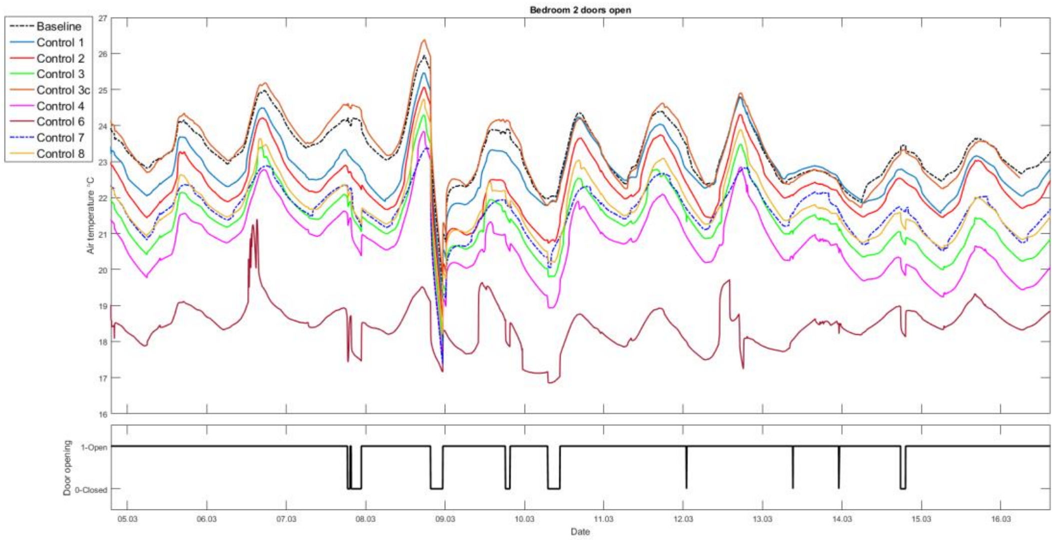

__Figure 3.22:__ building simulations with different control strategies during a period in March, with all internal doors kept open according to schedule.

For all strategies the bedroom temperature will be higher than for that with no opening. This is natural, as the temperature in the adjacent room hall 2 is higher. In addition, hall 2 contains a heat source in form of a radiator. This provides for a heat flow from hall 2 through the door opening to the bedroom. The bedroom temperature will be more similar to the temperature of hall 2 when the door is open. The radiator will add more heating power to keep the temperature in hall 2 according to the set point.

3.4.1.3 Bedroom 3

Bedroom 3 is the bedroom facing south, so this should be kept in mind when analysing the graphs. One notices in Figure 3.23 that this room is largely influenced by the solar gains, resulting in greater temperature fluctuations.

As for the other two bedrooms, the highest temperature for bedroom 3 will occur with the baseline strategy. The bedroom temperature would have been lower if the supposedly temperatures from the control panel (control 1) had been supplied by the air handling unit. Control 2 would further decrease the temperature ~2 °C in average from the baseline. When supplying a constant air flow of 16 °C (control 3) the bedroom temperature will range from around 18-23 °C, with 23 °C occurring when high solar gains are present. In order to further reduce the bedroom temperature, especially during the night, control 3c will ensure around 0.5 °C temperature reduction in average from control 3. The lowest bedroom temperature will occur when supplying air constant with 14 °C (control 4), resulting in an average of 18.5 °C. However, this strategy might lead to a cold draft. One possible solution to lower the bedroom temperature during the night, is to use night setback for the ventilation system (control 7). This is possible with the control panel in house 2. This would lead to an average of 20.7 °C, with the lowest of 17 °C occurring when window is open. The last strategy (control 8) is to have separate supply air temperature of 16 °C in bedrooms, and 21 °C in other rooms.

This would lead to a lower average temperature (19.9 °C) than control 7, ranging from 15.2 °C to 23.6 °C.

It was decided not to graph control 6 as the plot would look very much like control 5.

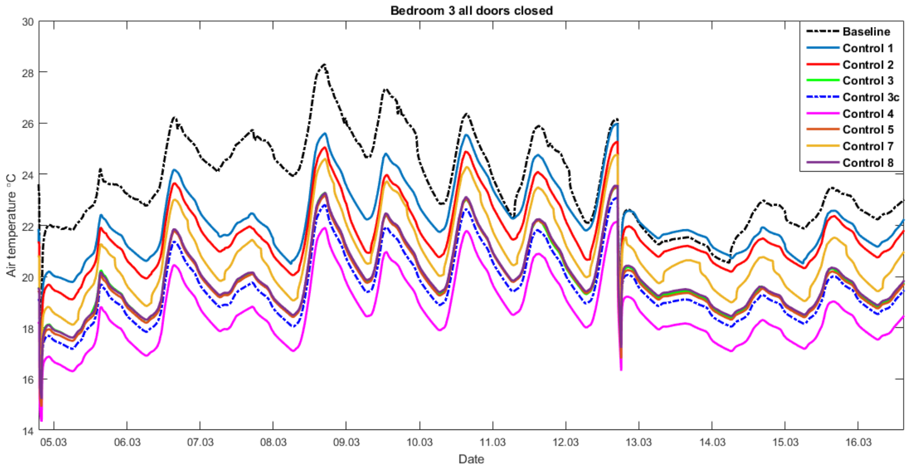

Figure 3.23*: building simulations with different control strategies during a period on March, with all internal doors kept closed.*

When adding opening of the door in bedroom 3 according to the actual schedule, the difference between the strategies will be less, as can be seen in Figure 3.24. The lowest average temperature (19.9 °C) occur with control 5, in which the window in bedroom 2 is kept open all the time and the door opened according to schedule. This shows that bedroom 3 will be largely influenced by the opening of the window in bedroom 2, when internal doors are kept open according to the schedule. The highest bedroom temperature will occur with the baseline strategy, with a maximum of 27.0 °C due to solar gains, and minimum 17.5 °C when the window is opened. Control 1 and control 2 will be almost identical, with average of 0.8 °C between them. The average for control 7 is slightly lower, and the strategy will not have enough time to cool down the room as much as control 3. With control 3, the temperature will range from 18 to 24 °C, with an average of 21.3 °C. Control 3c and control 4 will further reduce the average temperature to 20.9 °C for both. When having separate supply air temperature of 16 °C for the bedrooms (control 8, T_{avg}=21.9 °C), the bedroom 3 temperature will be slightly higher than when supplying 16 °C all over (control 3, T_{avg} =21.5 °C).

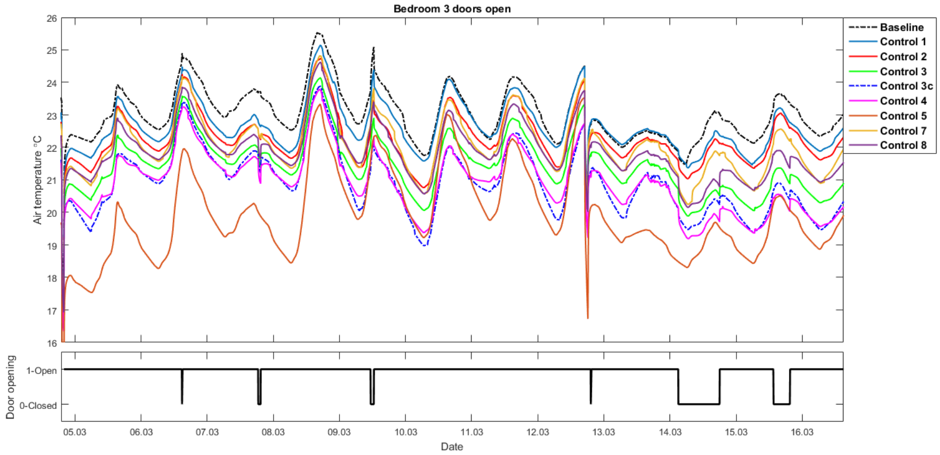

__Figure 3.24:__ building simulations with different control strategies during a period in March, with all internal doors kept open and closed according to measured schedule.

3.4.1.4 Bathroom

One notice from Figure 3.25 that it might be difficult to distinguish between the different control scenarios in the graph. This is mainly because of the thermostat-controlled electric floor heating that, most of the period, will keep the bathroom temperature higher than 24 ℃ for all strategies. The lowest temperatures occur when the window of bedroom 2 is open all the time (control 5), and when open if the temperature is above 16 ℃ (control 6). The highest temperatures can be found by using the baseline strategy. The peaks occurring (~27 ℃) is when the bathroom is influenced by high solar gains in the adjacent bedroom 3.

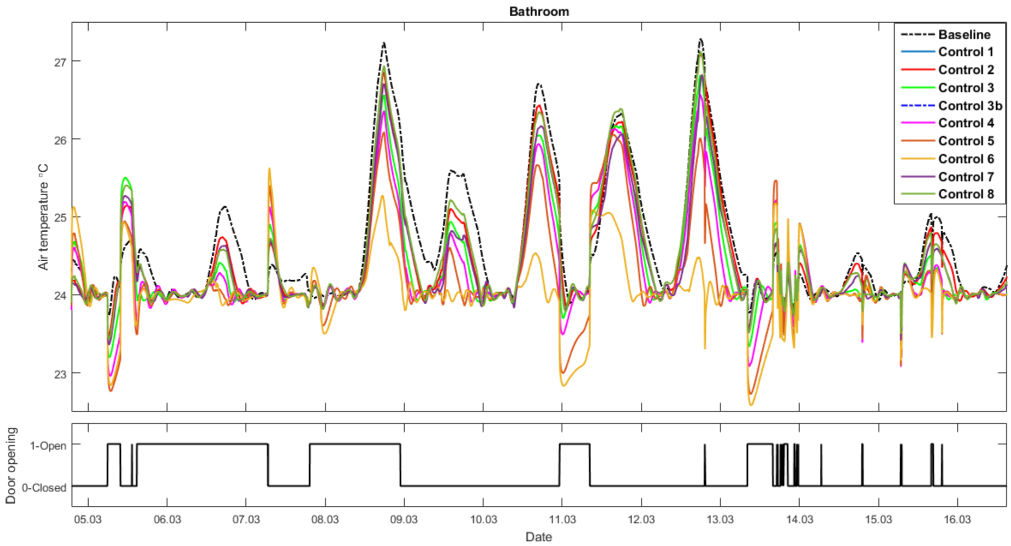

__Figure 3.25:__ building simulations with different control strategies for the bathroom during a period in March, with all internal doors kept open and closed according to measured schedule.

3.4.1.5 Hall 2

For hall 2 the highest temperature will occur for the baseline strategy (~25 °C) and the lowest for control 6 (~17 °C). The temperature is largely influenced by the opening of the window in bedroom 2, and will be in average 20 °C and 20.8 °C, for control 5 and control 6 respectively.

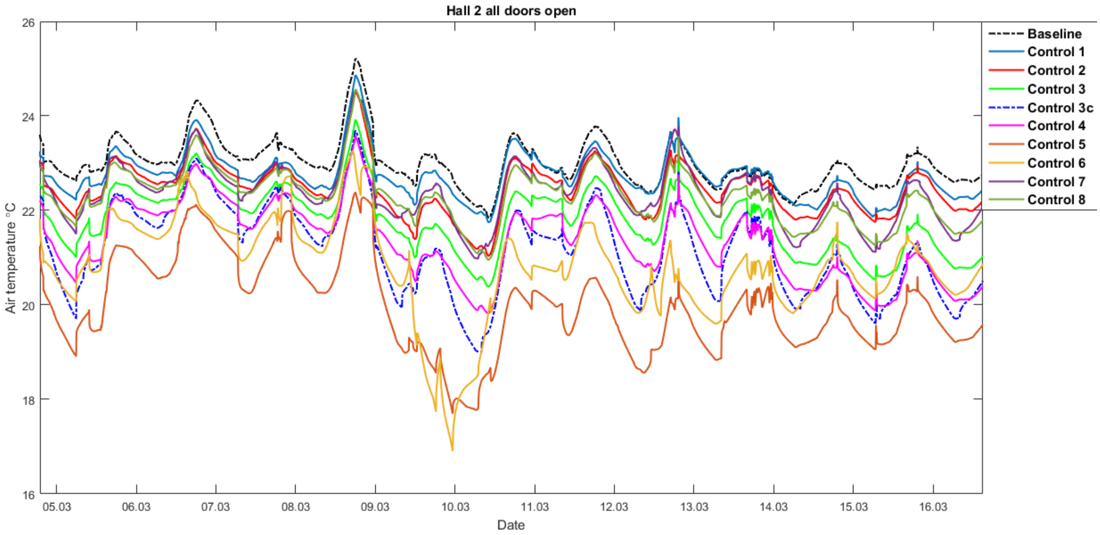

Figure 3.26: *building simulations with different control strategies for the bathroom during a period in March, with all internal doors kept open and closed according to measured schedule.*

When doors are kept closed, the highest average temperature will occur with the baseline and the lowest with control 4. As can be seen in Figure 3.27, control 1, control 2, control 3, control 5, control 7 and control 8 will be quite similar, with around 1 °C average difference from the highest to lowest.

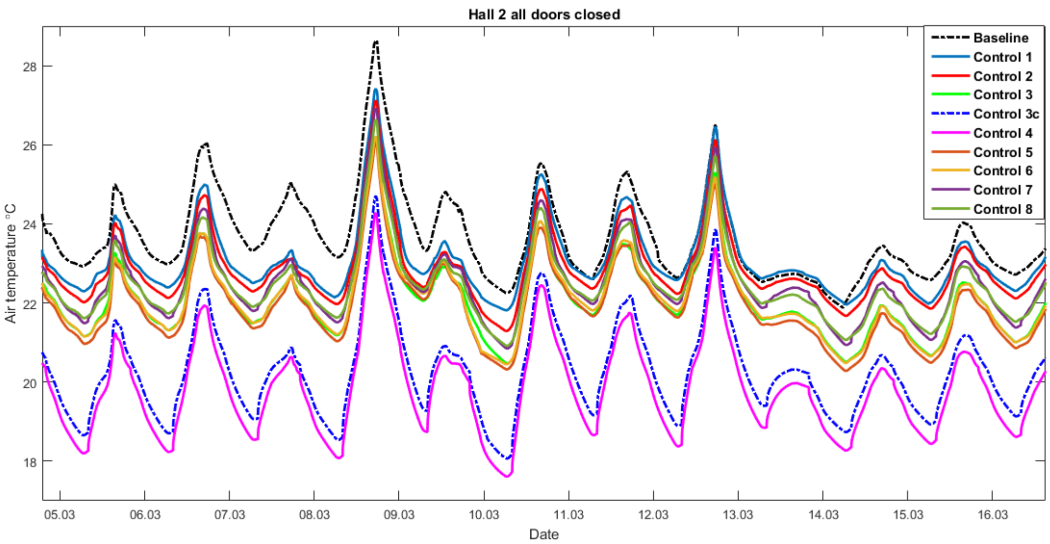

Figure 3.27: *temperature in hall 2 for building simulations with different control strategies, with all internal doors kept closed.*

3.4.1.6 Living room

Looking at Figure 3.28, it is clear that the temperature in the living room will not be as affected by the different control strategies as the bedrooms. One can see that the living room temperature will have a temperature decrease when the balcony door is opened. This temperature drop will be lowest for control 5 and control 6, in which the door and window in bedroom 2 is open for large periods, which is resulting in cold air flows from the bedroom window.

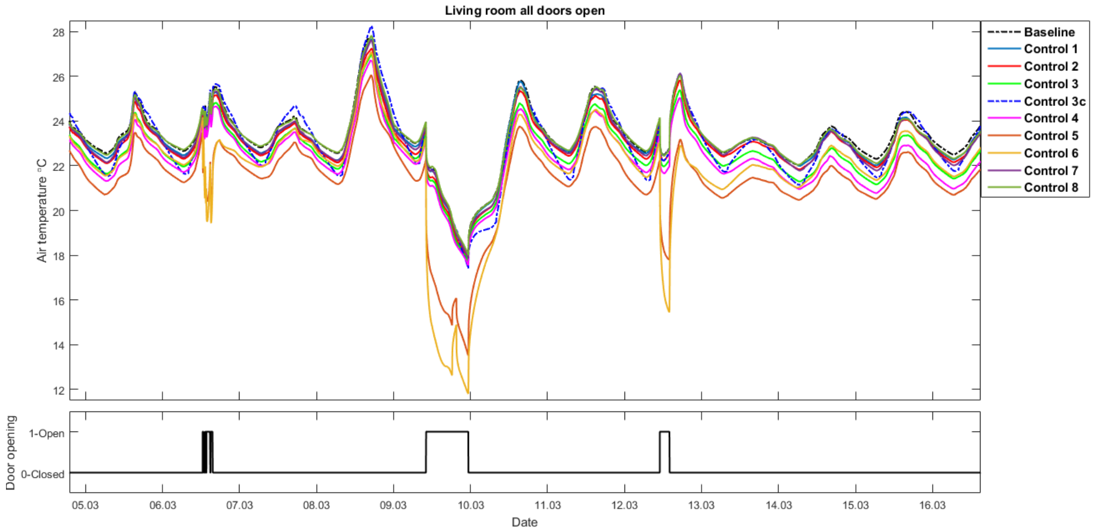

Figure 3.28: *building simulation comparison of different control strategies in the living room during a period in March, with all internal doors kept open and closed according to the measured schedule.*

In Figure 3.29, all internal doors in the second floor are kept closed and the balcony door in the living room is opened according to the measured schedule. For this figure, it is hard to distinguish between some of the strategies, as the living room will not be as affected as the rooms in the second floor. The baseline will have the highest average temperatures, while control 3c and control 4 will have the lowest temperatures. The rest of the strategies will be somewhere between the highest and lowest temperatures.

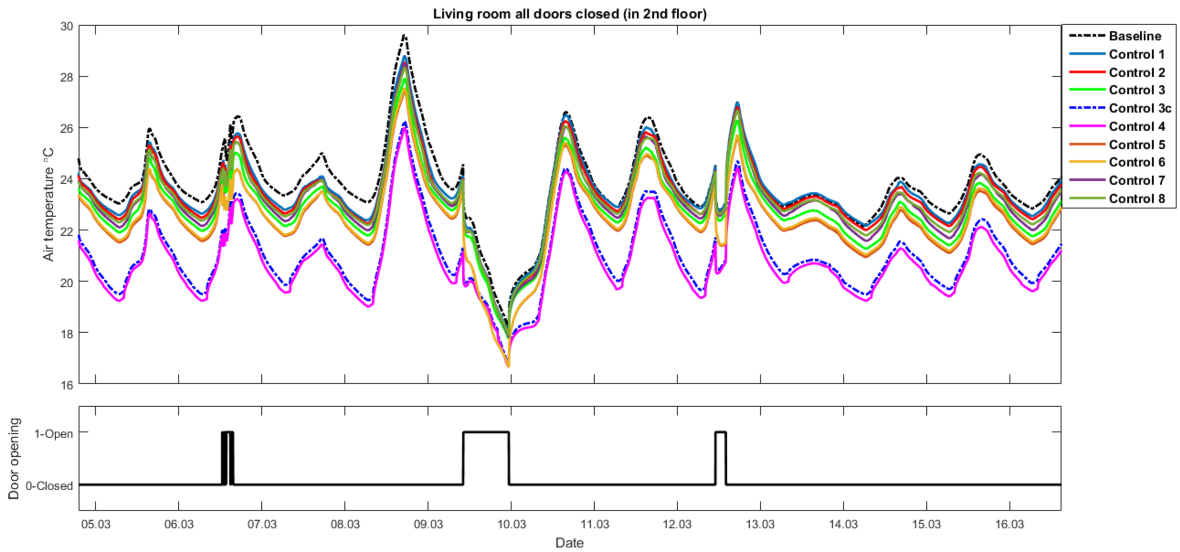

Figure 3.29: *building simulation comparison of different control strategies in the living during a period in March, with all internal doors in the second floor kept closed, living room balcony door opened according to schedule.*

The simulations show that when internal doors are closed, more substantial measures outside the considered zone have to be made to make considerable changes inside this zone. When the supply air temperature is lowered in the zone and internal doors are closed, the zone temperature will be affected with greater extent than if internal doors are open.

3.4.2 Yearly simulations

An important question to investigate is the correlation between thermal comfort and energy performance. High energy performance should not be implemented at the expense of thermal comfort and vice versa. Will it be more energy efficient to open windows in bedrooms to cool the room air, or would it be better to lower the set point temperature of supply air?

With the basis of the control strategies in mind, yearly simulations are performed to investigate the energy efficiency and thermal comfort during a year. When running a yearly simulation, the measured ventilation set point and openings of doors cannot be used. It is therefore necessary to develop schedules for ventilation and door openings that can be used on a yearly basis. The schedules are chosen to be constant each day during the whole year.

External screen is drawn when solar radiation on internal window surface exceeds 100 W/m^2. All windows and internal doors are initially kept closed, but some scenarios the window and/or the door in bedroom 2 are opened. It is used NS3700 internal gains and schedules, and ventilation flow rates as found in technical drawings from the ventilation contractor. Two different heating set point temperatures, 21 °C and 24 °C respectively, are applied for the space-heating sources the living room, hall 2 and bathroom. The different set point temperatures are used to see the difference in heat demand over the year. The set point temperature in the basement is constant at 21 °C. The model of house 2 is used for the yearly simulations, the end row house with three facades facing the ambient air. The control strategies used for the yearly simulations are summarized in Table 2. The weather file used is the typical meteorological year for Trondheim.

***Table 2**: summary of control strategies used in yearly simulations.*

Strategy	Internal doors	Window bedroom 2	Tset,SH [°C]	Tset,HR [°C]	Tset,HB
0	Closed	Closed	21/24	21	21
0b	Closed	Open 00:00-07:00 every day	21/24	21	21
2	Closed	Closed	21/24	21	16
3	Closed	Closed	21/24	16	16
4	Closed	Closed	21/24	14	14
6	Closed	Open if T> 16 °C (Max 20 %)	21/24	16	16
6b	Open 07:00-17:00 in bedroom 2	Open 00:00-07:00 every day	21/24	16	16
7	Closed	Closed	21/24	16 -> (20:00-08:00) 20 -> (08:00-20:00)	16 -> (20:00-08:00) 20 -> (08:00-20:00)

It is chosen to use the actual set points found on the display of the ventilation system for control 0, and are in practice actually control 1. The control 0b with window open during night, corresponding to user behaviour of house 3, is introduced. Control 5 is not investigated as it would lead to unacceptable low bedroom temperatures during the coldest days and high energy demand. Control 8 is neither investigated, as it would require a special design of the ventilation system, leaving it unable to be directly compared as regards energy use during a year. Such a special design could be by-pass solutions or separate heat coils for each room (Berge, et al., 2016).

The annual space-heating demand for the different control strategies are displayed in in Figure 3.30. The baseline strategy (0), with $T_{SET,SH}$ of 21 °C, uses 57 % for radiator heating, 25 % for AHU-heating and 18 % for electric floor heating in the bathroom and basement floor. When increasing $T_{SET,SH}$ to 24 °C, a larger part of the heat will stem from radiators, while AHU-heating will be equal and electric floor heating will be reduced. The 0b-strategy, with windows open during night, will increase the need for space-heating for both $T_{SET,SH}$ of 21 °C and 24 °C. The control 2-strategy will be slightly more efficient than the baseline for $T_{SET,SH}$ of 21 °C and 24 °C, see Table 3. When reducing $T_{SET,HB}$ to 16 °C (control 3) and $T_{SET,SH}$ to 14 °C (control 4), the space-heating demand will increase and a larger portion of the total heating demand will consist of electric floor heating. Control 6 will be almost identical to control 4, with slightly lower total heating-demand for $T_{SET,SH}$ =21 °C and slightly higher for $T_{SET,SH}$ =24 °C. The strategy with the highest space heating demand (control 6b), are when the window is kept open during night. It will consist of mostly radiator- and electric floor heating.

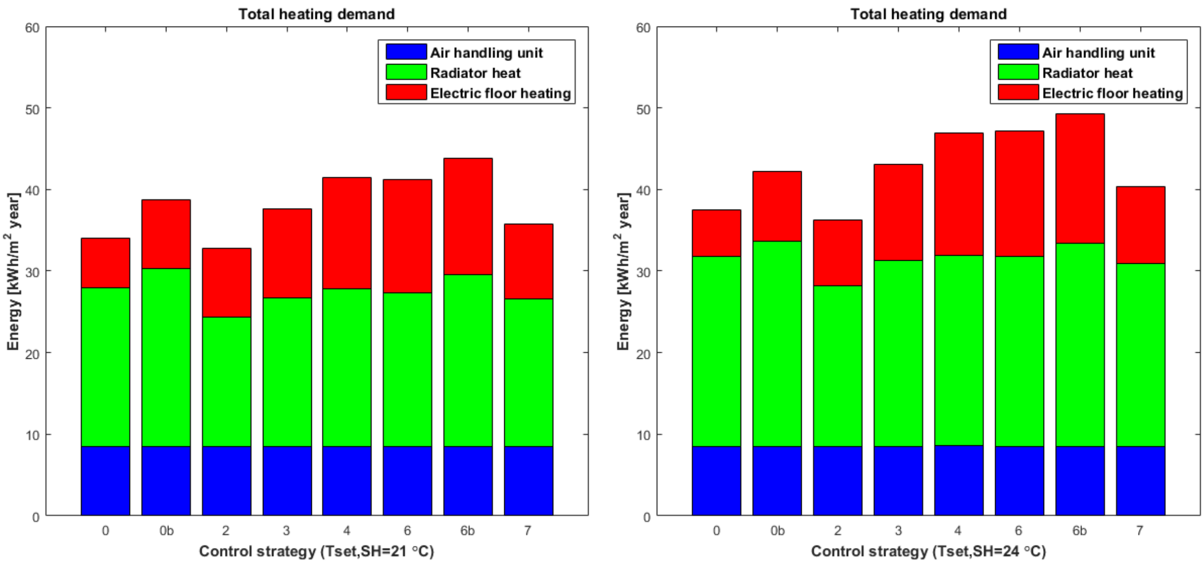

Figure 3.30: *total heating demand for different control strategies and different space-heating set point temperature (Tset,SH).*

The night-setback strategy (control 7) will have an energy efficiency of 95.5 % and 92.8 % compared to the baseline (0), for $T_{SET,SH}$ of 21 °C and $T_{SET,SH}$ of 24 °C respectively. All the energy efficiencies and heating demands are shown in Table 3.

Table 3: *heating demand in kWh/m² year for Tset,SH =21 °C and 24 °C, also showing the energy efficiency of the different control strategies with baseline strategy 0 as reference.*

Control strategy	Heating demand (Tset=21 °C) [kWh/m²year]	Heating demand (Tset=24 °C) [kWh/m²year]	Energy efficiency (0 as baseline, Tset=21 °C)	Energy efficiency (0 as baseline, Tset=24 °C)
0	34.1	37.5	100 %	100 %
0b	38.8	42.3	87.9 %	88.7 %
2	32.8	36.2	104.0 %	103.6 %
3	37.7	43.1	90.4 %	87.0 %
4	41.4	46.9	82.4 %	80.0 %
6	41.2	47.1	82.8 %	79.6 %
6b	43.9	49.2	77.8 %	76.2 %
7	35.7	40.4	95.5 %	92.8 %

It is important to find the strategy that will have a high energy efficiency, while the bedroom also is sufficiently cooled. A duration curve of the operative temperature during day and night in bedroom 2 are plotted in Figure 3.31, here using an approximate heating season lasting from October to April. Control 0b will have the lowest operative temperature during most of the period, along with control 6b. When the outdoor temperature rises, the bedroom temperature will be higher than for control 6, control 4 and control 3 because of the higher supply air temperature. However, the operative temperature will only be lower than 16 °C during 30 % of the time, so these strategies could provide unacceptable thermal comfort for the occupants in house 3, wanting 14-16 °C.

The highest operative temperature during the period will come from the baseline strategy. For control 6 the temperature will range from 15-17 °C, but will have the second lowest energy efficiency (62.1 %). This will ensure a temperature in good accordance with desired temperature of house 3 (14-16 °C), but not for house 2 (~20 °C). Looking at control 3, this strategy will provide an acceptable operative temperature (15-20 °C) at a relatively good energy efficiency (90.4 %). Control 2 will have a good energy efficiency of 104.0 %, but the temperature range is large (15-23 °C) and largely dependent on the outdoor temperature. Control 7 has a high energy efficiency of 95.5 %, and will keep the operative temperature below 20 °C 90 % of the time, ranging from 16 °C to 22 °C. Also control 4 will ensure temperatures from 14 °C to 19 °C, at an energy efficiency of 72.4 %.

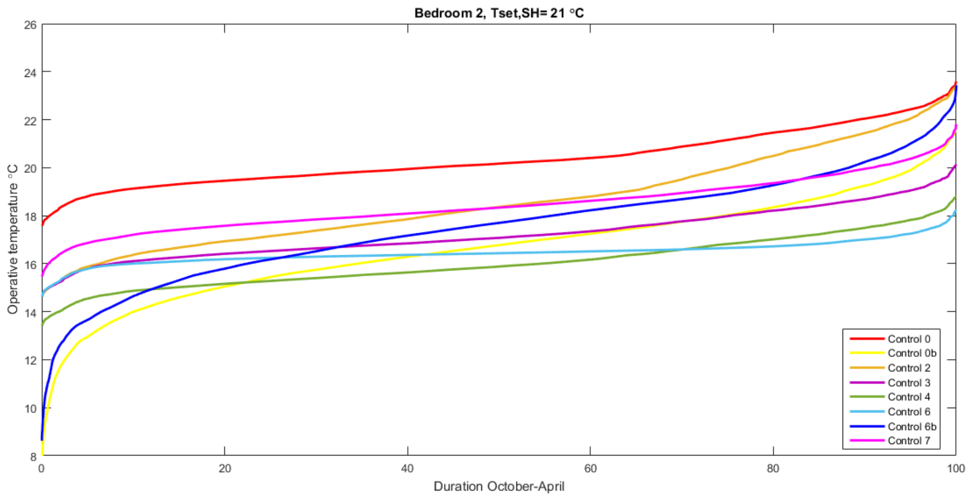

Figure 3.31: *duration curve for the operative temperature in bedroom 2 during the period heating season (October-April) with* Tset,SH *of 21 ℃.*

Low bedroom temperatures might lead to simultaneously low temperatures in rooms of occupancy during day time. A duration curve of the operative temperature in the living room during the same period is therefore plotted to investigate if this would lead to low living room temperatures.

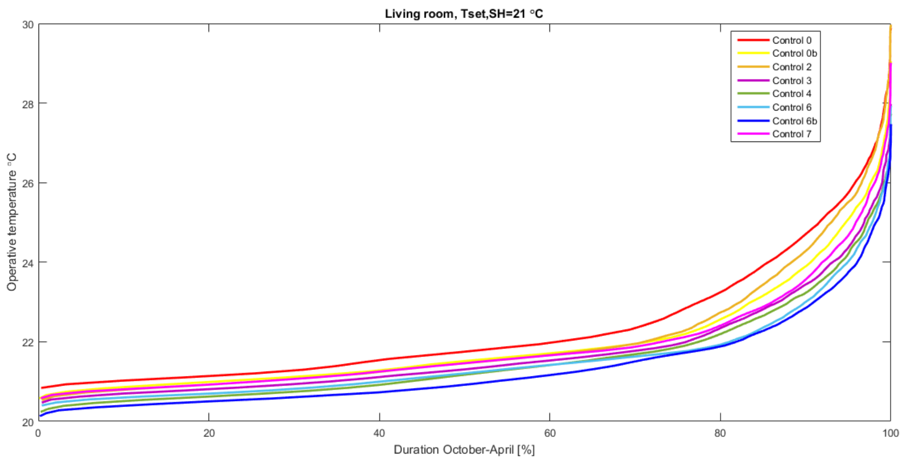

Figure 3.32: *duration curve for the operative temperature in the living room during October-April with Tset,SH of 21 ℃.*

Displayed in Figure 3.32, it is clear that the operative temperature in the living room will be greater than 20 ℃ all the time for all strategies. The highest temperatures will occur with control 0 and the lowest with control 6b, ranging from 20 ℃ to 27 ℃. There is no great distinction between the strategies, as all strategies will have operative temperature lower than 22 ℃ 60-80 % during the period. This is lower than desired living room temperature for house 2 (22 ℃) and house 3 (22-23 ℃). The temperature will stay higher than the space-heating set point of 21 ℃ 90 % of the time for control 0 (highest share) and 50 % of the time for control 6b (lowest share). For the rest of the strategies, this share will be 60-80 %.

Moving on the $T_{SET,SH}$ of 24 °C, the operative temperature in the bedroom and living room is illustrated in Figure 3.33 and Figure 3.34. The highest bedroom temperature will appear for the control 0, ranging from 18 °C to 23 °C. The lowest temperatures will occur with control 0b and control 6b, two strategies in which windows are opened 00:00-07:00. Control 6b will have greater temperature fluctuations because of the daily flushing of bedroom thermal mass by the opening of the bedroom door during daytime. The control 6 will ensure a stable temperature around 16 °C, in which the bedroom window opening is a function of the bedroom temperature. Low temperatures at a range of 15-19 °C will also occur with control 4. All the plots of the operative temperatures for the different control strategies are very similar to the plots with $T_{SET,SH}$ of 21 °C, only shifted higher on the y-axis.

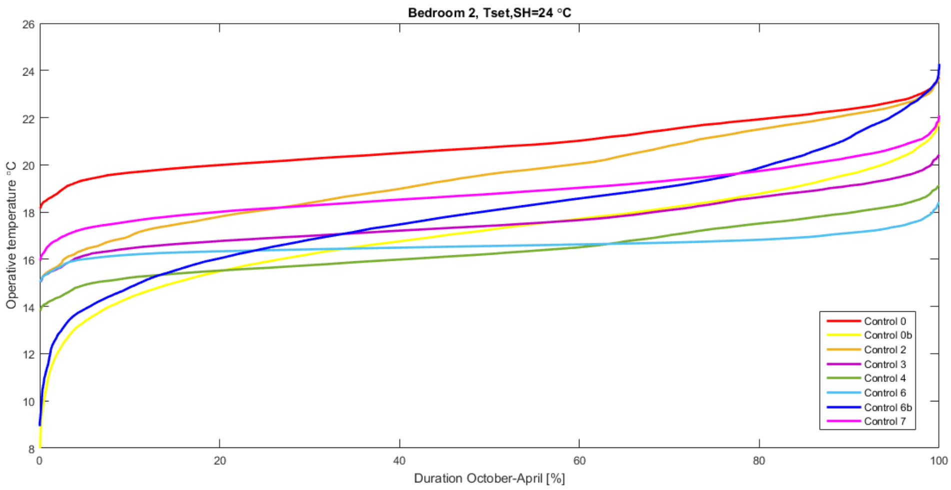

Figure 3.33:*duration curve of the operative temperature in bedroom 2 with Tset,SH of 24 ℃ during the period October-April.*

One might notice in Figure 3.34 that there are more distinct differences between the strategies compared to Figure 3.32. Still control 0 and control 6b will produce the highest and lowest temperatures, respectively. For control 0 the temperature will be higher than 22 °C 98 % of the time, while for control 6b it is 40 %. Control 3, control 4 and control 6 ensures living room temperatures higher than 22 °C 45-55 % of the period. For control 0b, control 2 and control 7 the share in which the temperature exceeds 22 °C is 75-80 %.

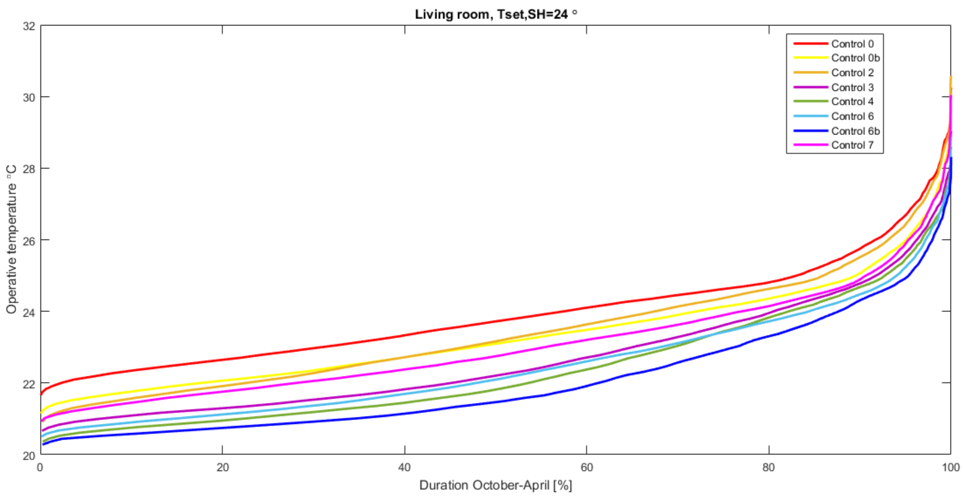

Figure 3.34: *duration curve of the operative temperature in the living room with Tset,SH of 24 ℃ during the period October-April.*

4 DISCUSSION

The different results presented in the thesis are discussed in this chapter. After each subchapter, a short summary of the main findings is listed.

4.1 INTERVIEWS

The desired bedroom temperature varied between the dwellings, with house 2 wanting ~20 °C and house 3 wanting ~15 °C. This indicates that people are different in form of what temperature they experience as satisfying to achieve thermal comfort.

Although the interview sample is small, there are findings supported in other literature. It was found that cooler bedroom temperature was preferred compared to the living room. Here the desired winter bedroom temperatures are 2 °C and 7-8 °C lower than the desired living room temperature, for house 2 and house 3 respectively. This is confirming results found in other studies, which found that a large portion of the inhabitants prefer to have a bedroom cooler than other rooms. This is discussed by Berge et al. (Berge, et al., 2016), and also found in a small study in the same passive house area (Georges, et al., 2016).

The occupants in house 2 keep the bedroom window open most of the day and night during summer. The occupants in house 3 keep the bedroom window open at least for the night during summer. As they are allergic to pollen, they try to keep the bedroom window closed as much as possible. Also in the winter house 3 keeps the window open during the night, except for the coldest days. House 2 opens the window sometimes during winter. This confirms findings from the study by Berge et al., in which it was found that nearly all occupants keep the window open for at least a few hours during the summer, and almost half of the respondents (n=27) keep the window open for at least a few hours during winter (Berge, et al., 2016). The motivation for keeping the window open is for both houses mainly due to the need for colder bedroom temperatures and to get fresh air. This is also found in the study by Berge et al., in which 96 % of the respondents stated cooler bedrooms as their motivation.

It could be further investigated if occupants would not open windows if a solution were available to keep the bedroom temperature level low. It is possible that old habits keep occupants opening the window, even if it is not needed. The user behaviour does not necessarily imply that required measures are taken to ensure a low bedroom temperature. For house 3 the supply air temperature is around 21 °C, while this behaviour does not suggest a resulting low bedroom temperature.

Both houses are satisfied with the operation of the heating system and reports that it is able to provide enough space-heating. This does not comply with reports from the study of apartment dwellings in the same passive house field (Georges, et al., 2016), but supports results from the study by Berge et al (Berge, et al., 2016).

Both houses are satisfied with the temperature in the living room, but house 3 is not satisfied with the bedroom temperature without using the window for cooling. House 2 is satisfied with the bedroom temperature during winter, but sometimes need to open window during summer. This stress the need for temperature zoning within the dwelling, also found in another study (Berge, et al., 2016). The temperature measurements are therefore used to see if unwanted temperatures in the different rooms occur, while the simulations are used to see if it is possible to apply temperature zoning and obtain high thermal comfort and energy efficiency.

Summary of most important findings:

- Occupants in house 2 wanted ~20 °C in the bedroom, and ~22 °C in the living room. House 3 wanted 14-16 °C in the bedroom, and 22-23 °C in the living room.
- It was desired lower bedroom temperature, which was also found in other studies in the same passive house field.
- The occupants in house 3 keep the window in the bedroom open 6-7 hours during night time all year. The occupants in house 2 open the window most of the day during the summer, and sometimes for a few hours in the winter.

4.2 MEASUREMENTS

The measurements for house 2 showed bedroom temperatures of 21-23 °C most of the time in bedroom 1 and bedroom 2. This is 1-3 °C higher than the desired temperature reported in the interviews. The temperature in bedroom 3 fluctuated between 22 °C and 28 °C. It is clear that the bedroom facing south (bedroom 3) is largely influenced by the solar radiation on the external surfaces. This is also found in the measurements of bedroom 3 in house 3, in which temperatures from 22 °C to 27 °C occurred. For the same house, bedroom 2 was the only bedroom for all measurement campaigns that had regular opening of the bedroom window. Here the bedroom temperature fluctuated between 16 °C and 21 °C almost cyclically during the period. The window was reported open 6-7 hours during night at approximately the same time throughout the period. It also corresponded quite well with reports from the occupants wanting 14-16 °C in the bedroom during the night. There were no occupants living in bedroom 1 in house 3, and the bedroom door was kept closed large portions of the time. When the door was opened during a period of 2-3 days, the temperature increased ~2 °C, nearing the temperature level in the adjacent hall. The bedroom temperature then decreased again when the door was closed. It is here evident that the opening of the internal doors will largely influence the bedroom temperature. In the same bedroom, it can be seen that the temperature is influenced to some degree by the opening of the window in the adjacent bedroom 2. There will be conductive heat transfer through the wall between the two bedrooms.

In house 2 the living room temperature averaged 22.7 °C, mostly ranging from 22-25 °C. This fits well with the reported desired living room temperature of ~22 °C. The highest living room temperature occurred when solar gains took place, leading to maximum 3 °C increase for the period. This indicates that the living room will be influenced by the solar radiation. This effect could be reduced by using solar shading, which was only used for two shorter periods during the period. The occupants had manually controlled external shading, but automatic control shading could be beneficial to avoid too high temperatures, especially during summer.

The living room in house 3 had an average temperature during the period of 23.6 °C, which matches well with the desired living room temperature reported to be 22-23 °C. The temperature is between 23 °C and 24 °C most of the time. The living room had automatic external solar screen on the largest window and manually controlled on the other window and balcony door. The conditions for the automatic solar shading to be drawn is unknown.

The houses had different layout and dissimilar placement of radiators. House 2 had radiators placed in the first floor and second floor, while house 3 had radiators in the basement and second floor. For house 2, the living room temperature was lower than the set point of 23.2 °C most of time for the first measurement campaign in December, and sometimes during the second campaign in March. However, the living room temperature is at a satisfactory level according to the occupants, which is also confirmed by the measurements. The radiator is able to produce a temperature level slightly under the set point temperature. This is as expected for the radiator operation, because of the thermostatic valve working as a P-regulator requiring an offset to operate. With the given boundary conditions during the measurements, this deviation do not result in unsatisfactory low temperatures. It would be interesting to investigate if the radiator is able to provide a decent living room temperature also during the coldest days.

In hall 2 in the second floor, the temperature is higher than the set point of the radiator of 22.4 °C most of the time for both measurement campaigns. The temperature on the radiator surface is higher during the first campaign than the second, which seems to result in a higher temperature in the room. There is a possible error for the measurements of the radiator, and there can be several reasons for this. One is that the temperature sensor does not measure the same temperature as the thermostatic valve. It is also possible that the radiator does not operate as it should or that the assumed set point temperature is not correct.

For the radiator in the basement in house 3 the set point temperature is 24 °C, while the temperature in the room is lower during the whole period. The radiator surface temperature was higher than the temperature on the surface of the flow pipe. This seems strange, even though the pipes and radiator surfaces consists of different materials with different thickness. All the other measurements of the radiators showed higher temperature on the radiator surface compared to the radiator flow pipe. In hall 2 in the second floor, the temperature was higher than the set point temperature of the radiator thermostat during the whole period. The different measurements regarding the radiator were almost equal, as can be seen in Figure 2.20. The low radiator surface temperature, combined with the almost equal temperature measurements, suggests that there is no or low flow through the radiator.

It is unknown if the stated nominal power of the radiator is correct, as the technical contractor went bankrupt. It was therefore not possible to obtain information about the radiators and ventilation system in house 3. It could have been interesting to measure the energy flow through the radiators, to see if the radiators work as designed and provide enough heating.

The measurements inside the air handling unit in house 2 showed relatively high temperatures for the supply air after the heating battery. The measurements did not comply with the set point temperature found on the control panel. The set point temperature was mostly 21 °C, with 19-20 °C applied for shorter periods. The measurements showed temperatures from 20 °C up to as high as 30 °C. However, the temperature sensors placed at the supply air terminals showed lower temperatures, from 23 °C to 25 °C. Two different explanations are proposed. The first proposal is that the temperature sensors placed inside the air handling unit is possibly influenced by radiation from the heating battery, and is therefore showing high temperatures. The second proposal is that the supply air is cooled down in the ducting from the air handling unit to the supply air terminal. It could also be a combination of the two proposals.

It was not possible to access the supply side of the air handling unit in house 3. Therefore, the operation of the heat recovery wheel and the heating battery could not be monitored. The control panel in house 3 was simpler than in house 2, and it was only possible to adjust the flow rate with three different settings, from 1 to 3. In this case it was constant on setting 2. There was no information about what temperature this corresponds to, as this is adjusted individually by the installer of the ventilation system. It was assumed a standard set point temperature of 21 °C, which was 1.5 °C lower than the average measured at the supply air terminals.

For the ventilation system, it would have been interesting to investigate the operation of the heating battery and heat recovery wheel. For house 2, the supply air seems to be overheated by the heating battery, leaving the air handling unit with temperatures as high as 30 °C. The heat recovery wheel seems to work fine, preheating the air close to the set point temperature. This excessive heating of the supply air leads to increased and needless energy use for the heating battery. The temperature measurements for both houses also show that the air is preheated before entering the air handling unit in the ducts from the intake. The supply air seems to be cooled down in the ducts from the air handling unit to supply air terminals. It would be interesting to investigate this heating/cooling of the air in the ducts to see if this should be regarded as a loss or a gain. This is normally regarded as a loss.

Summary of the most important findings:

- 1-3 °C higher temperature compared to what is desired, in bedroom 2 in house 2. The living room temperature in same house was in average 22.7 °C.
- In house 3, the average living room temperature (23.7 °C) was close to the desired (22-23 °C). Bedroom 2 had cyclically opening of the window during the night, with temperatures ranging from 16-21 °C. This was higher than the desired temperature of ~15 °C.
- Possible error in the measurements regarding the radiator in the second floor in house 2. The other radiators operated as expected.
- High temperature measured after heating battery in house 2. Possible radiation from the heating battery affecting the temperature sensor.
- Lower temperatures measured at supply air terminals compared to after the heating battery. Possible loss in the ventilation ducts.

4.3 CALIBRATION OF SIMULATIONS

An important task for the building simulations was to calibrate the IDA ICE-model with the on-site measurements performed. The basis of the model was made by using the specifications reported from the building contractor. The next step was to use the measurements to specify the user behaviour and boundary conditions that occurred during the measurement periods. Weather files was made from the measurements of the outdoor temperature and solar radiation measured at Gløshaugen weather station. Then the logged schedule of door and window openings was applied to the model, along with the operation of the ventilation system based on the temperature sensors placed inside the air handling unit. The radiator settings were applied based on user reports.

The calibration of house 2 resulted in 1-2 °C higher temperatures for bedroom 1, while the same occurred in bedroom 2, until the window was opened. After the opening, the simulations and measurements corresponded well. For bedroom 3 the simulations were able to reproduce a satisfactory temperature, while in periods with solar gains the measurements provided higher temperature. It is important to remember that all solar radiation in the simulation model was set to be diffuse. The weather station at Gløshaugen did only measure the total solar radiation, and the IDA-ICE weather file requires both diffuse and direct radiation. Therefore, the total radiation was assumed diffuse, which results in uncertainty of how the solar radiation affects the simulation model.

For hall 2, the temperature difference between simulations and measurements were small, with the simulations producing minor, higher temperatures. Hall 2 is connected to four other rooms in the second floor, leaving it vulnerable to changes in the adjacent rooms, especially if doors are open.

The simulations produced around 2 °C higher living room temperatures compared to the measurements during most of the period. It is important to have in mind that this room have a large area and volume, and the simulations assume a uniform temperature distribution in the zone. The temperature sensor is placed at a single spot, and it would be difficult to perfectly reproduce the measured temperature in the simulations.

One of the largest uncertainties with the measurements were tied to the door/window opening, as it was a binary signal. Because of the binary signal, the measurements of the door/window opening did not provide a definite positon of the door/window. While the bedroom doors in house 2 was reported open most of the time, simulations comparing the bedroom temperature with open and closed doors indicated that the door was more likely to be closed than open. There is a weakness in the measurements of the door/window openings. As mentioned in chapter 2.2.2, the measurements report the door as closed if the opening is less than 5 mm, and as open when the door opening is more than 5 mm. This means that the door can be reported as open, while in practice it is actually closed. In simulations it was used 100 % door opening, while it is unknown from the measurements if the opening was 1-100 % open. In addition, the occupants of house 2 said that they usually closed the doors, while the door opening measurements showed that the door was open for most of the time for all bedrooms. It is possible that the occupants felt that they closed the door, but it was actually slightly open. For future studies with the same kind of equipment, it could be nice to instruct the occupants to properly close the door. It could also be used more advanced equipment able to measure the exact position of the door.

It was not possible to perform measurements of the supply air inside the air handling unit in house 3, as mentioned in chapter 2.4.5. Therefore, the supply air temperature was not known for calibration of the simulation model. It was used the average measured temperature at the supply air terminals in the house. The operating conditions of the external window screen were unknown, and are therefore a source of uncertainty. The simulation produced 2-3 °C lower temperature in bedroom 3 than measured, mostly during periods with solar gains. When there were no solar gains, the difference between simulation and measurements were small. This suggests that the operation of the solar shading in the model is not exactly as the real performance of the shading. In addition, the total radiation is set to diffuse which most likely will affect the simulations. In bedroom 2, the model was able to reproduce the lowest temperatures occurring in periods when the window was opened, and the pattern of the temperature fluctuations. However, the simulation model produced higher bedroom temperatures than measured when the window was closed. It is not clear why there is such a difference. In bedroom 1, the simulation was in good accordance with the measurements. In hall 2, the measurements showed 2-3 °C higher temperatures than in the simulation. In the living room the simulation reproduced a satisfactory temperature, and the solar gains also here seem to be a decisive factor.

Summary of the most important findings:

- For house 2 the simulation produced 1-2 °C higher temperatures in bedroom 1 and the living room compared to measurements, while bedroom 2 and bedroom 3 produced satisfactory temperatures, except for some periods.
- For house 3, the simulation produced 2-3 °C lower temperatures in bedroom 3 compared to measurements when solar gains occurred. Temperature in bedroom 1, bedroom 2 and living room was satisfactory most of the time.
- Room temperatures were influenced by the door/window openings. Source of uncertainty as the exact door/window position was not measured.
- Room temperatures were affected by the solar gains. Source of uncertainty as the total radiation was set to diffuse in IDA ICE-model.

4.4 INVESTIGATION STRATEGIES

To find possible measures to apply in order to reduce the bedroom temperature while maintaining high energy efficiency and thermal comfort in the living room, preliminary investigation with different control strategies were performed. The measures introduced were opening/closing of doors, adjusting the supply air temperature, changing the thickness of the internal walls and adjusting the radiator thermostat set point temperature. The investigations showed that the opening of the doors mattered a lot for the temperature distribution inside the dwelling. When the internal doors were kept closed, the average temperature in both bedroom 1 and bedroom 2 decreased. For bedroom 3, the average temperature increased slightly. Before the window was opened in bedroom 2, the temperature was higher with doors kept closed. However, after the window was opened for a period in bedroom 2, the temperature stayed lower when doors were closed compared to when doors were open according to schedule. This suggests that the building need time to be heated up to the same temperature level. There was a higher temperature in bedroom 3 when solar gains occurred with the bedroom door closed. This was expected, as there will be less heat flow to hall 2.

When keeping internal doors closed and reducing the supply air temperature from the baseline, simulations showed that is possible to reduce the bedroom temperatures. When changing the supply air temperature from 21 °C to 16 °C, the simulations showed that the temperature in all bedrooms would decrease around 4 °C. This suggests that decreasing the supply air temperature is an effective measure to lower the bedroom temperatures.

Changing the internal wall thickness showed close to no effect on the temperature distribution in the second floor. This effect was not investigated very detailed and might lead to different results if approached more purposeful. It should be examined more carefully to conclude if this effect is insignificant or not, regarding the temperature zoning between rooms. One clear issue with the increased wall thickness is the rising cost and reduced floor area.

Summary of the most important findings:

- Large difference between doors simulated as closed and simulated as open.
- Decreasing supply air temperature is an effective measure to lower bedroom temperatures.
- Low effect on the temperature distribution when increasing wall thickness. Bedroom temperatures increase ~1 °C when increasing radiator set point temperature by 1-2 °C.

4.5 INVESTIGATING THERMAL COMFORT USING DIFFERENT CONTROL STRATEGIES

After the preliminary investigations, different control strategies were constructed. The parameters adjusted in the strategies were the temperature set point of the heat recovery wheel and heating battery, the opening of doors and windows, and the set point temperature of the radiators.

The baseline strategy provided the highest temperatures in all rooms when simulating the period 04.03.16-16.03.16. The operation of the heat recovery and heating battery has been discussed earlier as an issue. Therefore, a strategy with the set point temperature found on the control display was added (control 1), instead of the measured values. The simulations showed that the temperature in all bedrooms would be reduced around 1 °C from the baseline. This overheating of the supply air will result in increased energy use and might lead to less thermal comfort. Limiting the set point of the heating battery to 16 °C (control 3) and internal doors kept closed, resulted in temperatures of ~18 °C in bedroom 1 and bedroom 2, and 18-22 °C in bedroom 3. When doors were open according to the schedule, this resulted in temperatures around 21-23 °C in the same rooms. The opening of the door generates for a more homogenized temperature distribution in the second floor.

With internal doors kept closed, the most dramatic temperature changes occurred when opening the window in bedroom 2 (control 5 and control 6). Here the temperature in bedroom 2 was ~17 °C for control 6, and fluctuating between 12 °C and 17 °C for control 5. Even with no opening of the window in bedroom 1 and internal doors closed, the temperature in bedroom 1 was 17-18 °C for control 5. Bedroom 3 was not as largely influenced by the opening of the window in bedroom 2, when internal doors were kept closed. This suggests that it is possible to introduce temperature zoning, at least when there is no adjacent wall between the rooms and internal doors are closed. When the bedroom doors were open (Figure 3.22 and Figure 3.24), there was only 1-2 °C difference between bedroom 2 and bedroom 3 (control 5). Without opening the window, control 4 produced the lowest temperature in bedroom 2. Along with control 5 and control 6, these strategies would satisfy the occupants in house 3 desiring 14-16 °C. For control 4, the temperature was ~16 °C when doors were kept closed. Control 2 and control 7 would ensure a satisfactory bedroom temperature for the occupants in house 2 (desiring ~20 °C). For the occupants in house 3, desiring ~15 °C, this would be experienced as too warm.

The living room temperature was not as affected by the different control strategies as the rooms in the second floor. In addition, there was little difference in the living room when comparing with or without door openings in the second floor, see Figure 3.28 and Figure 3.29. Here the largest average difference between the strategy with the highest temperature (baseline) and with the lowest temperature (control 5), was around 2 °C. The living room temperature fluctuated mostly between 21 °C and 25 °C for all strategies. Control 6 ensured ~17 °C in bedroom 2 and ~23 °C in the living room, when internal doors were kept closed. This indicates that it is possible to introduce temperature zoning between different floors, here the first and second floor. Without opening the windows, the temperature in bedroom 2 was 16-17 °C for control 4 ($T_{SET,HR}$=14 °C), and ~18 °C for control 3, control 3c and control 8. Control 4 could satisfy the occupants in house 3 desiring 14-16 °C, but the possible draft may be an issue. The occupants in house 3 would then have to open the window (control 5 and control 6) to achieve temperatures close to the desired. This suggests that it is possible to introduce temperature zoning with ~16 °C in bedroom 2 and 22-24 °C in the living room, with internal doors closed for the given period.

Summary of the most important findings:

- With internal doors kept closed and without opening any windows, supplying air at 14 °C (control 4) would ensure 16-17 °C in bedroom 2 and 22-24 °C in the living room. Here, a possible draft could an issue. If opening the window, control 5 would produce 16-17 °C and control 6 14-16 °C in bedroom 2. The corresponding living room temperatures will be 21-24 °C.
- For the occupants in house 2, control 2 and control 7 would produce the temperatures closest to what is desired in the bedroom (~20 °C).

4.6 Investigating thermal comfort and energy efficiency using yearly simulations

The energy efficiency and thermal comfort were investigated using yearly building simulations for different control strategies with $T_{SET,SH}$ of 21 °C and 24 °C. The baseline strategy resulted in a heating demand of 34.1 kWh/m^{2}year for $T_{SET,SH}$ =21 °C, and increasing to 37.5 kWh/m^{2}year when increasing the space-heating set point temperature to 24 °C. This is more than double of the standard reference value for a passive house of about 15 kWh/m^{2}year, which will most likely be around 20 kWh/m^{2}year when using the Nordic climate as reference (Passipedia, 2015). When increasing $T_{SET,SH}$, the percentage of the total heating consisting of radiator heat increased from 33 % to 55 %. The energy from the AHU heating battery and electric floor heating was reduced.

The space-heating demand when using constant window opening for seven hours during night (control 0b), increased 14 % and 13 % from control 0, for $T_{SET,SH}$ of 21 °C and 24 °C respectively. This shows that constant, yearly window ventilation will increase the space-heating demand considerably. When using $T_{SET,HR}$ of 21 °C and $T_{SET,HB}$ of 16 °C, limiting the heating battery operation to the coldest days, the use of the heating battery and radiator will be reduced, while the electric floor heating will increase. This results in an energy efficiency of 104.0 % for $T_{SET,SH}$ =21 °C, and 103.6 % for $T_{SET,SH}$ =24 °C.

The strategy resulting in the largest heating demand is control 6b, in which the bedroom window is opened 00:00 to 07:00 and bedroom door is opened 07:00-17:00. This leads to an annual heating demand of 43.9 kWh/m^{2}year ($T_{SET,SH}$ =21 °C) and 49.2 kWh/m^{2}year ($T_{SET,SH}$ =24 °C), a situation in which a daily flushing of the bedroom thermal mass will occur. Just by opening the door during the day, the heating demand will increase 5-7 kWh/m^{2}year from when kept closed (control 0b). This stresses the importance of deliberate user behaviour when trying to reduce energy consumption in dwellings.

4.6.1 House 3 desired temperature level

It is important not to only achieve high energy efficiency, but also high thermal comfort. Let us first consider the bedroom temperature of 14-16 °C desired by the occupants in house 3, here with $T_{SET,SH}$ of 21 °C . If only contemplating the bedroom temperature, control 4 and control 6 will have temperatures closest to 14-16 °C for the largest share of the time. A possible solution is control 3, that will ensure a bedroom temperature lower than 17 °C 60 % of the time. When also considering the energy efficiency, control 3 ranks best with 90.4 %. Thereafter comes control 6 with 82.8 % and control 4 with 82.4 %. As control 4 might lead to a cold draft (Georges, et al., 2016), this strategy is discarded. If excluding the possibility of opening the window, control 6 will also be discarded. Reasons for not opening the window can be pollution and noise. The occupants in house 3 are allergic to pollen, while they also keep the window open all year. This behaviour can aggravate the indoor environment. This leaves control 3 the only viable option.

When also considering the desired living room temperature for house 3 of 22-23 °C, things get trickier. As the $T_{SET,SH}$ here is 21 °C, this implies a temperature level close to 21 °C. The duration curve in Figure 3.32 shows that at least 60 % of the time the living room temperature will be below 22 °C for all strategies. Three quarters of the time the temperature will be lower than 22 °C in the living room for control 3. This indicates that there is no strategy able to fulfil all demands in a satisfactory manner. There is one action that would probably enhance the amount of time the temperature is at a desired level. The action is that temperature duration curve could be limited to the night time for the bedroom, and day time for the living room.

This would most likely decrease the amount of time the bedroom temperature is higher than desired, and decrease the amount of time the living room temperature is lower than desired.

Let us then consider $T_{SET,SH}$ =24 °C. The control strategies will rank the same in terms of energy efficiency. Regarding the desired bedroom temperature level, control 4 is the strategy that fits best. The temperature is 40 % of the time between 14-16 °C, but this is still a bit low percentagewise. A possibility is control 6, with temperatures between 15-17 °C 90 % of the time. If rejecting the strategy with window opening (control 6) and the possible draft of control 4, this leaves control 3 the best fit. However, the occupants would have to accept higher temperatures as 75 % of the time it will stay between 15-18 °C.

As $T_{SET,SH}$ is increased to 24 °C, the temperature level in the living room will also increase. Around 60 % of the time the temperature will be between 21-23 °C for control 3. Overall with $T_{SET,SH}$ of 24 °C, control 3 seems the best strategy but the occupants might have to accept some higher bedroom temperatures. However, the measurements performed showed bedroom temperatures between 16-19 °C during night. This indicates that the occupants accept this temperature level, as they did not report any discomfort during the period. In addition, they were satisfied with the living room temperature, which was in average 23.6 °C during the period. If assuming 23.6 °C as a maximum accepted living room temperature, this would increase the amount of time the temperature is at a desired level for control 3.

4.6.2 House 2 desired temperature level

Let us then consider a desired bedroom temperature of ~20 °C, as wanted by the occupants in house 2. This actually leaves only the baseline strategy applicable when $T_{SET,SH}$ is 21 °C, with the temperature between 19-22 °C. The rest of the strategies will at least have temperatures below 19 °C around 80 % of the time. With the baseline strategy, the living room temperature will mostly stay in the interval of 21-23 °C. The measurements in house 2 during the period showed an average living room temperature of 22.7 °C and no discomfort were reported (desired 22 °C). It is therefore assumed that a temperature interval of 21-23 °C can be accepted. This strategy also derives from the measurements performed in house 2, which means their behaviour seems to fit well with their desired temperature level.

If $T_{SET,SH}$ is increased to 24 °C, control 0 will also here be the most suitable option. The temperature level in the bedroom will range between 18-22 °C 80 % of the time. The same amount of time will also occur with control 7, but with lower average temperature. Control 3 will here be in the interval of 16-20 °C around 90 % of the period. For the baseline, the living room temperature is 22-24°C around 60 % of the time. The temperature is between 21 °C and 24 °C around 80 % of the period for control 3 and control 7. All demands considered, the baseline strategy (control 0) seems to be the best fit and matches quite well with the user behaviour of house 2.

Overall, the simulations indicate that it can be difficult to get satisfactory temperature zoning for the occupants in house 3, here wanting 14-16 °C in the bedroom and 22-23 °C in the living room. For the occupants in house 2, the baseline strategy will result in less unwanted temperature levels. However, it might be difficult to ensure both a bedroom temperature of 20 °C and a living room temperature of 22 °C during large portions of the time. For both houses, it might be difficult to get satisfactory temperature zoning without accepting deviations from their desired temperature level.

Summary of most important findings:

- When considering the desired temperature level of ~20 °C in the bedroom and ~22 °C in the living room by the occupants in house 2, control 0 is the best fit when regarding both the thermal comfort and energy efficiency.
- For the occupants in house 3, the desired temperature level is 14-16 °C in the bedroom and 22-23 °C in the living room. There is no strategy that are able to fulfil all the demands in satisfactory manner. Control 3 is the strategy closest to desired, which also have high energy efficiency.
- It might be difficult to get satisfactory temperature zoning inside the building. The occupants would have to enter some kind of compromise; either accepting deviations from the desired bedroom temperature or from the living room temperature.

4.7 LIMITATIONS AND UNCERTAINTIES

The most important limitations and uncertainties are summarized and listed here:

- The measurement uncertainty of the temperature sensors is +/- 0.5 °C.
- The house was not monitored during the measurement period, so unpredicted incidents may have occurred.
- There are several uncertainties in the building simulations. One important is that the simulations assume uniform temperature distribution and measurements are performed at one point. Another is that the total solar radiation is set to diffuse.
- There might be radiation from the heating battery affecting the temperature sensors, leading to possible error in the measurements of the air temperature after the heating battery.
- The energy consumption could have been measured to better calibrate and compare simulation models with measurements.
- Even though the opening of the door/window was measured, the exact position of the door/window is not known.

5 CONCLUSION

Two passive houses have been investigated using sequentially temperature- and door/window opening measurements for two weeks in March and April. It was also conducted detailed interviews with the occupants, along with building simulations in IDA ICE.

5.1 INTERVIEWS AND MEASUREMENTS

Although the interview sample was small, the occupants reported issues also found in other studies. Here the most important was the desire for temperature zoning inside the dwelling, especially cooler bedrooms. Both houses were in general satisfied with their dwellings. House 2 wanted to have around 20 °C in the bedroom, and 22 °C in the living room. House 3 wanted 14-16 °C in the bedrooms, and 22-23 °C in the living room. House 3 usually opened their bedroom window approximately seven hours each night all year, to lower the bedroom temperature to a satisfactory level. The measurements of the window openings confirmed this almost cyclically window opening. The bedroom temperature during night was measured to be 16-19 °C, in general slightly higher than reported as satisfactory. The measured living room temperature was in good accordance with the interviews, in average 23.6 °C during the period. For house 2, the measured bedroom temperature was 20-23 °C, which also here was higher than reported as satisfactory. The living room temperature matched well with the reports, here measured to be 22.7 °C in average.

5.2 CALIBRATION OF SIMULATION MODEL

The simulation model was calibrated with the measurements using the temperatures, door/window openings, set point temperature settings for radiators and electric floor heating, and the measured solar radiation at a nearby weather station.

For house 2, the building simulations for the same period as measured corresponded relatively well. The temperature in bedroom 1, bedroom 2 and the living room were 1-2 °C higher than measured. The temperature in bedroom 3 facing south showed higher simulated temperatures for periods with solar gains present. In house 3, it was not possible to access the supply air inside the air handling unit, so that the operation of the heat recovery and heating battery was unknown. Here the simulations matched well with measurements for bedroom 1 and bedroom 2, but bedroom 2 had higher temperatures during the day. In bedroom 3 the simulations produced temperatures 2-3 °C lower than measured, and in the living room simulations and measurements corresponded well.

5.3 CONTROL STRATEGY INVESTIGATIONS

The layout of the two dwellings were not exactly the same, with the basement layout differing. It was chosen to investigate different heating control strategies using the model of house 2. Opening the window proved to be the most efficient measure to reduce the temperature in the bedroom. With internal doors closed and supplying air at 14 °C, this ensured 16-17 °C in bedroom 2. This would most likely satisfy the occupants in house 3 wanting 14-16 °C, but not the occupants in house 2 wanting ~20 °C. One drawback with this strategy is that it might lead to a cold draft causing discomfort. Supplying air at 16 °C produced bedroom temperatures around 18 °C. This strategy ensured the lowest temperatures without opening the window and the possibility of a cold draft. The living room temperature for this strategy (control 3) fluctuated between 22-24 °C, which is in the range of the desired temperature by both dwellings. To ensure the temperature level closest to what is desired in the bedroom for the occupants in house 2, using a set point temperature of around 21 °C for the heat recovery wheel and limiting the set point temperature of the heating battery to 16 °C appeared to be the best strategy.

5.4 YEARLY SIMULATIONS

Yearly building simulations were conducted to investigate the energy performance and thermal comfort. Here the different control strategies for two different space-heating set point temperatures ($T_{SET,SH}$,) 21 °C and 24 °C, were used.

The most energy efficient control strategy proved to be the strategy with heat recovery wheel set point of 21 °C and heating battery set point of 16 °C. The second most energy efficient strategy was the baseline strategy with set point of 21 °C for both heat recovery and heating battery. The least energy efficient strategy was to keep the bedroom window open seven hours during night all year, with internal bedroom door opened during daytime. This resulted in an energy efficiency of 77.8 % and 76.2 %, for space-heating set point of 21 °C and 24 °C respectively.

For the occupants in house 2, the baseline strategy with no window and door opening proved to be the best fit. Here the bedroom temperature was closest to the desired of ~20 °C, but was exceeded for periods. The baseline strategy also proved to keep the living room temperature between 21-23 °C for larger periods, which is close to the desired of ~22 °C. Although the temperatures are not exactly as desired, this strategy was most suitable. The occupants would have to accept some deviations from the desired temperature level for periods. The simulations for this strategy resulted in a heating demand of 34.1 kWh/m^2year for a space-heating set point of 21 °C, and 37.5 kWh/m^2year for 24 °C.

As regards the occupants in house 3, the baseline strategy would produce too high bedroom temperatures, as the occupants wanted 14-16 °C. Without opening the window, the strategy with supply air temperature of 16 °C would produce the temperature level in the bedroom closest to what is desired. Although it is not exactly as desired, this strategy would ensure a temperature below 17 °C 60 % of the time. However, when also considering the desired living room temperature of 22-23 °C, this strategy might lead to occupants feeling cold with temperatures in the living room below 22 °C around 60 % of the time. When increasing the space-heating set point temperature to 24 °C, this would increase the level of satisfaction in the living room. On the contrary, the bedroom temperature will increase, while the level of satisfaction in the bedroom will decrease. With the investigated strategies, it is therefore necessary to compromise. Either higher bedroom temperatures have to be accepted, or lower living room temperatures. When supplying air with 16 °C, the resulting heating demand was 37.7 kWh/m^2year ($T_{SET,SH}$=21 °C) and 43.1 kWh/m^2year ($T_{SET,SH}$=24 °C), Based on the building simulations performed and with the given conditions, it might be difficult to introduce drastic temperature zoning within this kind of building typology. If desiring 14-16 ℃ in the bedroom and 22-23 ℃ in the living room, occupants would have to enter some kind of compromise.

6 FUTURE WORK

- There could be performed longer measurement campaigns to get more data and better basis for comparison. More dwellings could be investigated to increase data and to better investigate the diversities and similarities.
- The energy use during the period could be measured and compared with simulations to ensure good calibration of the model. This would further enhance the reliability of the simulation model, and the investigations would be more correct.
- A user guide of how to operate the building to get satisfactory temperature zoning could be developed. This could contain information of how to control the ventilation and heating system, along with how to operate the window and door openings. Ideally, one wishes not to use the window for temperature control and ventilation due to energy efficiency and indoor air quality (eg. pollen pollution). Measurements could be performed, and then the user guide should be provided and followed by the occupants and then do measurements again. A comparison of the thermal comfort before and after the provided user guide could be performed, along with a comparison with building simulations to see if the predicted user pattern corresponds with measurements. The energy use could also here be used to compare.
- It would be interesting to measure the exact position of the door, as the simulations showed large differences when the doors were kept closed and when kept open. Anyway, the occupants should be instructed to properly close the internal doors for future measurements.
- The operation of the ventilation system should be investigated further, as the temperature measurements was much higher than the set points found from the ventilation control panel.
- It could be investigated how to operate the opening of windows and doors when considering all rooms. In this thesis the focus has been limited to one bedroom. This was mostly because of the adult occupants using one specific bedroom for both houses. If some of the strategies are applied to all bedrooms, e.g. introducing window openings, this would most likely lead to increased space heating demand.
- The row house typology could be compared with other building typologies to investigate the similarities and diversities between different building typologies.

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LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

Equation number	Equation	Explanation
(1)	$T_{\mathrm{HRP}} = T_{BHR} + \eta_{\mathrm{HR}} \cdot (T_{EXT} - T_{BHR})$.	T_{HRP} - potential temperature after heat recovery. T_{BHR} - temperature before the heat recovery unit. T_{EXT} - extract air temperature. η_{HR} – temperature efficiency of heat recovery wheel.