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Thermal zoning during winter in super-insulated residential buildings

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MASTER THESIS

for

Student Eirik Selvnes

Spring 2017

Thermal zoning during winter in super-insulated residential buildings

Temperaturinndeling om vinteren i super-isolerte boliger

Background and objective

Many of the building concepts for current and future energy-efficient buildings are based on super-insulated building envelopes, such passive houses, zero emission buildings or nearly-zero energy buildings (nZEB). As the building is super-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. This strategy is currently investigated in a competence project supported by Husbanken and the Norwegian ZEB center. Previous investigations have shown that occupants are in general satisfied with the thermal comfort during winter in rooms equipped with a radiator, such as the living room. They rather complain about the bedroom temperature often experienced as too warm during winter, even if not equipped with a heat emitter. This leads many occupants to open the bedroom window during several hours every day to reduce the bedroom temperature, which might increase space heating needs significantly. Furthermore, it has also been shown in previous studies that the control of the radiators and AHU seem not able to solve this situation.

The objective of the Master thesis is to investigate different strategies to enable to create different temperature levels inside the building (especially bedrooms) without significant increase of the space-heating needs. The final objective is to ensure the robustness of these super-insulated buildings. Solutions can be based on building technology (such as internal wall insulation, buffer zones, floorplan layout) or on the mechanical ventilation system, typically decentralized systems, two-zone ventilation, or balanced inlet and exhaust in the same room.

The following tasks are to be considered:

1. Improve analysis of the detailed simulation results (IDA-ICE) from the specialization project.
2. Make a review of existing strategies or propose new strategies to improve temperature zoning.
3. Implement the most promising approaches in the existing IDA-ICE models and compare their performance with the standard case (essentially in terms of comfort and energy efficiency).
4. Discuss the different approaches (pros/cons) based on simulation, literature and applicability.

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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 lab)
☐ Field work

Department of Energy and Process Engineering, 5. February 2017

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Abstract

In the work of reducing the energy consumption of buildings, the passive house concept has been developed as a possible solution. These buildings have a low energy need for space-heating and is therefore often equipped with a simplified system for heat distribution, such as a few low-temperature hydronic radiators. Previous research on energy efficiency of passive houses and thermal comfort for the occupants identified the need for temperature zoning inside dwellings. Occupants reported the desire for lower bedroom temperatures, a preference that according to previous studies has been difficult to achieve without compromising on the energy performance of the building. To investigate why it is difficult to achieve thermal zoning in super-insulated buildings, and to find possible solutions to the issue, a simulation model of a detached house was developed. Dynamic simulations was carried out with the building performance simulation tool IDA ICE. The influence of thermal mass, internal gains, solar gains, envelope performance levels and occupant behavior was investigated.

The main factors that prevented thermal zoning was from the simulation results found to be related to internal and solar heat gains. The heat losses through the external construction are limited due to the super-insulated building envelope, and just large enough to balance the heat from internal and solar gains during milder periods. An additional heat loss has to be introduced in order to achieve a lower bedroom temperatures. This could be done by opening the bedroom window or supplying ventilation air at a lower temperature than the bedroom. Having cold bedrooms in the building gave a higher energy need for space-heating, even when the bedroom doors was closed all the time. This was linked to the cascade ventilation principle that residential buildings often are designed according to. As an attempt to solve this problem, a solution with both supply and return ventilation to the bedrooms was investigated. This solution was able to separate the bedrooms from the rest of the building to a greater extent, and thereby providing low bedroom temperatures at acceptable energy performance.

The solution did however face the same energy performance issues as the conventional solution when high bedroom temperatures was desired during the day, and low bedroom temperatures was desired during the night. The whole issue with thermal zoning therefore boils down to occupant behavior and preferences. More focus should be put on designing robust buildings that minimize the negative impact that different occupant behavior has on the energy performance of the building. A good starting point is to accept the fact that people have different preferences when it comes to temperature levels inside dwellings, and to use this as a basis of design. The solution with supply and return ventilation from the bedrooms is contributing to increase the energy performance robustness when window ventilation is being used, but the issue with thermal zoning and energy performance needs further research.

Sammendrag

Passivhuskonseptet har blitt trukket fram som en mulig løsning i arbeidet med å redusere energibruken fra bygningssektoren. På grunn av det lave energibehovet til oppvarming har passivhus ofte et forenklet opplegg for varmedistribusjon installert, som for eksempel noen få radiatorer. Tidligere studier av energieffektivitet og termisk komfort i passivhus har slått fast at det er et reelt behov for temperaturinndeling i boliger. Mange beboere er misfornøyde og ønsker kaldere soverom, noe som i følge tidligere studier er vanskelig å oppnå uten at det fører til et økt oppvarmingsbehov. For undersøke hvorfor det er vanskelig å få til ulike temperaturnivåer i passivhus, og for å finne mulige løsninger på problemet, ble en modell av en enebolig utviklet. Dynamiske simuleringer ble utført med bygningssimuleringsprogrammet IDA ICE. Faktorer som termisk masse, internlast, solinnstråling, isolasjonsgrad av bygningskropp og forenklet brukeradferd ble undersøkt.

Resultatene fra simuleringene viste at det var i hovedsak varmetilskudd fra internlast og solinstråling som reduserte temperaturinndelingen. Varmetapet gjennom bygningskroppen er veldig lavt for passivhus, og i mildere perioder var det bare akkurat stort nok til å balansere varmetilskuddet fra internlast og solinnstråling. For få kaldere soverom må derfor mer varmetap introduseres, enten ved å åpne soveromsvinduet, eller ved å tilføre ventilasjonsluft med en lavere temperatur enn romlufta. Kalde soverom viste seg å gi høyere energibehov til oppvarming, selv om soveromsdørene alltid var lukket. Dette ble koblet prinsippet man ofte designer ventilasjonsløsninger etter. Frisk luft tilføres soverom og stue, og avtrekk plasseres på kjøkken og bad, noe som fører til transport av luft mellom rom. En mulig løsning på dette var derfor å introdusere både tilluft og avtrekk for soverom og undersøke effekten av dette. Tiltaket førte til at soverommene i større grad ble adskilt fra resten av huset, og kalde soverom ble mulig å oppnå uten å øke oppvarmingsbehovet betydelig.

Løsningen ga imidlertid de samme utfordringene med tanke på energieffektivitet når brukerne ønsket varme soverom om dagen og kalde soverom om natta. Utfordringene med temperaturinndeling og energieffektivitet er sterkt knyttet til brukeradferd. Fokuset bør derfor ligge på å prosjektere robuste bygninger som minimerer påvirkningen som ulik brukeradferd har på energieffektiviteten til en bygning. Et godt utgangspunkt er å akseptere at personer har ulike preferanser når det kommer til temperaturnivå i boliger, og bruke dette som et designgrunnlag. Løsningen med både tilluft og avtrekk fra soverom bidrar til å gjøre bygget mer robust mot påvirkning fra bruk av vinduslufting, men mer forskning trengs for å løse problemet med temperaturinndeling i passivhus.

Preface

This Master's thesis of 30 ECTS credits represents the conclusion of the Master of Science grade in mechanical engineering, and of the five years of education at Norwegian University of Science and Technology in Trondheim. This thesis is a continuation of a project on the same topic that carried out in the fall of 2016.

I would like to thank my supervisor Laurent Georges for introducing me to this interesting topic, and for valuable input on the road. I would also like to thank the co-supervisors, and especially Martin Thalfeldt for reading through and giving feedback on the thesis at the end. I would also to thank the whole HVAC group at EPT for making my year as a research assistant a very educational and memorable time.

Finally, I would like to thank my beautiful wife Eirin for all the support you have given me on the road, I love you.

Hope you enjoy the reading.

Eirik Selvnes

Trondheim, 8th of October 2017

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Chapter 1

Introduction

In order to reduce the greenhouse gas emissions from the building sector, all new buildings in the European Union should be nearly zero energy buildings (nZEB) by the end of 2020 (Council of the European Union, 2010). In the work of reducing the energy consumption of buildings, the passive house concept has been developed as a possible solution. Due to the super-insulated building envelope, the space-heating need for passive houses is limited. This opens up the possibility of simplifying the space-heating distribution system in passive houses to air heating only, or to a limited number of heat emitters. The latter solution with a few low temperature hydronic radiators per dwelling is part of a competence project supported by Husbanken and the Norwegian ZEB center. The extra investment in additional insulation and a generally high performance building envelope, make passive house projects less profitable for contractors and housing developers. Therefore, the simplification of the space-heating distribution system is also welcomed by contractors, as an attempt to reduce building costs for passive houses.

In theory, a solution with a limited number of heat emitters in a dwelling is providing lower thermal comfort for the occupants in terms of control and flexibility compared to the more traditional practice of placing a heat emitter in each room. One could expect that rooms without a heat source (such as bedrooms) could be perceived as too cold during the heating season. Previous research has however shown that occupants are perceiving the bedrooms in passive houses and low energy buildings as too hot, which lead them to open the bedroom window during nighttime as an attempt to reduce the bedroom temperature. Previous studies have also demonstrated that this may lead to a large increase in energy need for space-heating. The desire for thermal zoning in residential buildings with a significant temperature difference between colder bedrooms and warmer living areas have been difficult to achieve without compromising on the energy efficiency.

The main objective of this Master's thesis is therefore to investigate possible strategies to create different temperature zones inside a dwelling without a significant increase of energy need for space-heating. The focus will naturally be on residential buildings and especially bedrooms. Gaining knowledge about the thermal dynamics of a bedroom is essential to be able to suggest strategies that could improve the thermal zoning in a dwelling. Therefore, the goal for this thesis is also to gain insight into how the bedroom behaves under different conditions, and why it is difficult to create thermal zoning in super-insulated buildings. Low energy buildings and passive houses have been designed to have very low energy need for space-heating, but if having people living there results in energy performance at the same level as current legislation, then what is the point of the extra investment? The final objective for this thesis is therefore to ensure the robustness of these super-insulated buildings concepts, such as the passive house.

The research method for this thesis is be based on the dynamic building performance simulation (BPS) tool IDA Indoor Climate and Energy (IDA ICE). A chosen building will be modelled, and the results obtained from the dynamic simulation of this model form the basis for the investigation. Possible solutions or strategies to improve thermal zoning inside the dwelling will be tested through simulations, and the performance of the solution is evaluated on the basis of thermal comfort, energy efficiency and applicability for new and existing buildings.

1.1 Thesis overview

The objective for this thesis has now been presented. Chapter two describes the background and framework more thoroughly, as well as giving an overview of the work that has been done on this topic through relevant literature. This will together with previous insight provide adequate knowledge to form hypotheses on why the problem with to hot bedrooms occur. The hypotheses will be presented in chapter three. The construction of the building model and modelling choices that was made are introduced in chapter four, while the results from the dynamic simulations are presented in chapter five. The results will be further analyzed and discussed together with and the findings in the literature and previous knowledge in chapter six. Finally, a conclusion of the work and investigations are made in chapter seven.

Chapter 2

Framework

This chapter will introduce the passive house concept and the background for this thesis. An overview of the work that has been done on this topic will be presented through relevant literature.

2.1 The passive house concept

In the work of reducing the energy demand from the building stock, the passive house concept has been developed as a possible solution. The original definition of passive house concept was introduced by the Passive House Institute in Germany. It states that a passive house is a building where the requirement for thermal comfort could be obtained by only using the ventilation system for heating and cooling (The International Passive House Association, 2015c). This is possible due to the significant improvement of the building envelope, by utilizing internal heat gains from people, equipment and lighting, as well as solar heat gains. The aim of the concept is to improve the thermal performance of the building envelope by five basic principles. These principles include a high level of thermal insulation, air-tight construction, high performance windows, thermal bridge free construction and efficient heat recovery of the ventilation air. As a result of these improvements the space-heating need is limited, and it is therefore possible to simplify the heating system of the building (Feist et al., 2005).

The passive house concept first was developed for temperate climates in Central Europe, but according to the Passive House Institute, the concept is applicable for any types of buildings, almost anywhere in the world. The passive house concept has for example been adapted to colder climates such as Scandinavian countries.

2.1.1 The Norwegian passive house standard

The Norwegian passive house standard NS3700 (Standard Norge, 2013) covers residential buildings while NS3701 (Standard Norge, 2012) covers the non-residential buildings. Norway is actually the only European country that has their own passive house standard, while other countries follow the original standard (Lavenergiprogrammet, 2016). The Norwegian passive house standard defines the maximum allowable net energy need for space-heating Q_{max} by taking the local climate and size of the building into account. This is calculated by using the heated floor area A_{fl}, and the yearly mean outdoor temperature ϑ_{ym} for the specific location. Georges et al. (2014) transformed the requirement into two simple equations, such that the maximum allowed energy need for space-heating can be calculated by using equation (2.1) and (2.2) below:

$$Q_{corr} = \max((250 - A_{fl}), 0) / 100 \tag{2.1}$$

$$Q_{max} = 15.0 + 5.4 \times Q_{corr} + (2.1 + 0.59 \times Q_{corr}) \times \max((6.3 - \vartheta_{ym}), 0) \tag{2.2}$$

If the maximum allowed net energy need for space-heating is taken as a basis for the design, different level of performance for the building envelope will then be produced, depending on the climate of the geographical location. This is done to even out the building costs for passive houses, encouraging the development of high energy performance buildings also in colder climates.

In addition to the requirement for energy need for space-heating, a number of minimum performance requirements for the different building components have to be fulfilled for a building to be defined as a passive house according to NS3700. These requirements are presented in table 2.1 below.

Table 2.1: NS3700 Minimum performance for building components and air tightness (Standard Norge, 2013)

	Minimum performance
U-value windows and doors	$\leq 0.8\,W/(m^2K)$
Normalized thermal bridge factor ψ	$\leq 0.03\,W/(m^2K)$
Heat exchanger annual efficiency	$\geqslant 80\,\%$
SFP factor	$\leq 1.5\,kW/(m^3/s)$
Leakage number at 50 Pa, n50	$\leq 0.6\,h^{-1}$

The passive house standard also states that the building should be designed in such a way that thermal comfort can be achieved without the need for mechanical cooling of rooms or supply air. Finally, at least 50% of the energy for space-heating and domestic hot water should be from other sources besides electricity and fossil fuels.

2.1.2 Typical heating and ventilation solutions in Norwegian passive houses

The original definition of the passive house is closely connected to the air-heating concept, but this is not adopted in the Norwegian interpretation of the passive house concept (Berge et al., 2016b). A more common solution for heating and ventilation used in Norwegian residential passive houses is the simplified hydronic heating loop. This heat distribution system usually consist of a low-temperature radiator in the living room/kitchen area, and floor heating in bathrooms. Bedrooms are only heated by the ventilation air, internal heat gains, and heat transmission from adjacent rooms. For detached houses and row houses the ventilation system is often unit based systems, meaning each house unit have their own air handling unit (AHU) installed. For apartments, either a large central ventilation system serving all the apartments in the building, or the unit based air handling units are used. A principle drawing of the two solutions is presented in figure 2.1 below. The latter one has gained more popularity due to easier control and the demand for user involvement and flexibility. The ventilation system is however always a single-zone ventilation system equipped with heat recovery, and often a heating coil for reheating is installed as well. The heating coil can be either be hydronic or powered by electric resistance heating.

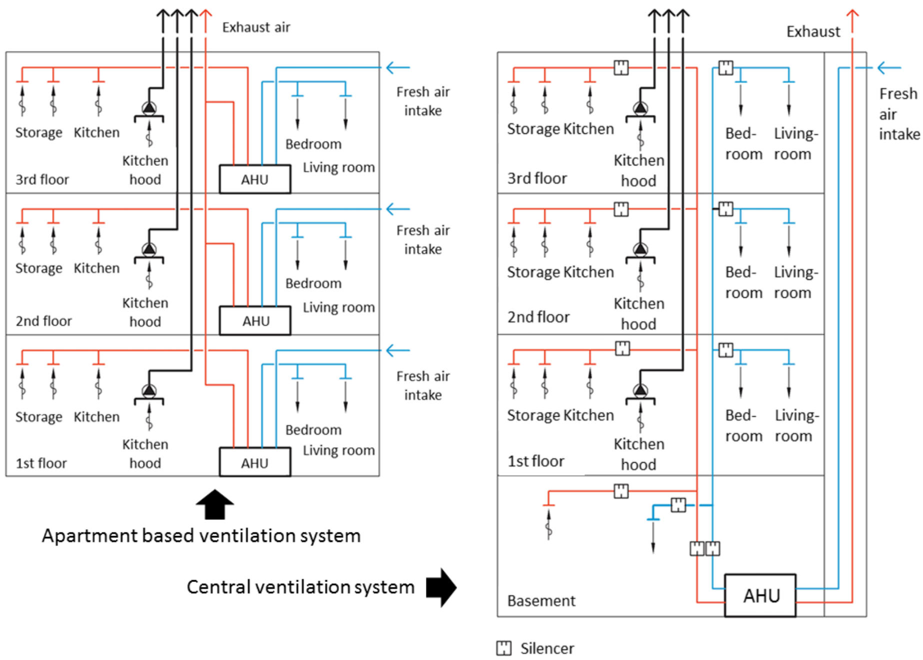


Figure 2.1: Principal drawing of balanced ventilation system with apartment based units (left) and central air handling unit (right). Translated from SINTEF Byggforsk (2015)

A common solution for supply and extract of air in residential buildings with balanced ventilation systems is based on the cascade principle, as illustrated by figure 2.2 below. This involve treating the bedrooms and living room as supply zones, the corridors as an overflow zone and bathroom, toilet, laundry room and kitchen as extract zones (Rojas et al., 2014). This allows for reduced airflow rates while maintaining a good indoor air quality. Another version is the *extended* cascade ventilation principle, which also treats the living room as an overflow zone if the floor plan allows it.

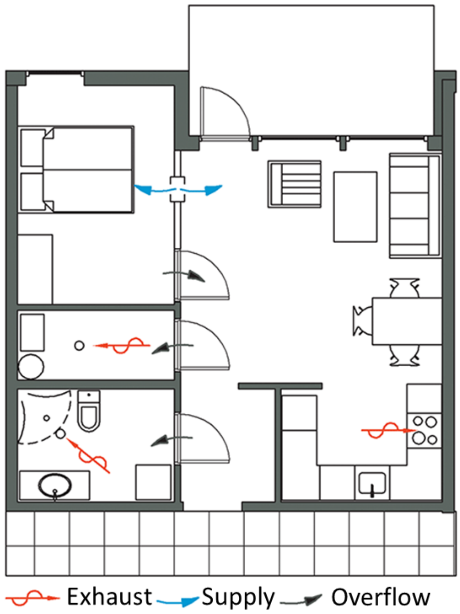


Figure 2.2: Principal drawing of a ventilation system based on the cascade principle. Translated from SINTEF Byggforsk (2015)

2.1.3 Example of a Norwegian passive house projects

The case project studied in several of the references in this thesis is Miljøbyen Granåsen.This is the largest passive house construction project in Norway, and is developed by Heimdal bolig. When finished, the project will consist of 17 detached houses, 67 row houses and 371 apartments all fulfilling the passive house standard NS3700 (Standard Norge, 2013). Miljøbyen Granåsen is part of the ”Evalueringer av Boliger med Lavt Energibehov” (EBLE) research project by Lavenergiprogrammet (Unknown). The housing project is also a part of Concerto and Eco-city research projects by the European Commission initiative research projects (ECO-City, 2013).

2.2 Thermal comfort

One of the most important objectives for the technical installations like HVAC in a building is to ensure thermal comfort for the occupants. A necessary, but not sufficient requirement for thermal comfort is thermal neutrality for the body as a whole. This means that one does not want higher or lower ambient temperature. Local discomfort can occur even if the the body as a whole is thermal neutral. The most important factors that influence the thermal comfort are air temperature, relative humidity, mean radiant temperature, air velocity and turbulence, metabolic rate and clothing level (NTNU-SINTEF, 2007). Thermal comfort is by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers therefore defined as "... the condition of mind that expresses satisfaction with the thermal environment" (ANSI/ASHRAE, 2013).

There are several more or less known models for thermal comfort, but two of the most known types are the heat balance model and adaptive comfort model. The heat balance model (also called the Predicted Mean Vote (PMV) model) was developed by Fanger and based on extensive research on parameters influencing the heat balance of the human body and the requirements for thermal comfort (Nilsson, 2007). The PMV is a psychophysical seven point index scale from -3 (Cold) to +3 (Hot) with 0 being the thermal neutral, expressing how a person feels regarding their thermal situation (Fanger, 1972). The model is based on the comfort equation with the factors from last paragraph as input, that calculate and predicts the mean vote of a large group of persons for a given thermal situation. By statistical analysis the relationship between PMV and PPD (Predicted Percentage of Dissatisfied) was established, which estimates the percentage of people of a large group that express dissatisfaction with the thermal environment. This thermal comfort model form the basis for several standards for thermal comfort requirements, like ASHRAE standard 55 (ANSI/ASHRAE, 2013) and ISO 7730 (International Organization for Standardization, 2005).

The other approach is called the adaptive comfort models, and according to these models a much broader temperature range is considered comfortable by occupants, compared to the heat balance models. This is explained as the occupants adaption to the varying boundary conditions. The adaptive models do not rely on a physiological model of the human body, but relate comfort temperatures and ambient temperatures empirically (The International Passive House Association, 2015a). The model suggest that contextual factors, such as having access to environmental controls and past thermal history, can influence the thermal expectations and preferences of the occupants (de Dear and Brager, 1998). The adaptive approach has been implemented in many standards, for example the standard NS-EN 15251. The adaptive approach with acceptable upper and lower temperature limits that vary with the outdoor temperature, assumes that occupants can freely open windows and adjust clothing level as needed. The adaptive model only applies to buildings without a cooling system installed.

2.3 Occupant preferences, behavior and thermal comfort

The introduction of super-insulated and airtight building envelopes with high performance windows has improved the energy performance compared to older and more leaky buildings. The improved performance has in addition to reducing the energy need for space-heating almost eliminated the effect of thermal bridges, stratification, unpleasant draft and radiation asymmetry from cold window surfaces (The International Passive House Association, 2017). One could therefore expect occupants in high performance buildings such as passive houses to be very satisfied with the thermal conditions.

Two studies investigated apartments (Georges et al., 2016) and row houses (Håheim, 2016) in a large passive house project in the middle of Norway called Miljøbyen Granåsen (see subsection 2.1.3). The studies investigated the trade-off between energy efficiency, flexibility to users and thermal comfort with a simplified space-heating system with radiators. The investigation was performed by field measurements, user interviews and detailed dynamic simulations. The interviews focused on the occupants' satisfaction with the thermal conditions, and especially how and why they adjusted the thermal conditions in the dwelling. The occupants were interviewed about their use of the radiators and additional heat sources, adjustment of the supply air temperature, adjustment of the supply air flow rate and their habit of window and door opening.

The interviews of the occupants in the apartments and row houses gave valuable insight into the desired thermal conditions within the dwellings. The occupants were in general satisfied with the thermal conditions in the living room and bathroom (areas equipped with heat emitters), but not the thermal conditions in the bedrooms. The bedrooms were by many perceived as to hot, as the desired temperature level ranged from 12-20°C. This is substantially lower than the desired temperature level in other parts of the building, ranging from 22-24°C. As an attempt to lower the temperature to the desired level in the bedrooms, window ventilation was reported used to some extent by all the occupants in the flats and row houses. Some occupants said they kept the bedroom window open a few hours before bedtime, others kept the bedroom window open all night, both summer- and wintertime. To achieve the desired thermal conditions in the living room, the set-point temperature for the supply air was reported set at a high level, typically 20°C.

The findings in the interviews of the occupants in the apartments and row houses are in compliance with the findings in a larger study by Berge et al. (2016b) investigating the user satisfaction of occupants living in the same passive house project, Miljøbyen Granåsen. The typical multifamily passive houses was equipped with the same simplified space-heating system as the houses in the studies by Håheim (2016) and Georges et al. (2016). In order to address how well the heating and ventilation solution worked from the occupants' point of view, a questionnaire was sent to 60 households to assess the thermal comfort in different rooms, of which 28 households answered. The study revealed that the occupants found the thermal conditions to be appropriate in the bathroom and living room during winter, but about 50% perceived the bedrooms as to hot. For summer conditions, a lower satisfaction with the thermal environment was discovered. About half of the respondents considered the thermal conditions in the living room as appropriate, the rest perceived the living room as to hot. Only 11% of the respondents perceived the bedroom temperature level to be appropriate. The study also revealed that the general dissatisfaction with the thermal conditions in the bedrooms led to extensive window ventilation, with the main reason being temperature control.

A similar type of investigation was earlier carried out by Berge and Mathisen (2016) on another high-performance residential house project, this time in the south-west part of Norway. This study used long term measurements with support from user surveys to investigate if the desired indoor climate conditions are met in the passive and low-energy dwellings. The user surveys assessed the perception of indoor air quality and thermal comfort, reported behaviour regarding indoor climate control and satisfaction with the heating and ventilation system. The occupants were in general satisfied with the indoor air quality and thermal conditions in the dwellings. A high degree of satisfaction was reported with the heating system in rooms equipped with a heat emitter, like the bathroom and living room. This is not the case for bedrooms, where the temperature is controlled through the supply air. Since the ventilation system is a single-zone ventilation system, the set-point temperature for the supply air is controlled from a panel in the living room. The study demonstrates that the preferred lower bedroom temperature is difficult to achieve in combinations with a single-zone ventilation system, which tend to homogenize the temperature within the building. To reach the desired bedroom temperature, extensive window ventilation was reported used.

People living in passive and low-energy residential buildings are in general satisfied with the indoor climate. The literature has however pointed out the need for creating thermal zoning inside the dwellings, due to the difference in desired temperature level in bedrooms and other rooms.

2.3.1 Measurements and energy use

Interviews and user surveys are suitable measures for mapping the occupants behavior and habits, and especially to determine the desired indoor temperature for different rooms and seasons. Coupled with a measurement campaign, it is a powerful tool for gaining insight in the *actual* thermal conditions inside passive houses. While interviews for example can discover the desired temperature level in the living room, a measurement campaign can unveil what the actual conditions are, and if there is a compliance between preference, measured temperature and occupant satisfaction.

In the case of the studies by Håheim (2016), Georges et al. (2016), Berge and Mathisen (2016), the measurements confirm the behavior and preferences discovered in the user interviews. A relatively high room temperature was measured in all rooms except bedrooms, typically between 23-24°C. This is consistent with long term measurement in another passive house project at Rosåsen in Sandnes (Thomsen et al., 2015). The average temperature over a year in the nine passive houses involved in this campaign was measured to be 23.2°C. The high measured temperature is in compliance with the stated preferences during the interviews, and confirms the satisfaction with the thermal conditions in the rooms equipped with a heat emitter. The measured temperature level in the living rooms is about 1°C higher than the average temperature level in Norwegian dwellings, according to a large project by The Research Council of Norway and Statistics Norway where about 3200 households participated (Halvorsen and Dalen, 2013). A considerably temperature difference between the bedrooms and living room was also found in this measurement campaign, confirming the preferred cooler bedrooms. The increased indoor temperature in high performance buildings in Norway agrees with findings from measurements in passive and low energy buildings buildings in Switzerland (Branco et al., 2004) and other parts of Central Europe (ENERBUILD, 2012).

At Miljøbyen Granåsen, the measured bedroom temperature varied more between the dwellings than the temperature in the other rooms. When a bedroom door was held open, a similar temperature level as the rest of the dwelling was measured. Keeping the bedroom door closed, a temperature difference of about 2°C from the rest of the dwelling was obtained. Keeping the bedroom door closed and opening the bedroom window, produced a significant temperature difference of 4-5°C, with the bedroom temperature ranging from 15-19°C during the two week measurement campaign. Berge and Mathisen (2016) investigated the relationship between duration of window ventilation and room temperature, and found a clear dependency between the two. Another interesting finding in this study was the measured duration of window ventilation in the bedrooms, which in average was 46% of the time. This means that the bedroom windows in average are open about 11 hours a day throughout the year. Although the bedroom windows were kept open a bit longer during the summer months, the window ventilation was considerable during winter months as well, in average 35-45% of the time from November to March.

Energy use

Low energy buildings and passive houses has been designed to have a small energy need for space-heating. Several studies have demonstrated how different occupant behavior and preferences can influence the energy performance of a dwelling. Results from the EU-funded demonstration project CEPHEUS (Cost Efficient Passive Houses as EUropean Standards) with over 221 dwelling units from five different European countries, shows that the energy need for space heating can vary as much as ±50% from the average (Schnieders and Hermelink, 2006). The study especially points out the indoor temperature as the largest contributing factor to the differences observed. A clear relationship between indoor temperature and measured energy use was also found in the passive house project at Rossåsen (Thomsen et al., 2015). Results from over 1800 apartments built to passive house standard, gathered by The Passive House Institute confirms the observed differences. The large variation in energy use for space-heating is not pointed out as an exception, but rather as a contribution to the normal distribution (The International Passive House Association, 2015b). It is also emphasized that this is also the case for measurements carried out on the building stock in general, not only on high performance buildings.

The correlation between window ventilation and energy use on the other hand is not significant, according to a study by Institut Wohnen und Umwelt (IWU) (*eng: institute for housing and environment* in Darmstadt. The study found that the increased heat loss due to window ventilation only contributed to an increase of 1-2 kWh/m^{2}year in most cases, and up to 17 kWh/m^{2}year in extreme cases (Ebel et al., 2001). The measured data did however not lead to conclusions about the heating consumption levels and window opening duration. One challenge with pointing out factors that contribute to increase or decrease the energy use of a building, is the number of factors that make up the whole system. By measurements only, it is often hard to identify the chain of cause and effects. It is at this point where simulations can be a helpful tool. In the studies by Håheim (2016) and Georges et al. (2016), simulation models of the dwellings investigated was built using IDA ICE and calibrated against the measurement results. The simulations were able to reproduce the measured temperature levels and dynamics in a satisfactory way. Using window ventilation as a measure for cooling the bedrooms had a clear impact on the energy need for space-heating in both studies. The energy efficiency was even lower when the bedroom window and doors were opened and closed daily, flushing the heat from the bedroom cyclically.

2.4 Strategies to improve

The literature has through user interviews, measurement and simulations demonstrated the need for thermal zoning in residential buildings, currently not taken into account during the design phase. Some strategies for improving the thermal zoning have been investigated, and a short presentation of findings is presented here.

2.4.1 Thermal insulation of the bedrooms

The simplified heat distribution loop means that bedrooms are only heated by the ventilation air, internal heat gains, and heat transmission from adjacent rooms. The most obvious and direct strategy for improving thermal zoning is to insulate the bedrooms from rest of the dwelling, to prevent heat transmission from other parts of the dwelling to the bedrooms. Based on the results from the measurements and post-occupancy evaluation at Løvåshagen cooperative in Bergen (Berge and Mathisen, 2016), simulations was carried out to investigate the effects observed in the study. The focus was on different control strategies for the ventilation system, but the effect of having insulation or not in the internal bedroom walls was also investigated (Berge et al., 2016a). The internal walls had a thickness of 70mm, and this gave a U-value of 2.23 W/m^{2}K for the non-insulated wall, while adding insulation reduced the U-value to 0.58 W/m^{2}K. The simulation results showed noticeable lower temperatures in the bedrooms, and a slight reduction of the space heating need in the range of 5-10% was also observed. The effect of increasing the thickness of the internal walls towards bedrooms more, meaning increasing the thermal resistance further, was not investigated in this study.

The same trend was found in a study of the suitability of air heating of passive houses in cold climates by Georges et al. (2014). The study investigated different materials and methods to construct the house, ranging from very heavy (heavy use of concrete) to very light (light timber frame) buildings in terms of thermal mass. The different construction modes then produced different thermal resistance for internal walls due to different construction materials being used. For light timber frame constructions, insulation of internal walls is often done to improve the acoustic performance of the construction (Georges et al., 2014). The highest level of thermal zoning was in the cases with highest thermal insulation level of internal constructions. The question is however if the observed effect is purely due to thermal insulation level, or if thermal inertia also contribute to the thermal zoning. The effect of internal bedroom wall thickness was more thoroughly tested by Håheim (2016). The houses at Miljøbyen Granåsen are built according to Scandinavian traditions, meaning a timber frame construction with insulation inside interior walls. The original interior wall thickness gave a U-value of 0.40 W/m^{2}K, and a step-wise increase of wall thickness to a U-value of 0.15 W/m^{2}K was investigated. The simulation results showed little or no decrease of the bedroom temperature with higher insulation level. The temperature difference to adjacent rooms was also unchanged.

2.4.2 Applying control strategies

It has been established that the energy need and temperature levels in dwellings are highly influenced by occupant preferences, behavior and how they interact with the technical systems in the dwelling. Varying set-point temperature for space-heating (indoor temperature) could contribute to a energy use varying as much as ±50% from the average, as seen in the literature. The question is how much do the control strategy or behavior influence the bedroom temperature. Do control strategies that provide acceptable thermal comfort in the whole dwelling, while keeping the energy use at an acceptable level, exist? This issue was investigated by both Håheim (2016), Georges et al. (2016) and Berge et al. (2016a) by using simulations as the main tool.

The investigation involved testing out different set-point temperatures for space-heating and supply air, and operation of bedroom doors and windows. A common result for all three studies is that the supply temperature has a significant impact on the bedroom temperature for dwellings with a single-zone ventilation system installed. The impact of a supply air temperature from 25°C down to 14°C was looked into, and a bedroom temperature of 18-20°C was achievable by reducing the supply air temperature to the lower range and keeping the bedroom door closed. This was the lowest obtainable temperature level in the bedroom without using window ventilation for cooling. It is also worth mentioning that the set-point temperature for the supply air was by many residents reported set to a high level (typically 20°C) due to comfort reasons in the living room and kitchen area. This was also confirmed by the measurements. Increasing the set-point temperature for space-heating from 21°C (from standards) to 24°C (from measurements) made the situation worse, where even a bedroom temperature below 20°C was difficult to achieve. For control strategies involving window ventilation, bedroom temperatures down to 16°C could be obtained, but this raised the energy need for space-heating significantly.

2.4.3 Multi-zone ventilation

The single-zone ventilation systems commonly installed in residential buildings today have according to Berge and Mathisen (2016) limitations when it comes to creating thermal zoning, due to the importance of supply air temperature for the thermal conditions in bedrooms. To prevent draught sensations and discomfort in the living room and kitchen area, a lower limit on the supply air temperature is set, and this prevent a sufficient cooling effect of the bedrooms. Berge et al. (2016a) therefore looked more into the possible benefit of having individual control of supply air temperature in the bedrooms by introducing a two-zone ventilation solution. The traditional solution with one set-point temperature for supply air for the whole dwelling, is changed to a solution where some of the outdoor air can bypass the heat recovery and enter the bedrooms directly. This solution make it possible to have a separate set-point temperature for the living room and bedrooms. Different set-point temperatures for the bedrooms were tested, and if further cooling besides ventilation air was needed to reach the desired temperature, the bedroom windows were opened by a PI controller. The simulation results showed a reduction of bedroom temperature by using this solution compared to the traditional one when window ventilation was not used. When a lower set-point temperature was applied such that window ventilation was necessary, this solution provided the desired condition at lower energy need for space-heating compared to the single-zone alternative.

Chapter 3

Hypotheses

Based on the literature and previous knowledge, three hypotheses on why high temperatures are observed in the bedrooms are formed:

1. To much heat flowing from heated to non-heated rooms compared to the envelope thermal losses. Increasing the insulation level of internal walls and/or creating a thermal buffer zone between the heated rooms and the bedrooms will decrease the bedroom temperatures.
2. The internal gains emitted in the bedrooms are higher than the envelope thermal losses, and a heat sink (e.g. an open window) must be introduce to reduce the temperature. Insulation of internal walls or buffer zones do not contribute to lower the temperatures because the heat is emitted inside the bedrooms.
3. A single zone balanced ventilation system tends to homogenize the temperature levels in the whole building. Too high set-point temperatures for the supply air contribute to heat the bedrooms significantly. Different control strategies and/or different ventilation solutions will lower the bedroom temperature to the desired level.

The hypotheses will be tested through detailed dynamic simulations, and the impact of construction modes, thermal inertia, insulation levels, internal gains, control strategies and different ventilation solutions on the bedroom temperature will be investigated.

Chapter 4

Method

To investigate a third type of building topology to complement the results obtained in the studies of the apartments and row houses, detailed dynamic simulation of a detached house is to be performed. The chosen case is the same as in a study of the suitability of air heating of passive houses in cold climates (Georges et al., 2014). A typical detached house topology was chosen from a house manufacturer catalogue, and detailed dynamic simulations with TRANSYS 17 was performed in this study. This study will use the same building geometry and construction methods, but with another simplified distribution system for space-heating, namely the solution with a few low temperature radiators. The methodology for the research will be carried out in the following order:

- Investigating the heat flows in the building by studying the heat balance for the bedroom, in order to see the impact the internal gains, solar gains, thermal mass and thermal resistance of the internal construction have on the bedroom temperature.
- Investigating the historical development of the building envelope performance to better understand what has changed.
- Studying the impact of human interaction with the technical systems of the building, and how different occupant preferences influence the energy performance and thermal conditions inside the building.
- Investigating a solution with both supply and return ventilation for the bedrooms to improve the thermal zoning. This will be done by studying thermal comfort and energy performance of this solution compared to the conventional solution.

4.1 Simulation tool

The chosen simulation tool to model the detached house is the detailed dynamic building performance simulation software IDA ICE 4.7. This simulation tool is developed by the the Swedish company EQUA Simulations AB, and uses the principles of equation based modelling and Neutral Model Format (NMF) (EQUA Simulation AB, 2016). It is a commercial tool with many large international customers, and is validated by many acknowledged standards like ASHRAE 140, EN 15255 and EN15265. According to EQUA Simulation AB (2016), the advantage of using a general-purpose variable time step solver, is that the simulation software automatically adapts to the nature of the problem. IDA ICE is also fully transparent, which makes it possible to inspect every underlying equation used in the software for every component. This also gives the opportunity to log any variable in the calculations, a powerful tool to investigate the details of the simulation results.

4.2 Mesterhus Nanne

Representing almost half (49%) of all the residential buildings, detached houses are the majority of residential building typologies in Norway (Statistisk Sentralbyrå, 2016). This makes it an important object to investigate, and the findings could be representative for a large share of the building stock. Since the earlier studies by Håheim (2016) and Georges et al. (2016) looked at the difficulties with thermal zoning and warm bedrooms in apartments and row houses, investigating a detached house would also complement the findings in these studies. The chosen building to models is extracted from the house catalogue by the Norwegian house manufacturer Mesterhus (Mestergruppen Bolig AS, Unknown). This is a typical two-storey detached house with three bedrooms located in the second floor, and a total floor area of 173.5 m^2. The drawings of the facades and the orientation of the case building are presented in figure 4.1 and 4.2 below.

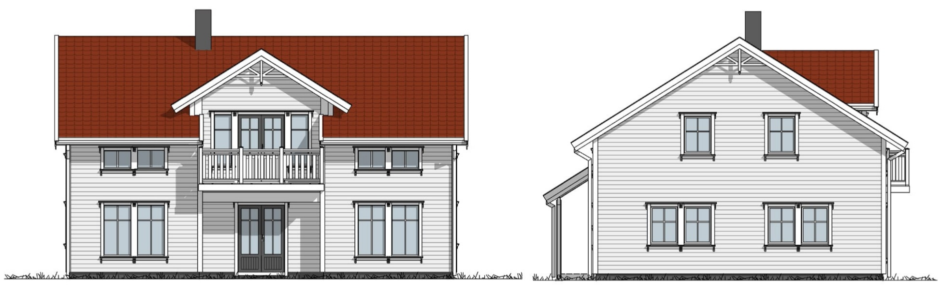


Figure 4.1: South and west facade of Mesterhus Nanne
Architect: Rigmor Torbergsen, Unikus AS for Mestergruppen Bolig AS (Mestergruppen Bolig AS, Unknown)

Figure 4.2: North and east facade of Mesterhus Nanne
Architect: Rigmor Torbergsen, Unikus AS for Mestergruppen Bolig AS (Mestergruppen Bolig AS, Unknown)

To create a simulation model of Mesterhus Nanne in IDA ICE, the internal measurements of the building need to be obtained. The simulation tool is taking the internal measurements as a basis, as it represents the internal air volume of the building. Then the wall thickness is extended outwards according to the defined construction element. The main building geometry was extracted from a SketchUp model created by Georges et al. (2014) in the air heating study, and used to build the simulation model. An illustration of the model is presented in figure 4.3 below.

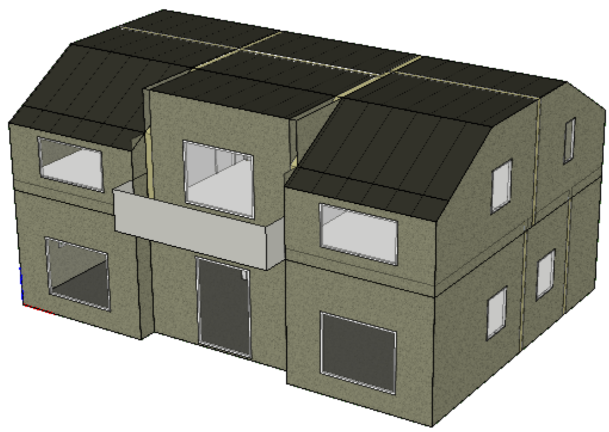
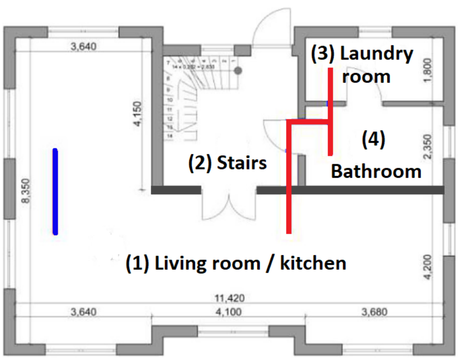


Figure 4.3: 3D model of Mesterhus Nanne from IDA ICE, south and west facade

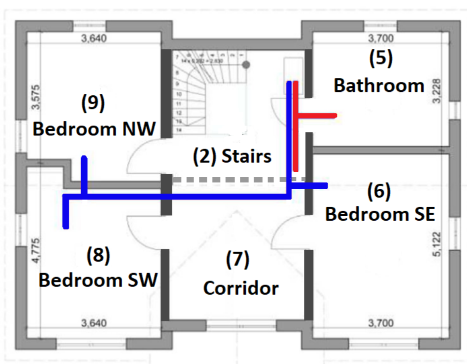
4.2.1 Floor plan and zones

The building is divided into nine zones, where each zone represent a room in this software. IDA-ICE assumes each zone as fully mixed, resulting in a uniform temperature distribution within each zone. This means that each zone can be represented as a single state, ignoring effects like thermal stratification. The kitchen and living room have an open floor plan, coupled into one room (zone 1). The entrance hall has an open staircase to the second floor (zone 2). This is modelled as a single zone with two-storey height and no floor. This is done to avoid a narrow horizontal opening between two zones, as there are uncertainties to how well simulated air flow represent the real case for this type of problems. A laundry/technical room (zone 3) is adjacent to the first floor bathroom (zone 4). The second floor consist of another bathroom (zone 5), the southeast bedroom (zone 6), the southwest bedroom (zone 8), the northwest bedroom (zone 9) and a corridor/upstairs living room (zone 7). Zone 2 and zone 7 are not divided with a wall, indicated with a dashed line. The connection between these two zones is a large vertical opening, giving a bidirectional flow. This is modelled as a bulk flow in IDA ICE, and the air flow is driven by the hydrostatic pressure difference between the two zones. One should be take precautions when looking at the simulation results, as this assumption may not be true (Georges et al., 2016).

A separation between two types of internal walls in the building is done. The internal walls with a light gray colour are dividing walls, while the walls with a dark gray colour are load bearing internal walls. The physical difference between the two types will be presented in subsection 4.2.3. The floor plan with internal dimensions and the ventilation layout is illustrated in figure 4.4 below. The heated floor area A_{fl} for the case building is 173.5 m^2 in total.



(a) First floor



(b) Second floor

Figure 4.4: Sketch of floor plan of Mesterhus Nanne with ventilation layout (blue is supply air ducts and red is extract air ducts). Adapted from Georges et al. (2014) and Mestergruppen Bolig AS (Unknown)

4.2.2 Location

In the initial study on the suitability of air heating, the Norwegian passive house standard NS3700 (Standard Norge, 2013) was the basis for the construction of the model. As presented in subsection 2.1.1, a maximum allowable net energy need for space-heating has to be documented during design stage for a building to be labeled as a passive house. This maximum limit on space-heating needs is highly influenced by the geographical location and the local climate. Table 4.1 below presents the calculated maximum allowable net energy need for space-heating Q_{max} if the case building would been built in the four different geographical locations used in the study of the air heating concept. The table also illustrate the difference in yearly mean outdoor temperature ϑ_{ym} and design outdoor temperature ϑ_{DOT} for the four different locations.

Table 4.1: Weather characteristics for the geographic locations with calculated maximum allowable net energy need for space heating. Adapted from Georges et al. (2014) and Sintef Byggforsk (2012)

	ϑ_{ym} [°C]	ϑ_{DOT} [°C]	A_{fl} [m^2]	Q_{max} [kWh/m^2 y]
Oslo	6.3	-20.0	173.5	19.2
Bergen	7.5	-11.7	173.5	19.1
Tromsø	2.9	-14.6	173.5	27.8
Karasjok	-2.5	-48.0	173.5	41.6

Climate file

The chosen location in this study is Oslo, as this is also used as a reference location for control calculations against the current legislation for building performance. Oslo has a temperate climate with four clear defined seasons, with hot summers and relatively cold winters (Meteorologisk institutt, 2010). The weather file used in this study is a ASHRAE IWEC 2 file obtained from the database accessible from IDA ICE. The weather file is a Typical Meteorological Year (TMY) weather file derived from typical real months, but not necessarily from the same year. The weather file provide hourly values for the air dry-bulb temperature, relative humidity of the air, direct normal radiation, diffuse radiation for a horizontal surface, wind speed and cloudiness.

Even though the climate file contain information about the wind speed at the location, a wind profile has to be determined by choosing the value of two parameters. These two parameters are parts of the power law for wind speed utilized by the program, and the wind speed is assumed to vary vertically. The two parameters therefore decides the shape of the wind profile. The wind speed is assumed to be zero on the ground, and increases to the measured wind speed in the climate file at the reference height (10 meters above the ground (EQUA Simulation AB, 2013)). The power law for wind profile used by the software is presented in equation (4.1) below.

$$U = U_{measured} \text{ x } a_0 \text{ x } \frac{H^a}{H_{ref}} \tag{4.1}$$

Where U is the wind speed at a specific height H, $U_{measured}$ is the wind speed contained in the climate file at the reference height, H_{ref} (usually 10 meters), a_0 and a is the two parameters set by our choice. The chosen wind profile is ”suburban”.

The wind is only relevant in the simulations if the pressure coefficients are set in the model, as pressure coefficients are needed to calculate the wind pressure on external surfaces. Real pressure coefficients are dependent on the shape of the building and the surroundings, but IDA ICE offers a simplified choice of auto-filling the pressure coefficients for the modelled geometry by choosing ”sheltered”, ”semi-exposed” or ”exposed” building. These preset value choices are based on a handbook data set from Air Infiltration and Ventilation Centre (AIVC) (**?**). The wind pressure are assumed to be constant over a surface, and is according to the IDA-ICE manual calculated according to equation (4.2) below.

$$P = \frac{1}{2} \text{ x } P_{coefficient} \text{ x } \rho \text{ x } U^2 \tag{4.2}$$

Where P is the wind pressure on the surface, $P_{coefficient}$ is the pressure coefficient, ρ is the density of air and U is the wind speed calculated from equation (4.1). The case building is modelled as a ”semi-exposed” building to represent the average building. Wind induced pressure on surfaces of a building can be very important when working with simulations that involve natural ventilation, as window ventilation in this study.

4.2.3 Construction modes & insulation levels

Different construction modes can be considered for the building to achieve the same envelope performance. Building tradition often originate from the availability of building materials and resources at the location, for example the extensive use of bricks from clay in the UK, or timber in Scandinavia. Five different construction modes were investigated in the study of the air heating concept, corresponding to five different levels of internal thermal mass due to different building materials being used. The difference in thermal inertia and heat capacity will influence how much energy in terms of heat the building can accumulate, and in theory how responsive the buildings will be to changes in boundary conditions, e.g. changes in the set point temperatures or the outdoor temperature. By using different construction materials, the thermal resistance (U-value) between the different zones will also be different due to the different properties of the materials. In this study, all five construction modes are used as a basis for further investigations, and all fulfilling the envelope performance of NS3700.

Information about the different construction modes was extracted from the input build files for TRANSYS 17, used in the same study of the air heating concept. The build files contained information about the thermal conductivity, density, specific heat capacity and thickness of the materials used to create the different parts of the building. Based on the information from the build file, default materials was created in the IDA ICE library. IDA ICE uses the layer based approach, so different layers of materials of a certain thickness is added together to in order to create construction elements. The thermal resistance and heat capacity for the whole construction element is then calculated automatically. Due to the layer based approach, the effect of the wall studs in a wooden framing having different thermal properties than the insulation is not possible to model. Instead, the timber frame with insulation is modelled as a single layer, where the properties are the average of wall construction. This can for example be 20% wood and 80% insulation, depending on the heaviness of the construction. The key information about the five different construction modes are presented in the table 4.2 below.

Table 4.2: Construction modes: Thermal inertia and U-values for the internal construction parts. Adapted from Georges et al. (2014).

Construction type	Inertia type	Inertia [MJ/K]	U_{floor} [W/m^{2}K]	U_{part} [W/m^{2}K]	$U_{bearing}$ [W/m^{2}K]	$U_{average}$ [W/m^{2}K]
Masonry heavy	Very-heavy	86	1.6	3.2	2.8	**2.53**
Mixed wood-masonry	Heavy	41	1.6	0.33	2.8	**1.58**
Wooden heavy	Medium	35	0.23	0.33	2.8	**1.12**
Masonry light	Light	26	0.21	0.33	1.1	**0.55**
Wooden light	Very-light	14	0.21	0.33	0.25	**0.26**

To investigate if the issue with warm bedrooms started to develop when the requirement for the building envelope performance increased, four additional building envelope performance levels are studied. The base case has a building envelope performance corresponding to the maximum allowed energy use for space-heating according to the passive house standard NS3700, calculated for Oslo climate (see table 4.1). TEK10 (Kommunal- og moderniseringsdepartementet, 2010) represent the current legislation for energy performance of buildings, while TEK07, TEK97 and TEK87 represent the historical legislation (Kommunal- og arbeidsdepartementet, 1987). In order to change the performance of the building envelope according to the TEK-versions, the thickness of the insulation layer for the different construction elements was reduced until the desired U-value was reached. This was done for all the five construction modes as well. The properties of the internal construction elements remains the same, as they are left unchanged.

For TEK10 and TEK07 there are two different approaches to fulfill the requirements. The first approach is quite similar to the approach stated by the passive house standard, where a maximum allowed energy need for the specific building type is set. Then the performance level for the building envelope is chosen in order to fulfill this requirement. The other approach is the traditional one, where a minimum performance requirement for each individual building component is set by the legislation. This approach has been used in this study for all the four TEK versions. The thermal resistance (U-values) of the external wall, floor, roof, windows and doors, air tightness and normalized thermal bridge factor for the four cases are presented in table 4.3 below. (Ingebrigtsen, 2016)

Table 4.3: Building performance: U-values for external construction, air tightness at 50 Pa (n_{50}), normalized thermal bridge factor (ψ) and heat recovery efficiency (η)

Insulation level	$U_{ext.wall}$ [W/m^{2}K{]}]	$U_{ext.floor}$ [W/m^{2}K]	U_{roof} [W/m^{2}K]	$U_{windows/doors}$ [W/m^{2}K]	n_{50} [h^{-1}]	ψ [W/m^{2}K]	η [%]
NS3700 (Basecase)	0.14	0.13	0.12	0.72	0.6	0.03	80
TEK10	0.18	0.15	0.13	1.20	1.5	0.05	80
TEK07	0.18	0.15	0.13	1.60	2.5	0.05*	70
TEK97	0.22	0.15	0.15	1.60	4.0	0.05*	0**
TEK87	0.30	0.20	0.20	2.40	4.0	0.05*	0**

* No information available, assumed similar to TEK10
** Natural ventilation would be used

For the two oldest building regulation editions, TEK97 and TEK87, a balanced mechanical ventilation system would not be a typical solution. A more common solution for older buildings is systems based on the natural ventilation principle, where natural driving forces like wind pressure and buoyancy contributed to the air change rate of the building. Fresh air would typically enter the building through air vents on the walls or windows and leave the building through ducts lead over the roof due to the buoyancy effect. Since the air change rate for this type of systems is highly dependent on the natural forces involved, modelling natural ventilation systems and airflows accurately is challenging. Therefore, the same mechanical balanced ventilation system is used in the two oldest building performance levels as well, although assuming no heat recovery is installed.

4.2.4 Doors and windows

IDA ICE has two options for modelling windows, the simplified and the detailed window model. The detailed window model offers the possibility of describing the optical and thermal properties of the window panes, gaps and shading devices in a glass construction, and the characteristics of the total glass construction are then calculated by the program according to ISO15099 (International Organization for Standardization, 2003). It is also possible to model a double glass facade with the detailed model. In this study, the simplified window model is used instead, which make it possible to have the key performance factors of the total window construction as direct inputs.

The windows for this buildings are based on the Pilkington Insulight™ Blue 50/27 (Pilkington UK Ltd, 2016). The two most influential factors are the thermal resistance of the window construction (U-value), and the solar heat gain coefficient (g-value), which describes the solar energy transmittance of a window. These factors are set to 0.7 W/m^{2}K and 0.25 respectively. Since external shading is not considered in this study, choosing a window type with both a high thermal insulation level and a solar control technology was considered. When historical performance levels were investigated, the performance of the windows was also reduced. By using the simple window model, it is possible to edit the U-value for the window according to the minimum demands set by the historical building regulation investigated (see table 4.3). The other physical properties of the windows still remain the same. The insulation performance of the external door is treated the same way, as the insulation properties are reduced gradually with older building regulation according to the values stated in table 4.3. Default internal door construction of wood are used, with a leak area of 0.01 m^2 to ensure proper overflow between supply and extract zones.

Opening of doors and windows is an important part of the study on thermal conditions in bedrooms. Opening of windows is modelled as relative opening (%) of height and width, together with the discharge coefficient of the flow (C_d). The discharge coefficient is the ratio of the actual discharge to the theoretical discharge through an opening, by default set to 0.65 by the program. When modelling the opening of windows, the opening is limited to 20% of the total window area as in the study by Georges et al. (2016), where this choice reproduced the temperature dynamics observed from the measurement in a satisfactory manner. Opening of the bedroom windows is also limited to the windows located on the east and west facade of the building (see figure 4.1 and 4.2). Internal doors are either closed or 100% open.

4.2.5 Distribution system for space-heating

The procedure used for sizing the hydronic radiators in this study is the design outdoor temperature (DOT) approach, a common heating design procedure. The DOT is the lowest average temperature during three days for that location recorded the last 30 years, and for Oslo the DOT is -20°C (Sintef Byggforsk, 2012). In IDA ICE, an ideal heater unit is placed in each zone, which delivers exactly the amount of heat needed to keep the set-point temperature in the zone without any dynamics. The DOT is held constant during the simulation, and no internal or solar gains are included in the simulation. This result in a steady-state power need, representing the worst case scenario for the different zones and the building as a whole, often called nominal or design conditions. This is done for the for all the building performance levels used in this study, from the NS3700 case to the TEK87 case. It is debatable if this approach is suitable for buildings that fulfill the passive house standard. Ignoring internal/solar gains in the sizing process could lead to possible over-dimensioning of heating equipment, because internal and solar gains contribute to a significant share of the energy need for space-heating.

A suitable radiator size is selected based on the technical data sheet provided by the manufacturer. The chosen radiator type to use in this study is the Compact [C22] (PURMO, 2016), which is available in a wide range of sizes. The delivered heat from a hydronic radiator is in addition to the physical characteristics determined by the mean temperature difference between the room and the hot water going through the radiator. The heat distribution system is for all cases modelled as a 60°C/40°C system, following a outdoor temperature compensation curve. This means that the supply temperature is 60°C with a 20°C temperature drop over the heating elements at nominal conditions. The supply temperature is gradually reduced with increasing outdoor temperature, since there is a strong relationship between the power need for heating and the outdoor temperature. For the passive house case, a distribution system with even lower temperatures could be used, like

50°C/40°C or 40°C/30°C. This is not considered in this study. By inserting the supply, return and room air temperature at nominal conditions in the data sheet, the delivered power is calculated for each of available radiator sizes according to equation (4.3) below.

$$\dot{Q} = K_{rad}\,\Delta T_m^n \tag{4.3}$$

Where $\dot{Q}$ is the heating power output from the radiator, K_{rad} is the radiator constant (according to size and design of the radiator), ΔT_m is the mean temperature difference between the room and radiator and n is the radiator exponent (according to size and design of the radiator) (Nilsson, 2007). The size, radiator expontent, nominal power, room temperature and supply & return temperature at nominal conditions are obtained from the manufacturer data, and used as an input to IDA ICE. The simulation software then calculates the needed massflow at full power to the radiator based on these input values. A illustration of the PURMO compact C22 with cross sectional dimensions is shown in figure 4.5 below.

Figure 4.5: PURMO Compact [C22] with dimensions in mm (PURMO, 2016)

For the simplified heat distribution loop, two radiators are modelled in the building, and they are placed in the combined living room and kitchen (zone 1) and the corridor/upstairs living room in the second floor (zone 2), see the floor plan in figure 4.4. In addition to the radiators, floor heating is assumed installed in the two bathrooms and the laundry room. The radiator in the first floor have a nominal output power sufficient to deliver enough heat to zone 1 and 2 during design conditions. The radiator in the second floor does the same for zone 6, 7, 8 and 9. For the buildings with performance level of TEK10 or historical TEK versions, the standard heat distribution loop is assumed installed. Here, at least one radiator is placed in each zone except the bathrooms and laundry room, where floor heating also in this system is assumed installed. The heat load for the combined living room and kitchen (zone 1) is split between three radiators.

4.2.6 Ventilation system

The Norwegian building code (TEK) is a function-based building regulation, which means that the technical requirements are specified in form of functions or performance (Kommunal- og moderniseringsdepartementet, 2010). The requirement in the regulation itself is often qualitative. There are therefore two ways to satisfy the requirements set by the building code. The most common way is to fulfill the pre-accepted quantitative performance found in the guideline to each chapter. The other alternative is do analyses on the chosen solution to verify that it fulfills the requirement set by the building code. This method do however require thorough documentation, where the pre-accepted performance often is set as a reference. An illustration of the process is presented in figure 4.6 below.

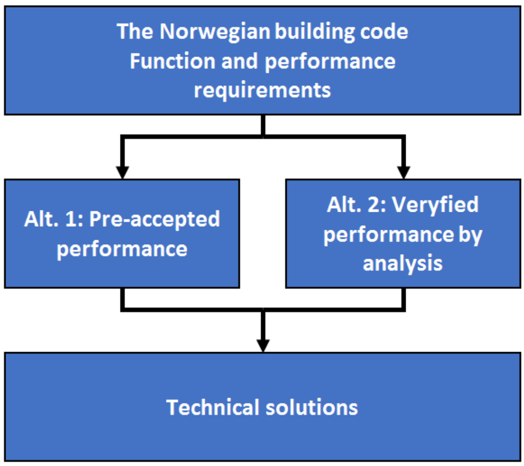


Figure 4.6: Illustration of the two alternatives to fulfill the requirements in the Norwegian building regulation TEK10

Chapter 13 "Environment and Health" in TEK10 concerns indoor air quality, thermal environment, sound levels, vibrations, moisture and wet rooms. The requirements are according to the guidance set to prevent health issues and general discomfort (Kommunal- og moderniseringsdepartementet, 2010). Indoor air quality and moisture levels are closely linked to the air change rate in a building, and section 13.2 therefore contain requirements for the ventilation rate for residential buildings. First, the minimum ventilation rate for residential buildings is set to 1.2 $m^3/h\,m^2$ floor area to ensure a minimum fresh air supply to the building. Bedrooms must be ventilated with minimum 26 m^3/h person to keep the CO_2 concentration in the bedrooms at the desired level. In addition, minimum ventilation rates for wet rooms is set by Table 4.4, representing the pre-accepted performance values for this type of rooms with large pollution and/or moisture production.

Table 4.4: Pre-accepted performance from chapter 13.2 in TEK10 (Kommunal- og moderniseringsdepartementet, 2010)

Room	Minimum ventilation rate m^3/h	Enhanced ventilation rate m^3/h
Kitchen	36	108
Bathroom	54	108
Toilet	36	36
Laundry room	36	72

The second column in table 4.4 is the enhanced ventilation rates, for example activating the kitchen hood fan while cooking, or increasing the extract rate from the bathroom while showering. Only the basic ventilation rates for this type of rooms is considered in this study, as the enhanced ventilation rates only are used for a short period of time during the day, and is strongly connected to user behavior. When designing the ventilation system and the airflow rates, there are three possible dimensioning factors that could determine the required airflow rate for the building, as discussed in the paragraphs above. To summarize, these factors are presented below with the calculated resulting airflow rate for the case building in brackets.

- General average fresh air supply of 1.2 $m^3/h\,m^2$ floor area [208 m^3/h]
- Supply of fresh to bedrooms of 26 m^3/h person [104 m^3/h]
- Extract ventilation from kitchen, bathrooms and laundry room [180 m^3/h]

The resulting largest airflow rate is produced by the requirement for general fresh air supply (208 m^3/h). This is often the case for detached houses in contrast to apartments, where the combined extract from kitchen and bathroom represent the largest airflow rate. When the dwellings increase in size, the general fresh air requirement become dominant. The design airflow rates for Mesterhus Nanne is presented in table 4.5 below.

Table 4.5: Ventilation flow rates

Zone	Room	Supply air m^3/h	Return air m^3/h
1	Kitchen/Living room	104	40
2	Stairs	0	0
3	Technical/Laundry room	0	40
4	Bathroom 1st floor	0	64
5	Bathroom 2nd floor	0	64
6	Bedroom SE	52	0
7	Corridor 2nd floor	0	0
8	Bedroom SW	26	0
9	Bedroom NW	26	0
Total		208	208

The airflow rates for the bedrooms are set according to the requirement in the building regulation, assuming bedroom SE is a double bedroom. The different bedrooms are named after the spatial arrangement in the building (SE = south-east = zone 6, SW = south-west = zone 8 and NW = north-west = zone 9), see the floor plan in figure 4.4. The ventilation system in this building is modelled according to the cascade principle discussed in subsection 2.1.2. Therefore, the rest of the fresh air is supplied to the combined living room and kitchen, while the stairs and the upstairs corridor is treated as overflow zones. Since the general requirement for supply air was the dimensioning value for this building, the extract ventilation rate has to be increased beyond the minimum requirements to have a balanced system. As table 4.5 shows, the extract rate from the bathrooms is increased to 64 m^3/h, while the extract rate from the laundry room and kitchen is increased to 40 m^3/h. It is also worth mentioning that the air terminals do not have a physical location inside the room in IDA ICE, as the zones (rooms) are assumed to be fully mixed fully mixed.

Air handling unit (AHU)

The ventilation system is modelled as a constant air volume system (CAV), meaning the airflow rates specified in table 4.5 are held constant. The supply and exhaust fans delivering the required airflow to the building have ideal pressure control and constant efficiency (EQUA Simulation AB, 2013). The fixed pressure head and efficiency are calculated automatically by using the specific fan power (SFP) as an input. The SFP value is set to 1,5 kW/(m^3/s) for each of the fans, in compliance with the minimum requirements set by NS3700 (see table 2.1). A regenerative rotary heat exchanger is assumed installed in the AHU, a common component in AHUs used in residential buildings due to the excellent heat recovery efficiency. A heat recovery efficiency of 85% is assumed for this model. A schematic overview of the standard AHU from IDA ICE is presented in figure 4.7 below.

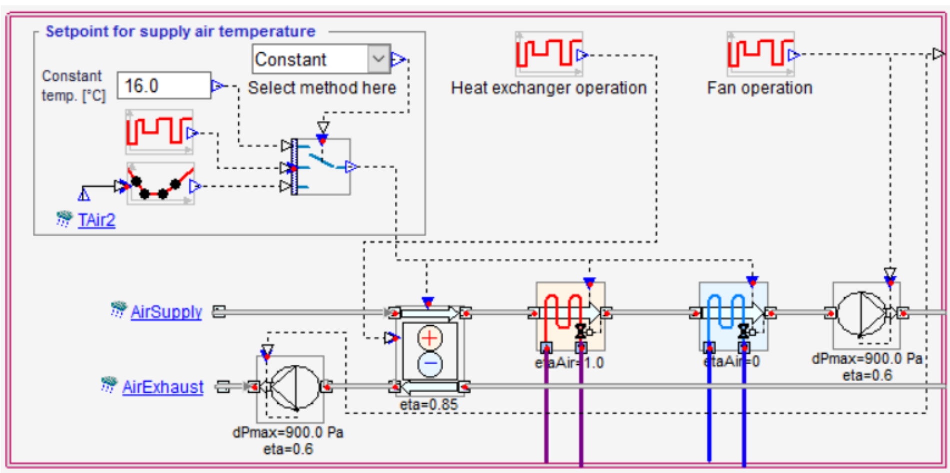
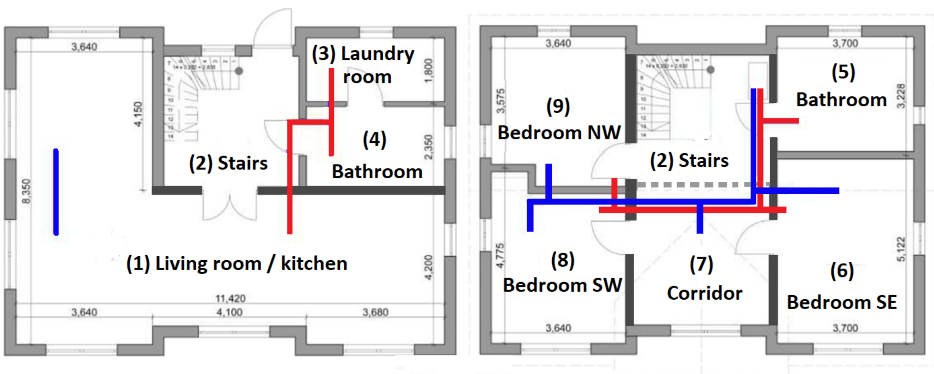


Figure 4.7: Schematic overview of the standard AHU modelled in IDA ICE

A hydronic heating coil is assumed installed after the heat exchanger, with the efficiency set to 100%. A cooling coil is also a part of the standard AHU, but the efficiency is for this component is set to 0%, meaning it is switched off. The set-point temperature for the supply air can be controlled in three ways in the standard AHU model. A constant set-point temperature, a set-point temperature according to a defined schedule or a outdoor temperature compensated supply temperature can be selected. A constant set-point temperature for the supply air is selected in this study. The rotary heat exchanger and the hydronic heating coil have sequential operation, meaning the heat recovery will be used as much as possible to heat up the cold intake air, and the heating coil will be used to reach the set-point temperature if necessary.

Supply and return air from bedrooms

A multi-zone ventilation system was investigated by Berge et al. (2016a), and the possible benefit of individual temperature control for the bedrooms was tested. Another solution to isolate the bedrooms more from the rest of the building is to introduce both supply and extract for the bedrooms in the building. This will remove the overflow of supply air from the bedrooms into the upstairs living room/corridor (zone 2). This means that a supply air terminal must be introduced to this zone to ensure sufficient air quality, and to better balance the extract flow rate from the upstairs bathroom. The new ventilation layout is presented in figure 4.8 below. This solution with both supply and extract ventilation from the bedroom will introduce more ductwork compared to the base case, but the extract ducts can follow almost the same route as the supply ducts.



(a) First floor (b) Second floor

Figure 4.8: Supply and return air from bedroom: New ventilation layout

As discussed earlier, there are two ways to demonstrate compliance with the building regulation TEK10. By following the pre-accepted values described in the guidance to the regulation, the airflow rates become as shown in table 4.6 above if both supply and extract ventilation are introduced to the bedrooms. The dimensioning factor for the ventilation system is no longer the general requirement for fresh air supply, but the total extract airflow rate from the bathrooms, kitchen, laundry room and bedrooms. Even if this means that the extract rates from the bathrooms, kitchen and laundry rooms can be lowered to the pre-accepted level set by the guidance, the total air change rate for the building has increased by approximately 37%. This is a considerable increase in ventilation rate, and could possibly lead to an increased need for space-heating and heating of ventilation air.

Table 4.6: Supply and return air from bedroom: Ventilation flow rates with pre-accepted performance

Zone	Room	Supply air m3/h	Return air m3/h
1	Kitchen/Living room	126	36
2	Stairs	0	0
3	Technical/Laundry room	0	36
4	Bathroom 1st floor	0	54
5	Bathroom 2nd floor	0	54
6	Bedroom SE	52	52
7	Corridor 2nd floor	54	0
8	Bedroom SW	26	26
9	Bedroom NW	26	26
Total		284	284

If the other approach for showing compliance with the building regulation is used as a basis, a reduction in ventilation air flow could be possible since the air change rate is significantly higher than the base case. One alternative is to reduce the ventilation rate down towards the base case level by introducing a day and night schedule, presented in table 4.7 below. This schedule aim to ventilate parts of the building where people are present, *when* they are present. During daytime the extract flow rate from the kitchen, laundry room and bathrooms are kept at the pre-accepted level, while the extract and supply ventilation rate for the bedrooms are kept slightly above the minimum ventilation flow rate of 0.7 $m^3/h\,m^2$ floor area set by the building regulation. This require that the ventilation rate is increased during other parts of the day, such that the requirement to the *average* minimum ventilation flow rate of 1.2 $m^3/h\,m^2$ floor area is fulfilled. For the night, the bedroom ventilation rate is increased to the pre-accepted level of 26 m^3/h per person. The extract ventilation rate from the kitchen, laundry room and bathrooms are reduced by one third (33%) of the pre-accepted value found in the guideline to the building regulation. The supply flow rate to the upstairs living room/corridor is reduced in relation to the extract flow rate in the upstairs bathroom.

Table 4.7: Supply and return air from bedroom: Ventilation flow rates with day and night schedule

Zone	Room	Day		Night	
		Supply air m^3/h	Return air m^3/h	Supply air m^3/h	Return air m^3/h
1	Kitchen/Living room	126	36	84	24
2	Stairs	0	0	0	0
3	Technical/Laundry room	0	36	0	24
4	Bathroom 1st floor	0	54	0	36
5	Bathroom 2nd floor	0	54	0	36
6	Bedroom SE	12	12	52	52
7	Corridor 2nd floor	54	0	36	0
8	Bedroom SW	10	10	26	26
9	Bedroom NW	10	10	26	26
Total		212	212	224	224

Even if the total supply of fresh air is higher for this case compared to the basecase, detailed analysis on the air flows and indoor air quality for each individual rooms/zone with an airflow rate that periodically deviate from the pre-accepted values must be carried out to ensure compliance against the building regulation. The main challenge will be to document that the reduced extract rate from the wet rooms during nighttime is satisfactory, although the reduced extract rate will happen during hours when the use of these rooms are at its minimum. The reduced airflow in bedrooms during daytime does also imply that the rooms are not occupied during these hours. This could be true for weekdays, but not necessary for weekends and holidays, thus a separate schedule could be required. A detailed analysis of this issue will not be carried out in this study, but the focus will be on the possibilities schedules like this offer. Precautions should therefore be made when applying this schedule.

4.2.7 Human interaction

In the previous studies of the apartments and row houses with passive house standard by Georges et al. (2016) and Håheim (2016), the impact of different control strategies on the thermal conditions and comfort in bedrooms was investigated. To look at this in more detail, and to complement the findings for the other two house typologies, the same type was approach is going to be carried out in this study also. The eight different control strategies investigated here are presented in table 4.8 below, and can be looked at as the occupants interaction with the technical systems in the dwelling. The control strategies include changing the the set-point temperature for the ventilation supply air ($T_{set,SA}$), changing the set-point temperature for space-heating ($T_{set,SH}$) and opening/closing of bedroom doors and windows. The different control strategies are given a number and name according to the different variations between them, in the order they are presented in the table below. The names are also a help to recall the set-points and the opening and closing of windows and doors of the different control strategies later on in this study if needed. The short names (C1 to C8) are used if it is possible.

Table 4.8: Control strategies

Control strategy	$T_{set,SA}$ °C	$T_{set,SH}$ °C	Bedroom doors open/closed	Bedroom windows open/closed
C1 20/22/c/c	20	22	always closed	always closed
C2 16/22/c/c	16	22	always closed	always closed
C3 14/22/c/c	14	22	always closed	always closed
C4 16/24/c/c	16	24	always closed	always closed
C5 16/var/c/c	16	24/16	always closed	always closed
C6 16/24/o/c	16	24	open 07:00 to 23:00	always closed
C7 16/24/c/o	16	24	always closed	open 23:00 to 07:00
C8 16/24/o/o	16	24	open 07:00 to 23:00	open 23:00 to 07:00

4.2.8 Internal gains

The super insulated building envelope of passive houses significantly reduces the energy need for space-heating due to less heat flow through the building envelope. The results is that a large share of the space-heating need can be covered by passive strategies, such as solar heating and internal gains from heat dissipated by people, electric appliances and the lighting system (Feist et al., 2005). Therefore, the influence of internal gains on the bedroom temperature is of great interest. IDA ICE offers the possibility to model all these three different types of internal gains. Three different levels of internal gains are considered in this study:

No internal gains

The heat supplied to the building from people, electrical appliances and the lighting system is ignored. The internal gain elements are deleted from the model. This establishes the basis to compare the other levels of internal gains with.

NS3700 internal gains

The internal gains given by the Norwegian passive house standard NS3700 are strictly followed in this case, see table 4.9 below. They are uniform in space, but operational hours are given. This typically gives lower internal gains during nighttime and higher internal gains during daytime, as the operational hours for lighting and electrical appliances are set from 07:00 to 23:00. The standard gives a mean value of 4.2 W/m^2 floor area, which results in a yearly heat supply of 58.7 kWh/m^{2}year.

Table 4.9: Internal heat gain from lighting, electrical appliances and occupants. Adapted from Standard Norge (2013)

	Operation time hours/days/weeks	Net power need W/m^2	Heat gain W/m^2
Lighting	16/7/52	1.95	1.95
Electrical appliances	16/7/52	3.00	1.80
Domestic hot water	16/7/52	5.10	0.00
Occupants	24/7/52	-	1.50

IDA ICE have the possibility to give in the heat gain for lighting and electrical appliances for each zone normalized per square meter. By using the values stated by the standard, this is easily done for those two types of internal gains. For the electrical appliances, a utilization factor of 60% is chosen, meaning 60% of the net power supplied to the appliances is dissipated into useful heat. For occupants, the software needs an input of number of people per square meter instead of heat gain. Therefore, a calculation based on the activity level (metabolic rate = MET) is necessary. The activity level is by default set to 1 MET, which corresponds to a heat gain of 58.2 W/m^2 body surface. That is the amount of heat one sitting, inactive person is assumed to emit. In IDA ICE, the body surface has been selected to be 1.8 m^2, corresponding to an average adult (EQUA Simulation AB, 2013). This means that one person emit 108 W of heat, and the number of occupants per square meter needed to have 1.50 W/m^2 of heat gain can be calculated and given in to the software.

Internal gains distributed in time and space

Internal gains are playing an increasingly important part of total heat supply for a building, and the interest for a more accurate model than the uniform one suggested by the passive house standard has emerged. In the air-heating study by Georges et al. (2014), internal gains varying in time and space with 1-hour resolution was created. It was created such that the mean value during a day is the same as in NS3700 (4.2 W/m^2 floor area). In addition, the daily load profiles and the yearly energy consumption of electrical appliances was created using measurement data from the Swedish Energy Agency (Enertech, 2009) and SINTEF (Sæle et al., 2010). A distinction between the daily profiles is done for weekdays and weekends.

To model the distributed internal gains, the lighting system was chosen as the basis. The original schedule create by Georges et al. (2014) distinguished between a radiative and a convective fraction of the heat gains. This can be implemented by using the ligthing system, where a 50% convective fraction was chosen. The total power for each zone during the day was set as the input power, and a 1-hour resolution schedule with relative values ranging from 0 to 1 according to the varying heat gain during the day was created. It is worth mentioning that IDA ICE by default applies a degree of smoothing of schedules to make the numerical operations more feasible.

Chapter 5

Simulations & results

5.1 Thermal dynamics of a bedroom

To be able to propose strategies to improve thermal zoning in a building, it is necessary to understand how the building behaves under different conditions. A house is a complex dynamic system, and the thermal conditions in one room is influenced by a vast number of factors. Since the objective of this study is to investigate strategies that could improve the thermal zoning in the building, and especially between the bedrooms and the rest of the building, the focus will naturally be on the bedrooms. The results presented will almost entirely be from the largest bedroom, located in the south-east corner of the building (see the floor plan in figure 4.4). The three bedrooms in the case building are quite similar both in size and shape, and the results could therefore be expected to be representative for the other two rooms as well. A more detailed discussion about the choice of bedroom is carried out in chapter six.

5.1.1 Heating season

The findings in the literature demonstrated that bedrooms are not only perceived as too hot during the warmest periods of the year, but also during winter season. It is therefore interesting to investigate and learn how the building behaves under cold conditions. Figure 5.1 below shows the outdoor air temperature and the resulting indoor air temperature in the south-east bedroom for a cold week in January. This week was not only chosen because of the low outdoor air temperatures observed, but also due to the large temperature variation. The simulation was performed with a set-point temperature of 21°C for space-heating, and a set-point temperature of 20°C for supply air, with the bedroom doors and windows being closed all the time. Internal gains according to the passive house standard NS3700 was used as an input. The simulation was performed for all the five construction modes (abbreviated CM) described in section 4.2.3 (see table 4.2).

The outdoor air temperature is relatively mild (0°C) at the beginning of the week, and then gradually decreased towards -20°C for the next days of the week. The coldest period observed is the night between the 17th and 18th of January, where a outdoor air temperature below -20°C occur. From the figure it can be observed that the temperature in bedroom SE follows the same trend, as gradually lower indoor air temperatures can be observed as the outdoor air temperatures drops. A significant difference between the five different construction modes can be observed during the cold week. Initially, the bedroom temperature is quite similar for all construction modes, with a temperature difference of about 1°C between the lightest (CM5) and the heaviest building (CM1) type. When lower outdoor temperatures occur, the differences between the five construction modes becomes more evident. The lightest building type (lowest thermal mass) is much more responsive to the changing outdoor air temperature than the heavier building types, resulting in a much lower bedroom temperature.

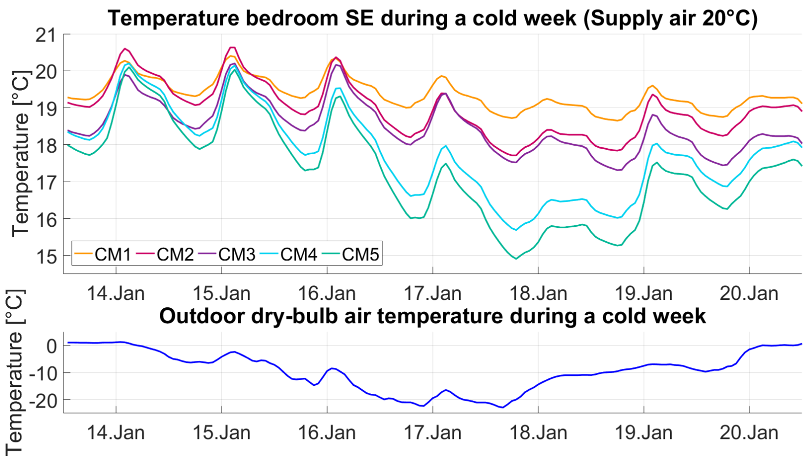


Figure 5.1: Thermal conditions in bedroom SE during a cold week with the five different construction modes

Due to rapid changes in the boundary conditions, rooms without a heat source (like bedrooms) never reach their steady-state temperature. These changing boundary conditions could be changes in the outdoor temperature, internal/solar gains, opening/closing of doors and windows, and changes in the set-point temperature for heating and ventilation air. To illustrate this, simulations with constant outdoor air temperature was performed along with the fully dynamic simulations. From figure 5.1 it is clear that CM1 and CM5 represent the two extremities, while the three other construction modes are found in between. The heaviest building (CM1) is therefore presented in figure 5.2 and the lightest building (CM5) is presented in figure 5.3. The dashed lines illustrate what the bedroom temperature would have been if the outdoor temperature was held constant at lowest (blue line) and highest (red line) temperature during the cold week investigated here. Therefore, the constant outdoor temperature cases illustrate the expected room temperature span for bedroom SE during the cold week. The yellow lines represent the real dynamic temperature evolution for the cold week, and are therefore similar to the ones seen in figure 5.1.

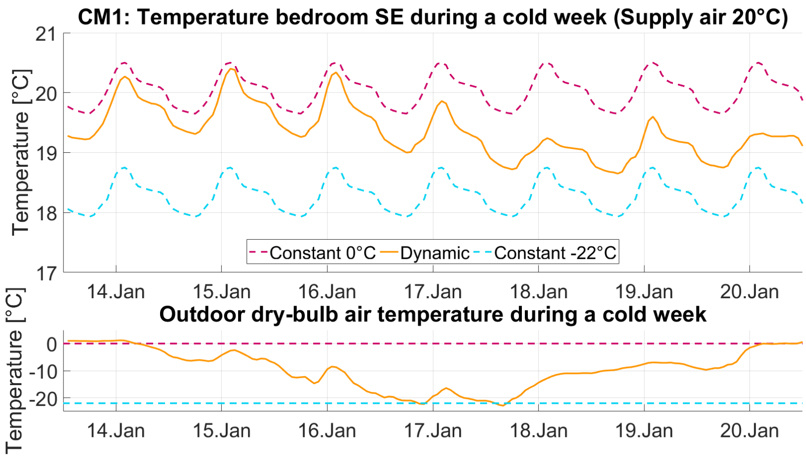


Figure 5.2: CM1: Temperature in bedroom SE with upper and lower temperature limits

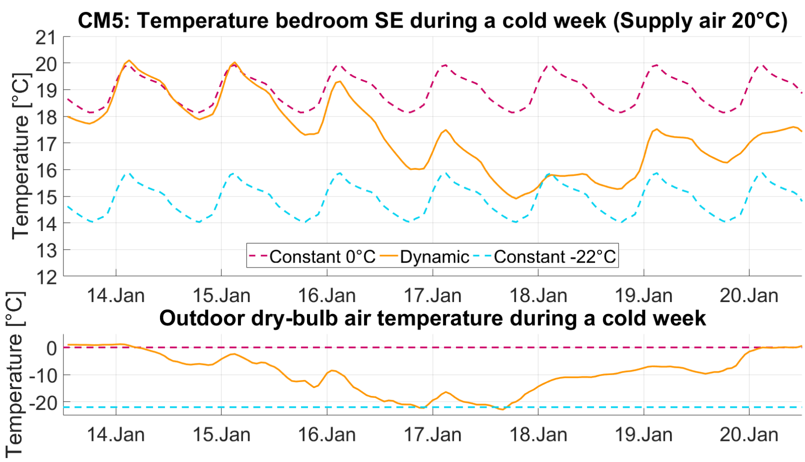


Figure 5.3: CM5: Temperature in bedroom SE with upper and lower temperature limits

It is clear that lightest building type (fig. 5.3) is more responsive to changes in the outdoor temperature (boundary condition) than the heavy one. The lightest building type give a room temperature much closer to the limits set by the constant outdoor temperature lines than the heavy building, which give a more stable, less fluctuating bedroom temperature. By examining the temperature difference between the two constant outdoor air temperature cases for the heaviest and the lightest building types, another difference can be observed. An average temperature difference of about 1.7°C between the two constant outdoor temperature cases is found for CM1, while a significantly larger temperature difference of 4.2°C can found for the CM5 cases. In addition to a smaller difference between the two constant outdoor temperature cases, the average temperature is also higher for the heaviest building type, both for the constant and dynamic situation.

An approach to understand the differences between the construction modes, and their behavior under different outdoor temperature conditions is to perform a heat balance for the bedroom. With fully dynamic outdoor temperature conditions, the heat balance is subject to constant change. Therefore, a heat balance for the constant outdoor temperature cases is performed, eliminating at least one dynamic factor from the system. Due to solar gains varying during the day, temperature fluctuations are still present in the bedroom, even though a constant outdoor temperature is imposed. The heat balance presented in figure 5.4 shows the *average* heat balance for the constant outdoor temperature cases for both the lightest and the heaviest building type. By following the same logic as before, the heat balance for the two extreme cases in terms of outdoor temperature for the week we are looking at create the upper and lower limits for the real heat balance with changing outdoor air temperature.

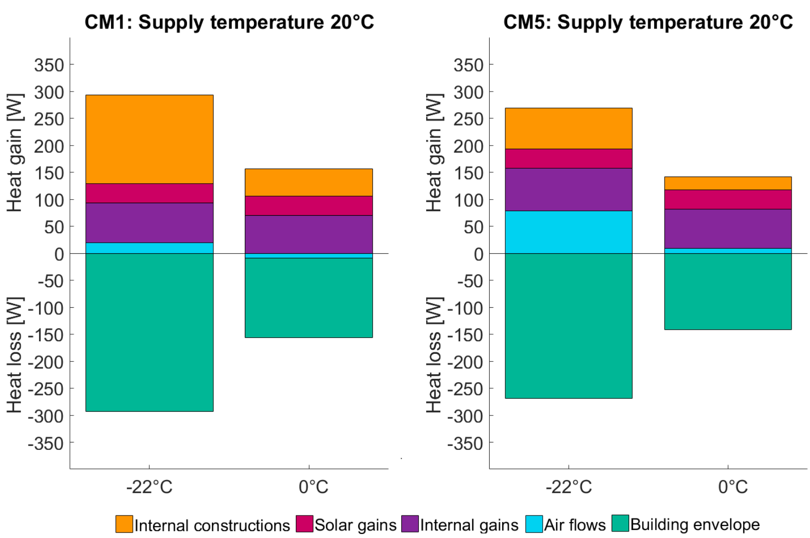


Figure 5.4: Heat balance bedroom SE during winter conditions

The first thing that can be observed from the heat balance is that the heat losses from the building envelope is as expected higher for lower outdoor temperatures. This is due to a larger temperature difference between the room air and outdoor air, giving larger driving forces for heat flow at low outdoor air temperatures. The heat loss through the building envelope includes heat losses through the external walls, roof, windows and thermal bridges. Another thing to notice is that the absolute value of internal and solar gains are the same for all four cases, since the same climate file and input in terms of internal gains is used. The heat gain from internal constructions include both conductive heat transfer through the structure and heat storage/release in the structure. The heat gain from internal construction is more important when the outdoor temperature is lower, as it contributes to a large share of the total heat gain to the bedroom both for the lightest and heaviest building type. When the outdoor temperature is about 0°C, the dominant heat contributions are the solar and the internal gains.

The impact of air flows on the heat balance is dependent on the temperature difference between the room air and the supply air, and the airflow rate delivered to the room. For the heaviest building type (CM1) the heating or cooling effect from air flows is very small. By examining figure 5.2, the average bedroom temperature for the -22°C case can be read to 18.3°C, and for the 0°C case it is very close to 20°C. When the supply air has the same temperature as the room air, no heating or cooling is provided, which is true for the 0°C case. For the -22°C case, the supply air is providing a small heating effect, since the average room air temperature is 1.7°C lower than the supply air temperature. The same trend can be observed for the lightest building type (CM5) as well, but the absolute heat gain from air flows during the coldest case is larger, due to an average bedroom air temperature of 15°C.

When examining figure 5.1, a clear difference in dynamics and bedroom temperature evolution throughout the week can be observed in the five cases. By looking at the properties of the five different construction modes in table 4.2, a difference in thermal resistance of the internal construction can also be observed along with the difference in thermal heat capacity. This is a result of different building materials and methods for making floors, dividing walls and load bearing walls being used for the five construction modes. The bedroom temperature for the different construction modes observed in figure 5.1 could therefore be a result of both difference in thermal resistance for the internal construction and thermal heat capacity.

To separate those two effects, a simulation for the same week is performed for CM1 (heaviest) and CM5 (lightest), but with the thermal resistance (U-value) of the internal construction of CM1 adjusted to match the CM5 level. This is done by adding a layer of insulation (EPS) to the internal construction elements in CM1. The effect of this adjustment can be observed in figure 5.5 below, and the adjustment has shifted the resulting bedroom temperature down about 1°C. The effect of thermal mass of the building is now more clear, illustrating that the heaviest building gives a more stable temperature, but are not able to provide low bedroom temperatures when the outdoor temperature is very low. During the first two days of the week the outdoor air temperature is relatively mild, and the average bedroom temperature is very similar for the two building types during this period.

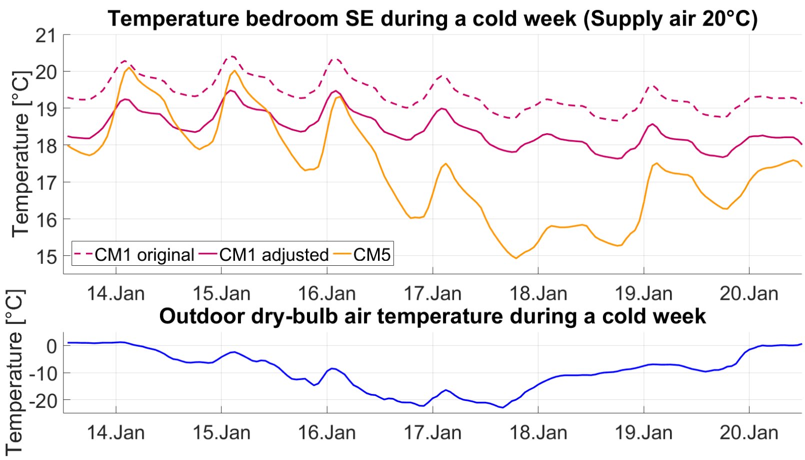


Figure 5.5: Temperature in bedroom SE with adjusted CM1

The results from the heat balance in figure 5.4 show that the supply of fresh to the bedroom can contribute to a significant share of the total heat gain for the bedroom, especially for CM5 when the outdoor temperature is very low (-22°C). The set-point temperature for the supply air is one of the factors that determine the heating or cooling effect the ventilation air has on the bedroom temperature, as discussed earlier. To see how a change in the set-point temperature for the supply air influences the heat balance and temperature for the bedroom, a simulation for the same winter week is performed with 16°C supply air temperature. The resulting temperature and heat balance are presented in figure 5.6 and 5.7 below.

From figure 5.6 it is clear that the temperature dynamic for the bedroom is preserved when the supply air temperature is changed for both the heavy and the light building type. This can be seen from the dashed lines in the figure, representing the previous case with 20°C supply air temperature. The lightest building type is more influenced by the change in supply air temperature, as the bedroom temperature is lowered by 1.4°C in average during the week, compared to only 0.7°C for the heaviest building type.

The heat balance for bedroom SE was again performed with a constant outdoor air temperature of -22°C and 0°C imposed. Comparing the heat balance for the bedroom when the supply air is set to 20°C (figure 5.4) and 16°C (figure 5.7), the heat balance do not change significantly even though the temperature of the bedroom is reduced. The most visible effect of lowering the supply air temperature, is that the ventilation air provides a cooling effect on the bedroom for the heaviest building type for both outdoor temperature levels. For the lightest building type, the ventilation air is now providing a cooling effect when the outdoor temperature is at 0°C. The heat supplied from solar and internal gains is as expected, unchanged.

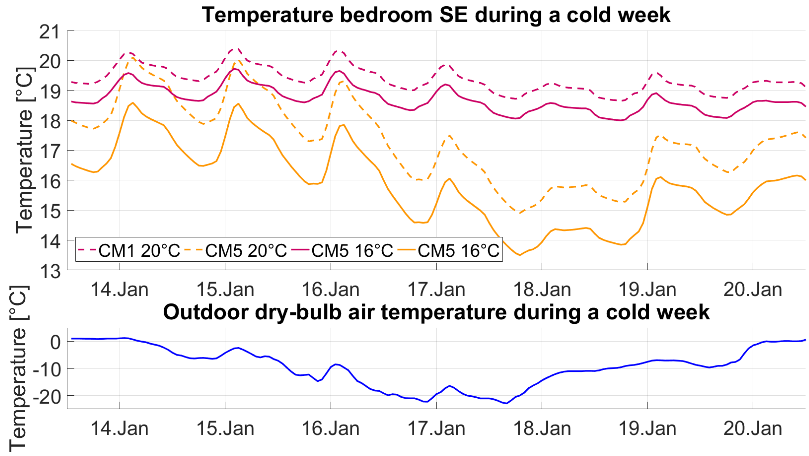


Figure 5.6: Temperature in bedroom SE with different supply air temperatures

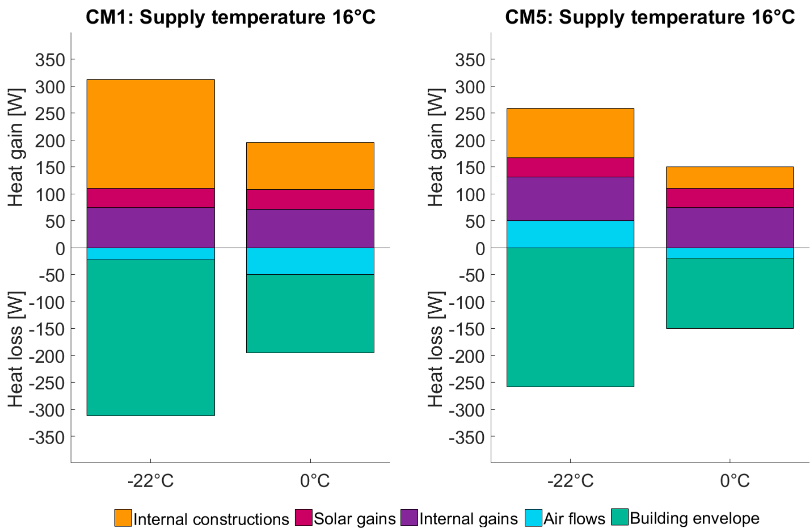


Figure 5.7: Heat balance bedroom SE during winter conditions with lower supply air temperature

5.1.2 End of heating season

The heating season for this study starts in the beginning of October and finishes at the end of April. The heating season does not only contain very cold nights, but also milder periods, illustrated by the duration curve for the outdoor temperature during heating season in figure 5.8 below. For 74% of the time the outdoor temperature is in the range -10°C to 5°C. The outdoor air temperature is below -10°C for only 11% of the time, while it is warmer than 5°C for about 15% of the time during the heating season. To investigate how the building behaves under the warmer periods of the heating season, a spring week in the beginning of April is looked more into. In addition to higher outdoor temperatures, the influence of increased solar gains could also be of interest.

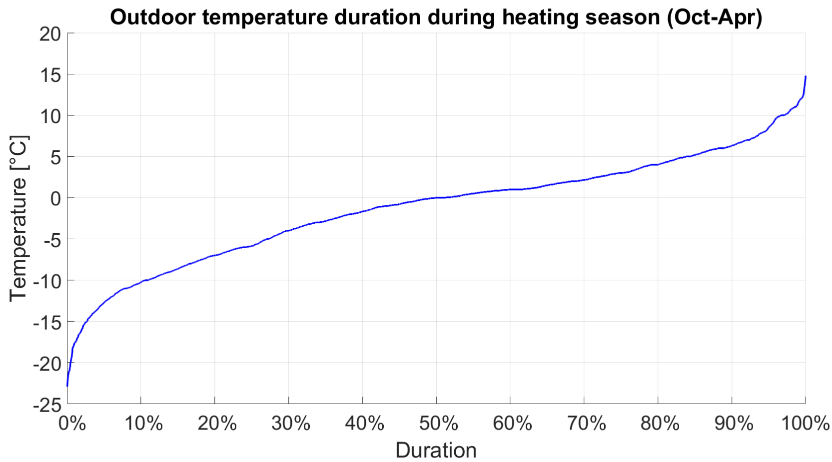


Figure 5.8: Outdoor air temperature for Oslo during heating season (Oct-Apr)

The outdoor temperature during this spring week early in April is changing a lot from nighttime to daytime as observed in the lower section of figure 5.9, a typical temperature dynamic during spring time for Nordic climate. As for the winter week, the simulation was carried out for all the five different construction modes and set-points for space-heating and ventilation supply air. The difference between the heaviest and lightest building type is distinct in this case also. The lightest building type is more responsive and influenced by the outdoor temperature as some days it offers both the highest temperatures during daytime, and the lowest temperatures during nighttime. This could also imply that the lightest building type could be more influenced by the increased solar gains during this spring week. The heaviest building type does not have the large amplitude in temperature fluctuations and is perceived as more stable. The thermal inertia of the different construction modes are therefore very visible during this spring week. The bedroom temperature is in general on a higher level than observed for winter time in figure 5.1

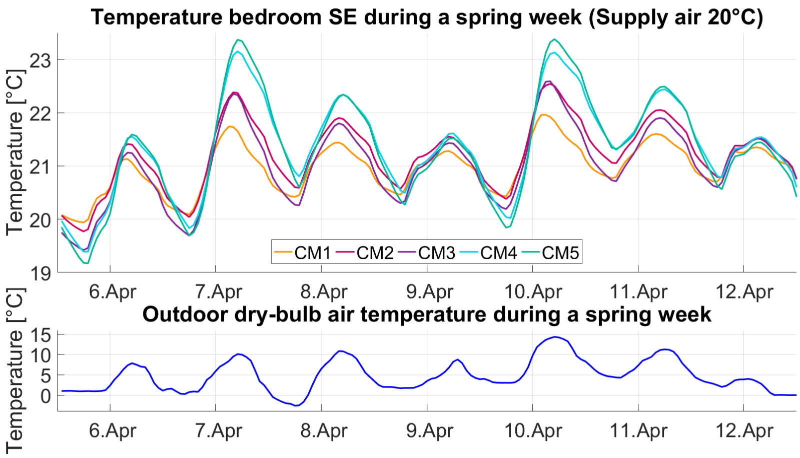


Figure 5.9: Outdoor air temperature during heating season (Oct-Apr)

By using the same approach as with the winter week, the dynamic bedroom temperature can be compared to the upper and lower limits set by the highest and lowest outdoor temperatures during the spring week. The upper limit (red, dashed line) represent what the bedroom temperature would have been if a constant outdoor temperature of 14.5°C was imposed, and the lower limit (blue, dashed line) represent what the bedroom temperature would have been if the outdoor temperature was held constant at -2.5°C. As before, the heaviest and the lightest building types are investigated, and CM2, CM3 and CM4 are expected to be found in between the two cases. The results of the simulations are presented in figure 5.10 and figure 5.11 below.

From the two figures, the influence of the rapidly changing outdoor air temperature is visible. Compared to the winter week situation, the dynamic temperature behavior is further from the upper and lower temperature limits set by the constant outdoor temperature cases. This highlights that the real dynamic bedroom temperature is never in steady state, especially when boundary conditions change as quickly as they do for this spring week.

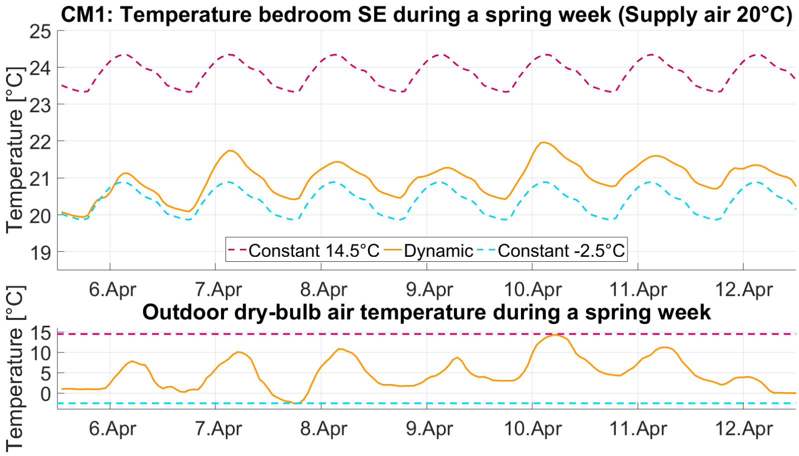


Figure 5.10: CM1: Temperature in bedroom SE during a spring week with upper and lower limits

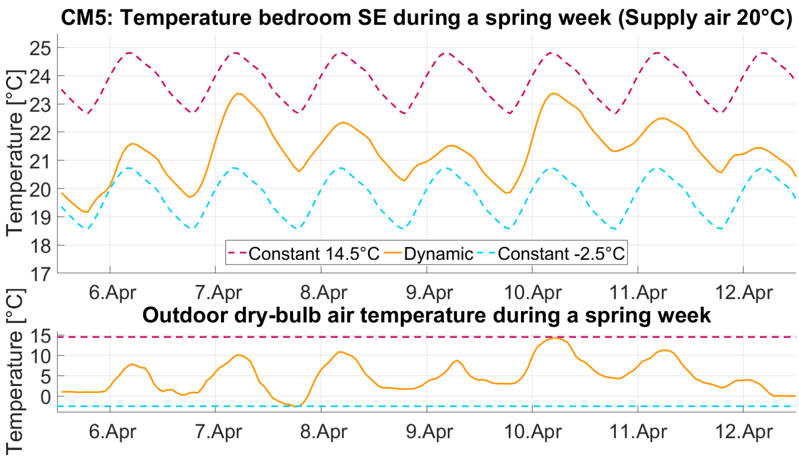


Figure 5.11: CM5: Temperature in bedroom SE during a spring week with upper and lower limits

To explore the spring situation further, and investigate if the heat balance is significantly different from the winter situation, the average heat balance for the constant outdoor temperature cases for the spring week was carried out. The results from the simulation are presented in figure 5.12 below. The largest difference from the heat balance for the winter situation is that the absolute value of heat losses is much lower. With higher outdoor temperatures, the driving potential for heat flow is reduced, due to smaller temperature difference between the indoor and outdoor air. The increased impact of solar gains is clearly visible, as it now contributes to a significant share of the total heat balance for the bedroom. The absolute value of the internal gains remains unchanged, but since the heat losses from the envelope is reduced to about half from the winter situation, the *relative* contribution to the total heat gain is increased.

The influence of the internal constructions on the bedroom heat balance is on the other hand significantly reduced compared to the winter situation. For the -2.5°C case, the internal constructions contribute with a small heat gain for both the heavy and the light building type. For the 14.5°C cases, this heat contribution is reduced to almost nothing. The ventilation supply air is providing a cooling effect for the bedroom for both building types and temperature levels, although the contribution is small for the -2.5°C case. This means that the average bedroom temperature is close to, or above the supply air temperature of 20°C. This is can be confirmed by examining the dashed lines in figure 5.2 and 5.11, representing the two constant outdoor temperature cases.

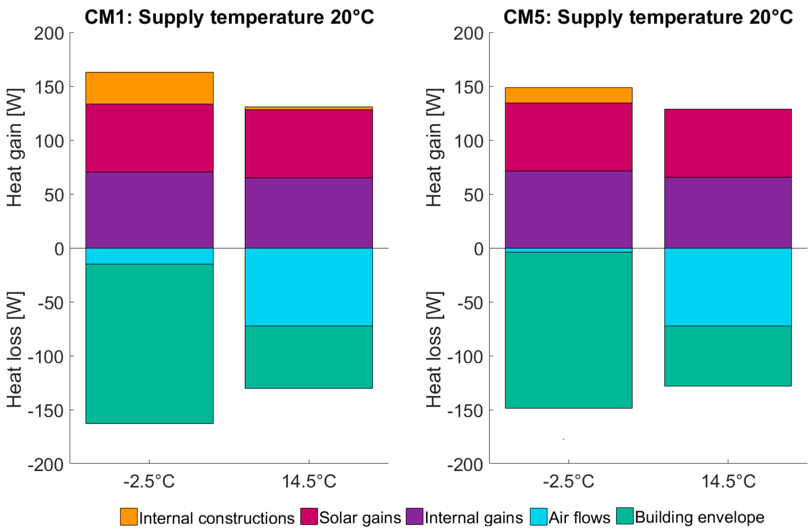


Figure 5.12: Heat balance bedroom SE during spring conditions

The simulation results from the winter and spring week have contributed to identify the differences between the different construction modes, and how thermal inertia impact the thermal dynamics of rooms without a separate heat source. While the lightest building type (CM5) appear to be more influenced by the changing boundary conditions, the heaviest building type (CM1) is less affected by this. To look at this in more detail, scatter plots for the bedroom temperature as a function of the outdoor temperature for both building types are presented in figure 5.13 below. The yellow and the red curves in the figure represent the polynomials that fits the data best by the least-square method. The yellow line is the first degree fitting, and the red line is the second degree polynomial. From the figure it clear that the bedroom temperature for lightest building type has a more linear relationship with the outdoor temperature than the heaviest building type. Lowering the outdoor temperature below 0°C does not impact the bedroom temperature too much for the CM1 building type, and the lower limit seem to be around 19°C. This supports the results obtained from the winter week simulation, where the two building types gave quite similar bedroom temperatures in the beginning of the week when the temperature was around 0°. When the outdoor temperature started to decrease the following days, a clear distinction between the two building types was observed.

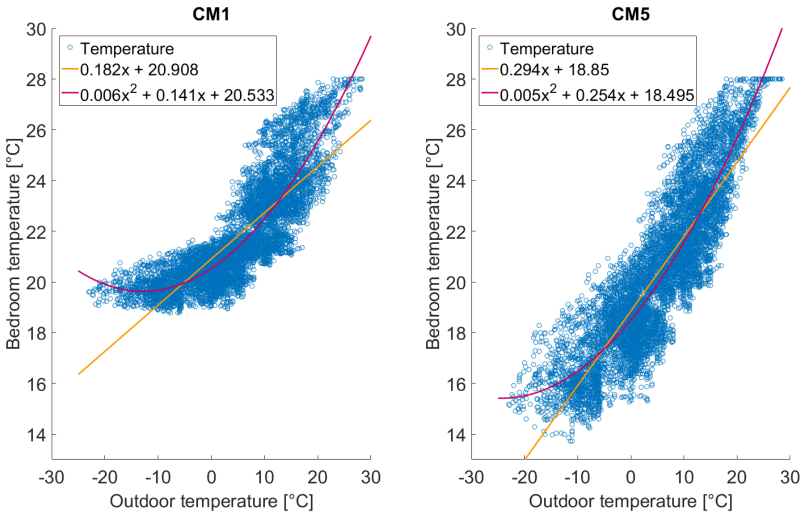


Figure 5.13: Bedroom temperature dependency on outdoor temperature

5.1.3 Internal gains

As described in subsection 4.2.8, the heat supply from people, electrical appliances and lighting can contribute to a significant share of the space-heating needs in passive houses. To be able to test hypothesis number two described in chapter 3, a simulation showing the impact of the internal gains on the bedroom temperature is necessary. First, the day-to-day dynamics are investigated by examining the cold winter week previously looked at. The impact of the three different types of internal gains (IG) on the heaviest (CM1) and lightest (CM5) building type is presented in figure 5.14 and 5.15 below. The curves for NS3700 internal gains are the same as in figure 5.1, as this type of internal gains has been used in the simulations so far.

The heaviest building type appear to be less influenced by the change of internal gains than the lightest building type. The temperature difference of including internal gains or not is in average only 0.9°C for CM1, while this result in a significant temperature difference of 2.2°C for CM5. For both building types, the average temperature for the whole week is about the same for the distributed and the NS3700 internal gains, even though the two cases have different profiles. The distributed internal gains have higher heat gain during the evening and night, when people are assumed to be present in the bedrooms. This results in lower heat gain during daytime, since the distributed internal gains is created such that the total heat gain during 24-hours is the same as for the NS3700 case.

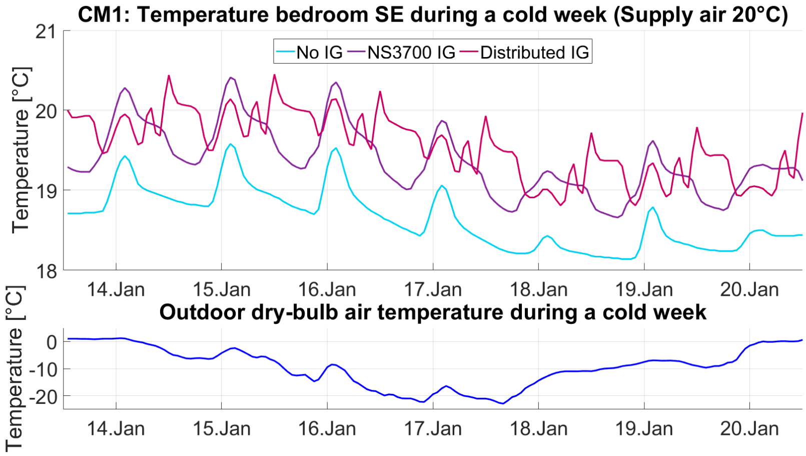


Figure 5.14: Impact of internal gains on the heavy building type during a winter week

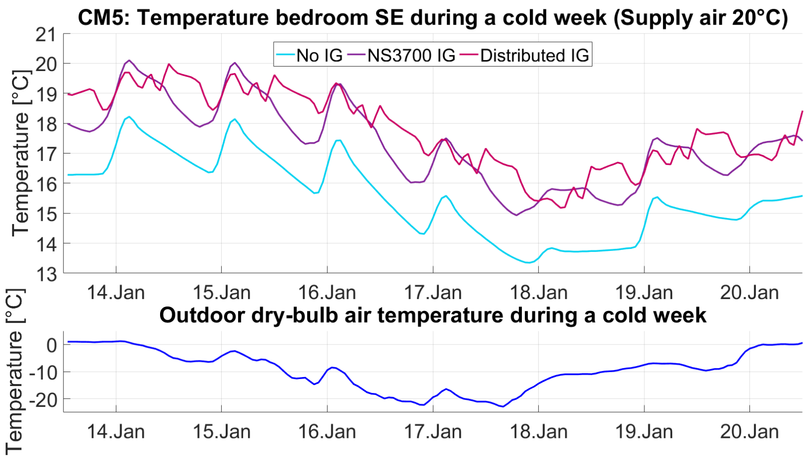


Figure 5.15: Impact of internal gains on the light building type during a winter week

From the previous graphs, the impact of different types of internal gains on the day-to-day dynamics is clear. By running yearly simulations with different levels of internal gains, the impact on the annual temperature duration could be investigated. It is by now established that CM1 and CM5 represents the maximum and minimum cases regarding temperature levels in the bedrooms, with the other construction modes (CM2, CM3 and CM4) located in between. In figure 5.16 below, the temperature duration for CM1 (dashed lines) and CM5 (solid lines) are plotted, and the span of the construction modes are illustrated rather than each individual construction mode. The focus is here on the heating season, so the figure presents the temperature duration for the heating season only.

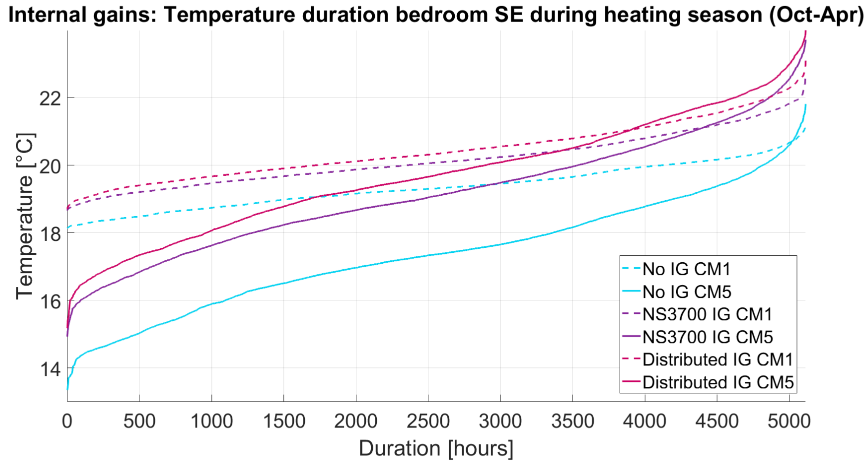


Figure 5.16: Impact of internal gains on bedroom temperature during heating season

Another alternative to present the same type of information given by the duration curve, is using a 100% stacked horizontal bar chart showing the percentage of time the bedroom temperature is within a certain range. The temperatures is gathered in two-degree sections, and temperatures above 20°C and below 14°C is gathered in separate sections as well. This is presented in figure 5.17 below. Since the focus is on achieving lower bedroom temperatures during the night, the duration bar chart shows the temperature duration for the hours between 23:00 and 07:00. This time period will later line up with the opening schedule for bedroom windows and doors.

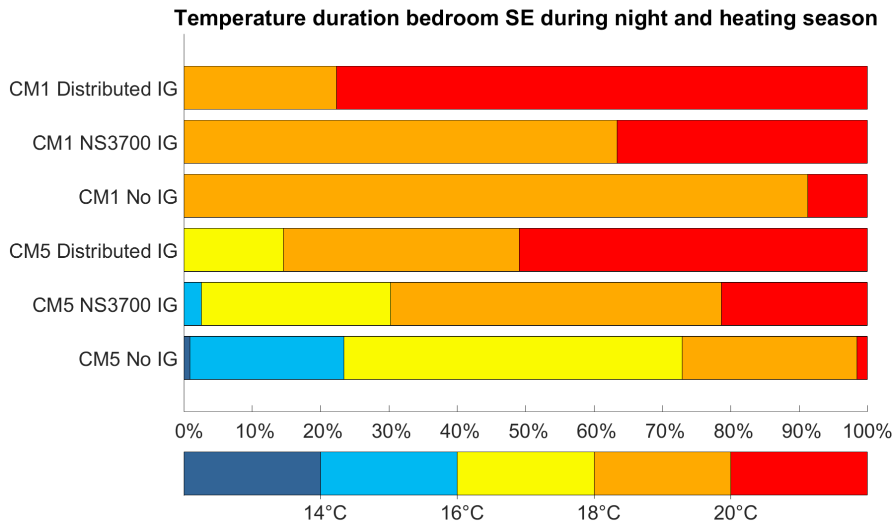


Figure 5.17: Impact of internal gains on bedroom temperature during night and heating season

Figure 5.16 and 5.17 confirms the difference between the two building types when it comes to thermal inertia. The heavy building type has a narrow temperature band reflecting the more stable temperatures seen in the day-to-day dynamics of the cold week in figure 5.14. The temperature is never below 18°C for any of the levels of internal gains for this building type, confirmed by figure 5.17. The duration curve and the bar plot do also clearly illustrate the impact the internal gains have on the two building types. Ignoring internal gains will underestimate the temperature level in the bedroom significantly, for both the heavy and the light building type, although a larger difference is seen for the lightest building. Ignoring internal gains give the impression that the bedroom temperature is only above 20°C for 20% of the time for CM1 and only 5% of the time for CM5. The difference between the evenly distributed internal gains stated in the passive house standard NS3700 and the artificially created distributed internal gains, is also visible from figure 5.16 and 5.17. By introducing internal gains varying in space and time, the percentage of time the bedroom temperature is below 20°C is lowered from 46% to 34% for CM1, and from 69% to 57% for CM5.

5.1.4 Insulation levels

To investigate if the issue with warm bedrooms started to develop when the requirement for the building envelope performance increased, five different building envelope performance levels are studied, as described under section 4.2.3. The rest of the simulations in this study were carried out with the internal gains distributed in time and space, as they are considered to more realistic and give the highest temperature level inside the bedroom. To look at how the different building envelope performance levels influence the bedroom temperature in more detail, the lightest building type (CM5) is used as an example. Figure 5.18 and 5.19 below show the bedroom temperature for the winter and spring week for the five different envelope performance levels.

By looking at the bedroom temperature for the two weeks, it is clear that the bedroom temperature is highly influenced by the insulation level of the external construction. Gradually decreasing bedroom temperatures can be observed with decreasing building envelope performance, with the standard case corresponding to the passive house standard giving the highest bedroom temperatures. For the winter week, there is in average 1.5°C step down to the next level, which is the current building regulation TEK10. The building regulations TEK10, TEK07 and TEK97 are resulting in quite similar bedroom temperatures, while there is an average 2°C leap down to the oldest building regulation TEK87, which is resulting in the lowest temperatures. Even though the insulation level for the external construction is reduced form one performance level to another, the dynamics are preserved for the building type. That being said, the temperature difference between two envelope performance levels is not constant, especially during the spring week, with the outdoor temperature changing quickly from night to day. The original performance level give more stable bedroom temperature compared to the oldest building performance level, which has higher temperature fluctuations.

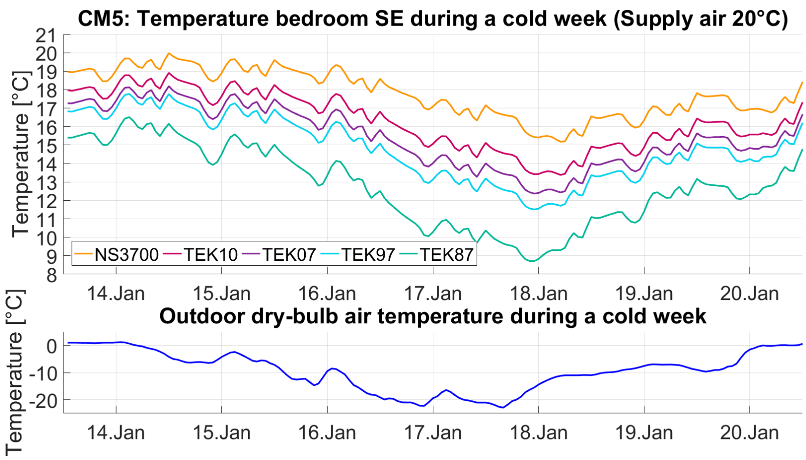


Figure 5.18: Impact of different insulation levels on bedroom temperature during a cold week

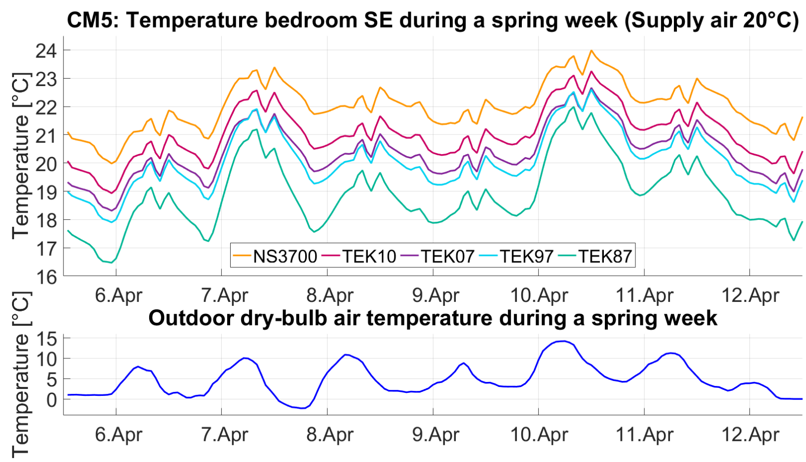


Figure 5.19: Impact of different insulation levels on bedroom temperature during a spring week

To see how the different envelope performance levels influence the bedroom temperature on longer terms than just a week, and also to compare the lightest building type (CM5) with the heavier building type (CM1), a figure showing the temperature duration for the heating season during the night is presented in figure 5.20 below. As seen before in this study, the heaviest building type produces slightly higher bedroom temperatures than the lighter building type, and the insulation levels is no exception. The figure supports the observations made for the winter and spring week, as there is a quite large leap between the passive house standard performance level down to the current building regulation TEK10. Reducing the envelope performance from the passive house standard to TEK10 increase the duration of bedroom temperatures under 20°C from 22% to 50% for CM1, and from 49% to 76% for CM5. There is a small difference between TEK10, TEK07 and TEK97 when looking at the duration for the whole heating season, as observed for the winter and spring weeks.

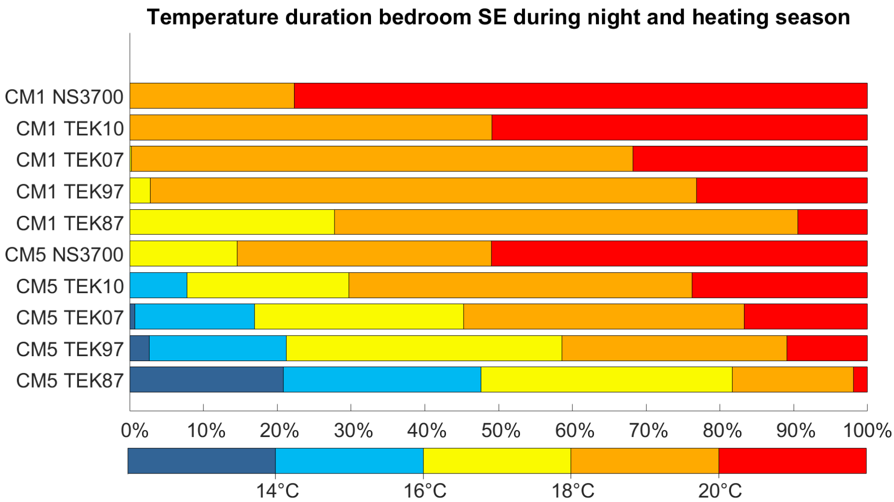


Figure 5.20: Impact of different insulation levels on temperature duration for bedroom SE during night (07:00-23:00) and heating season (Oct-Apr)

5.1.5 Human interaction

The investigations and simulations carried out so far have been without to much interference from occupants, maybe with exception of the distributed internal gains, that take into account that people are present in different rooms at different times during the day. The findings in the literature demonstrated that the users of the buildings play a key part in how the thermal conditions are in a dwelling due to different preferences and behavior, as well as energy performance. Simulations were carried out for all the eight different control strategies presented in subsection 4.2.7. The simulations were performed with the lightest building type and the distributed internal gains as input, and the cold winter week is also here used as a basis for the investigations for looking at the day-to-day dynamics. Presenting all eight control strategies in one figure will make it difficult to separate the different cases from each other. To increase readability the first six control strategies are therefore presented in figure 5.21 below. These control strategies are also presented in the same figure because they do not involve using window ventilation. The different control strategies have a significant impact on the thermal conditions in the bedroom. A clear distinction can be seen from control strategy C6 and the other control strategies, as this strategy involve closing the door at night, and keeping it open during the day. This cyclic behavior can easily be observed in the figure, and results in the highest bedroom temperature during the week.

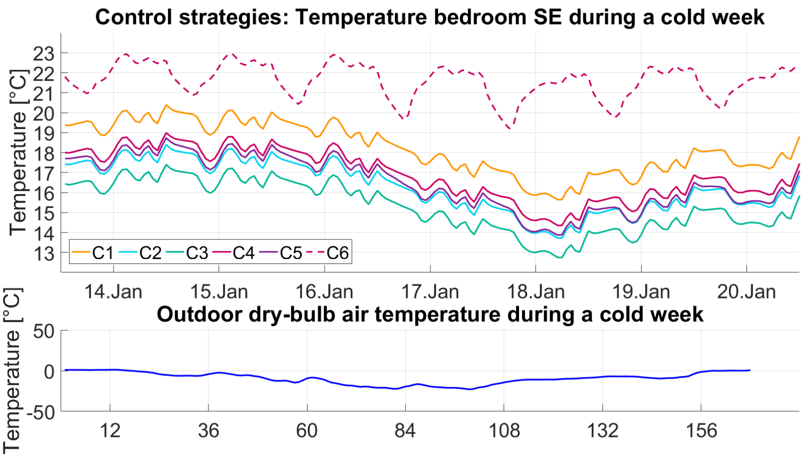


Figure 5.21: Impact of the first six occupant behavior/control strategies on bedroom temperature during a cold week

The first five control strategies (C1 to C5) do only involve changing the set-point temperatures for the supply air and space-heating, and the impact these two set-point have on the bedroom temperature is large. An average temperature difference of 3°C is observed between the two strategies that give the highest and lowest bedroom temperatures. Lowering the ventilation supply air temperature contribute to lower the bedroom temperature significantly. Reducing the set-point from 20°C (C1), down to 16°C (C2) and further down to 14°C lowers the bedroom temperature by 3°C in average. Increasing the set-point temperature for space-heating from 22°C to 24°C (C4) impair this effect, as it raise the bedroom temperature about 1°C. Introducing a night set-back schedule for the set-point temperature for space-heating (C5) lower the effect of raised space-heating temperature on the bedroom temperature.

The last three control strategies (C6 to C8) take the occupant behavior element a step further by introducing operation of windows and doors to control the thermal conditions in the bedroom. Using these type of measures for control has a more critical influence on thermal conditions than the previous control strategies, as seen in figure 5.22 below. Control strategy C4 (16/24/c/c) is included figure 5.22 above because it is the reference in terms of set-point temperatures, and represent the case where no doors or windows are operated. Control strategy C6 is the same as seen in figure 5.21, and do also here result in the highest bedroom temperatures. When closing the door at night, the temperature starts to drop, but only by one to two degrees. When the door is opened in the morning, the temperature rises towards the set-point temperature for space-heating, as heat from the upstairs living room/corridor flow into the bedrooms. This control strategy does not seem to be influenced by the outdoor temperature, as the dynamics is almost identical throughout the week. As seen from control strategy C7 (16/24/c/o) and C8 (16/24/o/o) in the figure, using window ventilation is a very effective measure for reducing the temperature in the bedroom. By using control strategy C8, it is possible to quickly reduce the bedroom temperature in the evening, and heat up the bedroom again in the morning within a adequate time period. Keeping the door closed while still using window ventilation to reduce the bedroom temperature (C7), result in very low bedroom temperatures, especially during periods with very low outdoor temperatures.

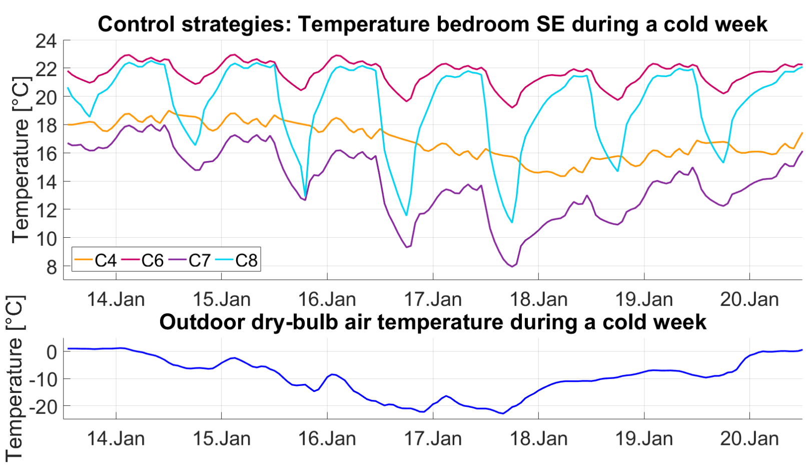


Figure 5.22: Impact of occupant behavior/control strategies on bedroom temperature during a cold week [C6-C8]

The impact of applying the eight different control strategies on the temperature duration for the whole heating season is presented in figure 5.23 below, and confirms the results seen in the day-to-day dynamics in figure 5.21 and 5.22 on the previous page. Lowering the set-point temperature of the supply air has a large influence on the temperature duration for the bedroom. By reducing the supply air temperature from 20°C (C1) down to 16°C (C2), the duration of bedroom temperatures below 20°C is increased from 38% to 84%. Control strategy C4 and C7 are quite similar when it comes to temperature duration, expect C7 offers slightly greater duration for temperatures below 16°C.

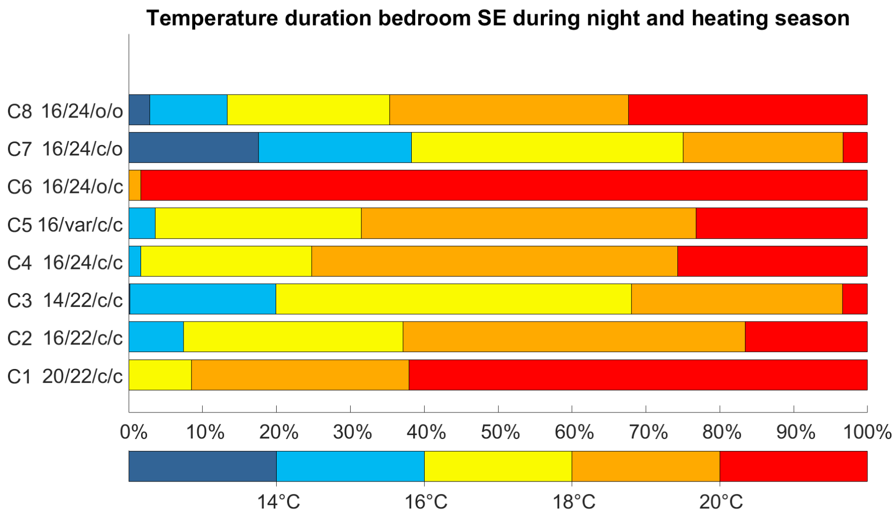


Figure 5.23: Temperature duration for bedroom SE during night (23:00 to 07:00) and heating season (Oct-Apr) with different control strategies applied

Although window ventilation has proven to be a effective measure for reducing the bedroom temperature, previous studies imply that it contribute to raise the energy need for space-heating significantly. To look at how the different control strategies or occupant behavior influence the energy need for heating the dwelling, the yearly energy need for C1 to C8 is presented in figure 5.24 below. The height of the bars represent the annual energy need for heating (normalized by area), which can be read from the left axis. A distinction between space-heating and heating of ventilation air is made. The energy efficiency of the different control strategies is indicated by the curve, and the value can be read from the right axis. The energy efficiency is here defined as the energy need for the reference control strategy divided by the the energy need for the control strategy looked at. The reference control strategy is in this case C1, and it has therefore a energy efficiency of 100%.

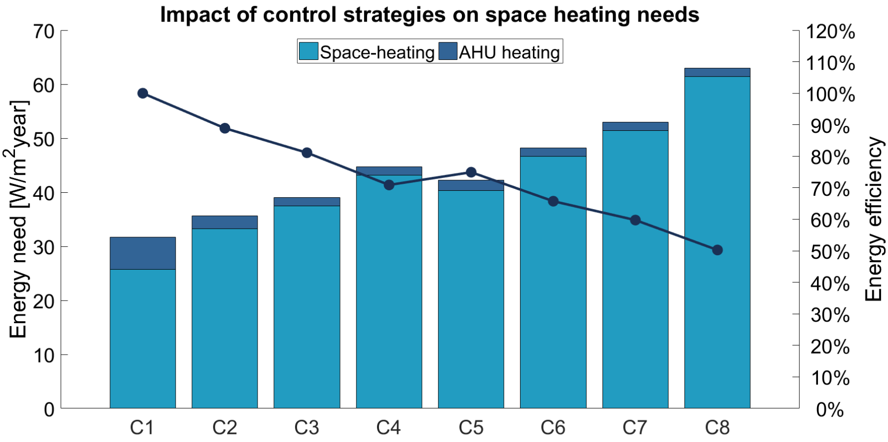


Figure 5.24: Impact of different control strategies on the energy need for space-heating

Starting from C1, lowering the set-point temperature for the ventilation air to 16°C (C2), and further down to 14°C (C3) increase the energy need for heating. The lowered set-point temperature reduce need for post-heating of ventilation air after the heat recovery by using the heat coil, as seen from the smaller "AHU heating" sections for C2 and C3. But this also limit the heat recovery from the extract air, and by injecting colder air into the zones, more heat from the space-heating system is required. This result in a reduction of energy efficiency to 89% for C2 and 81% for C3.

Raising the set-point temperature for space-heating to 24°C (C4) has a large impact on the space-heating need, and further reduces the energy efficiency to 71%. Introducing the night set-back schedule (C5) improves the energy performance in addition to lowering the bedroom temperature compared to C4. As observed from figure 5.21 and 5.22, opening the bedroom doors during daytime raise the bedroom temperature, and hence raising the average temperature in the whole dwelling. This increases the energy need for heating further, and give an energy efficiency of 66%. Opening the windows during the night, but keeping the door closed (C7) will reduce the bedroom temperature significantly, but also increase the heat transmission from adjacent rooms due to larger temperature differences. The worst control strategy in terms of energy efficiency is unfortunately also the most effective one. The daily flushing of heat from the bedroom give a large increase in space heating needs for control strategy C8, and an energy efficiency of only 50% compared to C1. This means that the energy need for heating is twice as large as for the reference control strategy.

Some of the participant in the user interviews by Georges et al. (2016) and Håheim (2016) stated that their behavior (adjusting set-points, window/door opening etc.) was related to habit, as the majority of them moved into the passive houses from a older buildings. An interesting question related to this subject is whether typical behavior and control strategies that worked for an older buildings, do not work the same way or have limited applicability on passive houses. To investigate this in more detail, the control strategies previously looked at was also applied for the five different envelope performance levels.

One control strategy to create thermal zoning reported as commonly used in older buildings, is similar to control strategy C6 in this study. When lower temperatures in a room was desired, the door was closed and the room was left to cool down. If higher temperatures was desired, the door was opened, and warm air was let into the room. Figure 5.25 on the next page presents this control strategy for the five envelope performance levels previously used in this study. Although the different insulation levels have different temperatures during daytime, there is one interesting thing to notice in the figure. When the doors are closed, the temperature starts to drop for all five performance levels. One important difference is the rate of temperature change, which is much higher for the less insulated buildings. This can be seen from the steeper temperature curves for the older building types, due to higher heat losses through the building envelope. There is also a significant difference between the passive house building and the building following the current building regulation TEK10.

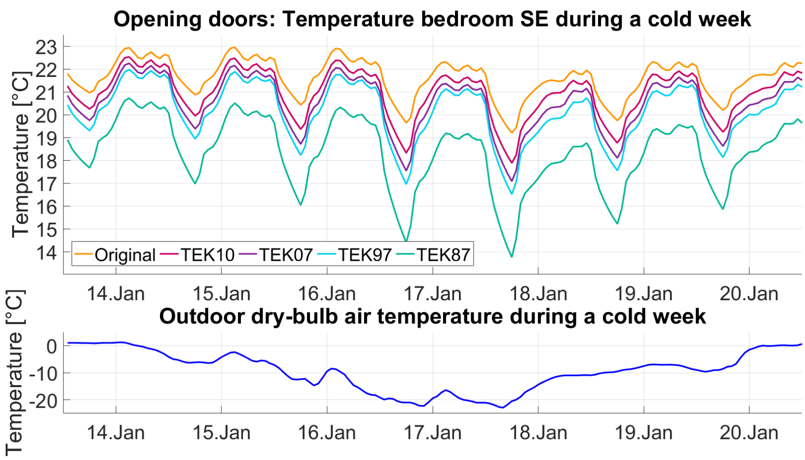


Figure 5.25: Impact of opening the bedroom door for different insulation levels during a cold week

The energy need for space-heating and heating of ventilation air is originally very low in passive houses. From the results in figure 5.24, the energy need for heating the passive house was doubled from the reference to the worst control strategy, which involved using window ventilation to cool down the bedroom. Does this mean that passive houses are more sensitive to occupant behavior than older buildings with higher energy need for heating? This is a question whether window ventilation result in a fixed increase in energy need, or if the relative increase in energy need for heating is the same for all building types. If the increase is fixed, using window ventilation in older buildings has less impact on the energy performance compared to passive houses. To answer these questions, the energy need for heating for the five different performance level is presented in figure 5.26 below. The impact of using window ventilation is investigated by applying control strategy C4, C6, C7 and C8, which is the same control strategies previously looked at in figure 5.22.

The first thing to notice from the figure is that the absolute energy need for heating is gradually increasing with lower energy performance level for the building as expected, independent of control strategy. A large increase in AHU heating is observed when going back to the historical building regulations TEK97 and TEK87. By looking at table 4.3 in subsection 4.2.3, this can be explained from the lack of heat recovery for the two cases. With no heat recovery, the whole temperature lift from the outdoor air to the setpoint temperature for the supply air has to be delivered by the heating coil, thus increasing the energy need significantly. As before, the curves represent the energy efficiency of the different control strategies compared to the reference. In this figure, every building performance level has C4 as its own reference control strategy, and the other control strategies are therefore compared to this one. This can be observed from the figure, as every C4 control strategy has an energy efficiency of 100%.

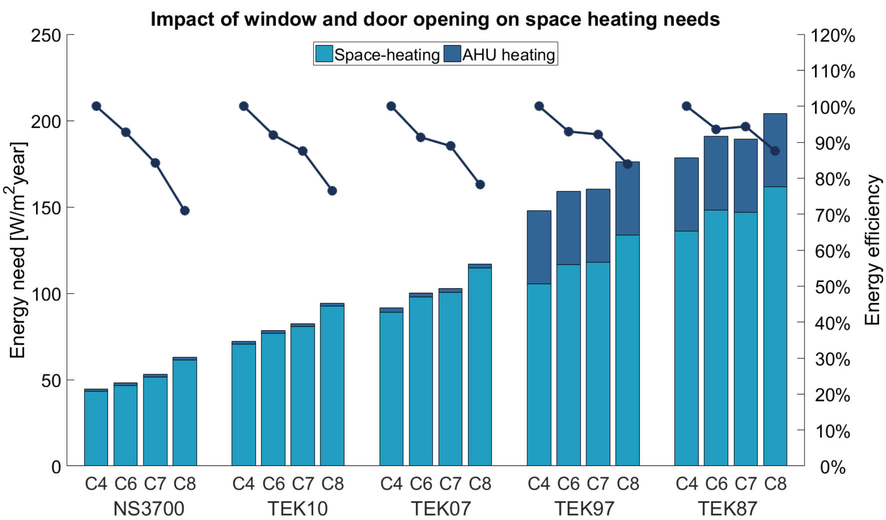


Figure 5.26: Impact of control strategies the energy need for space-heating with lower level of building envelope performance

By looking at energy efficiency for the control strategies for the different levels of building energy performance levels, it is clear that the relative impact of the control strategies is not the same for every building type. The drop in energy efficiency for the different control strategies is much larger for the passive house case, compared to older performance levels. That being said, it is neither a fixed *relative* increase, nor a fixed *absolute* increase in energy need for heating from one control strategy to the other. The absolute increase is larger for the older building performance levels compared to the passive house case, but not large enough to make the relative significance the same. Using window ventilation as a measure for temperature control in older buildings do not have the same consequences in terms of increased energy need as in passive houses. For the oldest building regulation TEK87, using window ventilation only contributes to drop in energy efficiency of 11% compared to the passive house case, where a drop in efficiency over 30% compared to C4 is observed.

5.2 Applying supply and return ventilation for bedrooms

Different types of strategies to improve the thermal zoning have been investigated in previous studies. These strategies included everything from from a higher insulation level between the bedroom and the rest of the building, introducing a two-zone ventilation system, finding an optimum control strategy for lowering the bedroom temperature. A strategy to separate the bedrooms from the rest of the building to a larger extent, is to introduce both supply and return ventilation for the bedrooms as discussed under subsection 4.2.6. The objective for this measure is to reduce the cascade effect. A hypothesis on why the energy need for space-heating is increasing when lower bedroom temperatures occurs, even though the bedroom door is closed all the time, is related to this effect. Cold air is flowing from the bedrooms and into zones with a high set-point temperature, and get heated up to this level before the air is extracted out of the building. This is close to what happens when the door to a cold room is opened, only on a small scale. By removing the overflow of air from the bedrooms to the other zones, the impact from cold bedrooms on space-heating needs could in theory be reduced.

As discussed in subsection 4.2.6, changing the layout of the ventilation system does not only imply changing the system physically, but that the airflow rates also have to be changed in order to comply with the building regulations on indoor air quality. Therefore, three different cases for this investigation on the supply and return ventilation for bedrooms is created. The abbreviations used for the three cases in the figures are written in parentheses. The first one is the basecase (BC), representing the passive house case as it was originally with airflow rates according to table 4.5. The next is the supply and return ventilation with airflow rates based on the pre-accepted principle (SR pre-accepted) presented in table 4.6. The third case is the supply and return ventilation with airflow-rates according to the schedule (SR schedule) presented in table 4.6. The bedroom temperature for the three cases and control strategy C4 (16/24/c/c) is presented in figure 5.27 below.

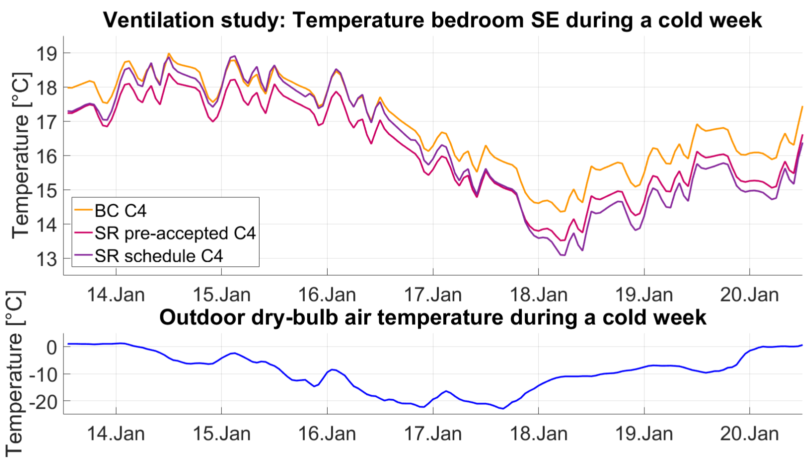


Figure 5.27: Supply and return ventilation for bedroom SE during a cold week

The figure above illustrate that the three different cases result in quite similar bedroom temperatures during the cold week. The effect from the reduced airflow rate during daytime for the case with day and night schedule for ventilation can be observed from the figure. The two cases with supply and return ventilation for the bedrooms are identical except from the ventilation flow rate during daytime. The bedroom temperature for the schedule case is rising from the same level as the pre-accepted air flow rate case towards the basecase during daytime. When smaller amount of air at 16°C is supplied, less cooling effect is provided for the bedroom, as long as the bedroom temperature is above this level. During the coldest period of the week the situation turns, as the bedroom temperature drops below the set-point temperature for the supply air. With a reduced airflow rate during daytime, less heat from the ventilation air is supplied to the room for the schedule case, and hence a lower bedroom temperature is achieved.

It is also interesting to look at how the three ventilation cases respond when different control strategies are applied. The same four control strategies that were applied to the different building envelope performance levels, were also applied to the three ventilation cases. The bedroom temperature for the three ventilation cases with control strategy C4 (16/24/c/c), C6 (16/24/o/c), C7 (16/24/c/o) and C8 (16/24/o/o) applied is presented in figure 5.28 below. The basecase has solid lines, the pre-accepted case has dashed lines, while the bedroom temperature for the schedule case is illustrated by the dotted lines in the figure. Very small differences in bedroom temperature between the three cases can observed when control strategy C6 and C8 are applied. Slightly higher temperatures during daytime for the schedule case can be observed for control strategy C6, due to the reduced airflow rates previously discussed. The absolute largest differences in bedroom temperature between the three cases take place when control strategy C7 is applied.

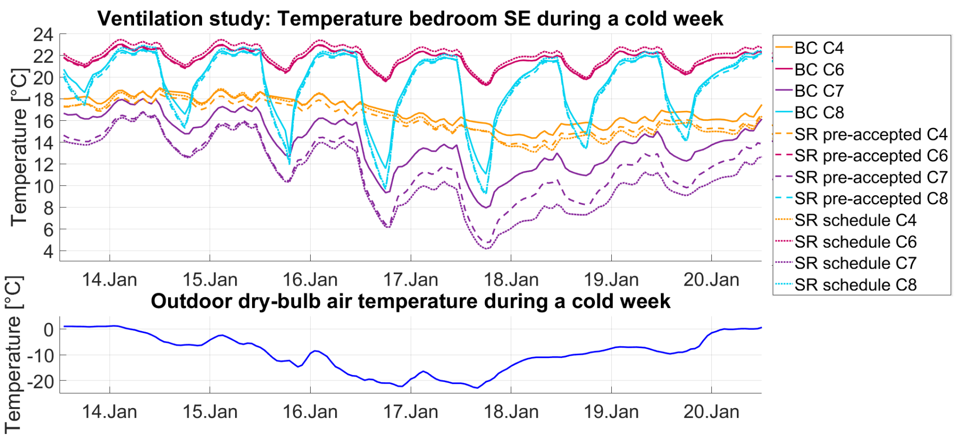


Figure 5.28: Supply and return ventilation for bedroom SE during a cold week with different control strategies applied

For the spring week, a larger difference between the three ventilation cases can be observed in figure 5.29 when different control strategies are applied. The schedule case with reduced airflow rates during daytime is giving the highest bedroom temperatures of the three cases. For the spring week, the outdoor temperature is higher, and more heat from solar gains is contributing to the heat balance for the bedroom as previously seen. With less cooling effect from ventilation air during daytime, the bedroom temperature rises to a higher level compared to the other two cases.

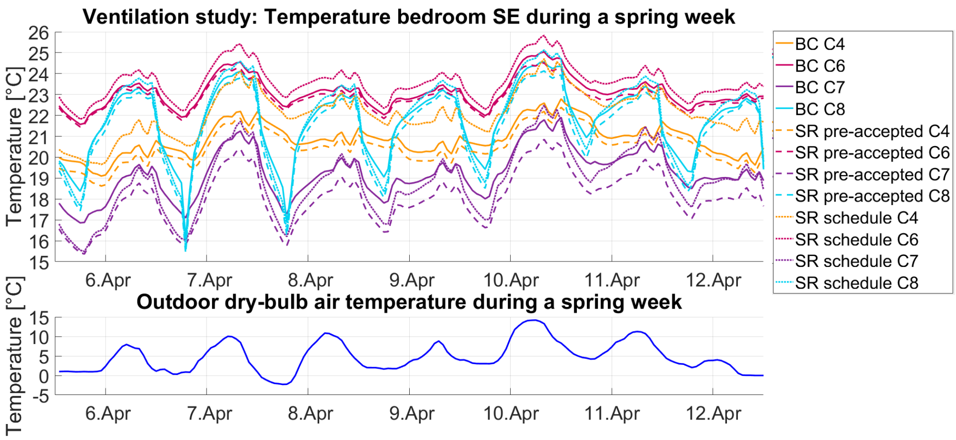


Figure 5.29: Supply and return ventilation for bedroom SE during a spring week with different control strategies applied

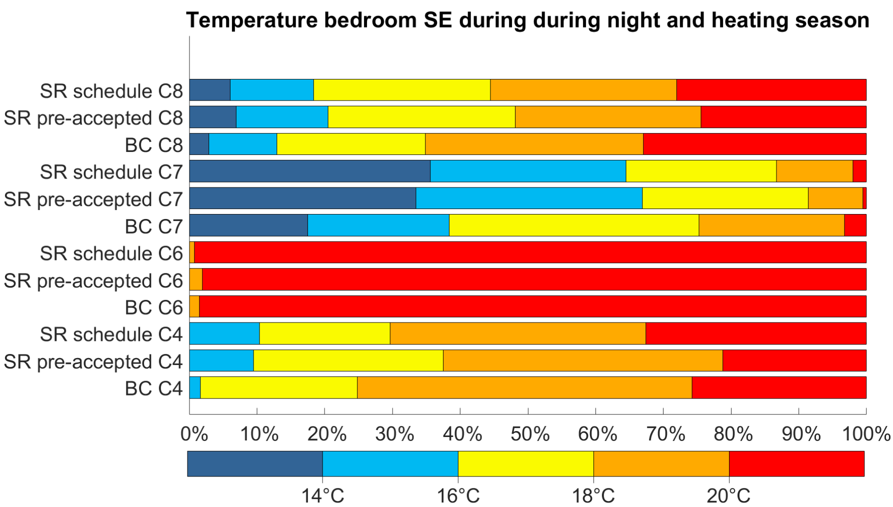


Figure 5.30: Temperature duration bedroom SE during night (23:00-07:00) and heating season (Oct-Apr) with supply and return ventilation

The temperature duration for the bedroom in figure 5.30 confirms the observations made for the winter and spring week. The difference between the three ventilation cases in terms of bedroom temperature is small for nearly all the different control strategies. The only exception is the control strategy C7, which involve opening the bedroom window during the night, and keeping the bedroom door closed all the time. By applying this strategy, the two cases with supply and return ventilation give lower bedroom temperature than the basecase.

The reason for implementing the supply and return ventilation solution in the first place, was to reduce the influence cold bedrooms have on the energy performance of the building. By separating the bedrooms from the rest of the building to a greater extent, the goal was to provide cold bedrooms and keep the energy efficiency at an acceptable level. This has earlier proven to be difficult. The energy performance for the three different cases with the different control strategies applied is presented in figure 5.31 below. As before, the bars represent the energy need for heating divided between space-heating and heating of ventilation air. The curves represent the energy efficiency of the different cases and control strategies. The blue curve represent the energy efficiency where control strategy C4 for each of the three ventilation cases is used as the reference (similar to figure 5.26). The energy efficiency for all C4 cases is therefore 100% according to the blue efficiency line. The red line represent the energy efficiency for the different cases where control strategy C4 for the *basecase* is used as a reference. Therefore, no red line exist for the basecase, as this would be identical to the blue line.

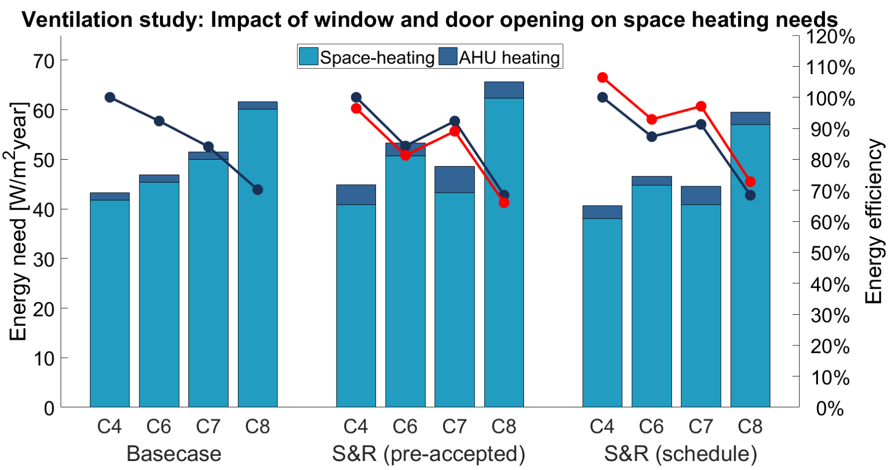


Figure 5.31: Impact of control strategies on the energy need for space-heating with supply and return ventilation for bedrooms

From the figure we can see that introducing supply and return ventilation for the bedrooms do have an impact on the energy performance for the different control strategies. By looking at the reference control strategy C4, using pre-accepted values for ventilation flow rates increase the energy need for heating slightly, due to an increased air change rate (+37%) in the building. By using the day and night schedule for the ventilation, a 5% increase in energy efficiency is actually observed for the reference control strategy (C4). Opening the bedrooms doors during daytime while the bedroom windows is closed all the time (C6), have a larger impact on the energy performance for the supply and return ventilation cases than for the basecase.

Keeping the bedroom door closed and using window ventilation as a measure for cooling down the bedrooms (C7) have less impact on the energy performance when a supply and return ventilation solution is implemented for the bedrooms. For the case using pre-accepted ventilation flow rates, an energy efficiency of 89% compared to the basecase reference (red line) is observed. For the solution using a day and night schedule for the ventilation flow rates, an energy efficiency of 97% was achieved compared to the basecase reference. That being said, this require that the bedroom door is kept closed all the time. By introducing door opening during daytime together with window ventilation in the night (C8), the energy efficiency for the supply and return ventilation solution is slightly poorer than for the basecase. The solution with supply and return ventilation for the bedroom is performing similar or better than the basecase in terms of energy efficiency when the bedroom door is kept closed (C4 and C7), but performs slightly poorer when the bedroom door kept open during daytime (C6 and C8).

Chapter 6

Discussion

The figures presenting the thermal conditions in this study have been from the largest bedroom in the south-east corner of the building. There are three bedrooms in this dwelling, and the two others are single bedrooms that share a common wall. Several factors could possibly have influenced the results for temperature levels in this study by choosing one of the smaller bedrooms as a basis for the investigations. The most significant factor is the difference in airflow rate for the large bedroom compared to the smaller ones. Since the large bedroom is a double bedroom, and the building regulation on indoor air quality and health set the requirement to fresh air supply per person, the airflow rate is twice as large. This could possibly enhance or reduce the cooling/heating effect the ventilation air has on the bedroom temperature, and the heat balance for one of the smaller bedrooms could appear slightly different than for the large bedroom. Another factor is that the two smaller bedroom share a common wall, while the large bedroom investigated in this study have the upstairs bathroom adjacent. The temperature level inside bathrooms is traditionally higher than for the rest of the building, giving an increased heat transmission to the largest bedroom compared to the smaller bedrooms. This could imply that the largest bedroom represent the worst case when it comes to high bedroom temperatures. All the three bedrooms have two external walls, but they have different orientation. This imply that the three different bedrooms have different level of solar gains. The two bedrooms facing south are expected to have quite similar solar heat gains, while the bedroom facing north will have less.

One of the first objectives in this study was to investigate why it is a problem to create thermal zoning in passive houses in the first place, and hypotheses for related to this issue were formed. The first hypothesis that was created explains that the thermal zoning issue occur because too much heat is flowing from heated rooms into the bedrooms, compared to the heat losses of the building envelope. The heat transmitted through the internal construction is the reason why it is difficult to create thermal zoning. Several of the studies discussed in chapter two also investigated the connection between warm bedroom and thermal insulation of the internal construction. From the findings in literature this hypothesis could hold to some extent. Insulating internal constructions like bedroom walls do contribute to an increased thermal zoning, proven by Berge et al. (2016a) where the effect of having insulation in internal walls lead to lower bedroom temperatures in addition to lower energy need for space-heating. This is supported by the study of the air heating concept by Georges et al. (2014), where the highest degree of thermal zoning was observed for the cases where the internal constructions had the largest thermal resistance. For the study by Håheim (2016), increasing the thermal insulation level did not improve the thermal zoning significantly.

The difference between the study by Håheim (2016) and the two others is the starting point. For Berge et al. (2016a), the starting point was an uninsulated wall, while the starting point for Håheim (2016) was an already insulated wall. This could imply that the thermal resistance of the internal construction is important for creating thermal zoning up to a certain level. This is in compliance with the findings in this study. The five different construction modes investigated in this study have different thermal resistance and thermal mass due to different building materials and techniques being used for constructing the building types. It is therefore hard to say if the difference in thermal zoning observed from the simulation is a result of thermal inertia or thermal resistance for the internal construction. From figure 5.5, the impact of those two effects became clearer, as the U-value for the internal constructions for CM1 was improved to match the CM5 level. This simulation demonstrated that thermal inertia play an important part along with thermal resistance of the internal construction when it comes to providing low bedroom temperatures.

Another interesting discovery from the simulations related to this hypothesis was found when looking at the heat balances for the bedroom. The heat balances for both the winter and the spring situation demonstrated that the internal construction only contribute to a significant share of the total heat gain at very low outdoor temperatures. At higher outdoor temperatures the heat losses through the external construction is smaller, and the heat balance is dominated by internal and solar gains. From the simulation results and the findings in the literature, the first hypothesis only hold to some extent. And as Georges et al. (2014) pointed out, insulation material is often added to the internal walls to improve the acoustic performance of light timber constructions, a commonly used building technique in Nordic countries. Insulating the bedrooms to a higher level beyond the current building tradition do not improve the desired thermal zoning significantly.

The results from the heat balances for the spring and the winter situations do also contribute to validate hypothesis two stated in chapter 3. The heat balances (figure 5.4 and 5.12) clearly demonstrate that the internal gains is contributing to a significant share of the total heat gain in passive houses, and especially for rooms without a heat source like bedrooms. Even though the absolute value of the internal gains remains constant throughout the year, the *relative* significance of internal gains on the heat balance increases as the outdoor temperature increases. Higher outdoor temperatures give smaller heat losses through the external construction, due to a smaller temperature difference between the inside and outside. For the heat balances at spring conditions, heat losses from the envelope is just large enough to counterbalance the heat from internal and solar gains. The importance of having solar shading on high performance buildings like passive houses is therefore emphasized by the heat balances. Another factor that make solar shading important in Nordic countries is the very low solar angle during the spring and autumn seasons. With more direct sunlight hitting the windows during the day, overheating could possibly be a problem if solar shading is not properly handled, also for bedrooms. The simulation results, and especially the heat balances, support to a certain degree the hypothesis that claim that the thermal losses from the envelope is so small that internal gains is enough to heat up the bedroom. Solar gains are however an equally important contribution to the heat balance for the bedroom. Even though the solar gains peak during mid-day, the high temperatures from the day is maintained to a certain degree throughout the day. The temperature drops slowly due to the high performance building envelope and increased thermal mass, compared to older and less insulated buildings.

The importance of including internal gains when assessing thermal comfort in bedrooms is clearly visible from the simulation results in subsection 5.1.3, both from to the day-to-day dynamics in figure 5.14 and 5.15, and from the temperature duration presented in figure 5.17. Ignoring internal gains will underestimate the expected temperature level significantly. Since internal gains have been proven to be an important part of the total heat supply for high performance buildings, the need for more detailed models of internal heat gain from people, equipment and the lighting system has emerged. The evenly distributed internal gains found in the passive house standard NS3700 could be sufficient for annual energy calculations, but lack the proper detail level for comfort calculations. The more detailed model for internal gains varying in space and time used in this study, set the heat gains in the different rooms at times when it is likely that people are present. Another factor that make the detailed internal gains more realistic is the absolute value of the heat gain. Since the heat gains vary in space and time, and the average heat gain for a day equals the value set by the standard, the heat gains have a higher heating power when they are present. As an example, a higher bedroom temperature during the evening and night is observed for the more detailed internal gains compared to the standard ones, as this is the time of the day when occupants most probably present in the bedrooms.

The final hypothesis on why the issue with warm bedrooms occur, and why it is difficult to create the desired thermal zoning, is related to the ventilation and heating systems and the operation of these technical systems. Several of the studies discussed in chapter two focused on the possibility of achieving the desired thermal comfort in bedrooms by applying different set-point temperatures for space-heating and ventilation supply air. The studies by studies demonstrated that these two factors have a significant impact on rooms that do not have a separate heating unit installed, like bedrooms. At high set-point temperatures for the ventilation air (20°C), the degree of thermal zoning is especially low. This confirms a part of the statement in hypothesis three, that the single-zone ventilation system counteract the thermal zoning due to the high supply air temperatures. The high set-points was reported used in the user interviews was justified as a strategy to achieve the desired level of thermal comfort in the living room areas. Since the ventilation systems used in new buildings are single-zone ventilation systems, ventilation air with the same temperature is supplied to the whole building.

The heat balances in figure 5.4 and 5.12 demonstrate the how the ventilation air influence the bedroom temperature, and confirms the findings from the studies by Georges et al.

(2016) and Håheim (2016). The ventilation supply air plays a significant part of the total heat balance for the bedroom. This is especially visible when the outdoor air temperature is in the higher range. When the heat losses from the building envelope become smaller due to increased outdoor temperature, a heat loss to maintain the bedroom temperature at an acceptable low level needs to be introduced. This additional heat loss could be from opening a window, or by providing cooling from the supply of ventilation air at a temperature below the room air, as seen from the heat balance for the spring case. The single-zone ventilation system do contribute to homogenize the thermal conditions in a dwelling, especially when a high set-point temperature for the supply air is applied, such that ventilation air contributes to heat up the bedrooms.

The final hypothesis claims that applying different control strategies for the technical systems could improve the thermal zoning to a level where acceptable thermal comfort is achieved. The simulation results from the study of the control strategies in subsection 5.1.5 demonstrate that the operation of the technical systems as wells as occupant behavior has a significant impact on the thermal conditions in the bedroom. It confirms the findings from the studies on the other two building types, where the same type of investigation was carried out. The whole discussion about what is achievable by applying control strategies, boils down to occupant preferences. The user interviews and measurements carried out by both Georges et al. (2016), Håheim (2016) and Berge et al. (2016b) at Miljøbyen Granåsen, discovered a range of temperature preferences for both the living room areas and bedrooms. This also is one of the reasons for the great variation in energy use for buildings discussed in subsection 2.3.1, as indoor air temperature is one of the main contributing factors. The results for temperature duration in this study was split into two-degree segments, and this could to some extent represent types of occupant preferences.

If the desired temperature level in the living room areas is 24°C, and the desired temperature range for the bedroom is between 18°C and 20°C, acceptable thermal comfort in the bedroom could for example be provided by supplying ventilation air at 16°C (C4). This is consistent with the findings from the studies on the row houses and apartments, where a temperatures down to 18°C was possible to obtain by using this strategy. An even lower bedroom temperature was possible to reach by applying this control strategy in this study, as the bedroom temperature is below 18°C about 30% of the time. This could be a result of a higher airflow rate being supplied to the bedroom in this study compared to the other two, and thus providing larger cooling effect. This could also explain why changing the set-point temperature for the supply air (control strategy C1, C2 to C3) have a larger impact on the bedroom temperature in this study compared to the studies on the apartments and row houses. Another factor that could contribute to the difference observed between the house typologies for the same control strategy is the number of external walls. While the bedroom in the apartments and row houses have just one external wall, the bedrooms for the detached house investigated in this study have two. This introduces more heat loss, and this could possibly result in lower bedroom temperatures.

It is also a question what is achievable without using window ventilation as a measure for temperature control. The simulations on control strategies demonstrated different impact on the annual energy need for space-heating and heating of ventilation air, and even among the control strategies that involved keeping the windows closed, the variation was significant. This separates the results of the detached house typology from the apartments and row houses. An increase in energy need was seen from figure 5.24 in this study when the supply temperature for the ventilation air was decreased from 20°C to 16°C and further to 14°C. For the apartment study by Georges et al. (2016), lowering the supply air temperature from 20°C to 16°C did however keep the energy efficiency at the same level, only shifting the energy need between the radiator and the AHU. Lowering it further down to 14°C did also increase the energy need in this case. Limiting the supply air temperature do contribute to decrease the bedroom temperature, but at the same time it limits the heat recovery from the extract air. By supplying colder air into the zones, more heat from the space-heating system is required.

One thing is to achieve the desired temperature level in the bedroom when the door is closed all the time (control strategy C1 to C5), keeping the bedroom temperature constantly lower than the set-point temperature for heating. Once opening of the bedroom during daytime is introduced (control strategy C6), the possibility to achieve low bedroom temperatures without using window ventilation is vastly reduced. This results in bedroom temperatures always over 20°C, as seen from the duration diagram in figure 5.23. Is it however realistic to assume that the bedroom door is closed all the time? The question is again closely connected to occupant preferences and behavior, as people use the bedrooms for different purposes. Assuming the bedroom investigated here is used by an adult couple, it may be realistic to think that the room is only used for sleeping, and thus only being occupied during late evenings and nights. This could justify keeping the bedroom temperature at a low level all the time by always keeping the door closed. The two smaller bedrooms could on the other hand be occupied by the kids or youths in the family. They may want to use the bedroom to a greater extent than the adults, for playing and other activities during the afternoons and evenings. This would lead to the demand for both high temperatures during daytime, and low temperatures during the night. As seen from the simulation results, closing the door to let the temperature drop is not even sufficient to achieve temperatures below 20°C. The only option to reduce the temperature sufficiently is in this case to increase the heat loss by opening the bedroom window.

The results from the simulations of the different performance levels for the building envelope demonstrated that there has been a change in how buildings behave dynamically. From the day-to-day dynamics and the temperature duration figure in subsection 5.1.4, the difference between the current legislation on energy performance for buildings and the passive house standard is also emphasized. Significantly lower bedroom temperatures is observed in the building by reducing the envelope performance to the TEK10 level. Of particular interest in the discussion about different building performance levels is the simulation results of door opening as a measure for temperature control seen in figure 5.25. This clearly illustrate that there has been a change how buildings respond to this particular control strategy. Opening and closing the door to the bedroom as a way of controlling the temperature, have a limited applicability with increasing envelope performance level. This could be one source of frustration for occupants living in passive houses, as this has been a common strategy to create thermal zoning earlier. Not only does the bedroom temperature drop at a greater rate of change with lower envelope performance, but the absolute temperature drop is also larger. While the historical and current building regulations TEK97, TEK07 and TEK10 have quite similar responses when the door is closed, there is a larger difference to the response of the building with passive house performance level. This could imply that this way of controlling the thermal zoning to some extent stopped working in the transition between the current building regulation TEK10 and the passive house standard.

It is also interesting to see the influence the different control strategies have on the energy performance of the buildings. One question is whether a building with a high performance envelope is more sensitive to occupant behavior than buildings with lower envelope performance. Occupant behavior is in this study limited to the control strategies, as they to some extent represent occupant preferences, and how they interact with the building and its technical systems. From the simulations results it is clear that the impact of occupant behavior on energy efficiency is larger for high performance buildings, especially when it comes to window ventilation. The question whether opening windows led to a fixed increase in energy need, was to some extent answered. The simulation results imply that the energy need gradually increases with lower performance envelope buildings when window ventilation is used. The increase is however not large enough to make the drop in energy efficiency equally large.

It is debatable if the energy need for the two oldest building regulations TEK97 and TEK87 is reproduced accurately enough, especially concerning the modelling of the ventilation system. As discussed briefly under subsection 4.2.3, the two oldest building regulations set no demand for heat recovery of ventilation air, and buildings built under these periods were likely to be naturally ventilated. As an attempt to take this into consideration, the heat recovery efficiency was set to 0% for the two oldest buildings. For a naturally ventilated building, neither the supply air temperature nor the airflow rate is constant. This is highly dependent on the outdoor conditions, and natural driving forces such as buoyancy and wind pressure determine the air change rate. The airflow rate is however kept similar for all the five performance levels in this study, even if this may not be the case for the two cases with natural ventilation. The share of AHU heating is significant for these two cases, which originates from the constant set-point temperature for the supply air. Here, the whole temperature lift from the outdoor air temperature to the set-point temperature for the supply air has to be delivered by the heating coil, since no heat recovery is available. In reality the supply air temperature would have been similar to the outdoor air temperature, and the AHU heating part of the energy need would not exist. Supplying colder air into the building would at the same time result in a higher energy need from the space-heating system. Since there is uncertainty concerning the airflow rates, there is also more uncertainty connected to the annual energy need for the two buildings following the building regulations TEK97 and TEK87 than three others.

The focus on energy efficiency in buildings has increased considerably the later years, which have led to stricter legislation on energy performance of buildings as seen in this study. Window ventilation has increasingly larger impact on energy efficiency with increasing building envelope performance. One could ask if this problem with increased energy need for heating as a result of windows ventilation has always been there, but the lack of knowledge and relative impact on the energy budget has prevented this from becoming a relevant topic. For naturally ventilated buildings, window ventilation could also have been a necessity for providing enough fresh air to the bedrooms. A factor that could have contributed to bring this issue into focus is the increased interest of measuring and documenting the actual energy use in high performance buildings compared to older buildings. With increased focus on energy efficiency, more research and detailed measurement campaigns have been carried out, especially on low energy concepts like the passive house. When an significantly larger energy need for heating is measured compared to what was expected, effort is put into revealing the reasons behind this.

One hypothesis on why the energy need for space-heating is increasing when lower bedroom temperatures occurs, is related to the cascade ventilation effect as discussed in subsection 5.2. The goal for investigating this strategy was to separate the bedrooms from the rest of the building to a greater extent. This strategy has another approach than the control strategies previously looked at, where the goal was to investigate what temperature levels is possible to obtain without using window ventilation for temperature control. Instead of avoiding using window ventilation, this strategy aims to minimize the effect window ventilation and cold bedrooms has on the rest of the building, and thereby keeping the energy performance sufficiently high. The solution with supply and return ventilation in the bedrooms was able to provide the same temperature level for the bedroom as the conventional solution when the different control strategies were applied. The interesting difference was however found when the energy performance was investigated. It is clear that introducing return ventilation for the bedrooms do contribute to separate the bedrooms from the rest of the building to a greater extend by preventing the cold air from leaving the bedroom. It can also be determined from the simulation results that this flow of cold air from bedrooms is the reason behind the increased energy need for space-heating observed, even when the doors are kept closed. Limiting the cascade ventilation effect make bedrooms with mechanical ventilation comparable to bedrooms in older buildings where the natural ventilation principle is applied. Since fresh air is provided by fresh air vents in more or less every room in naturally ventilated buildings, there is a limited need for overflow of air between rooms. The case with supply and return ventilation for the bedrooms was an attempt to mimic this behavior, in order to limit the impact the cold bedrooms has on the energy performance for building.

Even though the energy efficiency was maintained at an acceptable level for the cases where the bedroom doors were kept closed and window ventilation was used, this solution does not solve the problem entirely. A similar drop in energy performance as for the basecase was observed when door opening was introduced. The solution does however make the building more robust against different occupant behavior, as the influence of window ventilation was minimized in the cases where the bedroom door is kept closed. The control strategies that was applied in this study had the same schedule for door and window opening every day, and this is a simplification that could influence the energy performance of the solution in a negative or positive direction. The cost of this solution is the extra set of ductwork that have to be added to the bedrooms. Since a route for the supply ducts to the bedrooms has to be designed in any case, the additional effort to fit an extra duct for the return ventilation is minimal. This is a low-tech solution, especially if the case with pre-accepted airflow rates is applied. In that case, the solution is neither increasing the complexity of the system, nor adding more control equipment compared to the conventional solution. The extra investment cost due to more ductwork will be negligible compared to the cost of the complete technical system in the building. If the solution with variable airflow for day and night is chosen, control dampers (VAV-dampers) have to be fitted in addition to the extra ductwork. The applicability of the solution with supply and return ventilation for bedrooms is therefore good, despite that it does not solve the issue of occupants preferring cold bedrooms during the night and warm bedrooms during the day.

The solution with supply and return ventilation does solve the energy performance issue sufficiently when the bedroom are kept constantly at a low temperature by using window ventilation and keeping the doors closed. The problem does not seem to be window ventilation itself, but the daily process of cooling down and heating up the bedrooms. This imply that it does not matter whether the bedrooms are being cooled down to the desired level by the ventilation system or by using window ventilation. The reason behind the increased space-heating needs is the cold bedroom itself. For the occupants that require a high degree of thermal zoning within the building that vary between day and night, introducing a more advanced technical system with more control options would not contribute to increase the energy performance significantly. For the occupants that require a lower degree of thermal zoning, thermal comfort could be achieved at acceptable energy efficiency by operating the technical systems correctly. As the simulation results demonstrated, lowering the supply air temperature have a significant impact on the bedroom temperature level. The results also demonstrated that increasing the supply airflow rate enhances this effect. It is therefore useful that the occupants gain information about how the technical system in their home work, either from the contractors or the housing cooperative. Moving from an older dwelling into a passive house could for some people also be the first encounter with a balanced mechanical ventilation system. The lack of instructions and information how the ventilation system in the building work was identified as an issue by the occupants that were interviewed at Miljøbyen Granåsen. Even if people gain more information about the technical systems in their homes, micromanaging the behavior of occupants is neither possible nor a good idea.

Chapter 7

Conclusion

The objective for this study was to investigate the possibility of creating thermal zoning in low energy building concepts, such as the passive house. The literature demonstrated that occupants in passive houses are unsatisfied with the thermal conditions in the buildings, and the bedrooms was reported as to hot. The existing strategies to achieve thermal zoning increased the energy need for space-heating, and thus creating a trade-off between thermal comfort and energy performance for the building. That is the reason why further investigation on this issue was necessary.

The first part this study was to investigate the thermal dynamics of the bedroom, and why it difficult to create thermal zoning in super insulated buildings in the first place. The simulation results and the findings in the literature have contributed to determine the factors that have the largest influence on the thermal zoning. It is clear that the answer is composed of several elements, so a combination of the hypotheses stated in chapter 3 is needed to sufficiently explain the issue. The thermal resistance of the internal constructions do to some extent contribute to increase the thermal zoning inside the dwelling, but only when the outdoor temperature is low according to the heat balances. Following the common Nordic building tradition of using light timber constructions with insulation in partition walls will provide sufficient thermal resistance. Further insulation of the internal constructions beyond this level will not contribute to improve the thermal zoning. Thermal inertia have a larger impact on the thermal zoning, especially when it comes to reaching very low bedroom temperatures. The simulation results of the buildings with different construction modes demonstrated the effect of thermal inertia, and also separated it from the effect of thermal resistance of the internal construction.

The two most important factors that prevent a high degree of thermal zoning is the heat supplied from internal and solar gains. The heat balances demonstrated that the two factors contribute to a significant share of the total heat gain to a bedroom. This is especially true when the outdoor temperature is in the milder range, as the heat losses from the external construction is just large enough to compensate for the heat from internal and solar gains. The simulation results therefore demonstrated that an additional heat loss has to be introduced to achieve a higher degree of thermal zoning. The second hypothesis is therefore one of the three that is confirmed to the greatest extent. The third hypothesis does however also have an important role when it comes to creating thermal zoning inside a dwelling. The extra heat loss that has to be introduced could be from supplying air below the bedroom temperature. The simulation results from the different control strategies demonstrated that the supply air temperature have a significant impact on the bedroom temperature. Limiting the supply air temperature could be sufficient to achieve thermal comfort at acceptable energy efficiency for occupants preferring a low degree of thermal zoning.

The reason behind the increased energy need for space-heating that was observed with cold bedrooms was identified. This was found to be related to the cascade ventilation principle, since the cold air leaves the bedrooms to the other parts of the building and get heated up before it is extracted from the room. To limit this effect, a solution with both supply and return ventilation for the bedrooms was investigated. The solution improved the energy performance and made the building more robust against the negative impact that cold bedrooms have. The solution did however face the same energy efficiency challenges as the conventional solution when a high bedroom temperatures was desired during the day, and low bedroom temperatures was desired during the night. The investigations also revealed that it is not the window ventilation that is the reason behind the increased space-heating need, but the cold bedroom itself and the daily flushing of heat. The solution is nevertheless applicable since the impact of cold bedrooms was minimized in the situations where the bedroom door was kept closed. It is also a low-tech solution that have acceptable installation complexity and costs.

The whole issue with thermal zoning therefore boils down to the users of the building. The ideal occupant with an ideal behavior and preferences do of course exist, but dictating how people should behave in their homes and what the temperature should be in the different rooms, simply do not work. The focus should rather be on user flexibility and on designing robust buildings that minimize the negative impact that different occupant behavior has on the energy performance of the building as much as possible. A good starting point is to accept the different occupant behavior, and the fact that people have different preferences when it comes to temperature levels inside dwellings. This knowledge should therefore be used as a basis for the design of new buildings. The solution with supply and return ventilation from the bedrooms is contributing to increase the energy performance robustness when window ventilation are being used, but the thermal zoning issue is not solved jet.

The future work on this topic to improve the thermal zoning and robustness of passive houses could be angled in a more fundamental direction than this study have been. The simulation results revealed that an additional heat must be introduced for the bedrooms to achieve a high degree of thermal zoning. Exploring the possibilities of reducing the envelope performance for the bedroom walls, or designing separate bedroom departments of a building could be investigated. This could separate the bedrooms from the rest of the building to an ever greater extent, and possibly maintaining the energy efficiency at a high degree of thermal zoning.

Since the simulation results demonstrated the significance of solar and internal gains on the heat balance for the building, more research on the impact of solar shading should be carried out. Even though the solar gains peak during the middle of the day, the heat is accumulated in the building due to the high thermal mass of passive houses. The possible benefits of strictly placing the bedrooms on the northern side of the building could also be an interesting factor to explore further. This study did also demonstrate the influence of the supply air temperature on the thermal conditions in the bedrooms. Different type of ventilation solutions that limit the need for overflow of air between the bedrooms and the rest of the building could also be looked more into. Room-based ventilation units have developed to be a popular alternative to a central AHU, especially in retrofit projects. The performance of this type ventilation solution regarding energy efficiency, indoor air quality and thermal comfort could be explored. A room based ventilation unit does facilitate individual temperature set-points for different rooms, and could therefore possibly contribute to increase thermal zoning.

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