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An Exploration of Measured, Perceived, and Desired Conditions

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Trondheim, December 2016

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Preface

After working for several years on the design and engineering of high-performance buildings, I became quite curious about how these buildings perform in practice, particularly with regard to indoor climate quality and occupant satisfaction.

Previous studies have indicated a need for more well-founded knowledge about the actual, perceived and desired indoor climate conditions in high-performance buildings and suggested that there remains room for improvement.

Therefore, I gratefully seized the opportunity to study these issues in depth through a PhD study at the Research Centre on Zero Emission Buildings (ZEB). It has been a rewarding task to work together in this multidisciplinary group, and I am happy to have gotten acquainted with so many pleasant, highly competent and committed people in ZEB. I also gratefully acknowledge the financial support of the Research Council of Norway, the Bergen University College and the ZEB partners, in particular ByBo AS.

I am much obliged to my supervisors Hans Martin Mathisen, Matthias Haase and Elisabeth Nesbakken Haugen, who, in the early stages of my study, gave me valuable guidance and inspiration regarding the direction, design and implementation of my research. In particular, I would like to thank Hans Martin Mathisen, who throughout this entire process has advised me with his competent knowledge and has contributed considerably to the ideas, methodologies and implementation of my research.

The user survey at Miljøbyen Granåsen was developed and conducted in close collaboration with Judith Thomsen at SINTEF Building and Infrastructure. I am thankful for this interesting and fruitful cooperation, which also resulted in one published scientific paper.

I would also like to thank Laurent Georges for his cooperation in writing several scientific papers and his valuable guidance during my studies, particularly regarding the use of simulation software.

Last but not least, I would like to thank my family and friends, who have supported me throughout this long-lasting project.

Trondheim, July 2016

Magnar Berge

Abstract

The Directive of the European parliament on the energy performance of buildings instructs member states to ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings.

The directive further prescribes that measures to improve the energy performance of buildings shall take into account general indoor climate conditions to avoid possible negative effects.

Following these instructions, the purpose of this thesis is to contribute to the diffusion and further development of nearly zero-energy and sustainable buildings, where minimal energy – as little as possible – is used to provide indoor climate quality (ICQ) that promotes health and wellbeing.

The first step in this research was to perform a broad evaluation of ICQ in high-performance dwellings (HPDs). This evaluation included a comprehensive literature study, user surveys, and measurements of indoor climate parameters and window opening durations in two case projects in Norway. The results were compared to findings on HPDs in other studies across Europe. In the second step, the focus was narrowed to an evaluation of thermal comfort in the various rooms of a dwelling. In the last step, attention was turned specifically to the thermal conditions of bedrooms, and simulations were conducted to develop improved solutions for ventilation and heating.

The results of this research support earlier findings from studies on HPDs, where generally high indoor air quality (IAQ) is observed, both with regard to measured parameters and perceived IAQ.

Regarding thermal comfort, a generally high degree of satisfaction was also observed when evaluating the dwelling as a whole. However, when investigating thermal comfort in detail in various rooms, both the user feedback from the case projects and the measured temperature levels clearly indicate that different temperatures are desired in different rooms and that satisfaction with thermal conditions varies significantly across the different rooms.

The results indicate that the actual thermal conditions in the living room and bathroom are in accordance with the desired thermal conditions. In contrast, a clear discrepancy between actual and desired thermal conditions was observed in the bedrooms.

The measurements and performed simulations demonstrate that the increased temperature levels in the living room and bathroom and the use of one-zone mechanical ventilation with heat recovery (MVHR) contribute to an excessive heat supply to the bedroom during the heating season, which prevents the desired bedroom temperatures from being reached.

This oversupply of heat to bedrooms during winter may explain the long duration of window opening observed in bedrooms. Based on user feedback, the main driver of window opening appears to be

temperature control, not the need for an increased fresh air supply. Therefore, different MVHR solutions with a range of control strategies were investigated using detailed dynamic simulations. The results of the simulations demonstrate the substantial impact of the MVHR solutions on the thermal conditions in bedrooms. The clear potential of a two-zone MVHR solution was observed regarding the achievement of desired thermal conditions in bedrooms at the lowest energy cost.

Based on the findings in this study, the following implications are outlined:

1. The implementation of a two-zone MVHR is recommended for dwellings, in which the supply-air temperature to the bedroom is controlled independently from the supply-air temperature to the other parts of the dwelling.
2. The supply-air temperature to the rooms should be controlled using the set-point temperature of the room as a reference point in order to adjust the heat supply to the current heating or cooling demand.
3. Interior walls, which enclose bedrooms, should be insulated to reduce heat flow from neighbouring rooms.
4. To facilitate increased knowledge and awareness, appropriate user information should be provided to the occupants of HPDs regarding control of the indoor climate.
5. The acceptability limits for room temperatures in current standards and regulations should be reconsidered and differentiated to better accommodate desired temperatures in the different rooms of dwellings.

Content

1 Introduction

According to the Directive of the European parliament on the energy performance of buildings [1], "Buildings account for 40 % of total energy consumption in the Union. The sector is expanding, which is bound to increase its energy consumption. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union's energy dependency and greenhouse gas emissions." This directive instructs member states to ensure that "(a) by 31 December 2020, all new buildings are nearly zero-energy buildings and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings."

The directive further prescribes that "measures to improve further the energy performance of buildings should take into account climatic and local conditions as well as indoor climate environment and cost-effectiveness." In the course of setting minimum energy performance requirements, "these requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation, as well as local conditions and the designated function and the age of the building." [1]

Following these instructions, the purpose of this thesis is to contribute to the diffusion and further development of nearly zero-energy and sustainable buildings, where minimal energy – as little as possible – is used to provide indoor climate quality (ICQ) that promotes health and wellbeing. In this thesis, the term ICQ includes both indoor air quality (IAQ) and thermal comfort.

Looking at past developments in the building stock, extensive changes have occurred in recent decades in the way buildings are designed, constructed and used. These changes have, on the one hand, been driven by changing expectations of indoor climate design itself, driven by increased prosperity, changed regulatory requirements and greater user demands. On the other hand, the urgent need to reduce energy use in buildings has led to comprehensive changes in buildings and their technical installations. It is imperative to adequately evaluate the possible implications these changes have for ICQ.

Particularly with regard to heating and ventilation, which is the key issue in this thesis, fundamental changes are observed in high-performance dwellings (HPDs). A definition of the term HPD is provided in section 2.3. These changes affect ICQ and constitute a major change in occupants' ability to control their ICQ.

In contrast to older dwellings, where the fresh air supply was controlled by opening windows or ventilating apertures, the fresh air supply in HPDs is provided by mechanical ventilation with heat recovery (MVHR). The need for window ventilation during the heating season is supposed to be eliminated or at least substantially reduced.

The use of MVHR has created the possibility of supplying heat through the ventilation system. In the passive house concept, according to the definition of the Passive House Institute, air-heating is promoted as the main or even only heat source [2], whereas in other HPDs, post-heating of the supply air after it is processed by the heat exchanger is used to a lesser extent. In any case, both heat recovery and post-heating of the supply air affect the temperature level and temperature distribution within a dwelling.

Based on the above-mentioned technological and behavioural changes in the way residential buildings are ventilated and heated, the following research questions are posed:

1. How well are HPDs performing in practice with regard to the provision of desired indoor climate conditions?
2. How well are the technical solutions for heating and ventilation performing with regard to the provision of desired indoor climate conditions at the lowest possible level of energy use?

To respond to these research questions, the following objectives are pursued in the present work:

1. Assessment of the measured, perceived and desired indoor climate conditions in HPDs.
2. Evaluation of the extent and driving forces of occupants' heating and ventilation habits in HPDs and their impact on ICQ and space-heating demands.
3. Investigation of the potential for improved solutions for ventilation and heating in HPDs.

This research can be described as a three-step approach, where the treated subject area is gradually narrowed down, as illustrated in Figure 1.

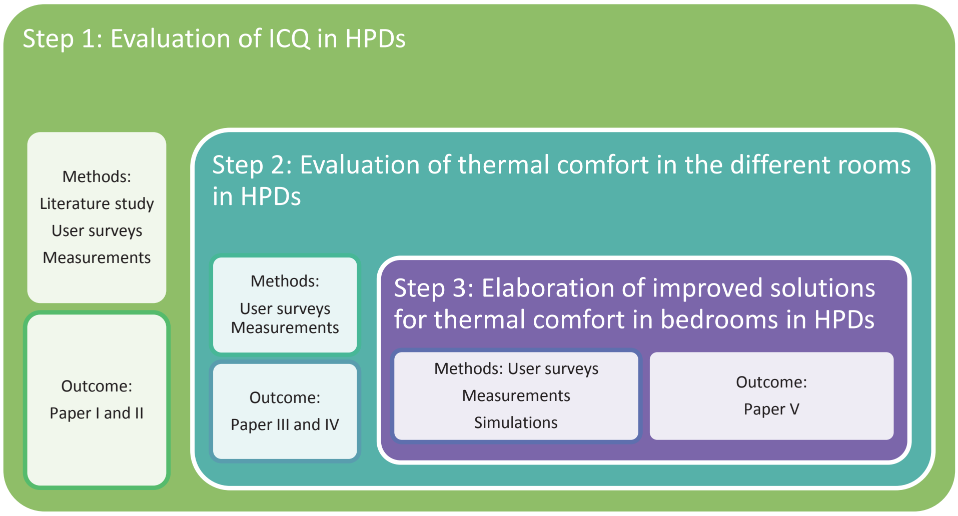

Figure 1 Illustration of research approach

As a first step, a broad evaluation of ICQ in HPDs was performed, including a comprehensive literature study, user surveys, and measurements of indoor climate parameters as well as assessment of window opening durations in two case projects in Norway. The results were compared to findings in other studies across Europe on HPDs that use various heating solutions. The main focus was on IAQ and thermal comfort, but other issues of indoor environmental quality (IEQ), such as acoustic comfort, were addressed to some degree.

In the second step, the focus was narrowed to the evaluation of thermal comfort in the different rooms in a dwelling.

In the last step, attention was focused specifically on the thermal conditions in bedrooms and on the elaboration of improved solutions for ventilation and heating.

A theoretical framework for this study is presented in the next chapter. First, relevant terms and issues regarding ICQ and HPDs are described. Then, a general exposition regarding the impact of the indoor climate on health and comfort is presented, and some historical experiences illustrating the impact of energy efficiency measures on the indoor climate are outlined. In the last sections of the framework chapter, the current state of research regarding ICQ in HPDs is described.

2 Theoretical framework

2.1 Indoor climate quality

The term *indoor climate quality* (ICQ) is used in this thesis as a collective term to describe both thermal comfort and IAQ. IAQ is defined by the physical, chemical and biological composition of the indoor air.

ICQ is an essential part of IEQ, which, in addition to ICQ, also takes visual and acoustic comfort into account [3, 4].

2.1.1 Indoor air quality

Acceptable indoor air quality is, in accordance with ISO 16814:2008 [5], defined as "air in an occupied space toward which a substantial majority of occupants express no dissatisfaction and that there is not likely to contain contaminants at concentrations leading to exposures that pose a significant health risk".

Awareness of the influence of IAQ on health can be traced back thousands of years, as is well documented in historical literature (e.g., contributions by Hippocrates or the recommendations in Leviticus regarding remedies to eliminate mould in buildings [6]).

In the 18th century, oxygen was discovered to be part of the air, and by the end of the 18th century the relationship between the intake of oxygen and release of CO_2 – due to the human metabolism – had been identified. Since this discovery, indoor CO_2 concentration have been acknowledged as a measure of IAQ [6].

The first professor of hygiene, Max Joseph von Pettenkofer, made pioneering contributions to knowledge of IAQ during the 19th century. He advocated the understanding that CO_2 is not noxious in itself but rather serves as a good indicator of other substances produced by humans. He stated that air with a CO_2 level above 1000 ppm is not fit for breathing and that the level should be below 700 ppm in rooms where people remain for long periods of time [6]. These limits are still found in current standards and regulations.

Pettenkofer also highlighted the importance of source control with regard to IAQ, which is reflected in his well-known quote: "A space, which includes a putrefying dunghill, will remain a disgusting abode, a stove for poor air in spite of ventilation" (cited in [7]).

According to Sundell [6], between the 1930s and 1960s there was little scientific effort directed at residential ventilation, IAQ, and health. The accepted view was that odor, comfort, and perceived IAQ were the relevant factors in setting guidelines for ventilation. The relationship between IAQ and health first appeared on the scientific agenda in the 1970s, with the discovery that some health risks could be attributed to pollutants such as formaldehyde and house dust mites.

Since then, a strong base of evidence has emerged regarding the association between IAQ and lung cancer, allergies, other hypersensitivity reactions, chemical sensitivity and respiratory infections [6]. There is, however, still limited scientific knowledge regarding the causal agents of these problems. For example, there is evidence supporting the association between damp buildings and adverse health effects, such as cough, wheeze, allergies and asthma, but the specific agents that cause these problems are not known [8-10]. According to Sundell, commonly measured pollutants, such as volatile organic compounds and mold spores, are of little importance for health effects; instead, he argues, we need investigations of other possible compounds and a deeper understanding of their biological mechanisms [6].

The following section outlines the established current evaluation criteria for IAQ, which form the basis of the present evaluation of IAQ in HPDs.

2.1.2 Evaluation criteria regarding indoor air quality

ISO 16814:2008 [5] proposes three different methods of evaluating IAQ:

- Method based on target concentration value, where IAQ is expressed based on the relationship between target concentration levels and acceptable levels.
- Method based on perceived IAQ, where IAQ is expressed based on the percentage of people who perceive that the air is unacceptable.
- Method based on the ventilation rate, where IAQ is expressed based on the relationship between the actual and minimum ventilation rates.

Regarding the method based on target concentration value, acceptable levels for a range of pollutants can be found in the ASHRAE Guideline 24-2008 [11], in the informative annex C to ISO 16814:2008 [5], or in the guidelines published by the World Health Organization (WHO) [12].

Because of the large amount of possible indoor air pollutants and the complexity and costs of pollutant assessments, it is common to use CO_2 concentration for IAQ classification in spaces where the occupants themselves constitute the main source of contaminants. Limit values for CO_2 concentrations in the various IAQ categories are given in EN 15251 [4] and ASHRAE Standard 62.2-2013 [13]. Assuming an outdoor CO_2 concentration of 400 ppm, limit values in accordance with EN 15251 [4] are given in Table 1.

Table 1 Limit values for IAQ classification based on CO_2 concentration according to EN 15251 [4]

Category	Classification	Limit value for CO_2 concentration (ppm)
I	High IAQ	750
II	Medium IAQ	900
III	Moderate IAQ	1200
IV	Low IAQ	> 1200

The method based on perceived IAQ is described in EN 15251 [4] and ANSI/ASHRAE Standard 55-2013 [14], where IAQ is classified into four categories depending on the percentage of people who perceive it to be unacceptable. The method described in these standards is based on the instantaneous judgement of the IAQ, and is commonly used to evaluate the current IAQ in office buildings.

An alternative method, based on perceived IAQ, is the use of a questionnaire that assesses perceptions of IAQ in a longer retrospective view [15-17]. One widely used questionnaire in Sweden and Norway is the Örebro-form [15], which provides results from a large sample of residential buildings from different construction periods [18, 19].

The method based on the ventilation rate requires measurements of the air exchange rate, which is then compared to minimum ventilation rates defined in existing standards, such as EN 15251 [4] or ASHRAE Standard 62.2-2013 [13], or national regulatory requirements [20].

2.1.3 Thermal comfort

Thermal comfort is, according to the ANSI/ASHRAE Standard 55-2013 [14], defined as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”.

Regarding the state of scientific knowledge of thermal comfort, pioneering research by Povl Ole Fanger [21, 22] still forms the basis of evaluation criteria defined in current standards such as ISO 7730 [23], EN 15251 [4], and ANSI/ASHRAE Standard 55-2013 [14]. Fanger studied large groups of people in different environmental conditions, with different metabolic rates and clothing insulation levels, to assess subjective evaluations of the thermal environment on a seven-point scale, ranging from -3 to +3, corresponding to the categories “cold”, “cool”, “slightly cool”, “neutral”, “slightly warm”, “warm”, and “hot”. Based on these thermal sensation votes, the index PMV (predicted mean vote) was defined. The PMV index can be used to predict the mean value of thermal sensation votes in a given environment and to evaluate thermal conditions in relation to criteria defined in regulations or standards, such as ISO 7730 [23], EN 15251 [4] and ANSI/ASHRAE Standard 55-2013 [14].

Thermal sensation varies across individuals and votes are scattered around the mean vote (PMV). Therefore, the PPD index (predicted percentage dissatisfied) is defined to quantify the percentage dissatisfied at a given PMV. Thermal dissatisfaction is defined by the votes “hot”, “warm”, “cool” or “cold”. The equation for PPD can be used to predict the percentage dissatisfied at a given environmental condition.

The method based on PMV and PPD, as defined in ISO 7730 [23], was developed specifically for the work environment. This must be considered when evaluating other environments such as dwellings. The method is also based on steady-state thermal conditions, which limits its applicability to non-steady thermal conditions.

Furthermore, ISO 7730 [23] does not distinguish between mechanically and naturally conditioned spaces when defining thermal comfort criteria. In contrast, in EN 15251 [4] and ASHRAE Standard 55-2013 [14], differentiated criteria are used for mechanically and naturally conditioned spaces, and the latter set of criteria is based on the adaptive model of thermal comfort and preference [24].

The adaptive model of thermal comfort is based on a comprehensive statistical analysis conducted in the ASHRAE RP-884 project on thermal sensation in relation to observed temperatures in 160 buildings around the world. In this study, occupants in naturally ventilated buildings were found to be tolerant of a significantly wider range of temperatures [24]. This increased tolerance is explained by both behavioural adjustments and psychological adaptation, such as expectation and habituation, which are not taken into account in the PMV model.

Based on these findings, the adaptive model is suggested for naturally ventilated buildings, which deviates substantially from the PMV model for buildings with natural ventilation [24], as illustrated in Figure 2. The differences between the PMV models for buildings with HVAC and buildings with natural ventilation are due to different behavioural adaptations, such as air speed and clothing.

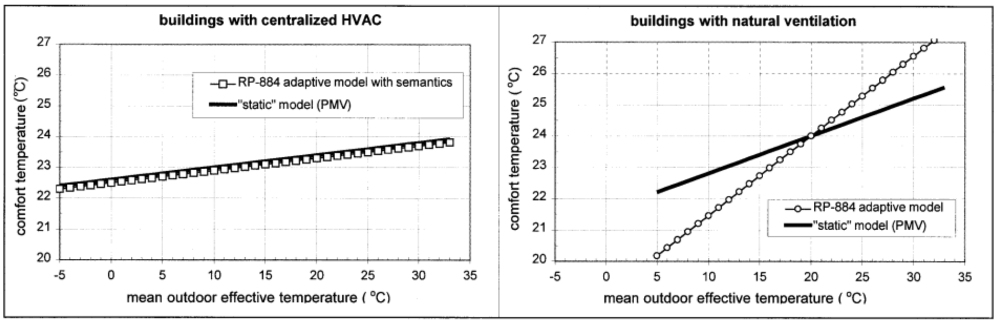

Figure 2 Adaptive versus static comfort model predictions, taken from [25] (Reprinted with permission; ©ASHRAE www.ashrae.org. ASHRAE Transactions, (Vol 104), (1998).

According to EN 15251 [4] and ASHRAE Standard 55-2013 [14], the PMV model must be applied in buildings where mechanical cooling is used, and the adaptive must be applied in buildings where no mechanical cooling is used and where the occupants can control window opening and are free to adjust their clothing. For cool and cold climatic regions, such as in Nordic countries, the adaptive model is generally relevant for summer conditions only.

2.1.4 Evaluation criteria regarding thermal comfort

In ISO 7730 [23] and ASHRAE Standard 55-2013 [14] no evaluation criteria are given specifically for residential buildings, whereas EN 15251 [4] contains specific criteria for residential buildings. EN 15251 [4] also distinguishes between the various areas in a dwelling. The acceptability limits for bedrooms given in EN 15251 [4] are the same as for living rooms, but in the Norwegian addendum it is noted that lower temperatures in bedrooms may be desired. Acceptable temperature ranges for classification category II are listed in Table 2. Category II is for normal expectation levels and is suggested for new and refurbished buildings.

Table 2 Acceptable temperature ranges for dwellings in the Norwegian addendum to NS-EN 15251[4]

	Acceptable temperature ranges (°C)	
Type of rom	**Heating season**	**Outside heating season**
Living room, bedroom, kitchen, office	20-24	23-26
Bathroom	22-24	22-24
Other rooms (hall, storage)	16-26	No limits

Regarding acceptable floor temperatures, NS-EN 15251:2007 [4] recommends that the floor temperature should never be below 20°C and that the temperature should be between 22 and 24°C in playrooms for children. It is noted that the heat conductivity and heat capacity of the flooring material influences perceived comfort, but a comparison of different floor materials is not provided.

When applying the adaptive model of thermal comfort, acceptable temperature levels are defined depending on the exponentially weighted running mean of the outdoor temperature Θ_{rm} [4], see Figure 3.

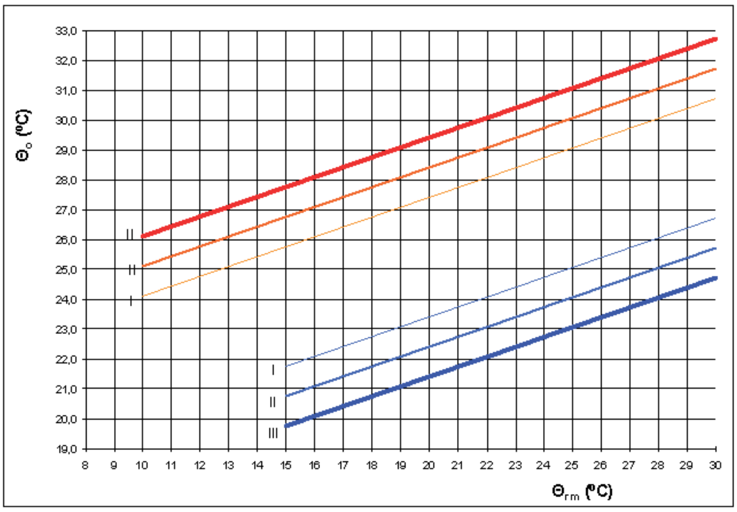

Figure 3 Acceptable operative temperature ranges Θ_o as a function of the running mean outdoor temperature Θ_{rm} for spaces without mechanical cooling, according to EN 15251 [4] (Reprinted with permission; © Standard Online AS 03/2016)

2.2 The impact of the indoor climate on human health and wellbeing

According to the World Health Organization (WHO), health is defined as "…a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity." [26].

Consequently, when evaluating the impact of the indoor environment on humans, possible adverse effects on health and perceived comfort both need to be addressed.

There is a vast body of knowledge on the association between indoor conditions and health. Taking a broad perspective, the indoor climate constitutes a substantial environmental burden and is a direct or indirect cause of many deaths and diseases [27]. Examples of common indoor pollutants linked to serious consequences are indoor smoke, indoor carbon monoxide and radon. Building moisture and biological agents are associated with the increased prevalence of respiratory symptoms, allergies and asthma as well as disturbance of the immunological system [8, 28].

The well-recognized and substantial impact of ICQ on human health and wellbeing establishes the fundamental premise of this work but is not further outlined in this thesis.

2.3 High-performance dwellings

In this study, the term HPD is used as a collective term for a dwelling where strict requirements regarding energy use and ICQ are applied. This study addresses buildings located in cool and cold climatic regions, where highly insulated and air-tight building skins and MVHR are utilized to achieve these performance criteria.

Examples of defined criteria, which form the basis for the above-mentioned definition of an HPD, are the criteria established by the Passive House Institute [29], the Active House Alliance [30], the Swedish Energy Agency [31], and Standards Norway [32].

The following chapters describe the various changes typically incorporated into HPDs in comparison to older building standards; the possible impacts on ICQ are also outlined.

2.3.1 Change in building structure

Compared to buildings constructed under earlier standards, HPDs have considerably higher insulation levels. The national building code established in Norway in 1949 required a maximum U-value of 0.9 W/m2K for exterior walls in wooden homes [33], which corresponds to ~5 cm mineral wool. In HPDs, insulation of 25-40 cm is typically used in exterior walls [34].

This increased insulation level changes the hygrothermal conditions both on the wall surfaces and inside the wall; this must be taken into account when assessing possible effects on the indoor climate.

Regarding building moisture, increased wall thickness requires increased drying time, necessitating moisture control during construction [35]. An increased risk of moisture damage in crawl spaces is observed when the floor is highly insulated, and therefore this should be avoided according to [35].

Thermal bridges, defined as local thermal flows that result from concentrations of materials with high thermal conductivity, cause increased heat loss. In addition, a cooling of the interior surfaces takes place, which may cause local thermal discomfort, condensation and mould growth. Consequently, the reduction or elimination of thermal bridges has exclusively positive effects on the indoor climate.

Increased air-tightness reduces the risk of moisture transport and condensation inside the building skin and consequently has a positive impact on the indoor climate [35].

2.3.2 Change in ventilation strategies

The history of mechanical ventilation goes back to the late 19th century and began with the availability of electric power [36]. In 1936, the British manufacturer Vent-Axia invented the first electrically operated window ventilator. One of the first customers for this ventilator was Sir Winston Churchill, who ordered an installation in Number 10 Downing Street [37]. The use of heat recovery to exploit energy in exhaust air first began in the 1970s [38].

Despite the long history of knowledge and technology in the areas of mechanical ventilation and ventilation heat recovery, market penetration of MVHR in residential buildings can be observed only as recently as the beginning of the 21st century. Since the 2007 revision of Norwegian building regulations, requirements for heat recovery [20] have led to a nearly exclusive implementation of MVHR in all new residential buildings in Norway.

A major force behind the implementation of mechanical ventilation is the comprehensive body of evidence regarding the association between ventilation and health. Many studies report a positive correlation between ventilation rates and health and comfort [39-42]. This knowledge has led to a general recognition of the importance of the air change rate and its implications for IAQ, which is reflected in established guidelines, standards and regulations [4, 12, 13, 20, 28, 43].

It should be noted that ventilation rates should only be used for regulatory purposes when taking into account actual outdoor exposures and the sensitivity of the exposed populations [44].

When comparing natural and mechanical ventilation in residential buildings, mechanical ventilation has proven to be more suitable for the provision of a steady and sufficient air change rate [45-47]. In many studies, the use of mechanical ventilation is directly associated with a positive health impact on the occupants [48-53].

However, mechanical ventilation systems also pose documented risks of adverse health effects. These are generally linked to failure in planning, commissioning, use, or maintenance [54-58].

Because MVHR constitutes an essential component of high-performance dwellings and has a substantial impact on both energy use and indoor climate, it is essential to evaluate the performance of MVHR systems. Such evaluations should address technological factors as well as how the occupants perceive and control the indoor climate in their interactions with the MVHR.

2.3.3 Change in heating strategies

Over the past several decades, the heating strategies used in dwellings have changed substantially. Künzel [55] describes the development of heating strategies in Germany after the second world war. Until the 1950s, heat was commonly provided by wood-burning or coal-burning stoves. Usually only one room or a few rooms were heated during winter to save fuel costs and limit the work load associated with heating. Because the ovens were manually operated, intermittent heating was used, usually with fuelling in the morning and the afternoon.

After the 1950s, when oil became cheaper, the use of central hydronic heating systems gradually increased. Thermostats were unprofitable due to low energy prices. Room temperature was therefore generally controlled by opening windows, which caused low indoor humidity levels during winter. As a positive consequence, problems with mould growth were nearly non-existent during this period [55].

The energy crises of the 1970s caused a significant change in heating strategies: heating habits changed, window ventilation was reduced, and overheating was limited by the installation of thermostats [55].

Since the energy crises, and driven by the need to reduce the greenhouse gas emissions of the building stock, energy requirements for buildings are gradually becoming more and more strict.

This development has had fundamental effects on heating strategy for residential buildings. The maximum required heat load in an older building in Central Europe is typically 100 W/m^2; in HPDs this value is reduced to 10-20 W/m^2 [34]. This substantially reduced heating demand in HPDs has led to the incorporation of heating into the ventilation system, which is required anyway to provide fresh air. Because the economic profitability of room-by-room heating is reduced due to the reduced overall heating demand, air-heating is promoted as a cost-efficient main heat source [2]. This concept of using the supply air for the heat supply is not adopted in all HPD concepts as defined above. Yet, heat recovery alone increases supply air temperatures, which has an impact on the thermal conditions of the whole dwelling. These issues need to be addressed when evaluating thermal comfort in HPDs.

2.3.4 Change in occupant wishes and behaviour

A comfortable home is a fundamental human need and desire, which seems not to have changed over the course of history. However, the distance between wanted and provided comfort has changed substantially. In line with general increased prosperity, the demands and expectations of occupants regarding general housing quality and living comfort have also increased. The possibility of comfort and cosiness in HPDs is appreciated by the occupants and has been found to be an essential influential factor in purchase decisions [59, 60].

Taking a retrospective view of occupant behaviour, a general adaptation to the actual possibilities and limitations of buildings is observed. In old and cold buildings, occupants previously adapted by changing their locations within the dwelling and the room and by adjusting their clothing [61]. The need to save energy led to the intermittent heating of a limited number of rooms [55].

In recent studies, energy saving behaviour in older buildings has also been observed: people have adjusted the temperature to a lower level than what provides an ideal level of comfort [62].

Studies of HPDs indicate changed energy saving behaviour, where occupants exploit the possibility of increased temperature levels. This is because, first, the whole building can easily be heated, and second, heating costs are relatively low even at elevated temperatures [63].

Window ventilation behaviour has also changed throughout history and is driven by various influential factors, such as the need to save energy, the need for fresh air, the need for temperature or moisture control, and the need to block noise from the outside.

Regarding window ventilation behaviour in historical perspective, outdoor temperature is found to be the dominant influential factor. Several studies show that the duration of window opening is substantially reduced at low outdoor temperatures [55, 64]. In a Dutch study, Van Dongen and Steenbekkers, cited in [64], found that at ambient temperatures around zero all air inlets were closed during the night in 90% of the bedrooms. Even with outdoor temperatures above 13ºC, only in 45% of the bedrooms were ventilation apertures opened during the night. Similar window opening durations were observed in a German study [55].

For HPDs, window ventilation during the heating season is claimed to be unsuitable for the provision of fresh air [34], which is instead provided by MVHR. However, extensive window ventilation during winter is also observed in buildings with mechanical ventilation [55, 65-67].

The above-mentioned German study also included buildings with mechanical ventilation, where a similar pattern of window ventilation – dependent on the outdoor temperature, as in buildings with only window ventilation – was observed, although with somewhat lower mean opening durations [55]. At outdoor temperatures between 0 and 10°C, a mean opening percentage of ~10% and 17% was observed for, respectively, buildings with and without mechanical ventilation systems. At outdoor temperatures lower than 0°C, a mean opening percentage of ~10% was observed for both building types.

In a study on passive houses that measured window opening durations in 21 dwellings, it was found that approximately one third of the occupants had their windows open the entire night [66].

The drivers of the observed window ventilation behaviour were not assessed in detail in the above-mentioned studies. Other studies have examined the factors that influence window ventilation behaviour, but whether and to what degree these drivers change in HPDs has not been specifically addressed [68]. Further investigations are required to explain the forces driving window ventilation in HPDs specifically and to develop possible improved solutions for the control of temperature and fresh air supply.

2.4 Retrospective view of the effects of energy saving measures on ICQ

Energy saving measures have been associated with both a decrease and increase in indoor climate-related symptoms [40, 69, 70].

It is suggested that substantial health benefits can be achieved by retrofitting houses [71]; this is explained by the reduction of fine particulate matter ($PM_{2.5}$) emissions and the reduction of particle precursors (SO_2 and NOx).

The adverse health effects of energy saving measures are generally associated with an increase in dampness and mould. Several studies report a deterioration of IAQ and occupant health as a consequence of energy saving measures [40, 72-74].

Changes in energy saving behaviour due to the energy crisis in the 1970s has also contributed to an increase in dampness and mould in dwellings [55].

Studies addressing the effects of energy saving measures on IAQ consistently emphasise the importance of maintaining or implementing a sufficient air change rate. In this regard, the benefits of mechanical ventilation are highlighted [40, 51, 75, 76].

2.5 Current state of research regarding ICQ in HPDs

A comprehensive literature study was conducted to capture the current state of research regarding ICQ in HPDs, using common search engines for scientific literature and a wide range of search terms.

Because scientific work is published not only in scientific papers but also often as reports, a search in the publication databases of scientific institutions was conducted. Many reputable research institutions across Europe have devoted a huge amount of effort to research on HPDs, and particularly on passive house buildings. Without claiming to provide a complete list, the following institutions stand out in this regard: the Passive House Institute (passiv.de), the Institute Wohnen und Umwelt (iwu.de), the Austrian Institute for Healthy and Ecological Building (ibo.at), the Fraunhofer-Gesellschaft (fraunhofer.de), the University of Natural Resources and Life Sciences in Vienna (boku.ac.at), the Research Institute for Regional and Urban Development (ils-forschung.de), the Technical Research Institute of Sweden (sp.se), and SINTEF (sintef.com). It is also worth mentioning the "Building of Tomorrow" initiative by the Austrian Federal Ministry of Transport, Innovation and Technology (hausderzukunft.at) and the "Buildings of the Future" initiative by the German Federal Ministry of Economics and Technology (enob.info), both of which provide a valuable store of reports on HPDs.

Out of the papers and reports found through the search described above, those meeting the following criteria were included in the review:

- Studies published in scientific journals, by scientific conferences or by the established scientific institutions mentioned above
- Studies on buildings in cool and cold climate zones as defined in [77]
- Studies that clearly present both building information and research methodology
- Studies that draw conclusions based on careful consideration of the statistical significance of their results

The found and reviewed literature demonstrates that there is an extensive and continually growing store of knowledge regarding ICQ in HPDs. Especially since the promotion of the air-heating concept by the Passive House Institute in Germany [2], extensive research has been performed to assess and evaluate the impact of this approach on ICQ.

In the course of the literature review, a large number of publications were found that addressed ICQ in HPDs. Studies with results based on measurements and results based on user evaluations were both found.

A comprehensive multidisciplinary review of the impact of energy saving measures, including measures applied in HPDs, is provided in [70]. The authors of this study included several scientists representing medical science, building biology science, and building science; they performed a holistic evaluation of indoor climate-related parameters and possible implications for ICQ and health. They addressed abiotic contamination (organic and chemical compounds, asbestos, radon), biogenic contamination (pollen, mould, anthropogenic emissions), and physical factors (temperature, air humidity, air speed). In addition, the possible impact of airborne ions on health was discussed. They concluded that the positive health impacts of MVHR clearly prevail in comparison to natural ventilation and mechanical exhaust ventilation. Furthermore, they noted that the removal of contaminants and moisture through permeable walls is negligible and that air exchange through leakage is generally insufficient. Regarding the possible adverse effects of MVHR on health, they noted low indoor humidity levels during winter, bacterial contamination on filters or earth tubes, and the entry of radon from the earth through air-heat exchangers.

In the following, the results from the scientific literature review are discussed in more detail. These results are thematically grouped into measured IAQ, perceived IAQ, measured thermal conditions and perceived thermal comfort.

2.5.1 Measured IAQ in HPDs

In many studies on HPDs, IAQ is evaluated and classified by using measured CO_2 concentrations as an indicator for the air exchange rate. Studies consistently indicate that the use of MVHR generally leads to a higher air exchange rate than natural ventilation and consequently facilitates better IAQ [46, 47, 78-80].

In a number of studies, indoor abiotic and biogenic contaminants were directly measured. These findings also strongly indicate the advantage of MVHR regarding the efficient dilution of contaminants.

In [81], two single family houses with MVHR were compared to one single family house with window ventilation; a lower airborne germ concentration was measured in the buildings with MVHR in comparison to the control building with natural ventilation. The researchers measured an increase in microbial volatile organic compounds (MVOC) in the indoor air between the filter change intervals, and they emphasise the importance of good maintenance routines to keep MVHR systems in optimal condition. In another study, cited in [75], a similar comparative study of 28 residential buildings with different ventilation solutions is described, where a reduction of mould spores by approximately 70% was observed in mechanically ventilated buildings in comparison to naturally ventilated buildings.

In a study of four passive houses, volatile organic compounds (VOCs), mould spores, radon, and ion concentrations were measured over a period of two years [82]. High levels of VOCs were measured during the construction period; however, these were reduced to an acceptable level within a few months. The more effective reduction in VOC levels – compared to experiences in other projects – was attributed to mechanical ventilation. It is noted that despite efforts in this project to minimize noxious substances through conscious selection of construction materials, relevant concentration levels were observed. In particular, very high levels of pentane were measured. Pentane is used in the production process of expanded polystyrene insulation (EPS). High insulation thicknesses in passive houses may consequently contribute to increased emissions from insulation materials.

Regarding mould spores, no increased indoor concentration in relation to the outdoor concentration was detected in the investigated passive houses [82]. A higher microbial number in the control building without mechanical ventilation was observed, which was explained by the lack of the filter that prevents some outdoor spores from entering the buildings.

In [79], the findings of VOC measurements in six dwellings are presented. VOC levels were measured after construction and prior to handover. The total VOC concentrations were found to be far below recommended limit values.

In [83], results are presented from a study in which the levels of VOCs and microbial contamination were measured in nine refurbished buildings and a newly built passive house. Regarding VOCs, a reduction to acceptable levels was found within a short period after construction, which was attributed to the efficient air change rate of the MVHR system.

A comparison of indoor contamination levels among seven newly built HPDs in France and typical French dwellings was performed in [84]. The results indicate lower contamination levels in the HPDs with regard to $PM_{2.5}$, radon, benzene and toluene, whereas higher levels were found for some contaminants; these are linked to emissions from construction materials in new buildings.

However, in some cases it was found that the MVHR system itself was a source of contamination [82, 83, 85], which demonstrates that there is a risk of adverse health effects associated with the implementation of MVHR. In [83], no clear indication was found of a positive effect from MVHR in terms of contamination levels. In contrast, in one building, increased bacterial contamination was found – relative to the outdoor concentration – when the air change rate was increased, which suggests that bacterial propagation may occur in MVHR systems.

Regarding indoor humidity levels during winter, some studies indicate a generally lower relative humidity level in HPDs. In a Swiss study [86], relative humidity levels below 20% were measured in two out of eighteen investigated dwellings, which was explained by the high room temperature. Measurements in two dwellings in a German study show relative humidity levels between 30 and 50% during winter, and a lowest measured value of 21%. In another German study on 22 passive houses [47], humidity levels between 40 and 50% were measured during winter in apartments, where occupants had reported perceiving dry air.

Clear positive effects of reduced humidity levels can be determined with regard to dampness and mould. House dust mites require a relative humidity level over 45-50% [28], relative humidity levels below this level will consequently contribute to the prevention of mites. For common building materials, fungal growth is prevented when the relative humidity level on surfaces is kept below 75-80% [28], which appears to be easily achieved in well-insulated HPDs with an appropriate air change rate.

Regarding possible adverse effects due to extremely low humidity, findings in studies by Wolkoff and Kjærgaard [87] on epidemiological, clinical, and human exposure indicate that low air humidity is associated with eye irritation symptoms and irritations in the upper airway; this calls for a re-consideration of the argument that the perception of dry air is caused by pollutants rather than low relative humidity. Their studies indicate that a relative humidity level of approximately 40% is better than levels below 30%. Wyon, Fang [88] showed that a five-hour exposure to low humidity levels (15% and 5%) led to a slight increase in subjective discomfort as well as physical deterioration regarding tear film quality, blink rates and skin dryness, which did not occur at a level of 25% or above.

Consequently, further research is needed to clarify the impact of actual humidity levels on discomfort and symptoms. Based on this research, a medically justified lower limit regarding indoor humidity levels could be defined.

Some possible measures to counteract low humidity levels are suggested in [89, 90]. These include reduction of the ventilation flow rate without compromising IAQ, moisture recovery, moisture storage in building materials, the use of plants, and drying clothes on a hanging unit instead of using a tumble dryer. In addition, cascade ventilation is cited as a measure to reduce the total air exchange rate, where the air is supplied in bedrooms, flows through the hall and living room, and is extracted in the bathroom and kitchen.

Some of the reviewed studies specify the use of counterflow or cross-counterflow heat exchangers [86, 91], in which no moisture is recovered. In cold climates, energy exchangers (which recover both latent and sensible heat) are recommended because they improve the humidity level of the indoor air and also increase efficiency [92].

Humidification should be used as a last resort because of the risks of bacterial activity in the humidifier and the increased perception of stuffy air at elevated levels of air humidity [93, 94].

2.5.2 Perceived IAQ in HPDs

The findings of the literature review clearly indicate a generally high level of satisfaction with the perceived IAQ in HPDs [47, 80, 86, 95-102].

In some of the studies, the perceived IAQ in HPDs is compared to the perceived IAQ in control buildings or the previous dwellings of the respondents. Such comparisons consistently suggest that perceived IAQ is improved in HPDs [47, 51, 80, 96, 98]. In a few studies, improved health is reported by the respondents [51, 96].

In several studies on HPDs, perception of dry air is reported [86, 96, 97, 103]. The perceived humidity levels appear to coincide with the measured low humidity levels during winter.

However, it should be noted that the perception of dry air does not necessarily reflect the actual humidity level, and the opposite is even observed in some studies. A Swedish study found a significant association between the perception of dry air and observed actual high humidity levels [104]. In [105], dwellings with and without MVHR were compared with regard to measured and perceived indoor air humidity. The measurements revealed no significant differences regarding measured humidity levels in naturally and mechanically ventilated buildings. Nevertheless, many occupants (40% of the respondents) in naturally ventilated buildings complained about moist air and, in contrast, many occupants (65% of the respondents) in dwellings with MVHR complained about dry air.

In climate chamber experiments by Andersen and Lundquist [106], “the humidity voting for the subjects varied widely and related poorly to the humidity conditions”. This misconception regarding air humidity is observed in several studies, and it is suggested that the perception of dry air is in fact not associated with physically dry air but rather with high temperatures and high pollutant levels due to low ventilation rates [93, 103].

Keul and Salzmann [103] found that perceived air humidity is influenced by measurements of actual air humidity. Occupants with access to hygrometers were significantly more discontent than occupants without access to hygrometers. This indicates a potential opportunity to increase occupant satisfaction with indoor air humidity using well-founded information regarding humidity levels and limit values.

When comparing HPDs to buildings from different construction periods [19], no clear trend of an increased complaint rate is observed. In [19], the highest complaint rate regarding indoor air humidity was found for buildings built in the period 1976 to 1985 [19]. Similar findings were reported in [104], in which a perception of dry air was associated with single-family houses built in the 1960s and 1970s.

2.5.3 Measured thermal conditions in HPDs

Regarding measured room temperatures in HPDs during the heating season, a general trend of higher room temperature levels in comparison to less-insulated buildings is observed [63, 86, 91, 101, 107, 108]. In some projects, mean room temperatures of up to 24°C during winter are observed [86, 107], which are substantially higher than the generally applied temperature level of ~20°C in indoor climate design and in energy simulations [109].

Regarding summer conditions, temperatures were measured in a range of HPDs and indicate no generally increased temperature levels in comparison to other building standards [47, 80, 86, 91, 95]. In [91], mean temperature levels between approximately 21 and 24°C were measured, and a temperature exceeded 27°C only in exceptional cases in some houses. In a study comparing passive house dwellings with low-energy dwellings [47], a lower overheating frequency was observed in the passive houses; in the passive house dwellings, 25°C was exceeded during 6.5% of the year, whereas this temperature was exceeded during 7.5% of the year in the low-energy dwellings. The reduced overheating was explained by the increased insulation level in the passive houses. It is, however, noted that solar shading and window ventilation are the dominant influential factors affecting thermal conditions during summer.

2.5.4 Perceived thermal comfort in HPDs

A generally high degree of satisfaction with thermal conditions during winter is reported in HPDs when evaluating the dwelling as a whole [47, 86, 96, 99, 100, 102]. Some complaints were identified and attributed to draughts from the ventilation outlets [95, 102], malfunction of the heating system [98], too-low temperatures in the bathroom [110], and too-high temperatures in the bedroom [96, 99].

The user feedback regarding thermal comfort in bathrooms and bedrooms indicates the potential for further improvement and calls for investigations of thermal comfort in the different rooms of dwellings.

A lower degree of satisfaction with thermal conditions during summer compared to winter is reported in several studies [47, 80, 100]. Nevertheless, in studies that compare passive house buildings with other building standards, no general aggravation regarding thermal comfort during summer in passive houses is observed. It is suggested that factors other than the energy standard – such as solar shading and window ventilation – predominantly determine thermal conditions during summer [47, 80].

3 Case study projects and applied research methods

This portion of the research was conducted using two residential HPD building projects in Norway as case studies. To assess the measureable indoor climate conditions, some dwellings in one case study were instrumented to measure indoor climate parameters as well as window opening durations. The evaluation of the perceived and desired indoor climate conditions as well as reported occupant behaviour was based on user surveys in both case studies. The evaluation of various MVHR solutions and control strategies for heating and ventilation was based on detailed dynamic simulations of one representative dwelling.

The case projects and applied methods are summarized in the following chapters.

3.1 Case study projects

3.1.1 The Løvåshagen cooperative

The Løvåshagen cooperative in Bergen, Norway was completed in 2008 and consists of 52 low-energy dwellings and 28 passive house dwellings according to the requirements in the preliminary version of the Norwegian standard NS 3700 [111].

A detailed description of the site, the building and the technical installation is provided in papers IV [112] and V [113].

3.1.2 Miljøbyen Granåsen

Miljøbyen Granåsen in Trondheim is an ECO city project, a demonstration project supported by the 6th framework programme of the CONCERTO Initiative launched by the EU. The first and second stages, with 17 detached houses and 45 terraced houses, were completed in 2012 in accordance with the requirements for passive houses in the Norwegian standard NS 3700 [111]. The survey was sent to the occupants of these two groups of buildings.

A detailed description of the site, the building and the technical installation is given in paper III [114].

3.2 User surveys

The questionnaires were developed based on a previous literature review of indoor climate surveys [15, 16, 98, 99, 115-117]. Regarding questions addressing the perception of indoor climate factors and related discomfort and symptoms, the Örebro-form [118] was considered to be suitable because a large database is available from earlier studies in Scandinavia, which can therefore facilitate a comparison [18, 19, 119]. The Örebro-form is explained in [15].

In addition to the standardized questions in the Örebro-form, questions addressing the perception and control of the thermal environment, specifically applicable to the investigated HPDs, were added.

In the Løvåshagen project, the link to the web-based questionnaire was sent by email in June 2012 to 86 occupants who had registered their email addresses with the board of the housing cooperative. The questionnaire was implemented and administered using the feedback platform Questback [120].

In the Granåsen project, the link to the web-based questionnaire was sent in May 2014 to 60 households using mailing addresses provided by the developer of the site. The questionnaire was developed in cooperation with Judith Thomsen at SINTEF Building and Infrastructure during the course of the EBLE research project (Evaluation of dwellings with low energy demand). The questionnaire was administered by Sentio Research Norge AS.

The questionnaire used in the Granåsen project was modified based on the findings from the survey in the Løvåshagen project, where different levels of satisfaction with the various rooms were suggested with regard to indoor climate conditions. Therefore, specific questions regarding the perceived indoor climate in the various rooms in the dwelling were added, which in the Örebro-form were only asked about the dwelling as a whole. In addition, questions from the Örebro-form regarding indoor climate-related symptoms were reduced to limit the questionnaire's length.

The content and analysis of the surveys are further described in papers III [114] and IV [112]. Copies of the questionnaires and accompanying letters are attached in the appendix.

3.3 Measurements

The measurement concept was developed and implemented in the Løvåshagen project based on guidelines given in [121]. Long-term measurements of indoor climate parameters and opening durations of windows and external doors were conducted in four apartments. In addition, the energy used for MVHR was measured to investigate the occupants' control of the supply air flow rate and temperature. In some of the apartments, the supply air flow rate in bedrooms was measured.

A detailed description of the monitored rooms, measured parameters, and measurement equipment is given in paper IV [112].

3.4 Simulations

Detailed whole-year and dynamic multi-zone simulations for a range of MVHR solutions and control strategies were performed for one representative dwelling in the Løvåshagen project. The simulation tool IDA Indoor Climate and Energy (IDA ICE) was used, which is a validated simulation software with several validation tests [122].

A detailed description of the investigated dwelling, simulated cases, and range of input values is given in paper V [113].

3.5 Limitations of applied methods

Due to the small sample size, the results of the user surveys have no statistical significance when comparing the case projects with other building standards. The findings do, however, indicate some important trends and give clear indications regarding the performance of the specific building concept and its MVHR solution, which is representative of new multifamily buildings in Norway. In addition, the results increase the explanatory power of additional surveys in future studies.

The room temperatures in the Granåsen project were reported by the occupants; some were based on stipulation and others on home thermometers. Therefore, the results have limited reliability and reported temperature levels should be verified by measurements in future studies.

The simulations were performed for one dwelling, but for different climatic conditions and a wide range of cases to increase the general applicability of the results. Nevertheless, the applicability of the findings and conclusion are limited to dwellings in multifamily buildings. Further studies are required to verify the applicability to other residential building types, such as single family houses.

4 Summary of main results

This summary of the main results is divided into three chapters to reflect the thematic focus of the research. The first chapter comprises findings from the initial overall evaluation of ICQ in HPDs. The second chapter presents and discusses the results regarding the thermal conditions in the various rooms in a dwelling. The third chapter focuses on findings regarding the thermal conditions in bedrooms specifically.

The summary is an excerpt of the research findings, which are presented in detail in the five published scientific papers.

4.1 Indoor climate quality in high-performance dwellings

The evaluation of ICQ in the investigated HPDs was based on a combined analysis of user feedback and measurements of indoor climate parameters as well as a comprehensive literature study of findings from other international studies.

The results of the conducted research support earlier findings from studies on HPDs, where generally high IAQ was observed with regard to both measured parameters and perceived IAQ. With regard to indoor humidity, the perception of “dry” air was reported and relatively low humidity levels were measured. Nevertheless, no indication of an aggravation in comparison to other building standards was found.

Regarding thermal comfort, a generally high degree of satisfaction was observed when looking at the dwelling as a whole. In line with the findings of other studies, an improvement compared to other building standards was observed.

However, when investigating thermal comfort in detail in the various rooms, both the user feedback from the case projects and the measured temperature levels in the Løvåshagen project clearly indicate that different temperatures in the various rooms are desired and that satisfaction with thermal conditions varies in the different rooms. These issues are specifically addressed in the next chapter.

A detailed presentation of the findings regarding the perceived indoor climate and occupant behaviour is provided in paper I [65] for the Løvåshagen project and in paper III [114] for the Granåsen project.

Paper II [123] focuses specifically on the suitability of air-heating from the occupants’ point of view; the findings in the Løvåshagen project were compared to the findings of other studies on HPDs across Europe in projects with various heating concepts.

The results of the measurements of indoor climate parameters and window opening durations in the Løvåshagen project are presented in paper IV [112] and contextualized in relation to the results from the user survey.

4.2 Thermal conditions in the various rooms in a dwelling

The results from the measurements and the user surveys demonstrate that temperature differentiation in the various rooms in a dwelling is occurring and is wanted.

The measured temperature levels in three apartments in the Løvåshagen project showed clear differences among living rooms, bedrooms and bathrooms (Figure 4).

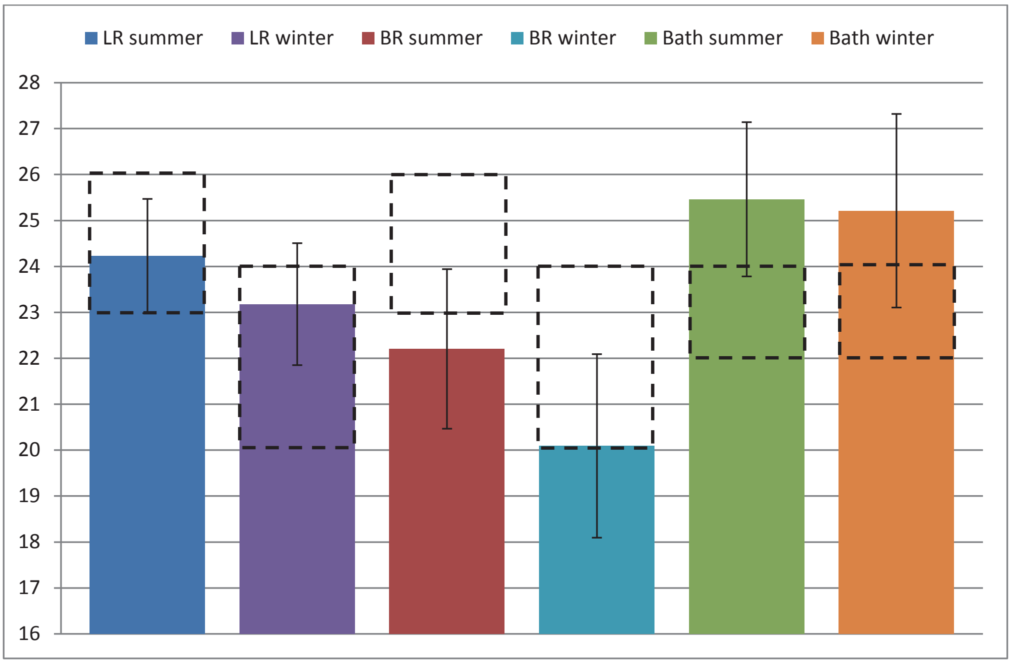

Figure 4 Mean seasonal temperatures in living rooms (LR), bedrooms (BR) and bathrooms (Bath) in three apartments in the Løvåshagen project with indications of the standard deviations for all hourly mean values. The dashed frames indicate the acceptable temperature ranges for category II in accordance with NS-EN 15251:2007+NA:2014 [4]

In the living rooms, a mean temperature of ~24°C during summer and ~23°C during winter was measured. For living rooms, the measured temperature levels comply with the requirements defined in NS-EN 15251:2007+NA:2014 [4], both when applying the adaptive approach for summer conditions and the acceptable temperature ranges for both summer and winter conditions.

In the bathrooms, a seasonal mean temperature of approximately ~25°C for both summer and winter was measured, which exceeds the upper acceptability limit of 24°C for category II as defined in NS-EN 15251:2007+NA:2014 [4].

In the bedrooms, mean temperatures of ~22°C during summer and ~20°C during winter were measured, which are considerably lower than the measured temperature levels in living rooms and bathrooms. These temperature levels fall below the lower acceptability limit given in NS-EN

15251:2007+NA:2014 [4] during summer and are at the limit during winter.

In the Granåsen project, the temperatures were not measured, but the respondents were asked to report typical temperature ranges during winter in the various rooms. The self-reported temperature levels support the findings from the measurements in the Løvåshagen project and strengthen the observed desire for temperature differentiation (Figure 5).

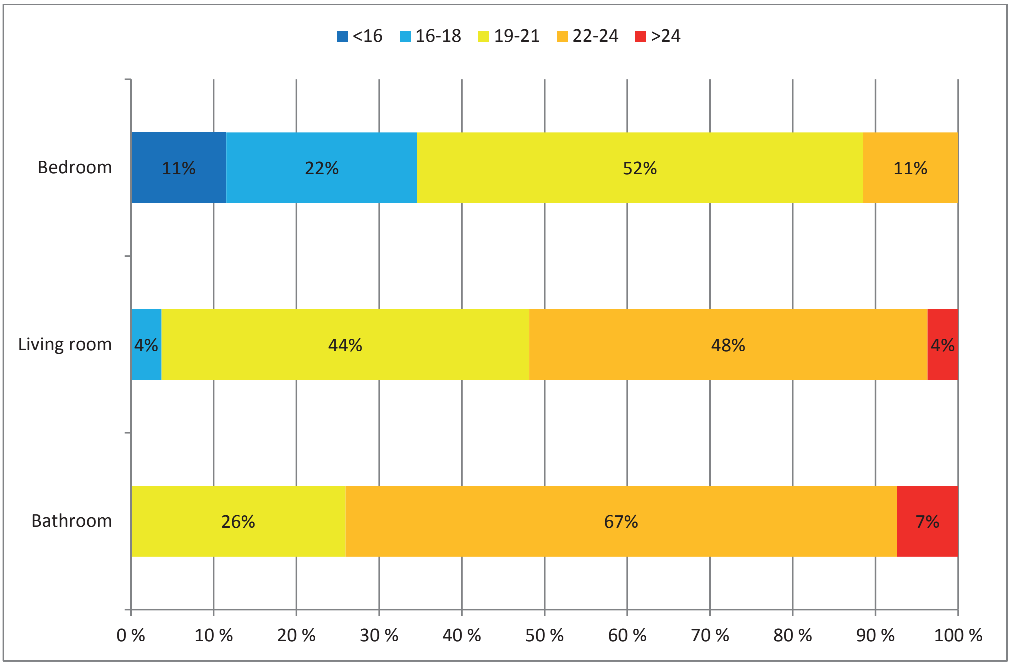

Figure 5 Distribution of self-reported typical temperatures during winter in the different rooms in the Granåsen project (n=28)

In addition to the observed temperature differentiation, a general temperature increase in living rooms and bathrooms in HPDs was observed, which is consistent with findings in HPDs in several other studies [86, 107, 124].

To test the compliance of the actual temperature levels with the desired temperature levels, the respondents in the Granåsen project were asked to assess their thermal conditions during winter. Regarding the living room and bathroom, 89% and 96% of the respondents (n=28), respectively, considered the thermal conditions appropriate.

In contrast, in the bedroom only 46% of the respondents (n=28) considered the thermal conditions appropriate, whereas 50% of the respondents considered the thermal conditions in the bedroom to be slightly warm or warm. The sensation of too-high temperatures in bedrooms was reported for a wide range of self-reported actual temperature levels (Figure 6).

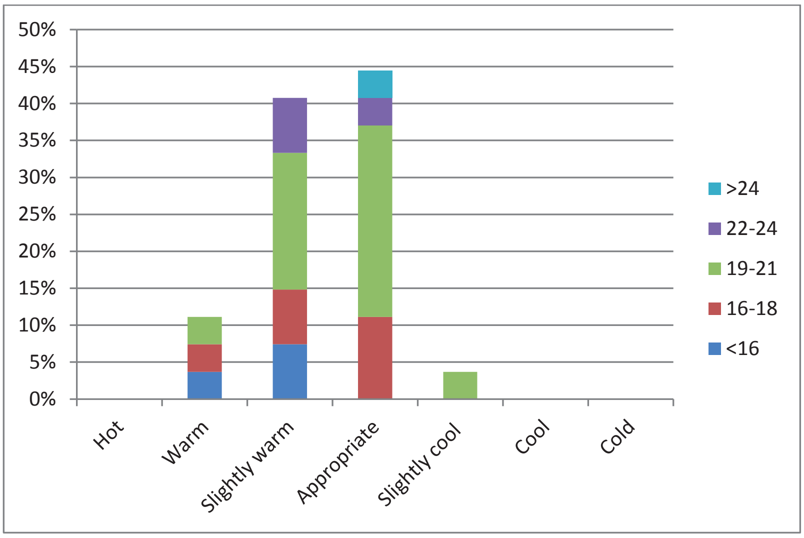

Figure 6 Distribution of reported thermal sensations during winter in the bedroom in the Granåsen project, with indication of reported temperatures (n=28)

The results indicate that the actual thermal conditions in the living room and bathroom are in accordance with the desired thermal conditions. In contrast, a clear discrepancy between actual and desired thermal conditions in bedrooms was observed. Therefore, a detailed investigation of the thermal conditions in bedrooms was conducted, comprising a detailed analysis of the measured thermal conditions and detailed whole-year simulations. The objective was to assess influential factors and to evaluate different MHVR solutions and control strategies. The results are summarized in the next chapter.

4.3 Thermal conditions in bedrooms

The results from the user surveys clearly indicate a lower degree of satisfaction with the thermal conditions and solutions for temperature control in bedrooms. The measured temperature levels demonstrate that the occupants generally keep a lower temperature in the bedroom than in other parts of the dwelling. Still, the measured temperature level appears to be higher than the preferred temperature level. The measurements and performed simulations demonstrate that the increased temperature levels in other parts of the dwelling and the use of a one-zone MVHR contribute to an increased heat supply to the bedroom.

This heat flow from neighbouring rooms and the MVHR counteracts the achievement of desired lower bedroom temperatures, and may explain the substantially longer durations of window opening in bedrooms in comparison to living rooms (Figure 7).

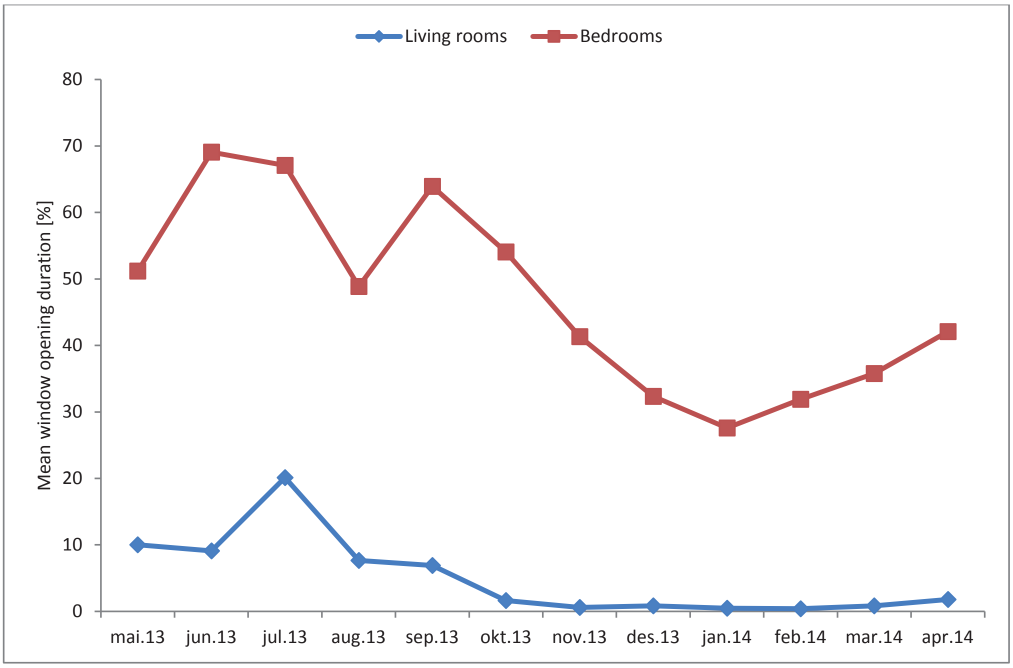

Figure 7 Measured monthly mean window opening durations in living rooms and bedrooms in three apartments in the Løvåshagen project

Based on user feedback, the main driver of window ventilation appears to be temperature control, not the need for an increased fresh air supply. These findings are consistent with findings from an earlier study in class rooms [125]. Both the measurements and the simulations regarding the thermal conditions in bedrooms indicate that the common one-zone MVHR solution, as used in both case projects, has its limitations regarding the achievement of desired thermal conditions in the bedroom. Even with substantial window ventilation during winter, the actual temperature levels appear to exceed the temperature levels desired by many occupants. Furthermore, the substantial window ventilation in bedrooms leads to an increase in space-heating demand.

Therefore, different MVHR solutions with a range of control strategies were investigated, using detailed dynamic simulations. The objective was to evaluate their suitability and limitations with regard to the thermal conditions in bedrooms and their impact on space-heating demand. For all cases, supplementary window ventilation in bedrooms is used for a range of set-point temperatures, corresponding to desired bedroom temperatures.

The results of the measurements and user surveys indicate that even if the heat-coil in the MVHR is switched off, the heat recovery alone may counteract the achievement of the desired temperature. Therefore, the alternative of a two-zone MVHR was investigated, where the supply air to bedrooms can bypass around the heat exchanger, and the supply air temperature is controlled using the desired bedroom temperatures as a set-point temperature (Figure 8).

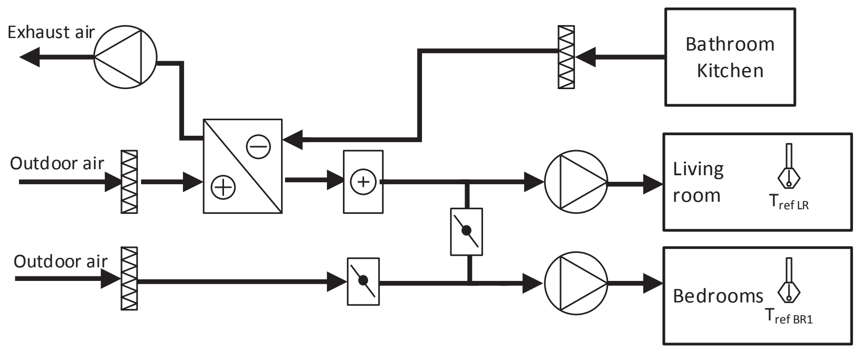

Figure 8 Schematic diagram of the alternative two-zone MVHR with reference temperatures in the living room and one bedroom

The results of the simulations for various set-point temperatures for window ventilation demonstrate the clear potential of a two-zone MVHR regarding the achievement of desired thermal conditions in bedrooms at the lowest energy cost. In Figure 9, the total space-heating demand as a function of the bedroom temperature is displayed for a one-zone MVHR with a constant supply air temperature and a two-zone MVHR with a demand controlled supply air temperature.

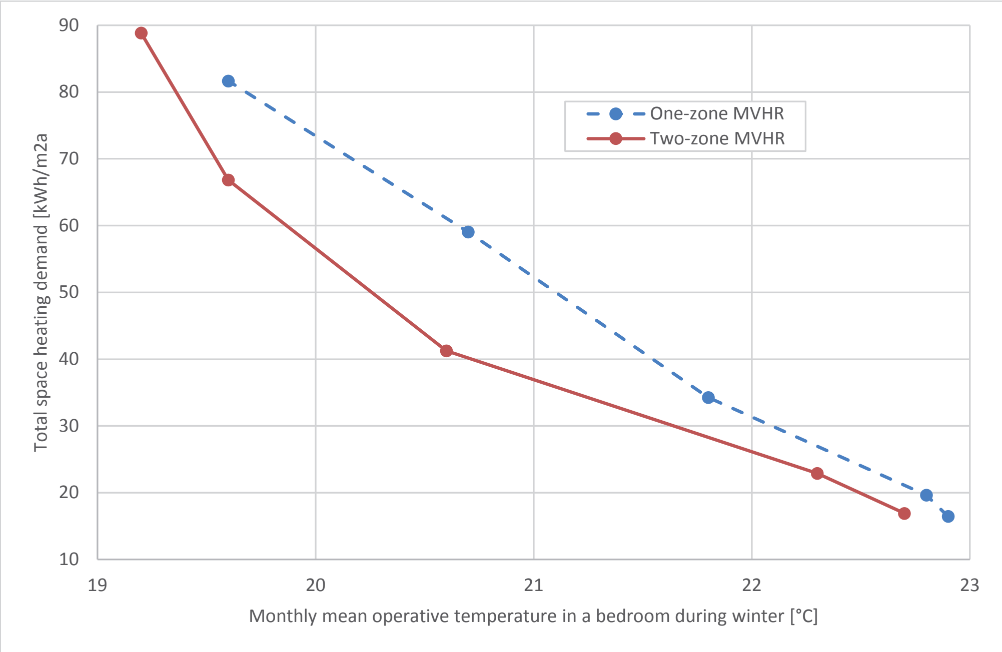

Figure 9 Total space-heating demand as a function of the operative temperature in a bedroom for a one-zone MVHR with a constant supply air temperature of 20°C and a two-zone MVHR with variable supply air temperatures using set-point temperatures in the living room and bedroom as a reference

The five points indicate the monthly mean operative temperatures for the different set-point temperatures for window ventilation at night in the bedroom. These temperatures are 17, 19, 21, 23 and 25°C. The resulting monthly mean operative temperatures range between ~19 and ~23°C.

In the cases presented, the interior walls were not insulated and the bedroom doors were kept closed at night only. Additional measures that can reduce the space-heating demand are to insulate interior walls surrounding bedrooms and to keep the bedroom doors closed all day.

The results of the simulations are presented in detail in paper V [113].

5 Conclusions

In the following section, the main findings of the study are presented. A response to the initially posed research questions is given and the achievement of the pursued objectives is described.

5.1 Main findings

The first objective was to assess the measured, perceived and desired indoor climate conditions in HPDs.

Regarding both perceived and measured IAQ, the results support findings from earlier studies and confirm the advantages of MVHR regarding the provision of fresh air. Consequently, the use of MVHR in dwellings is recommended.

Concerning thermal comfort, the findings indicate a generally high degree of satisfaction with the thermal conditions when looking at the dwelling as a whole. An improvement was observed compared to the thermal conditions in buildings constructed under older standards.

However, the detailed investigation of the thermal conditions in the various rooms in dwellings revealed clear differences regarding the agreement between desired and real thermal conditions.

A clear need for temperature zoning within the dwelling was observed. Regarding living rooms and bathrooms, the actual and desired indoor climate conditions appear to match quite well.

In bedrooms, however, the findings indicate a discrepancy between actual and desired thermal conditions. This mismatch is increased in HPDs in comparison to other building standards, first by elevated temperatures in other parts of the dwelling and second by the use of a one-zone MVHR.

The second objective was to evaluate the extent and driving forces of occupants' heating and ventilation habits in HPDs and their impact on ICQ and space-heating demand.

A general increase in temperature levels in HPDs was observed. The increased temperatures in the living room and bathroom appear to be desired by the occupants, but this increases the heat loss and space-heating demand.

In bedrooms, extensive window ventilation during the heating season was observed. The main driving force was found to be the desire to cool down the bedroom, which leads to a substantial increase in space-heating demand.

In the bathrooms, the occupants reported that the floor heating is used to supply heat all year round, presumably because floor tiles are perceived as cold on bare feet even during summer. The high temperature levels in the bathroom and this continuous heating certainly has an impact on the space-heating demand. In addition, floor heating during summer contributes to the risk of overheating the dwelling.

The third objective was to investigate the potential for improved solutions for ventilation and heating in HPDs.

A shortcoming of the commonly used one-zone MVHR was detected with regard to the provision of desired thermal conditions in bedrooms. A potential of a two-zone MVHR was observed, in which the thermal conditions are improved and the space-heating demand is reduced.

In response to the initially posed research questions, it can be concluded that HPDs generally perform well with regard to the provision of desired indoor climate conditions in living rooms and bathrooms. Regarding bedrooms, HPDs need to be improved to provide desired thermal conditions. Regarding the performance of the technical solution for heating and ventilation in HPDs, the commonly used one-zone MVHR in principle performs well for living rooms and bathrooms, but leads to a waste of energy due to window ventilation in bedrooms during winter.

Based on these findings, some practical implications and suggestions for future work are outlined to improve ICQ and to reduce the energy used for space-heating.

5.2 Implications for heating and ventilation strategies

To achieve desired bedroom temperatures, the implementation of a two-zone MVHR is recommended, in which the bedroom's supply air temperature is controlled independently from the supply air temperature to other parts of the dwelling.

The supply air temperature to the rooms should be controlled using the set-point temperature of the room as a reference to adjust the heat supply to the current heating or cooling demand. A constant supply air temperature, based on the set-point temperature of the supply air, is unsuitable for achievement of the desired thermal conditions.

For bathrooms, intermittent heating should be applied. The heat supply should be adapted to actual thermal comfort needs and user profiles.

5.3 Implications for building design and construction

Interior walls, which enclose bedrooms, should be insulated to reduce the heat flow from neighbouring rooms.

For bathrooms, the use of warmer floor materials should be considered to reduce the need for heat supply for local thermal comfort reasons only.

The building design, layout and orientation also influence the heat flow within a dwelling, which should be considered to facilitate temperature zoning in dwellings.

5.4 Implications for user information

The results of the user surveys indicate a need for increased knowledge and awareness regarding control of the indoor climate.

Appropriate information should be provided to the occupants of HPDs regarding the control of the indoor climate. The impact of habits (such as the opening of windows and interior doors) on indoor climate conditions, including humidity level and energy use, should be described.

5.5 Policy implications

The acceptability limits for room temperatures in current standards and regulations, such as EN 15251 [4] and ASHRAE Standard 55 [14], should be reconsidered to better accommodate comfortable temperatures in bathrooms and bedrooms. Particularly for bedrooms, the given acceptability limits do not reflect the desired temperature levels.

Current standards only set upper and lower acceptability limits. The implementation of additional standards regarding the controllability of bedroom temperatures to facilitate the provision of desired lower bedroom temperatures should be considered.

5.6 Implications for occupant surveys

In the assessment of perceived ICQ in dwellings, the questionnaires should distinguish between living rooms, bathrooms and bedrooms. Particularly with regard to perceived thermal conditions, current assessment methods, such as those defined in the Örebro model [15] or the ANSI/ASHRAE standard 55 [14], do not account for clear dissimilarities regarding the desired thermal conditions in the various rooms in dwellings.

5.7 Suggestions for future work

Further studies on a larger sample of occupants in different climatic regions should be performed to assess desired temperatures in bedrooms. Based on desired temperatures and feasible temperature ranges in the different climatic conditions, acceptable temperature ranges could be defined.

There is also a lack of research regarding the impact of bedroom temperature on sleep quality, health and performance.

The suggested two-zone MVHR should be further elaborated, taking demand controlled flow rates into account to exploit additional energy saving potential. In addition, the potential of separately ventilated zones without overflow from bedrooms should be further explored with regard to impact on ICQ and heating demand.

The observed elevated indoor temperature level in HPDs may have adverse effects on IAQ, such as extremely low relative humidity levels and increased emissions from materials, which should be further investigated.

It should be explored whether discomfort is wrongly blamed on the humidity level or is in fact caused by actual low humidity levels. One possible approach would be to compare different groups of respondents that are given different information regarding the level and impact of indoor humidity.

The potential for behavioural changes and their impact on ICQ and energy use through increased knowledge and awareness should be further explored.

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7 Appendices

Appendix 1: Paper I: M. Berge and H. M. Mathisen (2013). *Post-Occupancy Evaluation of Low-Energy and Passive House Apartments in the Løvåshagen Cooperative, Occupant Behavior and Satisfaction*. Passivhus Norden. Gothenburg

Appendix 2: Paper II: M. Berge and H. M. Mathisen (2015). *The suitability of air-heating in residential passive house buildings from the occupants' point of view – a review*. Advances in Building Energy Research, 9(2): 175-189.

Appendix 3: Paper III: M. Berge, J. Thomsen and H. M. Mathisen (2016). *The need for temperature zoning in high-performance residential buildings*. Journal of Housing and the Built Environment: 1-20.

Appendix 4: Paper IV: M. Berge and H. M. Mathisen (2016). *Perceived and measured indoor climate conditions in high-performance residential buildings*. Energy and Buildings, 127: 1057-1073

Appendix 5: Paper V: M. Berge, L. Georges and H. M. Mathisen (2016). *On the oversupply of heat during winter to bedrooms in highly insulated dwellings with heat recovery ventilation*. Building and Environment, 106: 389-401

Appendix 6: Questionnaire Løvåshagen (in Norwegian)

Appendix 7: Questionnaire Granåsen (in Norwegian)

Appendix 1

Paper I

M. Berge and H. M. Mathisen (2013). *Post-Occupancy Evaluation of Low-Energy and Passive House Apartments in the Løvåshagen Cooperative*, Occupant Behavior and Satisfaction. Passivhus Norden. Gothenburg

Post-Occupancy Evaluation of Low-Energy and Passive House Apartments in the Løvåshagen Cooperative — Occupant Behavior and Satisfaction

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Abstract

Experience with low-energy and passive house buildings forms the basis for the further development of zero-emission buildings. A post-occupancy evaluation of the Løvåshagen cooperative is therefore conducted by means of user surveys and measurement of indoor climate parameters, energy use and window opening time.

The goal of the post-occupancy evaluation is to obtain information about how occupants use and experience low-energy and passive house dwellings, especially with regard to heating and ventilation. In addition, the impact of user behavior on the indoor climate and energy use will be assessed.

In this paper, the results of the user survey regarding user habits and occupant satisfaction are presented.

The results show that low-energy and passive house apartments are used in ways that have a substantial impact on the indoor climate and energy use. The assessed extent of window ventilation and use of floor heating throughout the year around definitely increase energy use substantially and therefore partially explain the difference between the calculated and measured energy use. This difference will be quantified by measurements and parametric simulation in the continuation of the study.

Most respondents are satisfied or very satisfied with living in a low-energy or passive house dwelling. Nevertheless, a clear need for improvement with respect to heating and ventilation systems is detected.

It can be concluded that increased attention to the interaction between the occupant, the building design and the technical installation is needed in the development of zero-emission buildings.

Keywords: indoor climate, energy use, post occupancy evaluation, occupant behavior, occupant satisfaction

Introduction

Experience with low-energy and passive house buildings forms the basis for the development of zero-emission buildings. It is therefore essential to conduct post-occupancy evaluations of existing low-energy and passive house buildings to see how they perform in practice, how they are used and, last but not least, how they are experienced by the occupants.

As part of the activities in *The Research Centre on Zero Emission Buildings* (ZEB), a post-occupancy evaluation (POE) of the Løvåshagen cooperative in Bergen, Norway is conducted. The objective of the ongoing evaluation is to obtain a deeper understanding of how the occupants use and experience low-energy and passive house buildings, especially with regard to heating and ventilation. In addition, the evaluation will provide insight into how occupant behavior influences the indoor climate and energy use.

The Løvåshagen cooperative in Bergen is a pilot project designed according to criteria established by Enova[1] and completed in 2008. The cooperative consists of 52 low-energy apartments and 28 passive house apartments.

Figure 1 Illustration of Løvåshagen cooperative [ByBo AS 2009], showing low-energy apartments in the blocks to the left and back and passive house apartments in the two blocks in front with solar thermal collectors on the roof.

[1] **Enova is a public enterprise owned by the Ministry of Petroleum and Energy that was established in 2001 to promote more environmentally friendly consumption and generation of energy in Norway.**

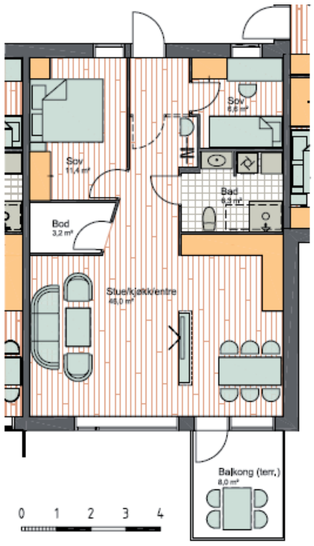

Figure 2 Typical apartment floor plan [ByBo AS 2009]

Each apartment is accessed via a gallery on the east or northeast side. The kitchens and living/dining rooms are oriented toward the west/southwest, whereas the bedrooms are mainly oriented towards the east/northeast. A floor plan of a typical apartment is shown in Figure 2.

The heating system in the passive house apartments consists of hydronic floor heating in the bathrooms and one radiator in the living room area. Each passive house apartment has a 200-liter water tank with a heat exchanger coil for the solar thermal collector. The ventilation unit is equipped with an electric heater battery that is used to increase the supply air temperature for thermal comfort reasons. Thus, the use of a traditional heating system separated from the ventilation system deviates from the original concept of passive house design, wherein the basic idea is to supply heat by post-heating the supply air and dispensing with a traditional heating system. The evaluation will therefore shed light on the occupants' experiences with the Norwegian adaptation of the passive house concept.

Balanced ventilation units with heat recovery of type Flexit SL4 R are installed in each apartment. The units are placed above the ceiling in the bathroom. Exhaust vents are placed in the bathroom and kitchen. Inlet vents are placed above the doors to the living room and bedrooms. In addition, there is a kitchen hood where the exhaust bypasses the heat exchanger.

The volume and temperature of the inlet air are controlled via a display in the living room area. There are three positions for air volume and six positions for post-heating of the inlet air.

The space heating demand for the passive house apartments is calculated to be 12.8 kWh/m^{2}a [Dokka and Helland 2008]. The total heat demand, including domestic hot water, is calculated to be 42 kWh/m^{2}a [Dokka, et al. 2010]. The solar thermal collector is estimated to provide 22.6 kWh/m^{2}a or 47 % of the total heat demand. The total delivered energy demand (electricity) is calculated to be 74 kWh/m^{2}a [Enova SF 2008].

In the low-energy apartments, the heating system is based on electricity, comprising floor heating in the bathrooms and one electric stove in the living room area. The total delivered energy demand (electricity) is calculated to be 101 kWh/m^{2}a [Enova SF 2008].

Based on measurements by the electricity supplier [BKK 2013], the median[2] of the measured total temperature-corrected delivered energy (electricity) for the passive house apartments in 2011 and 2012 was 126 KWh/m^{2}a. The calculated demand for delivered energy is exceeded by approximately 70 %.

[2] The median value is used to describe the central tendency of the distribution of delivered energy to reduce the influence of extreme values because some apartments are unoccupied and at least one apartment is used as a home office.

The median of the measured total temperature-corrected delivered energy (electricity) for the low-energy apartments in 2011 and 2012 was 126.5 KWh/m^2a. The calculated demand for delivered energy is exceeded by approximately 25 %.

Thus, the measured energy use exceeds the calculated energy use considerably for both the low-energy apartments and the passive house apartments. Surprisingly, the median of the measured energy use is basically the same for the low-energy apartments and the passive house apartments. This constitutes a major deviation from the expectation of lower energy use in the passive house apartments due to increased insulation and energy supplied by solar thermal collectors.

In the ongoing study, the causes for the deviation between the calculated and measured energy use will be identified and evaluated by means of user surveys and long-term measurements of energy use, indoor climate parameters and window opening time. The focus of the evaluation will be on user habits and the interaction between the occupant, the building and the technical installation.

Regarding user habits, which strongly influence the indoor climate as well as energy use, the following parameters are identified in user surveys and measurements: indoor air temperature, window opening time, use and maintenance of the ventilation system, purchase and use of electrical equipment and lightening, use of hot water and the choice and use of solar shading.

In this paper, the results of the user survey regarding user habits and satisfaction are presented.

In the continuation of the study, the impact of behavioral factors on indoor climate quality and energy use will be quantified by means of long-term measurements and parametric simulations. In addition, measured indoor climate parameters will be compared with occupant feedback. The results will form the basis for characterizing the potential for behavioral change on the one hand and the need for further development and adaptation of the buildings and the technical installation to the needs of the occupants on the other hand.

Methods

Occupant Survey

An occupant survey was conducted using a net-based questionnaire. The link to the questionnaire was sent by email to all occupants that had their email addresses registered at the board of the housing cooperative.

Of the 86 occupants to whom the questionnaire was sent, 34 responded. Of these 34, 14 lived in passive house apartments and 20 lived in low-energy apartments.

The questionnaire consisted of two parts. The first part consisted of questions based on the standardized MM form of the Örebro Model [Andersson, et al. 1988], which is used to map perceptions, complaints and symptoms related to the indoor climate. The second part consisted of questions regarding user behavior and occupant satisfaction, especially with regard to the heating and ventilation system.

Measurements

A measurement concept is implemented to facilitate the analysis of the interactions between occupant behavior, indoor climate and energy use. The long-term measurements will provide data regarding energy use, energy contribution of the solar thermal collector, indoor climate parameters (room air temperature, relative humidity and CO_2) and window opening time. In addition, measurements of the ventilation air volume and the radiant and operative temperature are conducted.

The measurement concept is implemented in two low-energy apartments and three passive house apartments, selected to represent low, average and high energy use.

Simulations

In the continuation of the study, parametric simulations of the indoor climate and energy use will be conducted for the apartments in which measurements are carried out. The simulations will be used to quantify the impact of the occupants' behavior on the indoor climate and energy use.

Results and discussion

In the following sections, the results of the occupant survey related to occupant behavior and satisfaction are presented. The results pertain to one housing project and therefore do not necessarily represent the general performance of low-energy and passive house buildings. Nevertheless, the results provide indications of tendencies, possible problems and potential improvements.

Window opening habits

The following figure shows the percentage of respondents that stated that they have the window in the bedroom open or tilted 8, 16 or 24 hours per day during the different seasons of the year.

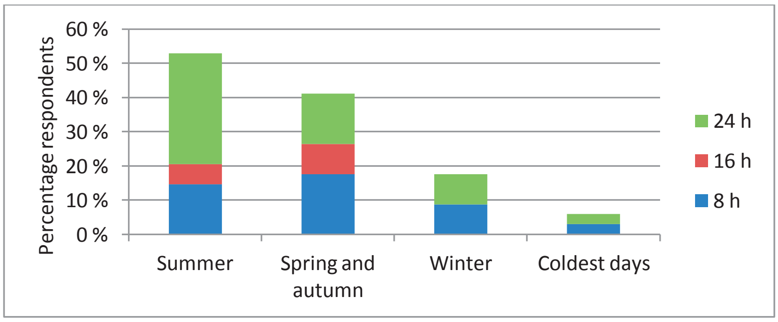

Figure 3 Percentage of respondents that stated that they have the window in the bedroom open or tilted 8, 16 or 24 hours per day

In the table below, the reasons for keeping the window open or closed are stated.

Table 1 Reasons for keeping the window open or closed

Reasons for keeping the window **closed**:	Reasons for keeping the window **open**:
Noise from outside (17 answers) Cold air from outside (11 answers) Dust/pollen from outside (2 answers) The ventilation system gives sufficient fresh air (12 answers) Reduction of heat loss/energy costs (6 answers)	Force of habit (3 answers) The ventilation system does not give sufficient fresh air (9 answers) Need for cooler air (2 answers)

The results show that the outdoor air temperatures during the different seasons of the year strongly influence the occupants regarding window opening time. At low outdoor air temperatures, the extent of window opening is considerably reduced. In the winter, more than 80 % of the respondents have the window open less than 8 hours per day, meaning that they most likely sleep with closed windows.

Approximately 40 % of the respondents open the window 8 hours or more per day during the spring and fall, which is expected to increase the heating energy use considerably.

There is a clear relation between outdoor air temperatures and window opening time for most occupants, even if there is a large variance. The majority of the respondents say that they keep the window closed to avoid annoyance by noise or cold air from outside. Thus, they rely on the ventilation system and consider it an advantage that they do not need to open windows to obtain fresh air.

Some respondents perceive the ventilation air volume supplied to be insufficient and therefore open the window. The ongoing measurements of the supply fresh air volume and CO_2 levels will be used to evaluate if the complaints concerning the perceived indoor air quality can be confirmed by deviations of measured from required values.

Heating habits in the bathroom

Regarding heating habits in the bathroom, 77 % of the respondents state that the floor heating is turned on all year, not only during the heating season.

Thirty-five percent of the respondents that stated that the floor heating is on all year would accept another floor material that would feel warmer, e.g., vinyl or water-resistant parquet, to reduce or even eliminate the need for floor heating solely for local comfort reasons. This reveals a potential for an optimized and integrated design solution for bathrooms.

For decades, nearly all bathrooms in Norway have been equipped with floor heating. The use of tiles has increased the need for floor heating for local comfort reasons. It has, in a way, become an indispensable user demand in Norway that bathrooms have to be equipped with tiles and floor heating. This also leads to a heat demand based on local thermal comfort reasons in periods during which there actually is no need for heating with regard to comfort for the whole body. The need for heating for the feet can even lead to a need for room air cooling, which typically is accomplished by opening the window. In low-energy and passive house buildings, the heating period is intended to be much shorter than in traditional buildings. Consequently, the supply of heat outside the heating season will increase the deviation between the calculated heat demand and the heat supply in low-energy and passive house buildings. The impact on energy use will be quantified in the further long-term evaluation.

In other countries, where floor heating is less common, the heat supply in bathroom is also based on the room air temperature demand. For passive houses with centralized air-based heating systems, a supplementary local heat source is usually used in bathrooms to facilitate a higher room air temperature than in other parts of the building. Feist, et al. [2004] recommend the use of local heat sources with fast response times, such as radiators, radiant heaters or convection heaters. Another recommended possibility is to make use of the heat losses from the heating system by placing non-insulated supply ventilation ducts over the ceilings in bathrooms. According to Feist, et al. [2004], a time-controlled supplementary local heat source will produce a negligible increase in energy use because heat losses from a warmer bathroom will reduce the heating demand in other parts of the building. This might even justify the use of electric heating for local supplementary heaters, provided that the central air heating system is based on an environmentally friendly energy source [Feist 2004]. Measurements in the passive house project Stuttgart Feuerbach revealed that supplementary direct electric heating increased energy use by just 0.5 kWh/m^{2}a [Feist 2004].

Consciousness of energy use

The user survey contained a question concerning how conscious the occupant is of issues that influence energy use. The three possible answers were “Not conscious,” “Somewhat conscious” and “Very conscious.” The figure below shows the answers with respect to the different issues.

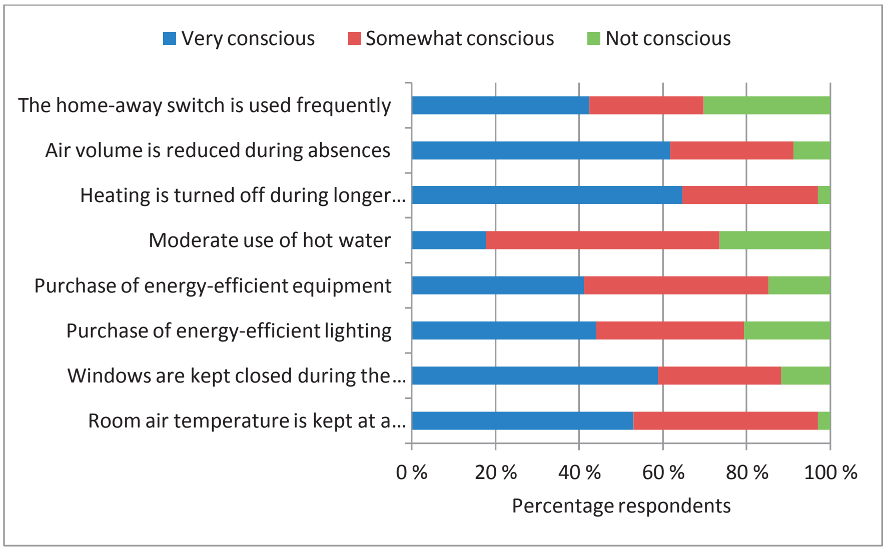

Figure 4 Consciousness of occupants regarding issues that have an influence on energy use Comment on the home–away switch: A switch is placed next to the entrance door, where the occupants can switch off circuits for all lighting and some wall outlets.

The results show that about half of the respondents consider themselves to be very conscious about all issues except the use of hot water, of which only 20 % consider themselves to be very conscious. Almost all the respondents are at least somewhat conscious of issues that influence energy use.

Approximately 80 % of the respondents state that they would like to learn more about indoor climate and energy use, preferably from a short flyer or on a website. This indicates a potential for behavioral change by means of information that leads to increased awareness of issues related to indoor climate and energy use.

Summer overheating

In all of the passive house apartments and some of the low-energy apartments, the living room and kitchen are oriented toward the west. In the rest of the low-energy apartments, the living room and kitchen are oriented toward the southwest. All of the apartments have relatively large window areas and therefore are exposed to unwanted solar gains during the summer. Apartments oriented toward the west are especially prone to overheating due to the low solar angle in the afternoon.

No solar shading was installed by the project developer, but an opening in the facade for the mounting of exterior shading was provided. Exterior shading has been installed by 18 % of the respondents, and 70 % of the respondents use interior shading, such as curtains or blinds. Twelve percent of the respondents state that they have no shading at all.

The figure below shows the proportions of the respondents who stated that they were never, sometimes or often are bothered by overheating during the three months preceding the survey. The figure also shows the distribution of installed solar shading.

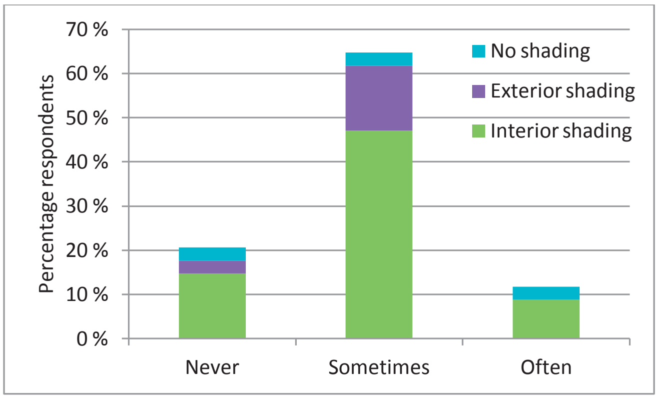

Figure 5 Percentage of respondents that stated that they never, sometimes or often were bothered by overheating in the 3 months preceding the evaluation

All the respondents that stated that they were often bothered by overheating (4 respondents) live in passive house apartments oriented toward the west.

Despite a quite high percentage of respondents that reported that they are sometimes bothered by overheating, there is a generally high level of satisfaction with the room temperatures, which 77 % of the respondents consider to be good or very good.

In the continuation of the study, the relationship between perceived thermal comfort and measured indoor climate parameters will be evaluated.

Satisfaction with the heating system

Despite a generally high level of satisfaction regarding the room temperatures, there are clear differences in the satisfaction with the heating systems in the different rooms.

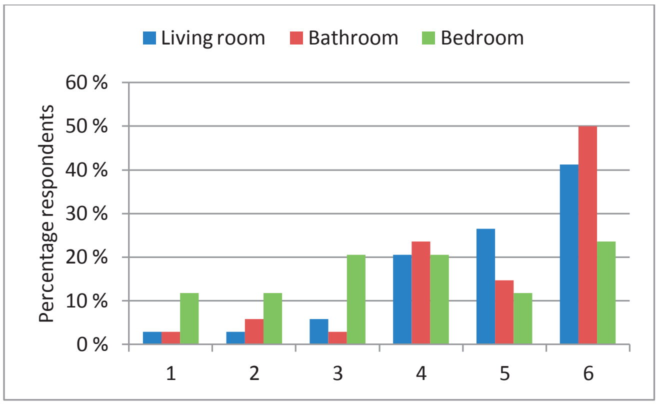

Figure 6 Satisfaction with the heating system in the different rooms on a scale from 1 to 6, where 1 is "very dissatisfied" and 6 is "very satisfied"

There is a high level of satisfaction with the heating system in the living room area and the bathroom, whereas quite a high percentage of respondents are less satisfied with the heating system in the bedroom.

The dominant reason for discontent with the heating system in the living room area and the bathroom is the difficulty of adjusting the temperature.

The following causes are specified regarding the discontent with the heating system in the bedroom:

- Difficulty of adjusting the temperature (4 answers)
- Lack of a local heat source (2 answers)
- The inlet air should be cooler (10 answers)

Thus, the dominant reason for discontent with the heating system in the bedroom is that the inlet air is perceived to be too warm. As mentioned earlier, there is generally a high level of satisfaction with the temperature conditions in the apartment, and only a few respondents states that they open the window to cool down the sleeping room. This indicates that the occupants have adapted to the concept of fresh air supply through a ventilation system but nevertheless would prefer cooler air in the bedroom.

It is obviously a waste of energy to heat a bedroom when actually a cooler bedroom is desired, especially if it leads to supplementary window ventilation. One technical solution for this issue would be to bypass the supply air to the bedrooms around the heater battery after the heat exchanger. This would, however, necessitate a local supplementary heat source in case of a higher temperature being desired at times, e.g., when the bedroom is used as a children's room in the daytime. As mentioned earlier, studies show a negligible increase in energy use by supplementary local heat sources, and therefore, even the installation of simple electric heaters could be justified [Feist 2004].

Satisfaction with the ventilation system

The figure below shows the stated satisfaction with the ventilation system on a scale from 1 to 6, where 1 is "very dissatisfied" and 6 is "very satisfied." Eighty percent of the responses are on the upper half of the scale, and 62 % of the respondents state that they are "satisfied" or "very satisfied."

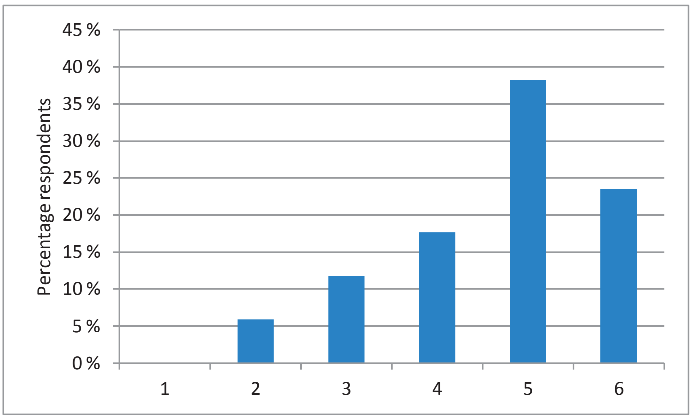

Figure 7 Satisfaction with the ventilation system on a scale from 1 to 6, where 1 is “very dissatisfied” and 6 is “very satisfied”

The reasons for discontent are the following: noise (1 answer), perception of dry air (2 answers), too little fresh air (2 answers), difficulty of controlling the air volume/temperature (1 answer) and difficulty of changing the filter (2 answers).

The respondents were asked to assess the degree of difficulty of the initial use of the ventilation on a scale from 1 to 6, where 1 is “very difficult” and 6 is “very easy.” No one considered the initial use to be “very difficult.” However, the answers were evenly distributed from “difficult” to “very easy,” which indicates that there is potential for improvement regarding the user-friendliness of and/or instructions for the use and maintenance of the ventilation system.

Regarding control of air volume, approximately 50 % of the respondents state that the air volume is controlled according to the current demand, and 33 % state that the air volume is usually set to level II.

Regarding post-heating of the air, 24 % of the respondents state that the temperature level is always set to level I or II, i.e., the lowest levels. Sixty-seven percent of the respondents state that the temperature is controlled according to the current demand. One respondent does not know how to control the temperature.

In the further evaluation, the relationship between the use of the ventilation system and window opening habits will be analyzed. In addition, the impact on the indoor climate and energy use will be quantified.

Satisfaction with indoor air quality

The figure below show the responses regarding satisfaction with the indoor air quality, which 76 % of the respondents consider to be “good” or “very good.”

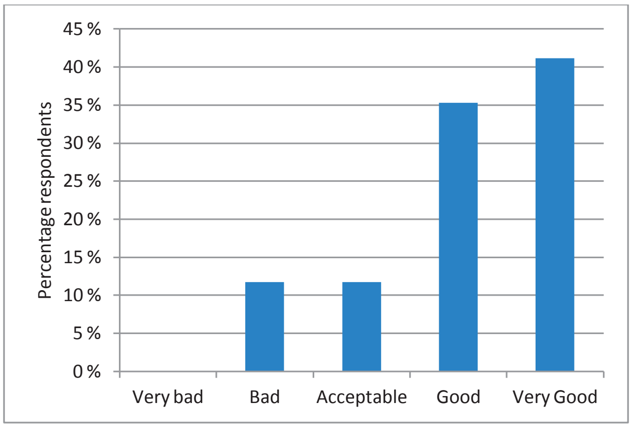

Figure 8 Assessment of perceived indoor air quality

The following reasons for discontent are specified: air feels sticky (3 answers), smell from cooking spreads within the apartment (1 answer), tobacco smoke or other odor from other apartments (1 answer) and little ability to control the ventilation (1 answer).

In the further evaluation, the perceived indoor air quality will be compared with the measured indoor air quality.

Changes in indoor climate-related symptoms

The respondents were asked to rate to what degree they have noticed change in indoor climate-related symptoms after moving to the Løvåshagen cooperative.

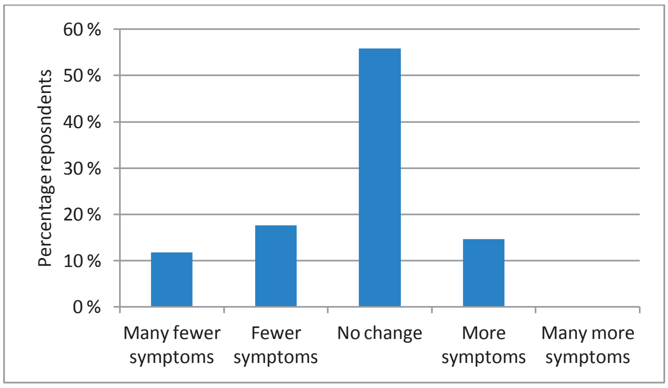

Figure 9 Change in indoor climate-related symptoms

Most of the respondents stated that they have not noticed any change in indoor climate-related symptoms. Approximately 30 % of the respondents stated that they now have fewer or even many fewer symptoms. Some respondents state that they now have more symptoms.

Additional results from the user survey regarding the indoor climate and its impact on health and comparisons with other studies are published in[Klinski, et al. 2012].

General satisfaction with living in a low-energy or passive house dwelling

The figure below shows the general satisfaction with living in a low-energy or passive house dwelling on a scale from 1 to 6, where 1 is “very dissatisfied” and 6 is “very satisfied.”

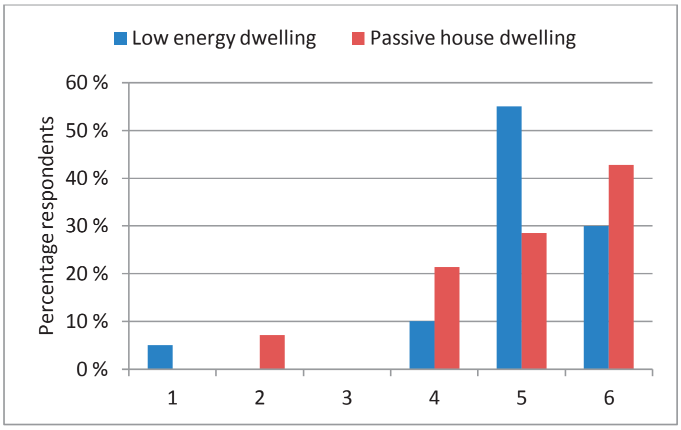

Figure 10 General satisfaction on a scale from 1 to 6, where 1 is “very dissatisfied” and 6 is “very satisfied”

The results show a generally high level of satisfaction: 85 % of the respondents living in low-energy apartments and 72 % of the respondents living in passive house apartments are satisfied or very satisfied.

A few respondents are dissatisfied or even very dissatisfied and indicate that their expectations concerning energy use, thermal comfort and indoor air quality are not met.

Conclusions

The results from a user survey concerning user habits show that low-energy and passive house apartments are used in ways that have a substantial impact on the indoor climate and energy use. The assessed extent of window ventilation and use of floor heating throughout the year definitely increase energy use substantially and therefore partially explain the difference between the calculated and measured energy use. This difference will be quantified by measurements and parametric simulation in the continuation of the study.

The clearly dominant specified reason for window ventilation is that the ventilation is perceived to not provide enough fresh air. The ongoing measurements of indoor climate parameters and air volume will be used to evaluate whether the discontent with the indoor climate can be confirmed by measured values.

Even if there is a generally high level of satisfaction with the thermal conditions in the dwellings, many respondents would prefer cooler bedrooms. Thus, solutions for temperature differentiation within dwellings should be considered and further developed.

The results indicate that window ventilation use is not due to the force of habit but rather a real need to change the perceived indoor climate, either with regard to thermal comfort or air quality. Thus, a crucial precondition for a reduction or elimination of window ventilation during the heating season is the faultless performance of the heating and ventilation system in providing satisfying thermal comfort and indoor air quality.

Nearly 80 % of the respondents stated that the floor heating is on all year, which obviously has a substantial impact on energy use. Because the intended heating season in low-energy and passive house dwellings is considerably shorter than in traditional dwellings, continuous heating in low-energy or passive house dwellings will increase the difference between heat demand and supply. This indicates a need for the implementation and further development of local heating solutions for bathrooms, where the interactions between the material use, the heating system and the occupant are taken into account to a greater extent.

Regarding summer overheating, only respondents living in passive house apartments oriented toward the west reported that they were often bothered by overheating. No respondents living in apartments with exterior shading reported that they were often bothered by overheating.

Most respondents are satisfied with the ventilation system. Nevertheless, the results indicate a potential for further improvement regarding user-friendliness and instructions for use and maintenance of the ventilation system.

Most respondents are satisfied or very satisfied with living in a low-energy or passive house dwelling. Nevertheless, a clear need for improvement is detected with respect to the heating and ventilation systems.

It can be concluded that increased attention to the interactions between the occupant, the building design and the technical installation is needed in the further development of zero-emission buildings.

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Appendix 2

Paper II

M. Berge and H. M. Mathisen (2015). *The suitability of air-heating in residential passive house buildings from the occupants' point of view – a review*. Advances in Building Energy Research, 9(2): 175-189.

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Appendix 3

Paper III

M. Berge, J. Thomsen and H. M. Mathisen (2016). *The need for temperature zoning in high-performance residential buildings*. Journal of Housing and the Built Environment: 1-20.

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Appendix 4

Paper IV

M. Berge and H. M. Mathisen (2016). *Perceived and measured indoor climate conditions in high-performance residential buildings*. Energy and Buildings, 127: 1057-1073

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Perceived and measured indoor climate conditions in high-performance residential buildings

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ABSTRACT

The implementation of mechanical ventilation systems with heat recovery (MVHR) in new high-performance residential buildings constitutes a fundamental change from traditional heating and ventilation strategies. A MVHR with one ventilation zone, which is commonly used in new residential buildings, will supply approximately the same temperature to all rooms and consequently contribute to balancing the room temperatures within the dwelling.

This change affects air change rates, the air distribution between rooms and temperatures, and consequently calls for an evaluation of the impact on the perceived and actual indoor climate and of to what degree the desired indoor climate conditions are provided. Therefore, a post-occupancy evaluation (POE), consisting of a user survey and long-term measurements, is performed for a high-performance residential project in Norway.

The results support earlier findings that indicated an improved indoor climate in high-performance residential buildings with MVHR compared with other building standards.

However, the findings clearly demonstrate a need for temperature zoning in residential buildings. The preferred lower bedroom temperatures appear to be difficult to achieve in common high-performance building concepts with MVHR. An important factor that influences bedroom temperatures was found to be the control strategy for the supply air temperature, where a potential for improvement was observed.

1. Introduction

Major changes in the indoor environment have been observed over the last century, resulting from the efforts to reduce the energy use in buildings on the one hand and driven by increased requirements and changed user behaviour and comfort wishes regarding the indoor climate on the other hand.

For some of the changes, clearly useful synergy effects are exploited, in which the energy use is reduced and the indoor climate is improved at the same time. For example, the reduction of thermal bridges and the improved thermal performance of windows have unequivocally reduced energy use, improved thermal comfort and reduced the risk for mould growth.

However, with regard to changed ventilation and heating strategies in new high-performance residential buildings, such as defined in [1–5], an unconditional and distinct appraisal cannot be provided. Traditionally, fresh air and heat in residential buildings were generally controlled and supplied separately in each room by simply controlling the opening durations of windows or ventilating apertures and controlling local heat emitters, such as radiators or floor heating.

In highly insulated and airtight residential buildings, a dedicated outdoor air system with mechanical exhaust and supply ventilation with heat recovery (MVHR) is used for the provision of fresh air. The need for window ventilation during the heating season is supposed to be substantially reduced or even eliminated [6].

Regarding heating strategies, the use of a MVHR allows for a supply of heat from the heat exchanger and the heat coil, which constitutes a fundamental change compared to the traditional heat supply by local heat emitters. The heat provided through the supply air, in the following called air-heating, can cover the heating demand to a larger or lesser extent. In passive houses, air-heating is even promoted as the dominant heat source [7].

These changed heating and ventilation strategies constitute a major change compared to traditional ventilation and heating strategies. Consequently, there is a need to thoroughly investigate and evaluate the impact on the indoor climate, which comprises

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0378-7788/

the indoor air quality (IAQ) and thermal comfort. The potential implications for the health and comfort of the occupants of high-performance buildings is not yet adequately investigated [8].

Earlier studies indicate that the use of a MVHR generally improves the IAQ due to a higher air change rate compared with a natural ventilation strategy [9–15], even though in cases an aggravation of the indoor climate is observed, generally caused by failure in planning, installation, use or maintenance [16,17]. Shortcomings regarding controllability can lead to dissatisfaction, misapplication, and ultimately to abandonment of the mechanical ventilation system [18].

With regard to thermal comfort, considerable improvements are observed in high-performance residential buildings when compared to less insulated and leaky buildings [19–21].

However, in many existing studies regarding the indoor climate in residential buildings, the dwelling is treated as a whole. Little scientific work was found regarding the impact of new heating and ventilation strategies on the indoor climate specifically in the various rooms. Some studies on residential passive houses with MVHR indicate that bedrooms are perceived as too warm even in winter [19,22,23], which may explain the substantial extent of window ventilation observed in some passive houses during the heating season [24].

There is a need for increased knowledge regarding the interaction between the user and the actual, perceived and preferred indoor climate conditions in the various rooms in high-performance residential buildings. These issues are therefore addressed in the present study. The objective is to contribute to the further development of heating and ventilation solutions that provide a good indoor climate in the various rooms in a dwelling at the lowest possible energy use.

To explore this knowledge gap, a post-occupancy evaluation (POE) was performed for the first multifamily project in Norway built according to the criteria defined in the preliminary Norwegian standard for low-energy and passive house residential buildings, prNS 3700 [25]. This project contains the most common heating and ventilation solution in new high-performance residential buildings in Norway, which makes the case project representative for new residential high-performance buildings in Norway and similar building concepts around the world.

The POE comprised measurements of indoor climate parameters, energy use as well as window opening durations. In addition, a user survey was conducted to assess the perceived indoor climate, user habits and behavioural drivers. Based on the results of the survey, a comparison with older multifamily buildings is performed to explore a tendency with regard to the perceived indoor climate. Furthermore, based on the feedback regarding the perceived indoor climate conditions in the various rooms in combination with measured indoor climate parameters, an evaluation of the heating and ventilation strategy is conducted.

2. The case project

The Løvåshagen cooperative in Bergen, Norway, was completed in 2008 and consists of 52 low-energy apartments and 28 passive house apartments according to the requirements in the preliminary version of the Norwegian standard NS 3700 [25]. This standard distinguishes between low-energy and passive house residential buildings, with a heating demand limit of respectively 30 and 15 kWh/m^{2}a for apartment buildings with a total floor area over 250 m^2 (Fig. 1).

The building structure consists of floor slabs and partition walls in reinforced concrete between the apartments and light-weight construction for interior and exterior walls as well as the roof. Regarding the air-tightness of the building envelope, a random sample of apartments was tested, which fulfilled the requirements of a maximum air change rate of 0.6 h^{-1} at a pressure difference of 50 Pa.

Each apartment is accessed via a gallery on the east or northeast side. The kitchens and living/dining rooms are oriented towards the west/southwest, whereas the bedrooms are primarily oriented towards the east/northeast. A floor plan of a typical apartment is shown in Fig. 2.

The heating system in the passive house apartments consists of hydronic floor heating in the bathrooms and one radiator in the living room area. Each passive house apartment has a 290-l water tank with a heat exchanger coil for the solar thermal collector.

In the low-energy apartments, the heating system is based on electric floor heating in the bathrooms and one electric radiator in the living room area.

Flexit SL4R MVHR units are installed in each apartment. The units are placed above the ceiling in the bathroom and equipped with a heat wheel with a maximum heat recovery efficiency of ~80% [27]. Exhaust air inlets are placed in the bathroom and kitchen. Supply air outlets are placed above the doors to the living room and bedrooms. In addition, there is a kitchen hood where the exhaust bypasses the heat exchanger. An electric heat coil with a rated power of 900 W is placed in the supply air after the heat exchanger for heating the supply air temperature to the set-point temperature. The ventilation is based on constant air volume (CAV), in which the flow rate and temperature of the supply air are adjusted by the users on a Flexit CI50 control panel, which is placed in the living room area. The user can choose between three levels for the air flow rate, where level two is intended for normal use. The set-point temperature for the supply air is adjusted on a six-point position scale in the range between 15 and 25 °C and is controlled by a sensor placed after the heat coil in the supply air duct. The factory preset for the supply air temperature is 20 °C. The set-point temperature for the supply air controls the speed of the heat wheel and the power of the heat coil when heat recovery is insufficient to reach the set-point temperature. A schematic diagram of the used MVHR system is shown in Fig. 3.

3. Methods

3.1. User survey

An occupant survey was conducted using a web-based questionnaire. The link to the questionnaire was sent on June 6th, 2012 by email to all occupants that had their email addresses registered at the board of the housing cooperative.

Of the 86 occupants to whom the questionnaire was sent, 34 responded, which corresponds to a response rate of 40%. Of these 34 respondents, 14 lived in passive house apartments and 20 lived in low-energy apartments.

The questionnaire was developed based on a previous literature study on user evaluations regarding the perception and control of the indoor climate [19,28–34] and a review on questionnaire design [35,36]. The developed questionnaire contained two parts. The first part consisted of questions based on the standardized form according to the Örebro model [29]. The Örebro model was chosen because it is well-established and widely used in Scandinavia to map perceptions, complaints and symptoms related to the indoor climate [37–42]. The Örebro model [29] assesses the thermal evaluation in an overall retrospective view. This is in contrast to other standardized methods, such as described in ANSI/ASHRAE Standard 55 [43] and NS-EN 15251 [44], in which an instantaneous thermal sensation is assessed on a seven-point comfort scale.

The results of standardized questions were compared to the results from a comprehensive study on multifamily buildings [45],

Fig 1. Illustration of the Løvåshagen cooperative [26], showing low-energy apartments in the blocks to the left and back and passive house apartments in the two blocks in the front with solar thermal collectors on the roof.

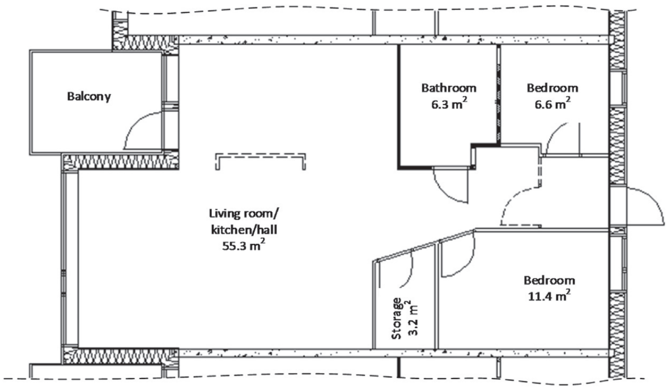

Fig. 2. Typical apartment floor plan.

in the following called BETSI-study, where thousands of residential buildings in Sweden with different construction periods were evaluated with regard to the perceived indoor environmental quality. The purpose of this comparison with buildings from earlier construction periods was to investigate if a tendency regarding the perceived indoor climate becomes apparent for an early detection of room for improvement.

Because of the small sample in the case project, the statistically explanatory power is limited. This was pointed out by plotting the confidence intervals of the weighted mean rating in the various graphs, in which the responses in the case study were compared with results from the BETSI-study. The confidence intervals were calculated based on the student t-distribution and using a significance level α of 5%. The weighted mean ratings regarding the perceived IAQ and thermal comfort were calculated by multiplying the various scale options with the number of responses and dividing by the total number of responses. In the BETSI-study the sample sizes range between 590 and 1417 for the different construction periods, whereas the sample size in the case project is 34.

Nonetheless, despite the small sample in the case project, the results of this survey amount to the increasing base of data from new high-performance buildings, which may be used for future statistical analyses.

In addition to the standardized questions according to the Örebro model, the questionnaire consisted of additional questions regarding user attitudes, user behaviour and occupant satisfaction, particularly with regard to the heating and ventilation system and the perceived indoor climate in the various rooms. For questions regarding the satisfaction level with the heating and ventilation system, a scale from 1 to 6 was used, where 1 corresponds to "very dissatisfied" and 6 corresponds to "very satisfied". This "dice throw" scale was chosen to commit the respondents to either the positive or negative end of the scale. For the scale options 1–3 follow-up questions were provided for the assessment of reasons for dissatisfaction.

3.2. Measurements

Long-term measurements of the indoor climate parameters and opening durations of windows and external doors were conducted in four apartments with measurement intervals of twenty seconds. In addition, the energy use for the MVHR was measured to evaluate the occupant's control of the supply air flow rate and temperature. In some of the apartments, the supply air flow rate in bedrooms was measured. An overview of the monitored low-energy (LE) and passive house (PH) apartments and measured parameters is presented in Table 1.

Regarding the indoor climate parameters in bedrooms and living rooms, the room air temperature (T), the relative humidity (RH) and the CO_2 concentration were measured using Wisensys WS-DLC sensors. The sensors were mounted on the walls at a height between 1 and 2 m and located to ensure a placement with free air movement. This sensor has a self-calibration technique for CO_2 measurements to outside conditions (approximately 400 ppm). For some of the sensors, the self-calibration was not switched on, which resulted in a steady decrease below the reference outside value of 400 ppm and a consequent parallel drift of the indoor concentration values. Therefore, a post-calibration of the measured values was performed through an adjustment based on the trend lines, which

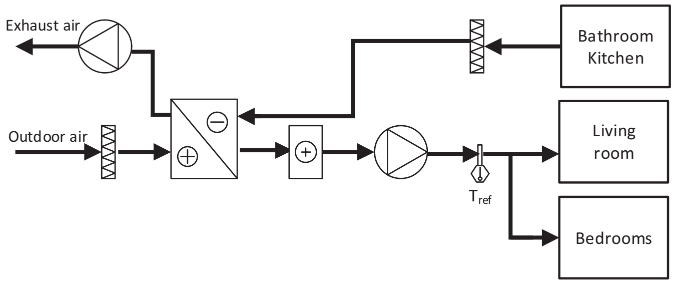

Fig. 3. Schematic diagram of the MVHR system with indication of position of temperature sensor (T_{ref}).

Table 1
Monitored apartments.

Apartment	Features	Monitored rooms	Measured parameters	Measuring period
Mapt1 (LE)	Floor area: 96 m^2	LR: living room	CO2, T, RH in bedrooms and living rooms.	May 2013–April 2014
	Orientation main facade: west	Bath: bathroom	T and RH in bathrooms.	
	Number of bedrooms: 3	BR1: bedroom for 2 adults towards the west	Supply air flow rates in bedrooms.	
	Ceiling height: 2.4 m	BR2: bedroom for 1 child towards the east	Opening duration of windows and exterior doors.	
	Floor level: 2	BR3: bedroom for 1 child towards the west	Energy use MVHR.	
Mapt2 (LE)	Floor area: 75 m^2	LR: living room	CO2, T, RH in bedrooms and living rooms.	May 2013–April 2014
	Orientation main facade: west	Bath: bathroom	T and RH in bathrooms.	
	Number of bedrooms: 2	BR1: bedroom for 2 adults towards the east	Opening duration of windows and exterior doors.	
	Ceiling height: 2.4 m	BR2: bedroom for guests towards the east	Energy use MVHR.	
	Floor level: 2			
Mapt3 (PH)	Floor area: 75 m^2	LR: living room	CO2, T, RH in bedrooms and living rooms.	May 2013–April 2014
	Orientation main facade: west	Bath: bathroom	T and RH in bathrooms.	
	Number of bedrooms: 2	BR1: bedroom for 1 adult and 1 child towards the east	Supply air flow rates in bedrooms.	
	Ceiling height: 2.4 m	BR2: bedroom for 1 child towards the east	Opening duration of windows and exterior doors.	
	Floor level: 1		Energy use MVHR.	
Mapt4 (PH)	Floor area: 89 m^2	LR: living room	CO2, T, RH.	December 2012–May 2013
	Orientation main facade: west	Bath: bathroom	Supply air flow rates in bedrooms.	
	Number of bedrooms: 3	BR1: bedroom for 2 adults towards the west	T in supply air, exhaust air and intake air.	
	Ceiling height: 2.4 m	BR2: bedroom for 1 child towards the east	Opening duration of windows and exterior doors.	
	Floor level: 3	BR3: bedroom for 1 child towards the west		

were derived using the monthly minimum values of the measuring period.

In bathrooms, the room air temperature and relative humidity were measured using Wisensys WS-DLTc sensors. This sensor was also used to monitor outdoor parameters.

In one MVHR unit, the temperature and relative humidity in the supply air duct, the exhaust air duct and the intake air duct were measured using MSR145S sensors.

The flow rates at the supply air outlets and exhaust air inlets were measured using a Wöhler SWF234 ventilation flow meter.

The window opening durations were measured using a magnetic contact and a Wisensys WS-DLXct sensor, which logged the percentage of the window opening duration. The opening width was not measured by the magnetic contact; the measurement gave therefore no information on whether the window is fully opened or tilted.

The power and energy use of the MVHR were measured using a Wisensys WS-DLRs plug-in energy meter.

An overview over the used measurement equipment and their accuracy is given in Table 2.

Regarding the analysis of the measurement data, the measured indoor climate conditions are used to map the actual conditions and to conduct a comparison with the perceived conditions in the various rooms. Furthermore, the measured indoor climate conditions are analysed in detail in relation to the control strategies by the occupants, such as regarding window opening habits.

Because of the small sample, the statistical explanatory power of the measurements is limited. However, the applied exploratory research will contribute to an early detection of possible problems and to identify needs for further research and development.

4. Results

4.1. User survey

In the following sections, the results of the user survey are presented. These results are thematically grouped into perceived

Table 2
Measurement equipment and accuracy.

Parameter	Equipment	Accuracy
CO_2, T, RH	Wisensys WS-DLC	CO_2: ±40 ppm + 3% of reading @ 22 °C Humidity: ±1.8%RH from 10% to 90%RH; ±4%RH otherwise Temperature: ±0.3 °C @ 25 °C; ±0.5 °C from 0 °C to +50 °C; ±1.2 °C from −20 °C to +80 °C
T, RH	Wisensys WS-DLTc	Humidity: ±1.8%RH from 10% to 90%RH; ±4%RH otherwise Temperature: ±0.3 °C @ 25 °C, ±0.5 °C from 0 °C to +50 °C, ±1.2 °C from −20 °C to +80 °C
T, RH	MSR145S	Humidity: ±2% @ 10–85% RH, 0 °C to 40 °C; ±4% @ 85–95% RH, 0 °C to 40 °C Temperature: ±0.5 °C @ −10 °C to +65 °C
Window opening duration	WS-DLXct	Detection levels: closed Vin <1 V; open Vin >2 V
Air flow rate (m^3/h)	Wöhler SWF234	Error <5%

indoor climate, reported habits regarding indoor climate control and satisfaction with the heating and ventilation system.

4.1.1. Perception of indoor air quality

In the case project, 76% of the 34 respondents consider the perceived indoor air quality to be "good" or "very good". In comparison to the results regarding multifamily buildings in the BETSI study [45], the highest weighted mean rating of the IAQ is observed in the case project (Fig. 4).

Occupants that rated the IAQ as "acceptable" or "bad" specified the following reasons for their discontent: air feels stuffy (9% response; n = 34), smells from cooking spread within the apartment (3% response; n = 34), tobacco smoke or other odours from other apartments (3% response; n = 34) and little ability to control the ventilation (3% response; n = 34).

The majority of the respondents (56%) stated that they have not noticed any changes in indoor climate-related symptoms after moving to Løvåshagen. Thirty percent of the respondents stated that they now have fewer or considerably fewer indoor related symptoms, and 12% (; n = 34) stated that they now have more symptoms.

Ten percent of the respondents reported often being bothered by the perception of dry air. This number is somewhat lower than that reported in buildings constructed in the period from 1976 to 1985 in the BETSI study [45] but higher than in all other construction periods.

4.1.2. Perceived thermal comfort

In the case project, 76% of the 34 respondents considered the perceived thermal comfort to be "good" or "very good". Compared to the results regarding multifamily buildings from the BETSI study [45], the weighted mean rating of the thermal environment in the case project is consistent with the general findings for buildings constructed after 1986 (Fig. 5).

The following reasons for discontent were specified: too cold during winter (6% responses), too warm during summer (9% responses; n = 34), room temperature varies with the outdoor temperature (6% responses; n = 34), cold floors during winter (3% response; n = 34), and difficult to adjust the temperature (3% response; n = 34).

All of the apartments have relatively large window areas that are oriented towards the south or west and might therefore be exposed to unwanted solar gains during the summer. Exterior shading has been installed by 18% of the 34 respondents, and 70% of the 34 respondents use interior shading, such as curtains or blinds. Twelve percent of the respondents stated that they have no shading at all.

All of the respondents that stated that they were often bothered by overheating (12% of 34 the respondents) live in apartments oriented towards the west, which shows that apartments oriented towards the west are particularly prone to overheating during summer due to the low solar angle in the afternoon.

4.1.3. Reported behaviour regarding indoor climate control

The weighted mean reported window opening duration in the bedroom during summer is 10 h per day, whereas during winter, it is 4 h (Fig. 6).

The main reasons stated for keeping the window in the bedroom closed is to avoid noise (50% response; n = 34) and cold air from the outside (32% response; n = 34), whereas the clearly dominant reason for keeping the window open is the need for cooler air (59% response; n = 34).

Regarding heating habits in the bathroom, 77% of the 34 respondents reported that the floor heating is turned on all year, not only during the heating season.

Thirty-five percent of the respondents that stated that the floor heating is on all year would accept another floor material that would feel warmer, e.g., vinyl or a water-resistant wooden floor, to reduce or even eliminate the need for floor heating solely for local comfort reasons.

Regarding temperature control of the supply air, 24% of the 34 respondents stated that the temperature level always is set to level one or two, i.e., the lowest levels. Sixty-seven percent of the respondents stated that the temperature is controlled according to the current demand. One respondent did not know how to control the temperature.

Regarding control of the supply air flow rate, approximately 50% of the 34 respondents stated that the supply air flow rate is controlled according to the current demand, and 33% (; n = 34) stated that the supply air flow rate is usually set to level two, which is intended for normal use.

4.1.4. Satisfaction with the heating and ventilation system

A high level of satisfaction with the heating system in the living room and bathroom was reported, where the mean degree of satisfaction was 4.9 for both rooms on a scale from 1 ("very dissatisfied") to 6 ("very satisfied").

In contrast, the mean degree of satisfaction in the bedroom was 3.8, which is significantly lower than in the other rooms at a 0.05 level. The following reasons were specified regarding the discontent with the heating system in the bedroom: the supply air should be cooler (29% response; n = 34), difficulty of adjusting the temperature (12% response; n = 34), and the lack of a local heat source (6% response; n = 34).

The mean degree of satisfaction with the ventilation system was 4.6 on a scale from 1 ("very dissatisfied") to 6 ("very satisfied"). The reasons for discontent are as follows: noise (3% response; n = 34), perception of dry air (6% response; n = 34), too little fresh air (6% response; n = 34), difficulty of controlling the air flow

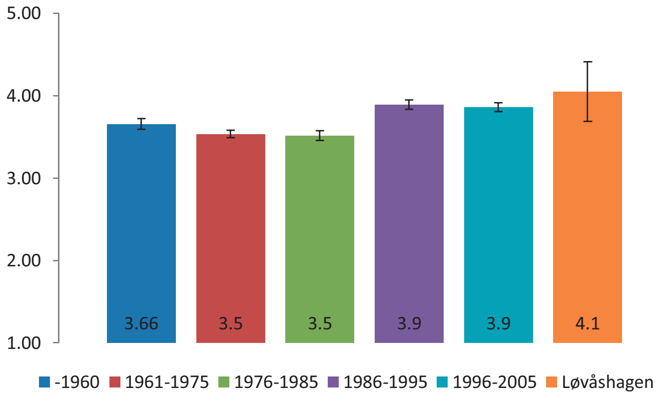

Fig. 4. Weighted mean evaluation of IAQ in the case project in comparison with results from the BETSI study on a scale from 1 (very bad) to 5 (very good) with indication of the confidence interval ($\alpha = 0.05$).

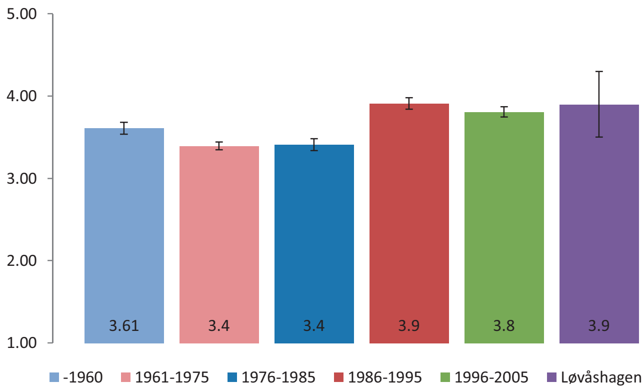

Fig. 5. Weighted mean evaluation of thermal environment in the case project in comparison with the results from the BETSI study on a scale from 1 (very bad) to 5 (very good) with indication of the confidence interval ($\alpha = 0.05$).

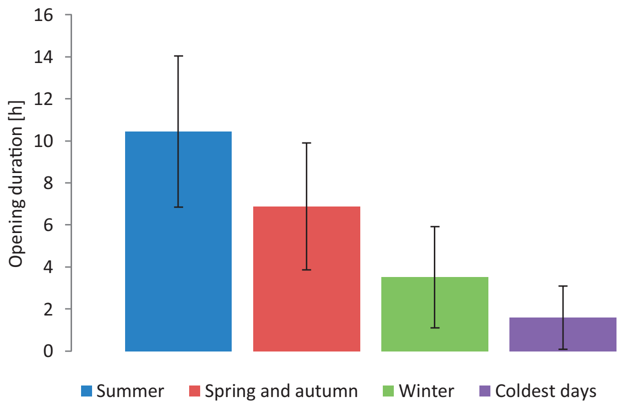

Fig. 6. Weighted mean reported window opening duration in the bedroom with indication of the confidence interval ($\alpha = 0.05$).

Table 3
Measured supply air flow rates [m^3/h].

Room	Mapt1	Mapt3	Mapt4	Required [46]
Bedroom 1	50	23	25	52
Bedroom 2	24	25	24	26
Bedroom 3	25	NA	NA	26

rate/temperature (3% response; n = 34) and difficulty of changing the filter (6% response; n = 34).

4.2. Measured supply air flow rates in bedrooms

The measured supply air flow rates in bedrooms for normal use (level two) are listed in Table 3.

The measured supply air flow rates show that the flow rates in two bedrooms are approximately half of that required.

4.3. Measured window ventilation habits

The opening duration was measured for all windows and exterior doors in three apartments (Mapt1, Mapt2 and Mapt3). The monthly mean opening durations for the windows, including terrace doors for living rooms and for windows in bedrooms, are presented in Fig. 7.

For living rooms, a low monthly mean window opening duration is observed, even during summer. Substantially higher window opening durations are observed in the bedrooms, both during summer and winter.

4.4. Measured indoor climate conditions

In the following sections, the results from the long-term measurements of CO_2 levels, indoor air humidity and room temperatures are presented.

4.4.1. CO_2 levels

Using the IAQ classification in EN 15251 [44] as a benchmark, the measured hourly mean CO_2 levels show a high IAQ (class I: CO_2 < 750 ppm) 85% of the time as a mean for all ten measured rooms (Fig. 8). A medium IAQ (class II: CO_2 levels between 750 and 900 ppm) is measured 8% of the time. A moderate IAQ (class III: CO_2 levels between 900 and 1200 ppm) is measured 5% of the time. A low IAQ (class IV: CO_2 > 1200 ppm) is measured 2.2% of the time.

The greatest extent of CO_2 levels above 1200 ppm is observed in the bedrooms Mapt2 BR1 and Mapt3 BR2. Given that CO_2 levels above 1200 ppm occur during sleep and assuming a typical sleep duration of 8 h, the measurements indicate a low IAQ 16% of the sleep duration in Map2 BR1 and 19% of the sleep duration in Mapt3 BR2.

In Mapt3, the supply air flow rate is generally set to level one rather than the standard level two, which may explain the measured CO_2 levels. Nevertheless, the occupant of this dwelling considers the IAQ as being very good and is very satisfied with the ventilation system. The window in bedroom Mapt3 BR2 is opened only 2% during the winter season.

In bedroom Mapt2 BR1, the supply air flow rate was not measured, but the high CO_2 levels strongly suggest that a too low supply air flow rate is adjusted, as observed in other apartments.

When examining the relationship between window ventilation and CO_2 levels in bedrooms, the results show essentially no correlation between CO_2 levels and the window opening duration for most rooms (Fig. 9). Although the highest CO_2 levels are observed when windows are closed, the relatively high values at 100% window opening duration and the otherwise even distribution suggest that other factors have a larger impact on the CO_2 levels, such as the occupancy, supply air flow rate and air flow through the apartment.

The lack of correlation between CO_2 levels and window opening durations is in contrast to the influence of the window ventilation on the temperature. The clear decrease in temperature with increasing window opening duration supports the feedback from the occupants, which indicates that the main motivation for window ventilation is to control the indoor temperature, not the IAQ.

4.4.2. Indoor air humidity

The lowest monthly mean of the RH is 25% in the bathroom in Mapt2 in January 2014, where the monthly mean temperature is 27 °C. For all other measured rooms, the monthly mean indoor RH levels range from approximately 30% during the coldest period to 55% during summer.

The lowest daily mean RH level during the coldest days in January 2014 is 17% in the bathroom in apartment Mapt2 at a daily mean temperature of 27 °C. The lowest daily mean relative humidity values in bedrooms and living rooms are 20 and 21% with daily mean temperatures of 19 and 23 °C, respectively.

In EN 15251 [44], no recommended absolute upper or lower RH limits are given. However, it is noted that high humidity levels may increase the occurrence of microorganisms and that very low RH levels (<15–20%) may cause irritation of the eyes and airways.

4.4.3. Room temperatures

The measured mean seasonal temperatures show clear differences between living rooms, bedrooms and bathrooms (Fig. 10).

For the living rooms and bathrooms, there is little variation between the summer season (May to September) and winter season in terms of the mean temperature. In the bedrooms, the mean temperature during the winter season is approximately 2 °C lower than that during the summer season.

4.4.3.1. Room temperatures during summer. When comparing the measured temperatures to acceptable upper and lower temperature limits in accordance with EN15251 [44], the mean temperatures during summer in the living room are within the acceptable temperature range.

In contrast, the measured mean temperatures in bedrooms and bathrooms are outside the acceptable temperature ranges as defined in EN 15251 [44], but they are not necessarily outside the desired temperature ranges. In bedrooms, the mean temperature during summer is approximately two degrees lower than the acceptable lower limit stated in EN 15251. In bathrooms, the mean temperature during summer is approximately 1.5 ° higher than the acceptable upper limit stated in EN 15251.

When applying the adaptive approach to thermal comfort, as defined in EN 15251 [44], the evaluation of measured air temperatures in bedrooms and living rooms during the warmest period show that the upper acceptable operative temperatures for category II are only exceeded for one living room (Mapt2 LR). The acceptability limit is exceeded 8% of the time during the period from July 20th to August 31st 2013 (Fig. 11), which is less than 1% of the year.

The temperature limit for category I (high level of expectation) is exceeded 11% of the time in living room Mapt2 LR in the considered time period, which is 1.2% of the year. In two bedrooms, Mapt1 BR2 and Mapt1 BR3, the temperature limits for category I are exceeded 2% of the considered time period, which is 0.2% of the year.

A clear relationship between the window opening duration and room temperature during summer is observed (Fig. 12). This illustrates the efficiency of window ventilation to avoid overheating when the outdoor temperature is lower than the indoor temperature, which is frequently the case even during summer in Nordic countries. For all rooms where the upper acceptability limits in cat-

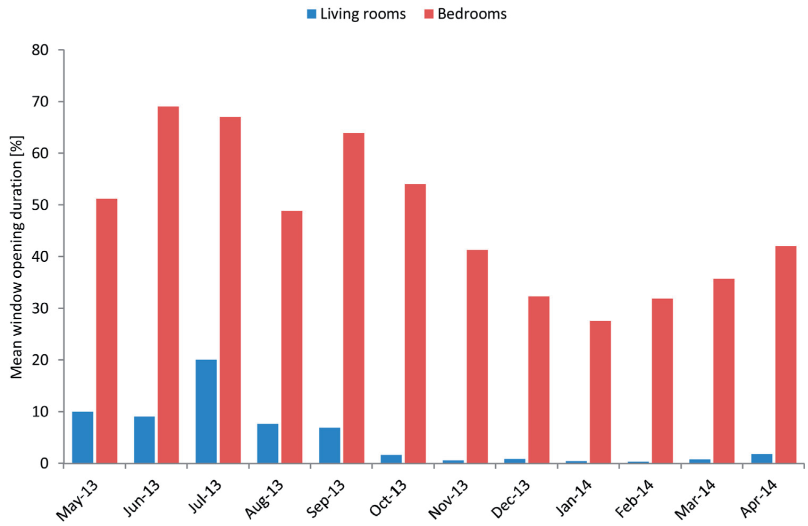

Fig. 7. Monthly mean window opening durations in living rooms and bedrooms in three apartments.

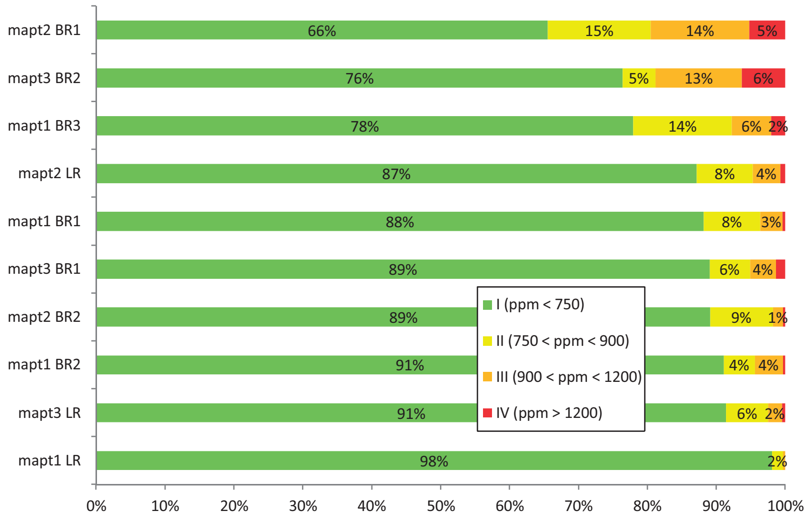

Fig. 8. Percentage of hours in the different IAQ categories according to EN 15251:2007 [44] based on hourly mean values during the monitoring period from May 2013 to April 2014.

egory II are exceeded, the window opening durations are relatively low. The window in living room Mapt2 LR is closed all the time in the considered period, and the terrace door is open 14% of the time.

The measured temperatures also demonstrate the efficiency of exterior solar shading in reducing the room temperature. Living room Mapt3 LR is the only one of all considered rooms that has exterior shading. All three living rooms are oriented towards the west and have a similar degree of insolation. Despite the relatively low window opening duration in Mapt3 LR, the maximum temperature is significant lower than that in the other living rooms.

The hourly mean temperatures for the warmest day in August 2013 show a maximum indoor temperature in bedroom Mapt1 BR2 of 26.1 °C on August 24th and a maximum outdoor temperature of 26.6 °C (Fig. 13).

Bedroom Mapt1 BR2 is oriented towards the east and exposed to insolation some hours during the morning. This bedroom has only one exterior wall and is placed next to the bathroom and technical niche with the hot water boiler and the MVHR. The temperature in the bathroom is between 26 and 29 °C on August 24th, which indicates that the heat flow from the bathroom contributes to the high temperature levels in bedroom Mapt1 BR2. The window is opened only at night, which reduces the temperature by some degrees, but considerably less than is observed in Mapt1 BR3.

For Mapt1 BR3, which is oriented towards the west, a clear impact of the insolation is observed. The temperature significantly increases in the afternoon. When the window is opened in the evening, the temperature substantially decreases during the night; from August 26th to 27th, the temperature decreases by 8° within

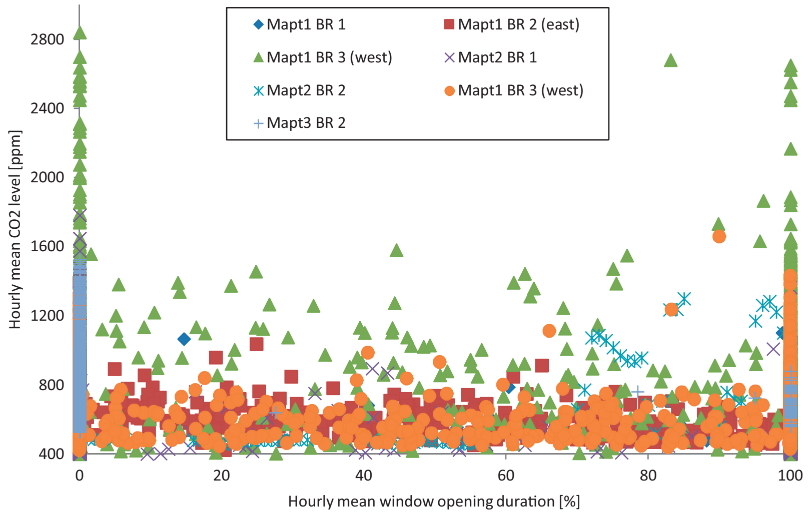

Fig. 9. Hourly mean CO_2 levels in bedrooms in relation to the window opening duration for October 2013 to March 2014.

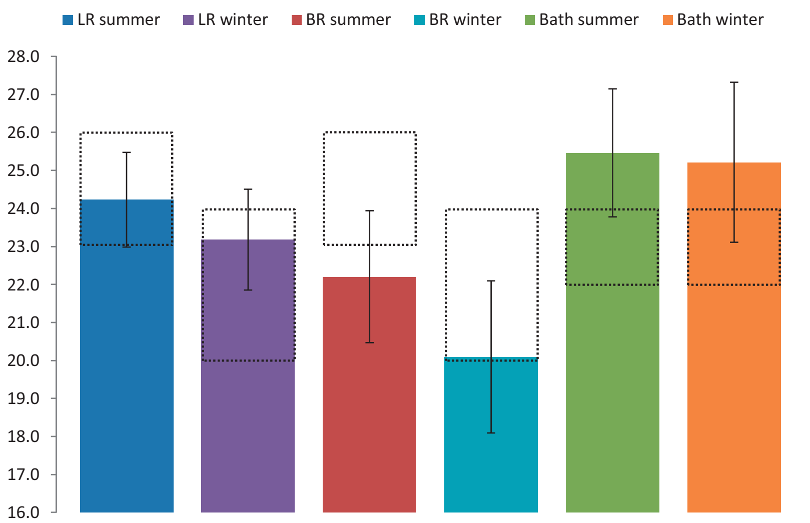

Fig. 10. Mean seasonal temperatures in living rooms (LR), bedrooms (BR) and bathrooms (Bath) in three apartments (Mapt1, Mapt2 and Mapt3) with indication of the standard deviation. The dashed frames indicate the acceptable temperature ranges for category II in accordance with EN 15251 [44].

12 h. The bedroom has 2 exterior walls, which also contribute to the drop in temperature during the night.

In bedroom Mapt1 BR1, a nearly constant temperature is observed. This bedroom has one exterior wall and is placed next to the neighbour's bathroom, separated by a concrete wall. The window is oriented towards the west and is opened constantly during the considered period, except on August 25th. A possible explanation for the lower temperature variation in Mapt1 BR1 compared to the other bedrooms may be the heat flow from the neighbouring rooms and the heat storage in the concrete wall.

In one apartment (Mapt4), the temperatures inside the MVHR unit were measured. Sensors were placed in the exhaust air duct before the heat recovery wheel, in the supply air duct after the heat coil and in the intake air duct before the heat recovery wheel. The measured temperatures indicate that heat recovery occurs during warm periods in summer (Fig. 14).

The set-point temperature is clearly set to the lowest possible set-point temperature (15 °C), which necessarily leads to heat recovery when the intake air temperature is below 15 °C. The heat recovery cannot be switched off on the control panel. The intention of the lower set-point limit is to avoid draught from the supply air, but it obviously reduces the potential cooling capacity and consequently contributes to a higher temperature level.

4.4.3.2. Room temperatures during winter. When examining the relationship between window opening durations and temperatures in bedrooms during winter, a clear trend of a reduced indoor temperature with an increased window opening duration is observed

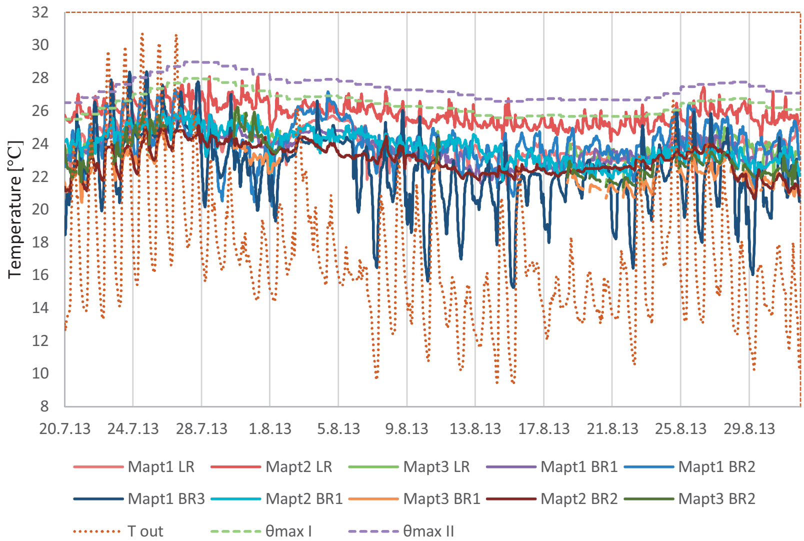

Fig. 11. Hourly mean air temperatures in living rooms and bedrooms during warmest period in July and August 2013. Upper acceptability limits for operative temperatures θ_{max} according to EN 15251:2007 [44] are shown for category I (θ_{max} I) and category II (θ_{max} II) based on the running mean of the outdoor temperature.

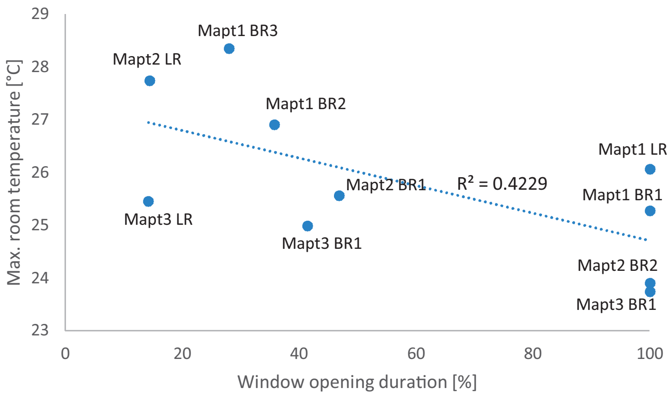

Fig. 12. Maximum hourly mean temperatures in bedrooms and living rooms on July 24th in relation to the window opening duration.

for most bedrooms (Fig. 15). Some of the bedroom windows are nearly always closed or always open, and therefore, no trend can be derived.

In bedroom Mapt1 BR1, the window opening duration is 100% nearly all of the time in January, and the daily mean temperature ranges between 18.8 and 21.3 °C. In contrast, in bedroom Mapt3 BR1, the window is closed all of the time in January, and the daily mean temperature ranges between 17.2 and 19.6 °C.

One cause for the higher temperatures in Mapt1 BR1 despite the extensive window ventilation appears to be the heat supplied by the MVHR, which in turn may be the driving force for the window ventilation behaviour. A clear relationship between the measured energy use for the heat coil in the MVHR and window opening duration is observed. For Mapt1, a daily mean energy use of 4.6 kWh/day is measured during the heating period (October to March), with a mean window opening duration in Mapt1 BR1 of 94%. For apartments Mapt2 and Mapt3, the mean energy uses for the heat coil are 1.6 kWh/day and 0.3 kWh/day, respectively, and the mean window opening durations for the master bedrooms are 18% and 11%, respectively.

Even within the apartment, large differences in temperature profiles in the various rooms are observed, as illustrated for one apartment in Fig. 16.

In Mapt1 BR2, a clear pattern of the temperature dependence on window ventilation is observed; the window is open every night, and the temperature drops to approximately 16 °C. In the morning, the window is closed, and the temperature increases to approximately 22 °C within a few hours. In contrast, the temperature in BR1 is approximately 19–20 °C all day, and the window is open for the entire period, except during the daytime on January 15th. Possible causes for the different temperature profiles are the air flow in the apartment on the one hand and the heat flux from adjacent rooms on the other hand. In addition, Mapt1 BR1 is placed next to a partition wall, which is made out of 200 mm concrete, whereas the other bedrooms are enclosed by light-weight wood frame walls.

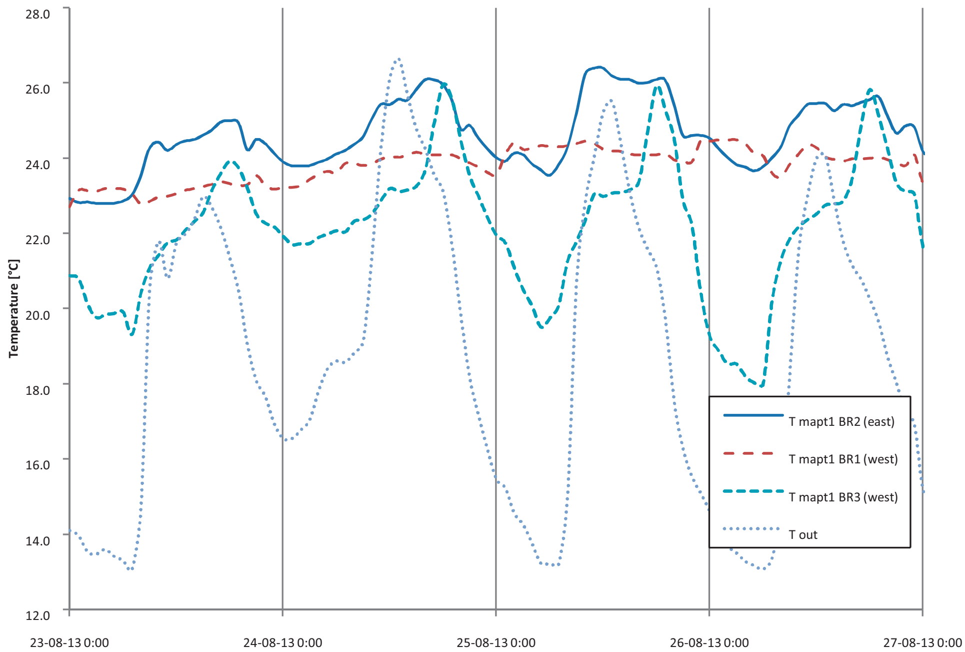

Fig. 13. Hourly mean temperatures in bedrooms in Mapt1 and outdoor temperature during the four warmest days in 2013.

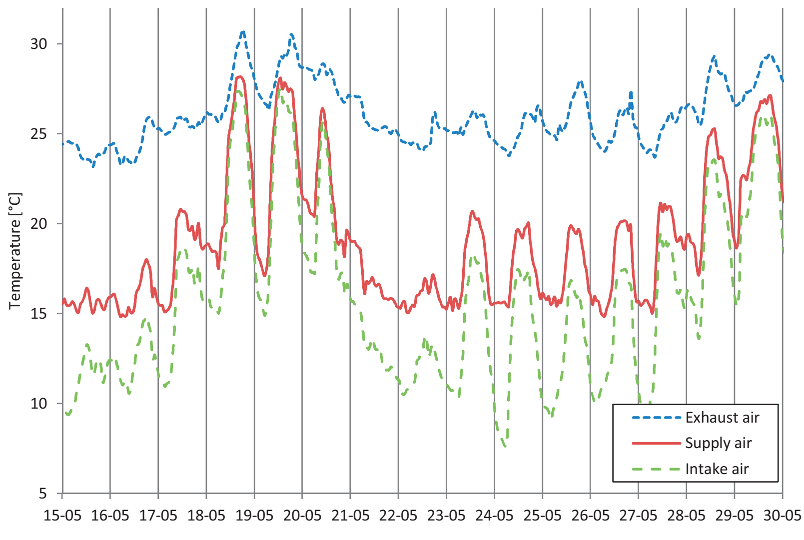

Fig. 14. Measured temperatures for a warm period in May 2013 in the MVHR unit in apartment Mapt4.

The heat capacity of the concrete wall will contribute to a reduction of temperature peeks.

The dominant wind direction in the considered period was from the east and southeast. Bedroom Mapt1 BR2 is located towards the east, bedroom Mapt1 BR1 is located towards the west, and the living room is located between the two bedrooms. Consequently, the temperature profiles in the bedrooms suggest that there is a dominant air flow through the apartment from the east to the west; at night, outdoor air flows into Mapt1 BR2, passes through the living room and Mapt1 BR1, and leaves through the window in Mapt1 BR1. The room temperature is effectively reduced in BR2, whereas the temperature in BR1 is basically constant because of a temperature increase when passing the living room. When the window on the windward side (Mapt1 BR2) is closed during daytime, a slight temperature decrease in the bedroom on the leeward side (Mapt1 BR1) is observed, which suggests that the air flow through the apartment is reduced and a direct air exchange through the window in Mapt1 BR1 is taking place. This illustrates that the air change rate in a

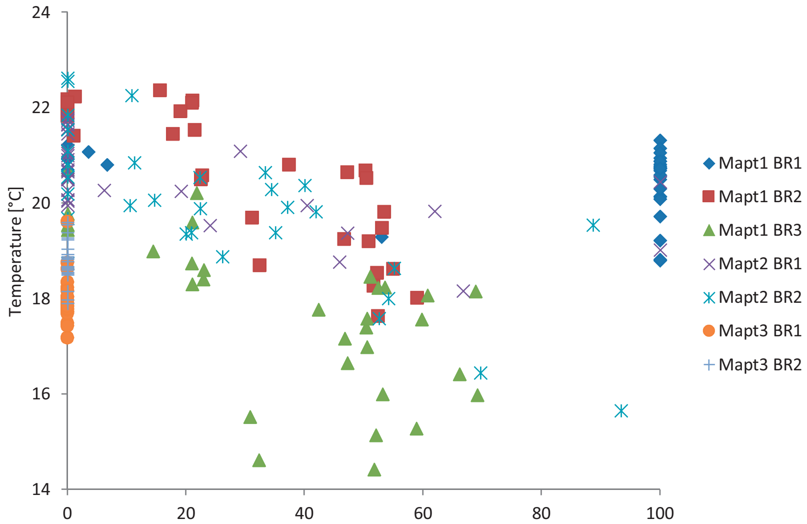

Fig. 15. Daily mean temperatures in bedroom in relation to the window opening duration in January 2014.

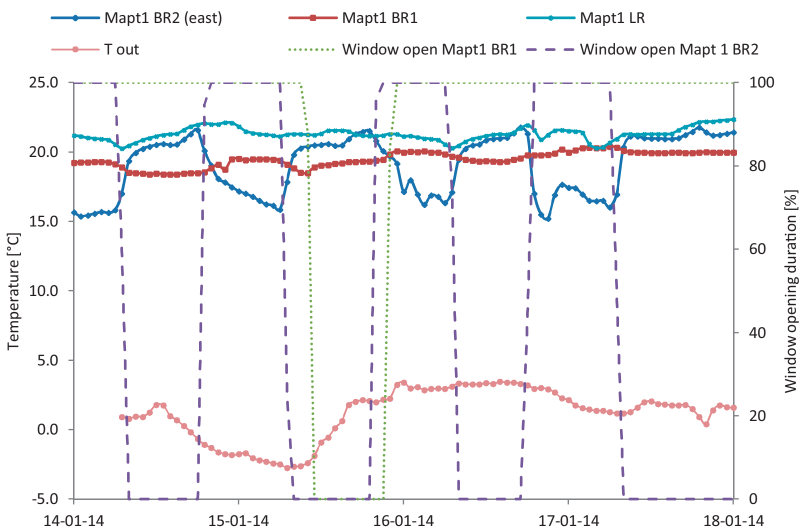

Fig. 16. Hourly mean temperatures in the bedrooms (BR1 and BR2) and living room (LR) in apartment Mapt1 during the coldest days in the measuring period along with the window opening durations.

room is not only dependent on the window opening pattern in the considered room but also on the window opening pattern for the whole dwelling and the wind direction. An air flow through the dwelling constitutes a limitation of window ventilation regarding the control of the indoor climate.

The measured energy use for the MVHR in Mapt1 indicates a high set-point temperature of the supply air during winter, which contributes to the high room temperature levels. The extensive window ventilation even during the coldest period suggests that the temperatures in the bedrooms are undesirably high, at least during sleep, and therefore, the temperatures are reduced by opening the windows.

In Fig. 17, the hourly mean temperatures of the supply air and the temperatures in the living room and bedroom 1 in Mapt4 as a function of the intake air temperature are plotted for December 2012. The window in this bedroom is kept closed for almost the entire month (2% opening duration).

A strong relationship between the intake air temperatures and supply air temperatures is observed, which shows that the users of this dwelling are adjusting the set-point temperature based on the outside temperature (Pearson $r = 0.68$; $p = 0.000$). The set-point of the supply air temperature is reduced to the lowest set-point level at relatively low intake temperatures, which reduces the exploitation of the heat recovery potential.

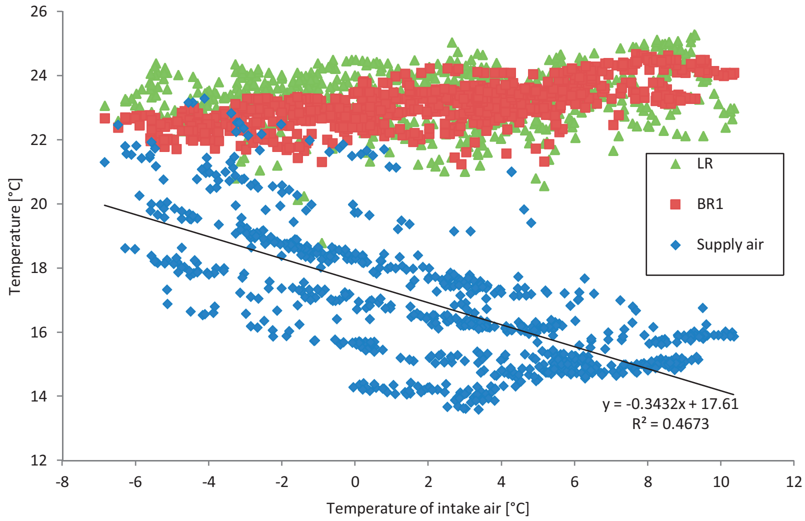

Fig. 17. Hourly mean temperatures during December 2012 in the living room (LR), bedroom 1 (BR1) and supply air in dwelling Mapt4 as a function of the intake air temperature.

No relationship between the intake air temperature and the temperatures in the living room is observed (Pearson $r = 0.17$; $p = 0.000$). The temperatures in the living room are also independent from the supply air temperatures, indicating that the temperature in the living room is primarily controlled by the radiator.

In contrast, there is a relationship between the intake air temperatures and the temperatures in the bedroom (Pearson $r = 0.69$; $p = 0.000$). The temperatures in the bedroom increase with increasing intake air temperatures, despite the reduced supply air temperatures. This increase in bedroom temperature is, on the one hand, caused by a reduced heat loss to the outside but, on the other hand, also by the constraint of the lower limit of the supply air temperature, which consequently limits the cooling capacity of the supply air. The lower set-point limit is set by the manufacturer of the MVHR unit to 15 °C to avoid draught from the supply air outlets, but this in fact leads to an unintentional, and possibly unwanted, increase of temperatures in the bedroom.

The highest temperatures in the bedroom are observed at the lowest supply air temperatures, which demonstrate that other factors more significantly contribute to the heat balance in the bedroom, such as the heat loss to the outside and heat gain from neighbouring rooms and internal heat loads.

5. Discussion

5.1. Indoor air quality

The feedback from the occupants and the measured CO_2 levels indicate a good IAQ, which provides further support to earlier findings that showed an improvement in the IAQ in mechanically ventilated residential buildings compared to naturally ventilated buildings. The reported reduction in indoor climate-related symptoms supports findings in other studies [14,21], where occupants reported an increased wellbeing regarding indoor climate-related symptoms after moving to a new high-performance building with MVHR.

The measured CO_2 levels show that a low IAQ (CO_2 levels > 1200 ppm) occurs approximately 2% as a mean for all measured rooms. In comparison, measurements in a study on naturally ventilated buildings show that the CO_2 level of 1400 ppm is exceeded 70% of the time [12].

In some of the bedrooms, high levels of CO_2 are observed, most likely caused by an incorrect adjustment of the supply air flow rate. In several rooms, the measured flow rates did not comply with national regulations [46]. Some of the occupants are disturbed by noise of the ventilation system at night and therefore reduce the flow rate level to level one, which is intended for use at absence. This demonstrates the need for quality control during planning and installation of ventilation systems.

5.2. Indoor air humidity

The perceived and measured actual humidity levels indicate that discomfort and health risks associated with too high indoor humidity levels are substantially reduced in comparison to less insulated buildings with low air change rates [47,48]. This clear improvement regarding the indoor climate is attributed to the high insulation levels, the reduced thermal bridges and, in particular, to the air change rate due to the MVHR. These results provide further support to earlier findings that indicated an improved indoor climate due to reduced humidity levels in buildings with mechanical ventilation [9–15].

Some respondents are bothered by the perception of dry air, which is consistent with the findings in other studies on high-performance residential buildings with MVHR [19,24,49]. In bedrooms and living rooms, the long-term measurements show that the lowest daily mean RH is approximately 20%, which in accordance with EN 15251 is defined as “very low humidity”. Similar low RH levels have been measured in other high-performance residential buildings with MVHR [24,50].

The question arises as to whether the perception of dry air is in fact caused by physically low humidity levels, which was not clarified in this study. The question commonly used in indoor climate surveys regarding the perception of dry air might actually act as a leading question, where the blame of discomfort may be incorrectly placed on the indoor air humidity level. Keul and Salzmann [49] found that the perceived air humidity is influenced by measurements of the actual air humidity; occupants with access to hygrometers were significantly more discontent than were occupants without access to hygrometers. This indicates a potential to increase the satisfaction with the indoor air humidity by well-founded information regarding humidity levels and limit values.

In a comprehensive interdisciplinary literature study regarding the physiological impairments of individuals at low indoor air humidity, it was concluded that low humidity has a significant negative effects on the eyes, skin and mucous membranes [51]. Therefore, the user feedback regarding the perception of dry air should be taken seriously. Further research is needed to clarify the impact of actual humidity levels on discomfort and symptoms, from which a medically justified lower limit regarding indoor humidity levels could be defined.

5.3. Thermal comfort

The user survey indicates a general high degree of satisfaction with the overall thermal conditions, and no indication for an aggravation in comparison with other building standards was found. For buildings constructed after 1986 a significantly increased satisfaction with the thermal conditions was observed in comparison to buildings built before. This may be explained by the general improvements in buildings built after 1986, such as increased insulation level and more efficient heating solutions. The mean rating in the case project appears to be on the same level as buildings constructed between 1986 and 2005, which, however is not statistically affirmed. Further studies on larger samples of high-performance buildings are required to draw statistically firm conclusions.

A few respondents reported being bothered by overheating, which is attributed to the lack of exterior shading on windows exposed to substantial insolation and a low extent of window ventilation.

The occupant feedback regarding the perception and control of the indoor thermal conditions in combination with the conducted long-term measurements of the indoor temperatures, energy use for the MVHR, and window opening durations provided profound insights regarding the perception and control of the thermal conditions in the various rooms.

Both the occupant feedback and the measured temperatures clearly indicate that different temperatures are wanted in the various rooms in residential buildings and demonstrate the limited applicability of the evaluation criteria defined in current standards, such as EN 15251 [44] or ASHRAE 55 [43].

The adaptive approach in EN 15251 [44] is very appropriate when evaluating thermal conditions in living rooms, but it appears to be inapplicable when evaluating bedrooms and bathrooms. The same mismatch is found when comparing measured temperatures with acceptable temperature ranges for the control of existing buildings, as defined in the national addendum to EN 15251 [44].

5.3.1. Thermal comfort in living rooms

For living rooms, the measured temperatures comply with the requirements defined in EN 15251 [44], both when applying the adaptive approach for summer conditions and the acceptable temperature ranges for both summer and winter conditions.

During the winter season, the mean temperature in the three monitored living rooms is 23.2 °C, which is approximately 1 K higher than the mean temperature level in living rooms observed in a large sample ($n > 3000$) of the Norwegian building stock during a measurement campaign in September and October 2012 [52]. The measured elevated temperature levels in the case project during the heating season support the earlier observed general trend of elevated temperatures in high-performance buildings [53,54].

The study on room temperatures in Norwegian dwellings [52] revealed that many keep a lower temperature than their comfort temperature to save energy costs. Buildings with heat pumps or flat-rate allowance of energy costs were associated with higher indoor temperatures.

These findings suggest that the comfort temperature in living rooms is approximately 23 °C, which, however, need to be verified in a larger study on high-performance residential buildings. This tendency of higher temperatures will first increase the energy use for heating and second have an impact on the thermal flow within a dwelling. These issues therefore need to be taken into account in the energy and indoor climate design and evaluation of high-performance residential buildings.

During the summer season, the mean temperature in the three monitored living rooms is 24.2 °C, which appears to be the comfort temperature level in living rooms during summer. Higher measured temperatures correlate with low window ventilation, which indicates that occupants accept, or even prefer, higher temperatures during summer and control the room temperature during summer using window ventilation. The applicability of the adaptive approach, as defined in EN 15251, is therefore confirmed for living rooms.

5.3.2. Thermal conditions in bedrooms

For bedrooms, the measured seasonal mean temperatures are lower than the lower acceptability limit defined in EN 15251 [44] for the summer season and approximately at the lower limit for the winter season. This apparent undershoot of recommended temperatures, however, does not appear to reflect the subjective evaluation by the occupants. Some occupants report that even lower temperatures in bedrooms would be preferred. These findings support earlier studies that indicated that lower temperatures in bedrooms than in other rooms are generally preferred [52,55,56], which is in contradiction to the lower limits defined in EN 15251 [44].

Peeters, Dear, Hensen and D'haeseleer [55] proposed an alternative adaptive comfort temperature curve specifically for bedrooms, ranging from a lower limit of 16 °C at reference external temperatures below 0 °C up to an upper limit of 26 °C at reference external temperatures above 21.8 °C. This comfort curve certainly better applies as a base for acceptability limits for bedrooms than those given in EN 15251 [44] and ASHRAE 55 [43]. However, the curve is primarily based on measured temperatures in bedrooms in Belgian dwellings and does not necessarily reflect the preferred temperatures. Several studies on thermal comfort in high-performance residential buildings have shown that the lowest satisfaction is found for bedrooms during summer [19,24,57], which suggests that the comfort temperature in the bedroom in fact does not vary considerably between summer and winter. Further studies are necessary to define comfort temperatures specifically for bedrooms in high-performance buildings, which should then be used as a base in the derivation of acceptability limits.

Mean temperatures in bedrooms of 22 °C during summer and 20 °C during winter were measured. The bedroom temperatures during winter are consistent with temperatures found in a German study [58] and slightly higher than the temperatures found in the measurement campaign in the Norwegian building stock autumn 2012, where a mean temperature in bedrooms of approximately 19.5 °C ($n > 2900$) was observed [52].

The detailed analysis of bedroom temperature profiles as a function of window opening durations shows that window ventilation does not necessarily provide the intended cooling effect in all rooms. The comparison of the temperature profiles in the various rooms in one apartment indicates an air flow through the apartment, dictated by the wind direction, which leads to an effective cooling of some bedrooms by outside air, whereas other bedrooms are cooled less due to a preheating of the air flowing through the apartment.

The temperature profiles also indicate a heat flux from neighbouring warmer rooms, such as bathrooms and living rooms. In this respect, a trend of increased temperatures in bathrooms and living rooms aggravates the provision of preferred lower bedroom temperatures.

Clear limitations of a MVHR with one ventilation zone in the provision of desired temperatures in bedrooms were identified in this study, both during summer and winter. During summer, the observed heat recovery of the exhaust ventilation air, even at the lowest possible set-point of the supply air temperature, reduces the cooling potential of the supply air. During winter, a high set-point temperature for the supply air leads to increased temperatures in the bedrooms. A reduced set-point temperature during winter will increase the ventilation heat loss and unintentionally also cool the living room. A conflict of goals between energy savings and thermal comfort becomes apparent, which calls for further research and development regarding heating and ventilation strategies in residential buildings.

5.3.3. Thermal conditions in bathrooms

In bathrooms, a seasonal mean temperature of approximately 25 °C for both summer and winter was measured, which is higher than the upper acceptability limit of 24 °C defined in EN 15251 [44]. The measured temperature level is consistent with findings in a study from Japan [59], where an optimum temperature in bathrooms was found to be in a range between 24 and 26 °C. In [60], the found comfort temperature for bathrooms was 24.6 °C. In the measurement campaign in the Norwegian building stock, a mean temperature in bathrooms of approximately 23 °C was found. The increased mean temperature found in the present study may be caused by a random statistical variation due to the very limited sample ($n = 3$) or in fact is an indication for a change in comfort temperature in high-performance buildings, which should be clarified in further studies.

The low variation between summer and winter suggests that the comfort temperature in bathrooms is independent of the outside temperature. This is in contradiction to the adaptive approach in EN 15251 [44] and also to the modified comfort temperature curve specifically derived for bathrooms, as proposed in [55].

Over the past decades, an increased use of floor heating has been observed around the world [61]. In Norway, practically all new bathroom floors are equipped with tiles and floor heating. The survey indicates an extensive use of floor heating also during the summer, most likely for local comfort reasons. The use of floor heating to achieve a comfortable floor temperature during summer will first increase energy use and may subsequently lead to uncomfortably high room temperatures in the bathroom and neighbouring rooms. In the case project, the floor heating was equipped with a thermostat but not with a timer function, which obviously increases the energy use and may aggravate the thermal conditions in the dwelling. An application of a floor material with a lower comfort temperature could reduce energy use without compromising on thermal comfort. In [62], comfort temperatures for different floor materials are listed, where the recommended lower temperature limit for a tessellated floor is 26 °C, whereas for a pinewood floor, it is 18.5 °C.

Another possible measure would be to substitute floor heating in bathrooms with demand-controlled heat sources with higher responsiveness, such as radiators, radiant heaters or convection heaters. Simulations for a row house in a passive house standard indicate a reduction of the total energy demand for heating by approximately 7% when using a convective heater to heat the bathroom from the general indoor temperature of 21 °C to 24 °C two times daily for one hour rather than continuously maintaining 24 °C in the bathroom [58].

5.4. Indoor climate control

There is a high degree of satisfaction with the heating system in the living room and bathroom, where the temperature is locally controlled. This indicates that the chosen heating strategy for these rooms is suitable for the provision of thermal comfort. The heat sources should, however, be equipped with a timer function to reduce the energy use and unnecessary and unwanted heat flow to bedrooms.

A significantly lower satisfaction with the heating strategy in the bedroom is observed, where the temperature is controlled by manually adjusting the set-point temperature of the supply air via a display in the living room. The primary reason reported for discontent is that the supply air is perceived as being too warm. The findings illustrate that energy efficiency measures have substantially reduced or even eliminated problems with too low temperatures on the one hand, but, on the other hand, they have introduced a new challenge – to achieve preferred lower temperatures in bedrooms.

Extensive window opening durations in bedrooms are observed, even during winter, primarily to reduce the temperature, not to increase the fresh air supply. Window ventilation contributes to obtaining desired temperatures in bedrooms, but it obviously increases the heat loss.

A low set-point limit of the supply air temperature of 15 °C is chosen by many occupants at relatively low outside temperatures even during winter, and this lower limit appears to be an unwanted constraint in the provision of thermal comfort in bedrooms.

A low set-point temperature also reduces the heat recovery potential and consequently increases the energy use for heating. The opposite, a high set-point, can lead to unwanted high room temperatures, particularly in bedrooms, which in turn may lead to window ventilation and consequently also increase the energy use for heating. These findings illustrate the limitation of a one-zone MVHR. A conflict of goals between energy savings and thermal comfort becomes apparent, which necessitates a further elaboration of possible optimized solutions. One possible approach would be to facilitate a controllable bypass of the supply air to the bedrooms, where the supply air to a certain degree passes around the heat exchanger, controlled by the set-point temperature in the specific bedroom.

Regarding the control of the supply air flow rate, the occupants can adjust the flow rate for the whole apartment, but not individually for each room, according to the current demand. The daily CO_2 profile clearly illustrates the effects of a constant air flow rate, where CO_2 levels at presence indicate at times a moderate or low IAQ, whereas CO_2 levels at absence are at nearly the outdoor CO_2 level. This occasional undersupply and oversupply of fresh air contains a potential for improved IAQ and reduced energy use by demand-controlled ventilation [63], which should be further exploited.

Most respondents are in general satisfied with the ventilation system, but many reported difficulties with the initial use. In addition, the observed mismatch between the chosen set-point temperature of the supply air and wanted bedroom temperature indicate that the occupants lack the ability to control the temperatures, even if they understand how the system works. One occupant did not know that it was possible to change the supply air temperature, even though he had lived in the dwelling for several years. These findings indicate a potential for further improvements of MVHR systems regarding the design of user-friendly control solutions. On the other hand, the clear need regarding the initial information and instruction is observed.

6. Conclusions

The perceived and measured IAQ in the case project are consistent with findings in other studies on high-performance residential buildings, and consequently confirm the advantage of mechanical ventilation in residential buildings regarding the provision of fresh air. The perceived and measured low humidity levels during winter call for a further investigation of the impact on health and comfort and an implementation of counteractive measures. In addition, the findings revealed a need for increased user knowledge and awareness regarding the impact of user behaviour on indoor humidity levels.

The results clearly demonstrate the need for temperature zoning in residential buildings. Higher bathroom temperatures and lower bedroom temperatures are generally preferred in comparison with the temperature in other parts of the dwelling. Based on findings in this study and other studies on high-performance buildings, we suggest that comfort temperatures for winter and summer conditions specifically for living rooms, bedrooms and bathrooms are defined in the indoor climate design of residential buildings.

The user feedback and the measured room temperatures indicate that thermal comfort in living rooms and bathrooms is achieved in the case project, both during summer and winter. It can therefore be concluded that the chosen building concept and heating strategy is generally suitable for providing thermal comfort in living rooms and bathrooms.

In contrast, the mean degree of satisfaction with the heating solution is significantly lower in the bedroom than in the other rooms. The findings indicate that preferred lower bedroom temperatures have become more difficult to achieve in high-performance buildings with MVHR, even at low outdoor temperatures during winter.

An important factor that influences the bedroom temperatures was found to be the control strategy for the supply air temperature. On the one hand, the lack of knowledge and awareness of the occupants regarding the control of the supply air temperature leads to an oversupply of heat to bedrooms. On the other hand, the lower limit of the set-point temperature, a possible internal heat flow in the dwelling and the reduced heat loss through the building skin constitute technical constraints, which call for further studies for improved technical solutions.

The control of the supply air temperature via a sensor in the supply air duct appears to be a major obstacle regarding the provision of thermal comfort in bedrooms. The supply air temperature in bedrooms should therefore always be controlled by a set-point temperature in bedrooms with a sensor in or near the bedrooms. MVHR should be equipped with a controllable bypass around the heat exchanger and heat coil, which facilitates a temperature control in bedrooms independent from other rooms, but at the same time, the heat recovery potential is exploited to a maximum in association with the air exchange in other parts of the dwelling.

This study revealed an extensive use of window ventilation in bedrooms, which is mainly driven by the desire for lower bedroom temperatures, not necessarily for increasing the fresh air supply. However, an air flow through the dwelling due to window ventilation may actually provide the opposite of the intended effect in bedrooms when the window is located on the lee side. This clearly demonstrates a limitation of window ventilation for controlling the indoor climate in bedrooms. In addition, window ventilation during winter can substantially increase the energy used for heating [64]. Consequently, there is a need for an optimized heating and ventilation solution that improves thermal comfort and reduces the energy use for heating.

A general need for quality control during planning, implementation and adjustment of MVHR systems was detected, such as regarding the adjustment of flow rates and initial settings of the control system, which have an impact on both the IAQ and the thermal conditions.

The evaluation criteria for thermal comfort in current standards, such as EN 15251 [44] or ASHRAE 55 [43], should be reconsidered and revised to better accommodate for desired temperature ranges in residential buildings. In particular, for bedrooms, the defined limits do not appear to reflect the desired temperatures, both when applying the adaptive approach and acceptability ranges. It is suggested to introduce demands regarding controllability of bedroom temperatures, which enables the occupants to adjust the bedroom temperature within a feasible range independently from other rooms in a dwelling. Further research is required to assess desired bedroom temperatures and to define feasible temperature ranges based on climatic conditions. For bathrooms, it is suggested to raise the acceptable temperature range limits to match with the found comfort temperature for bathrooms of approximately 25 °C.

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Appendix 5

Paper V

M. Berge, L. Georges and H. M. Mathisen (2016). *On the oversupply of heat during winter to bedrooms in highly insulated dwellings with heat recovery ventilation*. Building and Environment,106: 389-401

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On the oversupply of heat to bedrooms during winter in highly insulated dwellings with heat recovery ventilation

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ABSTRACT

The study presented in this paper originated from observations made regarding the thermal conditions during winter in highly insulated dwellings with mechanical ventilation with heat recovery (MVHR). Previous observations indicate an oversupply of heat to bedrooms and a successive extensive window ventilation, which leads to an increased space-heating demand.

Detailed simulations were conducted to explain the causes for the observed thermal conditions and to elaborate improved solutions for heating and ventilation during winter. Various MVHR solutions and control strategies, as well as building design solutions, were investigated regarding their impact on the thermal conditions in bedrooms and on the space-heating demand.

The results clearly illustrates that the supply-air temperature and the temperatures in the living room and bathroom have substantial effects on the thermal conditions in the bedrooms. A one-zone MVHR solution, with approximately the same the supply-air temperature to all rooms, has clear limitations regarding the provision of thermal comfort in bedrooms.

The clear potential of a two-zone MVHR solution, where the supply-air temperature to the bedrooms is controlled independently from other rooms, was observed. With a two-zone MVHR solution, the thermal conditions in bedrooms can be improved and the space-heating demand can be reduced.

1. Introduction

The study presented in this paper originated from observations made regarding the thermal conditions during winter in highly insulated dwellings with mechanical ventilation with heat recovery (MVHR) during a post-occupancy evaluation (POE). As a follow-up project, detailed simulations were performed in an effort to explain the causes for the observed thermal conditions and to elaborate improved solutions for heating and ventilation during winter. The objective of this study was to contribute to the development of improved MVHR solutions and temperature control strategies that provide thermal comfort in bedrooms at the lowest possible energy use.

The following remarkable observations were made during the POE of a multifamily low-energy building project in Norway [1], which represents a typical design of new multifamily buildings. The POE comprised measurements of the indoor climate and window opening durations as well as a user survey with questions regarding the perceived indoor climate and user habits.

1. A general increased temperature level during winter was measured in the monitored dwellings, compared to typical temperature levels commonly observed in older dwellings.
2. A high degree of satisfaction with the thermal conditions in living rooms and bathrooms was reported, which indicates that increased temperatures are wanted in these rooms.
3. A significantly lower degree of satisfaction was reported regarding the thermal conditions in bedrooms, which indicates a mismatch between real and desired bedrooms temperatures during winter.
4. Substantial window opening durations in bedrooms during winter were measured.
5. The main driver for window ventilation during winter was reported to be the desire to cool down the bedroom.

In the monitoring campaign a living room temperature of ~23 °C and a bathroom temperature of ~25 °C were measured during

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winter as the mean from three apartments [1]. These observed temperatures support findings from other low-energy buildings, in which substantially higher temperatures during winter are observed than the commonly observed temperatures of ~20 °C in older residential buildings [2,3]. In a passive house multifamily building in Austria, a temperature of 23.8 °C was measured as the mean value from six bedrooms during the heating season [4]. In a study comprising 33 passive houses in Austria, Germany, Switzerland and Italy, the measured mean temperatures during the heating season were between 21 and 24 °C [5]. In a study on passive houses in Sweden comprising single-family and multifamily houses, most tenants reported that they desired a temperature of 22–23 °C, and they wanted to vary the temperature between rooms [6].

Elevated temperatures in living rooms and bathrooms affect the temperatures in bedrooms due to the heat flow through the interior walls and doors. Consequently, this heat flow may prevent the preferred lower bedroom temperatures from being reached.

Furthermore, a MVHR with an approximately uniform supply-air temperature to all rooms in the dwelling, referred to as one-zone MVHR, confronts the occupants with a conflict of goals regarding thermal comfort and energy saving when controlling the supply-air temperature. A low supply-air temperature may improve the thermal comfort in bedrooms, but results in lower heat recovery and increased energy use for space heating. In contrast, a high supply-air temperature may lead to increased window ventilation in bedrooms, thereby also increasing the energy use for space heating.

The lower degree of satisfaction with the thermal conditions in bedroom than in living rooms and bathrooms was also seen in other studies addressing the thermal comfort specifically for individual rooms in a dwelling [4,7–10]. The results in these studies were based on both quantitative and qualitative occupant evaluations in several hundred passive house dwellings.

Measured temperatures in the bedrooms in conventional buildings show a mean temperature of ~20 °C during winter [2,3]. However, the preferred bedroom temperatures vary within a wide range. In a Norwegian study on temperatures in dwellings [2], mean bedroom temperatures of below 16 °C during the measuring campaign during autumn were measured in ~30% of the bedrooms. This indicates that many occupants prefer to sleep in a cooler bedroom, which seems to be difficult to achieve with the current design of buildings and MVHR solutions without a substantial window ventilation during winter. When looking at thermal comfort in bedrooms applying the PMV-index in accordance with ISO 7730 [11], comfort temperatures in the range between 12 and 18 °C are found when assuming typical winter duvets, whereas a comfort temperature between 20 and 22 °C are found when assuming summer duvets [12]. Consequently, thermal comfort in bedrooms is not only dependent on the thermal conditions, but also highly dependent on user preferences and habits regarding clothing and choice of bedding.

The measured window opening duration in bedrooms during winter were in accordance with findings in other studies on highly insulated dwellings, in which substantial window ventilation in bedrooms was observed during the heating season [4,7–9]. Regarding the drivers for window ventilation, the reported wish to cool down the bedroom matches with observations made in a study on classrooms, in which the main driver for window ventilation was found to be temperature control, not the desire for an increased supply of outdoor air [13].

These observations raise the question to what degree the increased temperatures in highly insulated dwelling and the use of a one-zone MVHR affects the thermal conditions in bedrooms and the space-heating demand. This question was addressed in the present study, in which detailed dynamic simulations were performed for one dwelling in the case project. The dwelling was chosen because the supply air temperature was measured in addition to room temperatures, which facilitates a comparison of the simulation results with field measurements. The investigated dwelling consists of a typical building design and MVHR solution for new multifamily buildings in cool and cold climate zones and thereby makes this study highly relevant for a broad audience.

Earlier studies on temperature distribution in highly insulated dwellings with MVHR indicate limitations of current MVHR solutions with regard to the provision of desired thermal conditions in the various rooms.

In Ref. [14], detailed dynamic simulations were conducted for different control strategies and a range of influential factors, such as the interior wall insulation and the opening schedule of internal doors. The highest temperatures were found in bedrooms and the lowest in bathrooms; these results are exactly the opposite of commonly desired thermal conditions, which might explain the findings observed in real buildings.

In some studies it is claimed that temperature zoning not is necessary in residential buildings. The reasoning is based on a moderate temperature level in the dwelling of ~20 °C [3,15]. Regarding bedrooms, it is argued that thermal comfort is also achieved at a temperature of 20 °C, and therefore no temperature zoning is required [12].

However, with the observed increased temperatures in highly insulated dwellings and the introduction of a MVHR the premises have changed. Consequently, there is a need to reconsider temperature zoning in residential buildings, to explore heating and ventilation strategies as well as building design solutions that facilitate the provision of desired temperatures in the various rooms. In particular, the potential of a MVHR in which the supply air to the bedrooms bypasses the heat exchanger and heat coil, referred to as two-zone MVHR, should be further explored with regard to energy savings and thermal comfort.

A study on MVHR with different supply-air temperatures to the bedrooms was performed in a multifamily building in Austria, in which 11 of the 39 dwellings were equipped with a bypass solution. The supply air to the bedrooms could bypass the heat coil but not the heat exchanger [16]. The measured temperatures in the bedrooms with this bypass solution were found to be ~1 K lower than in the bedrooms without bypass solution. An occupant survey revealed that 52% of the respondents without a bypass solution used window ventilation permanently to reduce the bedroom temperature, whereas, for the dwellings with a bypass solution, that number was reduced to 14%. It should be noted that the supply air to the bedrooms could only bypass the heat coil and not the heat exchanger, which may explain the small difference in the temperatures.

In the present study, various MVHR solutions and control strategies were investigated to evaluate their suitability and limitations with regard to the thermal conditions in bedrooms and their impact on the space-heating demand. In addition, different insulation levels of interior walls, different opening schedules for bedroom doors and different outdoor climatic conditions were investigated.

In the parametric study, window ventilation in bedrooms is controlled by a range of set-point temperatures, corresponding to the desired bedroom temperatures.

The results will contribute to furthering knowledge about the effects of building design, MVHR solutions and control strategies as well as occupant behaviour on the thermal comfort in bedrooms and the impact on the space-heating demand.

2. Case project

The case apartment is part of the Løvåshagen cooperative in Bergen, Norway. The project was completed in 2008 and consisted of 52 low-energy apartments and 28 passive house apartments. The passive house apartments were built according to the requirements of the preliminary version of the Norwegian standard NS 3700 [17]. The case apartment is located on the top floor at the end of a building block. Windows are mainly oriented toward the west and north and are little exposed to insolation during winter due to the low solar angle and the surrounding topology (Fig. 1).

The apartment has a gross internal area of 88.6 m^2 and contains three bedrooms such that bedroom 1 is designed for two occupants and bedrooms 2 and 3 are for one occupant each (Fig. 2).

The building structure consists of floor slabs and partition walls made of reinforced concrete between the apartments, and light-weight construction for the interior partitions, exterior walls and roof. Only the interior partition walls enclosing the bathroom and toilet are insulated. A description of the building elements and their thermal properties are given in Table 1.

The heating system in the apartment consists of hydronic floor heating in the bathroom and toilet, and one radiator with a rated power of ~1000 W in the living room area.

The decentralized MVHR unit, which is a common solution in new multifamily buildings in Norway, is a Flexit SL4 R [18] and is placed above the ceiling in the bathroom. Extract-air inlets are placed in the bathroom and kitchen. Supply-air outlets are placed above the doors in the living room and bedrooms. In addition, the kitchen hood has an exhaust that bypasses the heat exchanger. An electric heat coil with a rated power of 900 W is placed in the supply air after the heat exchanger for heating the supply-air temperature up to the set-point temperature. The heat recovery efficiency of the heat wheel is ~80% [19].

The users adjust the flow rate and set-point temperature of the supply air on a Flexit CI50 control panel [20], which is placed in the living room area. There are three levels for the airflow rate, in which level two is the nominal one corresponding to a normal building use with occupation. The set-point temperature for the supply air is adjusted on a six-point position scale in a range between 15 and 25 °C. It is controlled by a sensor placed after the heat coil in the supply-air duct. The factory pre-set of the supply-air temperature is 20 °C.

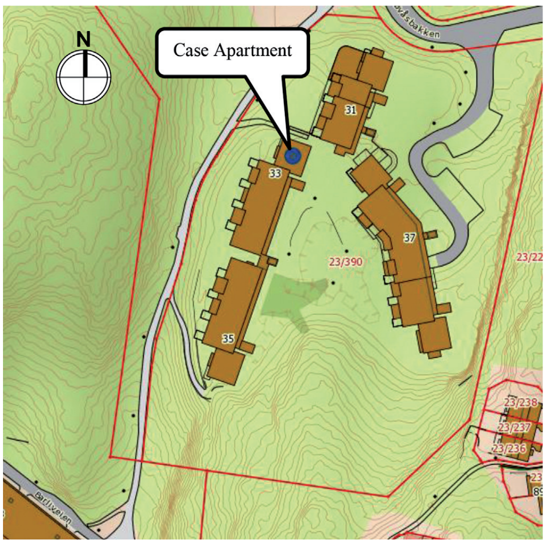

Fig. 1. Master plan with the location of the case apartment.

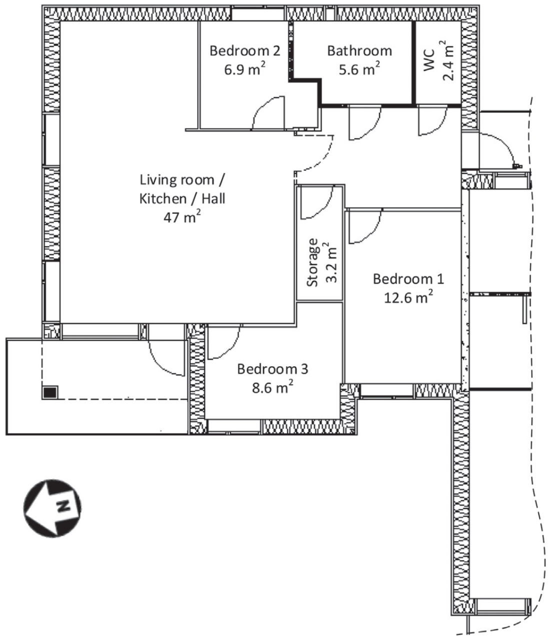

Fig. 2. Floor plan of the case apartment.

Table 2 gives the design ventilation flow rates, which are based on the Norwegian regulation on technical requirements for buildings [21]. There is no timer function or demand control; the flow rates are constant based on the user control. Assuming a constant nominal ventilation level, the total air change rate is 0.6 h^{-1}.

3. Simulation of thermal environment and space-heating demand

3.1. Simulation software and model

This study used the simulation software IDA Indoor Climate and Energy (IDA ICE), which is a whole-year detailed and dynamic multi-zone simulation tool. IDA ICE has been validated using several benchmark tests [22]. The case apartment was simulated with adiabatic walls to the apartments below and next door.

3.2. Considered MVHR solutions

The following MVHR solutions were evaluated regarding their impact on the thermal environment and the space-heating demand:

- Case A: One-zone MVHR with a reference temperature in the supply air (Fig. 3).
- Case B: One-zone MVHR with a reference temperature in bedroom 1. The heat wheel speed and heat coil are controlled by the heating set point for the bedrooms.
- Case C: Two-zone MVHR with the reference temperatures in bedroom 1 and the living room, with mutual extract in

Table 1
Description of the building elements with their thermal properties.

Building element	Description	Thermal properties
Windows	Nordan F-Tech passive with 3-layered glass 4E-16G-4-16G-E4 and insulated frame.	g-value: 0.37 Light Transmission-value: 0.58 U_g = 0.53 W/m^{2}K U_f = 0.90 W/m^{2}K
External doors	Swedoor external door	U = 1.0 W/m^{2}K
External wall toward north and south	Timber frame wall with 400 mm insulation and 13 gypsum board on the inside	U = 0.10 W/m^{2}K
External wall toward east and west	Timber frame wall with 350 mm insulation and 13 gypsum board on the inside	U = 0.12 W/m^{2}K
Internal wall without insulation	70 mm metal frame wall with 13 mm gypsum board on both sides	U = 2.23 W/m^{2}K
Internal wall with insulation	70 mm insulated metal frame wall with 13 mm gypsum board on both sides	U = 0.58 W/m^{2}K
Floor slab between dwellings	250 mm reinforced concrete	U = 3.33 W/m^{2}K
Partition wall between dwellings	200 mm reinforced concrete	U = 2.94 W/m^{2}K
Roof	Timber joist with 500 mm insulation with 13 mm gypsum board on the bottom side	U = 0.09 W/m^{2}K

Table 2
Nominal ventilation flow rates (m^3/h).

	Supply	Exhaust
Living room/kitchen	22	36
Bedroom 1	52	–
Bedroom 2	26	–
Bedroom 3	26	–
Bathroom	–	54
WC	–	36
Sum	126	126

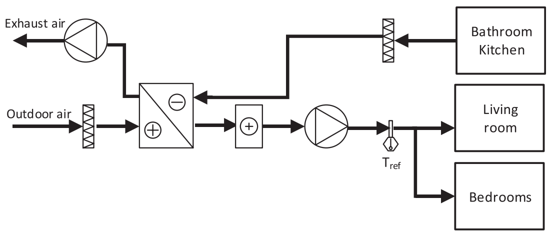

Fig. 3. Schematic diagram of the existing one-zone MVHR with a reference temperature in the supply air.

bathroom, toilet and kitchen. This is modelled by two air-handling units (AHU) in IDA-ICE where the AHU that serves the bedrooms only has heat recovery and no heat coil. In reality, one AHU could serve the whole dwelling, as illustrated in Fig. 4.

- Case D: One-zone MVHR with a constant set point of 15 °C for the supply air is used to avoid a draught and ideal space-heating units are in all rooms.

The ventilation routes through the apartment is dictated by the air supply in the bedrooms and living room and the air exhaust in

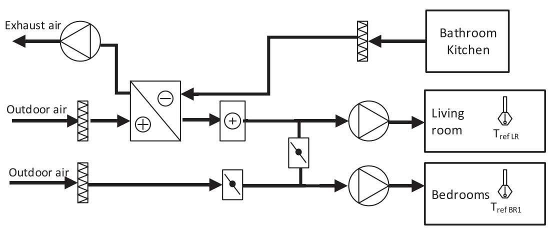

Fig. 4. Schematic diagram of the alternative two-zone MVHR with reference temperatures in the living room and in one bedroom.

the kitchen, bathroom and WC. The air flow between rooms in given by the passage through open doors or a leakage area under the doors when the doors are closed.

For all cases, constant air volume (CAV) operation is assumed. The potential of demand controlled ventilation in terms of indoor climate and heating demand deserves proper exploration but is not in the scope of this paper.

The alternative to using the temperature in the living room or the hall as a reference for the supply-air temperature, as is commonly used in air-heated passive houses [12], is not analyzed in this study. Earlier findings indicate that this control strategy results in the highest temperatures in the bedrooms [14] and consequently counteracts the provision of lower bedroom temperatures.

Another alternative is not to use a mechanical air supply to the bedrooms, but rather rely only on fresh air supplied by window ventilation. This is not considered in this study because earlier findings indicated air change rates that were too low in bedrooms with window ventilation, in particular at low outdoor temperatures [23,24].

3.3. Simulation of window ventilation

Based on the observation that supplementary window ventilation is used to achieve the desired temperatures, the window opening in IDA ICE is defined by the opening schedule, the difference between the zone temperature and the upper set-point temperature and the outdoor temperature (Fig. 5). Window opening is ideally controlled in the range from fully closed to fully open. The calculation model used in IDA ICE is described in Ref. [25].

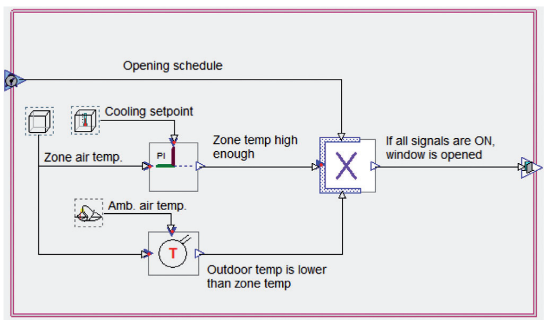

Fig. 5. Schematic window opening model in IDA ICE.

3.4. Considered varying preconditions and control strategies

The following varying simulation scenarios and control strategies that have an impact on the thermal environment in bedrooms and the space-heating demand are considered:

- Window ventilation
- Insulation level of the walls enclosing bedrooms
- Opening schedule of bedroom doors
- Number of desired cooler bedrooms
- Outdoor climatic conditions

Window ventilation in bedrooms during the night was controlled by an upper set point for the air temperature corresponding to the desired temperature by the user. The building was simulated in open terrain without obstacles and was therefore exposed to the wind.

Table 3 gives an overview of the simulated MVHR solutions and control strategies. For all cases, the total space-heating demand was calculated for various cooling set-point temperatures for window ventilation in bedrooms. The various cooling set-point temperatures correspond to the occupants' desired temperatures, which dictate the window opening behaviour. The total space-heating demand consisted of the energy demand for local space-heating units in the living room, bathroom and toilet as well as the energy demand for the heat coil in the air-handling unit (AHU).

All cases were simulated for a range of set-point temperatures for window ventilation in bedrooms between 17 and 26 °C such that the highest set point was chosen to represents the case in which basically no window ventilation during the heating season is used to control the bedroom temperature.

For cases B, C and D, the temperatures in the bedrooms are controlled by a lower heating set point for. Therefore, if supplementary window ventilation is eventually needed to control the upper set point, the upper set-point temperature for the window ventilation control is set 1 °C higher than for heating to avoid simultaneous heating and cooling.

All cases were simulated for the following alternative scenarios and control strategies:

- Interior walls enclosing bedrooms are insulated with 100 mm mineral wool or are not insulated.
- Interior doors to bedrooms are kept open all day, kept closed all day or kept closed at night only (22:00–06:00). For the closed interior doors, a leakage area of 0.01 m^2 is applied in IDA-ICE.
- Window ventilation is applied for one, two or all three bedrooms

The influence of the climatic conditions is evaluated by applying climate data from two locations in addition to the location of the case project. The location of Oslo (Norway) is applied to represent a colder climate during winter, and Frankfurt (Germany) is applied to represent a climate with higher insolation levels during winter. ASHRAE IWEC Weather files are used for these different locations [26]. In Table 4, the yearly mean temperatures and representative mean temperature during winter and summer for the three analyzed locations are given.

3.5. Other fixed input parameters

The following input and control parameters are kept unchanged for all of the simulated cases:

- Local heat sources in the living room (radiator) and bathroom (floor heating); controlled by thermostats.
- Constant set-point temperature in the living room: 23 °C.
- Constant set-point temperature in the bathroom and WC: 25 °C.
- Interior shading by a tightly woven drape with a solar gain factor of 0.44 on all windows when the room temperature exceeds 25 °C.
- Window opening in the living room based on a PI controller with a set-point temperature of 26 °C for cooling to avoid overheating during summer.
- Windows in the bedrooms are closed during the day (06:00–22:00) and opened at night using a PI controller with various set points, as defined in the simulation cases.
- The door between the hall and living room is always open.
- The doors to the bathroom and toilet are never open.

The heat gain from lighting and equipment is taken from NS3700 [27], with 1.95 W/m^2 and 1.8 W/m^2, respectively, applied 16 h per day from 06:00 to 22:00.

Heat gains from the occupants are not applied according to NS3700 [27] but instead are defined to reflect a more realistic user

Table 3
Simulated MVHR solutions and control strategies.

Case	Description	Control strategy for supply-air temperature	Range of investigated set-point temperatures for cooling by window ventilation in bedrooms at night [°C]
A.I	One-zone MVHR with the supply-air temperature as reference temperature	Constant 15 °C	17, 19, 21, 23, 25
A.II		Constant 20 °C	
A.III		Constant 25 °C	
A.IV		Supply-air temperature in dependence on outdoor temperature: $T_{SA} = 25$ °C when $T_{out} < -5$ °C; $T_{SA} = 15$ °C when $T_{out} > +10$ °C	
A.V		Supply-air temperature in dependence on daytime: $T_{SA} = 20$ °C during day (06–22); $T_{SA} = 15$ °C during night (22-06)	
B	One-zone MVHR using the temperature in bedroom 1 as the reference temperature	The set-point temperature for heating in bedroom 1 is set 2 °C below the set-point temperature for cooling by window ventilation and without an upper limit.	18, 20, 22, 24, 26
C	Two-zone MVHR with reference temperatures in living room and bedroom 1 with central exhaust	The set-point temperature for heating during the daytime in bedroom 1 is set 1 °C below the set-point temperature for cooling by window ventilation and without upper limit. The set-point temperature for heating at night is set 2 °C lower than the set point for cooling during the daytime.	18, 20, 22, 24, 26
D	One-zone MVHR without post-heating the supply air. Ideal room heating units	The set-point temperature of the supply air (15 °C) using heat recovery, but no post-heating is used. The set-point temperature for the local heating units is set 2 °C below the upper set-point temperature for cooling by window ventilation, with an upper limit of 22 °C.	18, 20, 22, 24, 26

Table 4
Yearly mean temperatures and representative mean temperature during winter and summer.

Location	Yearly mean temperature [°C]	Mean temperature January [°C]	Mean temperature July [°C]
Bergen, Norway	7.1	2.0	13.7
Oslo, Norway	6.7	−3.8	17.5
Frankfurt, Germany	10.1	2.4	19.5

behaviour. It is differentiated between the various zones and the different activity levels during day and night; see Table 5. The schedule for the heat gain from the occupants is given in Fig. 6 for the bedrooms and in Fig. 7 for all other rooms. In the bedrooms only, heat gains from the occupants are applied at night.

4. Results and discussion

First, the case of no window ventilation during the heating season is analyzed.

The different cases are numbered according to Table 3 in which the number after the underscore represents the set point for window ventilation.

For bedroom 1, monthly mean operative temperatures between ~22 and ~24 °C are observed during the coldest months for the various MVHR solutions and control strategies (Fig. 8). The operative temperature in the various rooms is in IDA ICE calculated as the average of the air temperature and the mean radiation temperature in the middle of the room [28]. The highest temperature level is seen for case AIII_25, in which the supply-air temperature is kept constant at 25 °C. The lowest temperature level is seen for the case AI_25, in which the supply-air temperature is kept constant at 15 °C. These findings clearly illustrate the substantial impact of the supply-air temperature on the bedroom temperature.

The temperature profile with the hourly mean values shows a similar pattern for the same simulation cases; see Fig. 9 for a period of three days in January. The temperature rises during the night due to the heat gains from the occupants and declines gradually during the day. The influence of the door-opening schedule is rather small when no window ventilation is applied.

When now looking at the results for a set-point temperature of ~19 °C for window ventilation, the monthly mean operative temperatures for bedroom 1 are reduced efficiently to a range between ~19 and ~21 °C during the coldest months (Fig. 10).

Large discrepancies are observed between the achieved operative temperatures in the bedroom for the different cases. During summer, small differences are observed, demonstrating the dominant influence of the outdoor temperature during this period. In contrast, during winter a significant influence of the MVHR solution and control strategy for the supply-air temperature is observed. The smallest discrepancy between the pre-set and achieved bedroom temperatures is observed for the two-zone MVHR (case C).

The temperature profile with hourly mean values for the case of a low set-point temperature (~19 °C) clearly illustrates the impact of window ventilation and the door-opening schedule for the case of a constant supply-air temperature (case AII); see Fig. 11. In contrast, for the two-zone MVHR (case C), the temperature appears to be achieved without window ventilation, and no clear influence of the door-opening schedule is observed.

Regarding the temperature distribution within the dwelling, small temperature differences between the bedrooms are observed, generally within 1 K. In the following discussions, the temperature in bedroom 1 is used to investigate the space-heating demand and the thermal environment in the bedrooms.

To investigate the impact of window ventilation on the space-heating demand, the space-heating demand is plotted for the various MVHR solutions, control strategies and different set-point temperatures for window ventilation in the bedrooms. The results clearly demonstrate the substantial impact of window ventilation on the space-heating demand for all of the investigated cases (Fig. 12).

For case AIII, in which the set-point temperature of the supply air is constantly 25 °C, and for case C, in which a two-zone MVHR adjusts the supply-air temperature according to the heat required, a considerable contribution of AHU heating is observed. For all other cases, the contribution of the AHU heating is zero or insignificantly low. For case B, in which the temperature in bedroom 1 is used as a reference for the supply-air temperature, a significant contribution of AHU heating is observed for the sub-case B_26, which is caused by the high set-point temperature in the bedroom and requires post-heating of the supply air to the bedroom.

The total space-heating demand for the dwelling and its dependence on the mean operative temperature in bedroom 1 during the coldest month is plotted in Fig. 13 for all of the simulated cases, assuming that the interior walls are insulated and the bedroom doors are closed at night only. The points on each line correspond to the four set-point temperatures. The results clearly illustrate the substantial increase in the heating demand when lower bedroom temperatures are desired, i.e., when window ventilation or a lower supply-air temperature is used to achieve the preferred bedroom temperature. The space-heating needs increase by approximately a factor of 4–5 compared to the case without window ventilation and under the assumption that this is during the energy evaluation of the project according to NS 3700 [27].

The results regarding the existing MVHR solution (case A) show that the lowest achievable monthly mean for all of the sub-cases of the existing solution is ~19 °C at a set-point temperature of 17 °C for window ventilation regardless of the control strategy for the supply-air temperature. These simulation results support the experimental results in the case project in which a bedroom temperature of ~19 °C was observed in bedrooms even if the window was constantly open during cold winter days with outdoor temperatures of approximately 0 °C [1]. In another apartment, where the bedroom window was kept closed in winter, the bedroom

Table 5
Specification of the heat gain from occupants.

Zone	Number of occupants	Presence 100% [h]	Presence 50% [h]	Activity	Met	Daily mean occupant heat [W]
Bedroom 1	2	8	8	Sleep	0.7	72
Bedroom 2	1	8	8	Sleep	0.7	36
Bedroom 3	1	8	8	Sleep	0.7	36
Other rooms	4	0	8	Seated quiet resting	1.0	72

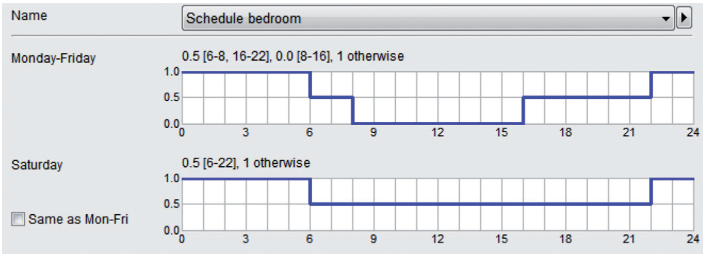

Fig. 6. Schedule of the internal heat gain from the occupants in the bedroom.

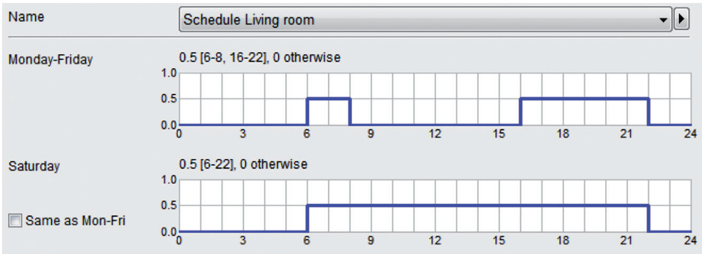

Fig. 7. Schedule of the internal heat gain from occupants in all rooms except the bedrooms.

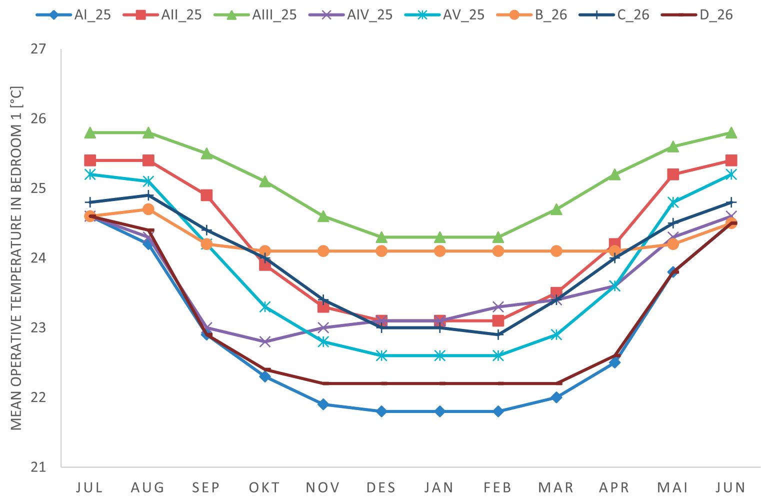

Fig. 8. Monthly mean operative temperatures in bedroom 1 for a set-point temperature of ~25 °C for window ventilation: the bedroom walls are insulated and the bedroom doors closed at night.

temperature in winter was measured as ~24 °C [1], which also matches quite well with the simulated temperature.

The highest space-heating demand in relation to the bedroom temperature is observed for the case of a constant supply-air temperature of 25 °C (case A.III), which consequently is the most unfavourable control strategy. Although a high set point leads to the highest exploitation of heat recovery, it still requires post-heating by the heat coil at times and leads to substantial heat losses when the bedroom windows are opened.

The use of the bedroom temperature as a reference temperature (case B) does not seem to reduce the space-heating demand in comparison to the existing control strategy. A somewhat lower temperature in the bedrooms can be achieved but with substantially increased heating demand.

The results of the simulated two-zone MVHR (case C) indicate that lower bedroom temperatures can be achieved at lower space-heating demand compared to all other cases. When comparing the space-heating demand at a monthly mean operative temperature of approximately 19 °C, a 15–25% lower heating demand for case C is observed in comparison to the different control strategies for the

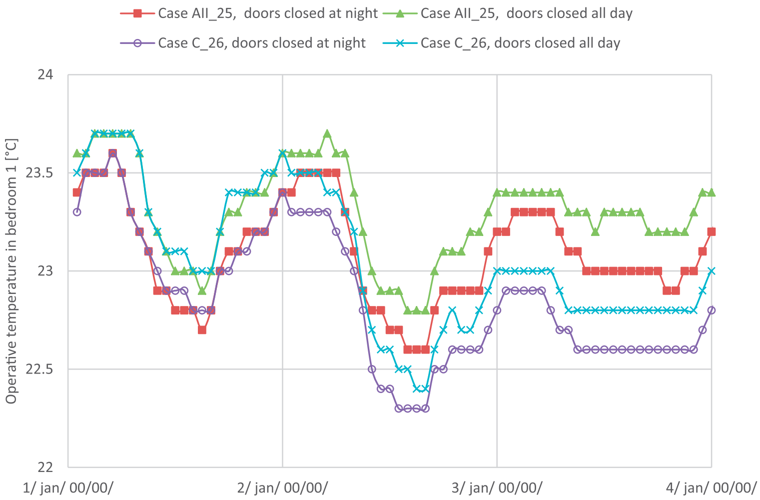

Fig. 9. Hourly mean operative temperatures in bedroom 1 for a period of three days and a set-point temperature of ~25 °C for window ventilation: the bedroom walls are insulated.

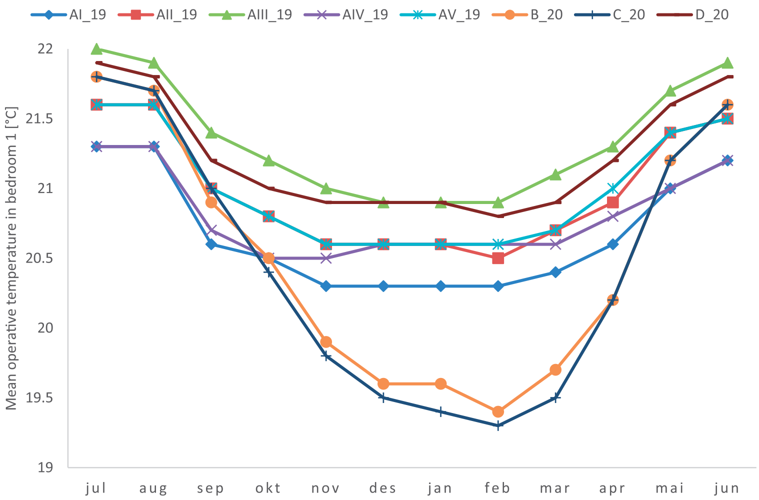

Fig. 10. Monthly mean operative temperatures in bedroom 1 for a set-point temperature of ~19 °C for window ventilation; the bedroom walls are insulated and the bedroom doors are closed at night.

existing MVHR solution. At a bedroom temperature of 20 °C, 25–50% decrease in the space-heating demand is observed for the two-zone MVHR.

An earlier study of possible measures for achieving lower bedroom temperatures (17–18 °C) during the heating season by bypassing the heat coil to provide the supply air to the bedrooms indicate a reduction in the total space-heating demand, which is explained by a reduction in the mean building temperature [3]. This reduction at lower bedroom temperatures is not observed when applying a higher temperature overall in the dwelling. In contrast, in the present study, an increase in the space-heating demand at lower bedroom temperatures is observed. The increased space-heating demand is caused by the need for bypassing not only the heat coil but also the heat exchanger to achieve the desired bedroom temperatures.

In the simulations, window ventilation is controlled by an upper temperature limit using a PI-controller, which prohibits the temperature from falling below the set-point temperature. In practice, window ventilation is generally controlled by the occupants, which may lead to large deviations from the actual desired temperature. Keeping the window open even if the temperature is already below the desired temperature, for example, during sleep at night, will increase the ventilation heat losses. Consequently, the potential of a two-zone MVHR to reduce the space-heating demand may in practice be higher than the simulations indicate. For case D with ideal room heating units, heating via local space-heating units in bedroom is only supplied for set-point temperatures of 22 °C or greater for heating in bedrooms. When comparing cases D and AI,

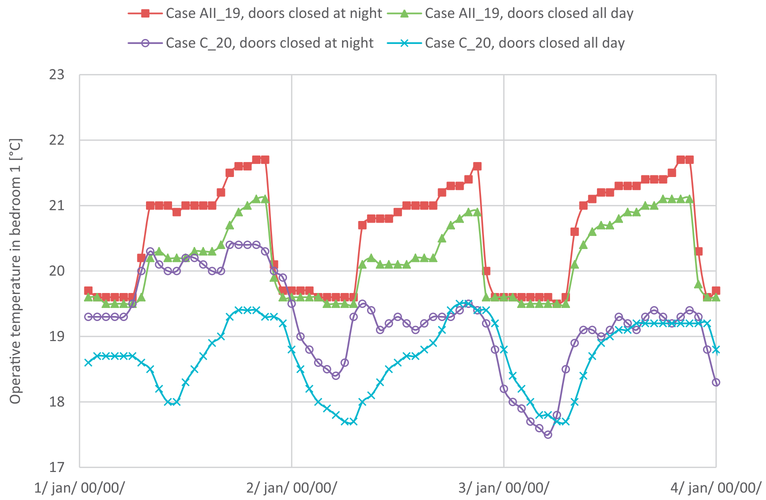

Fig. 11. Hourly mean operative temperatures in bedroom 1 for a period of three days and a set-point temperature of ~19 °C for window ventilation; the bedroom walls are insulated.

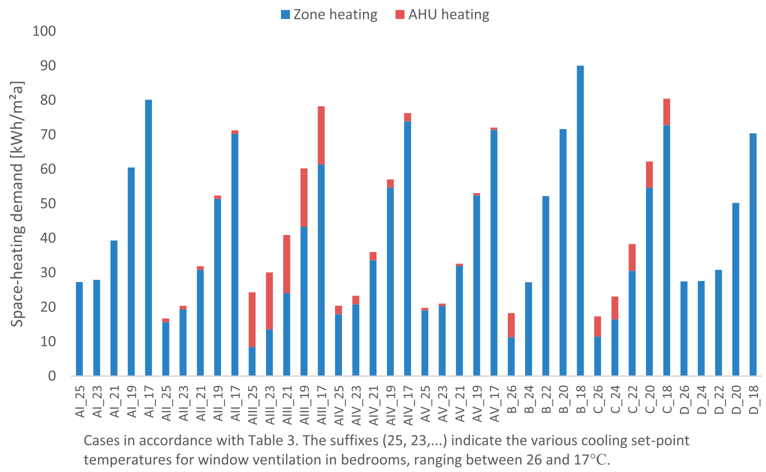

Fig. 12. Zone heating and post-heating of the supply air (AHU heating) as a function of the cooling set-point temperature for window ventilation in bedrooms (the bedroom walls are insulated, and the bedroom doors are closed at night).

notably, the space-heating demand is essentially the same, meaning that increasing the number of heat emitters in the building will not solve the problem of oversupply. These findings demonstrate that the oversupply of heat to bedrooms is in fact caused, to a large degree, by heat recovery of the exhaust air with high temperatures not by post-heating the supply air.

4.1. Influence of insulation level of interior walls

If no insulation is applied in the walls that enclose the bedrooms, the simulation of the various cases shows a slightly higher space-heating demand compared to the case with insulation (Fig. 14).

When lower bedroom temperatures are desired, the insulation of the bedroom walls contributes to a reduction in the total space-heating demand in a range of 5–10%.

4.2. Influence of opening schedule of bedroom doors

When the doors remain closed all day, the space-heating demand is substantially reduced for all cases compared to the baseline case in which the doors are closed during the night only (Fig. 15). The monthly mean temperature in bedroom 1 during the coldest month is 17 °C for the two-zone MVHR (case C) at a space-heating demand of 44 kWh/m^{2}a. In comparison, the lowest monthly mean bedroom temperature is 18.8 °C at a heating demand of 80 kWh/m^{2}a when the doors are closed during the night only. This clearly illustrates the substantial influence from opening the doors. These results agree with the findings in earlier studies on the thermal distribution within highly insulated dwellings in which the

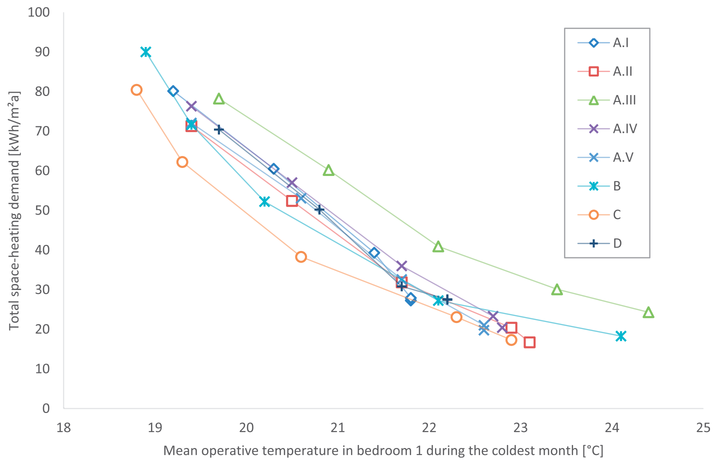

Fig. 13. Total space-heating demand for the dwelling as a function of the temperature in bedroom 1 when the interior walls are insulated and the bedroom doors are closed at night only.

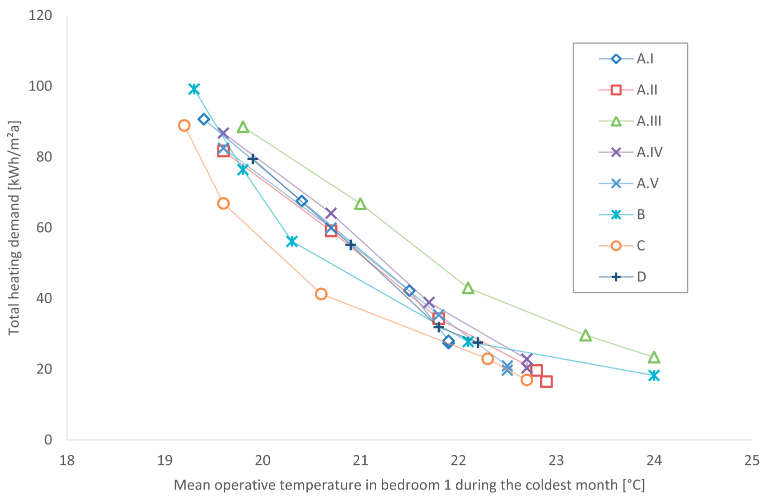

Fig. 14. Total space-heating demand for the dwelling as a function of the temperature in bedroom 1 when the interior walls are not insulated and the bedroom doors are closed at night only.

extensive impact from the schedule for opening interior doors was identified [14,15].

When doors are kept closed, the profile of case D, which represents the case with ideal room heating units, differs from the other cases at set-point temperatures above 22 °C because heating is taking place to reach the heating set-point temperature. This buckling in the profile could have been avoided by setting a lower upper limit for heating, which in the simulation was set to 22 °C.

When the bedroom doors are kept open all day, the two-zone MVHR (case C) still has the lowest space-heating demand as a function of the bedroom temperature. However, keeping the bedroom doors open all day and aiming for a low bedroom temperature of, for example, 19 °C, results in an a space-heating demand approximately four times higher than the case with doors always closed. This finding illustrates the influence of occupant behaviours on the thermal environment and energy use and demonstrates the need for increased occupant knowledge and awareness.

4.3. Influence of number of cooler bedrooms

When a lower temperature is desired in only two instead of all three bedrooms, i.e., when one room is used as an office, a generally lower total space-heating demand is observed, and the differences between the different cases decrease (Fig. 16). Still, the lowest space-heating demand at lower bedroom temperatures is achieved with the two-zone MVHR (case C).

If a lower temperature is desired in only one bedroom, a slightly higher space-heating demand is observed for the two-zone MVHR (case C) compared to the existing one-zone solution.

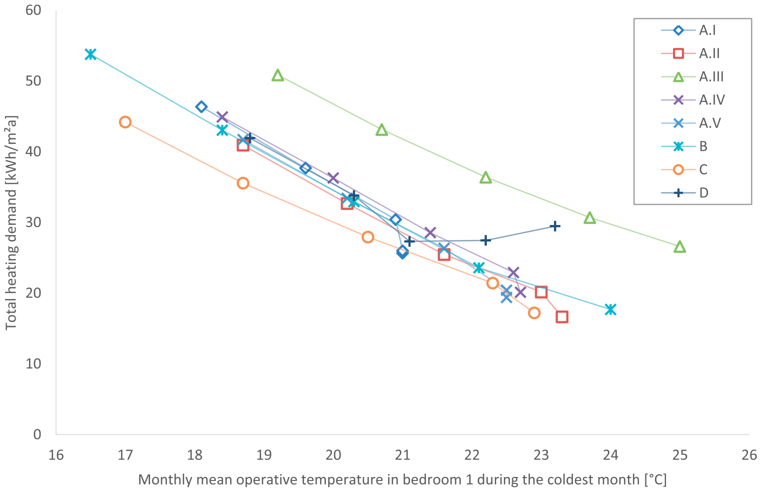

Fig. 15. Total space-heating demand for the dwelling as a function of the temperature in bedroom 1 when the bedroom doors are kept closed all day.

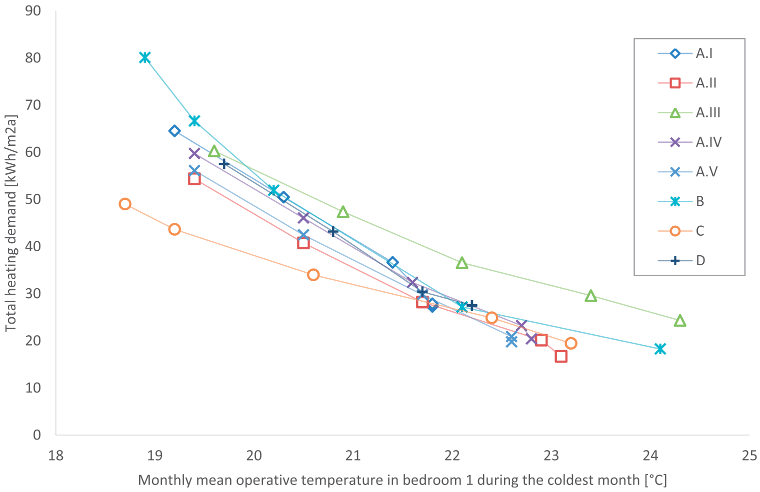

Fig. 16. Total space-heating demand for the dwelling as a function of the temperature in bedroom 1 when two bedrooms are treated as separate zones (the bedroom doors are closed at night).

These findings indicate that the implementation of a two-zone MVHR is the most beneficial with regard to energy savings when a lower temperature is desired in several bedrooms. Nevertheless, in terms of thermal comfort, in any case, a two-zone MVHR is more suitable than window ventilation for providing the desired bedroom temperatures because the influence of window ventilation varies with the outdoor temperature, wind direction and window opening pattern of the whole dwelling. Therefore, the findings suggest that it is generally beneficial to use a two-zone MVHR in dwellings for which lower bedroom temperatures may be desired.

4.4. Influence of the climatic conditions

The simulation results using different climatic conditions reflect the influence of the different outdoor temperatures and solar gains. The highest and lowest space-heating demands take place in Oslo and Frankfurt, respectively. The results from the space-heating demand in relation to the bedroom temperature indicate a similar pattern for all cases and all climatic conditions. Consequently, the advantages of a two-zone MVHR (case C) in terms of energy use and thermal conditions in the bedrooms can be generalized for a variety of climatic conditions.

4.5. Summary of main influential factors

To summarize the influence of the various MVHR solutions and control parameters on the thermal environment and space-heating demand, five representative cases are displayed in Fig. 17.

Case AII_25 represents the case in which the supply-air

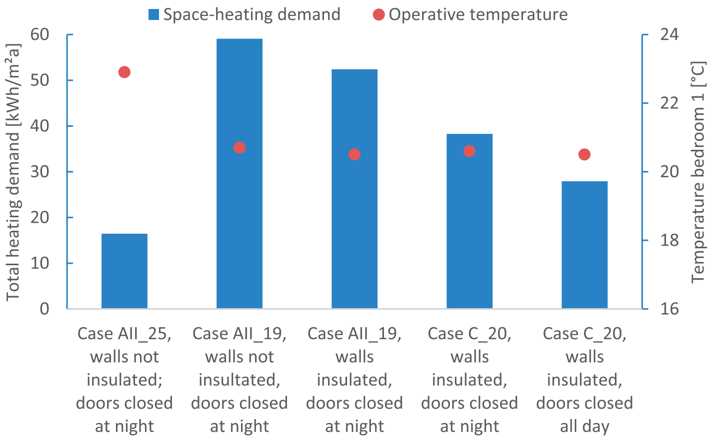

Fig. 17. Space-heating demand and operative temperature in bedroom 1 when applying different MVHR solutions and control strategies.

temperature is kept constant at 20 °C and no window ventilation is used during the heating season. The resulting space-heating demand is ~16 kWh/m^{2}a, and the operative temperature in bedroom 1 is ~23 °C.

If the occupant is using window ventilation to cool the bedroom, as illustrated by case AII_19, the operative temperature in bedroom 1 decreases to ~20 °C, and the space-heating demand increases to ~60 kWh/m^{2}a.

By insulating the interior walls enclosing the bedrooms, the heating demand decreases by 11%. When applying a two-zone MVHR, as represented by case C_20, the heating demand decreases by an additional 27%. Finally, by keeping the bedroom doors closed all day, the heating demand decreases by an additional 27%. The total reduction in the heating demand in relation to the starting point, represented by case AII_19, is 53% when applying all three measures.

When aiming on providing thermal comfort at the lowest possible energy use, the results clearly illustrate the necessity to address issues regarding the building architectonic properties, heating and ventilation systems and the occupant behaviours.

5. Conclusions

This study clearly illustrates that the supply-air temperature and the temperatures in the living room and bathroom have substantial effects on the thermal conditions in the bedrooms. The simulations support and explain the observations made during the POE of the case project. A high degree of temperature homogenization within the whole dwelling of well-insulated buildings is observed particularly when interior walls are not insulated. Interior partition walls that enclose bedrooms should therefore always be insulated in highly insulated residential buildings to facilitate desired temperature differentiation within the dwelling.

The commonly used one-zone MVHR contributes to the temperature homogenization. The possibility of reaching lower bedroom temperatures is limited even when extensive window ventilation is used, which is associated with a substantial increase in the space-heating demand. The lower temperature limit of one-zone MVHR solutions to prevent cold draughts restricts the cooling capacity of the supply air thereby preventing lower bedroom temperatures from being achieved. The use of the bedroom set-point temperature as a reference and supplying fresh air without a lower temperature limit facilitate lower bedroom temperatures but at the expense of a substantially higher space-heating demand.

It can therefore be concluded that a one-zone MVHR solution has clear limitations regarding the provision of thermal comfort in bedrooms, regardless of the control strategy for the supply-air temperature.

The clear potential of a two-zone MVHR solution for thermal comfort in bedrooms with different occupant preferences was observed. Low bedroom temperatures can be achieved with a smaller space heating demand that of one-zone MVHR solutions, at least when a low temperature is desired in several bedrooms.

A substantial effect from the bedroom door and window opening behaviour was demonstrated, confirming the need for greater occupant knowledge and awareness.

The present study was limited to a multifamily building with decentralized MVHR solutions. Further studies on other building types and MVHR solutions, such as centralized MVHR or hybrid ventilation systems, are required to determine the general validity of the conclusions.

Further studies should be performed to explore the potential of separate ventilation zones in which bedrooms have both supply outlets and extract inlets. This type of solution would reduce the flow of cool air passing from the bedrooms to the rooms where the extract inlets are installed thereby reducing the space heating demand.

Finally, the architectural design parameters of buildings, such as floor plan design, geographic orientation and thermal zoning, have not become less important in highly insulated residential buildings and should therefore be thoroughly considered and further investigated.

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Appendix 6

Questionnaire Løvåshagen (in Norwegian)

NTNU
Det skapende universitet

Beboerundersøkelse Løvåshagen borettslag

I forbindelse med et forskningsprosjekt ved NTNU ønsker vi å gjennomføre en beboerundersøkelse som skal gi økt kunnskap om innvirkning av brukeradferd på inneklima og energibruk i lavenergi- og passivhus.

Hensikten med undersøkelsen er å kartlegge opplevd inneklima i din bolig samt å kartlegge brukervaner som har betydning for inneklima og energibruk.

Vi ber deg om å ta deg ca. 10 minutter for å svare på spørsmålene.

Dette vil gi oss nyttig kunnskap og vil også kunne bidra til redusert energibruk og bedre inneklima i din leilighet.

---

2) I hvilket husnummer bor du?

- ○ 31
- ○ 33
- ○ 35
- ○ 37

---

3) I hvilken etasje bor du?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5

---

4) Eier eller leier du boligen?

- ○ Eier
- ○ Leier

---

5) Ditt kjønn

- ○ Kvinne

○ Mann

---

6) Hvor gammel er du?

○ under 20
○ 20-30
○ 31-40
○ 41-50
○ 51-60
○ 61-70
○ over 70

---

7) Antall voksne i husholdningen (over 18 år)

Velg alternativ

8) Antall barn i husholdningen (17 år og yngre)

Velg alternativ

---

9) Er det husdyr i husholdningen? (flere kryss mulig)

☐ Nei, ingen husdyr
☐ Hund(er)
☐ Katt(er)
☐ Fugl(er)
☐ Mus, rotte, hamster e.l.
☐ Annet

---

10) Røyker du?

○ Ja
○ Nei

---

11) Røykes det i boligen?

○ Aldri
○ Sjeldent (ca. 1-2 ganger i måneden)
○ Av og til (ca. 1-2 ganger i uken)
○ Ofte (hver dag)

---

12) Hvor lenge har du bodd i boligen?

○ Mindre enn 3 måneder
○ 3-6 måneder

- 6-12 måneder
- 1-2 år
- Mer enn 2 år

13) I hvilken boligtype bodde du i før du flyttet til Løvåshagen?

- Leilighet
- Rekkehus
- Enebolig
- Annet

14) Hvilken type ventilasjon hadde du i forrige bolig?

- Naturlig ventilasjon (vinduslufting/ventiler i yttervegg)
- Periodisk mekanisk avtrekk fra bad/kjøkken
- Kontinuerlig mekanisk avtrekk fra bad/kjøkken
- Balansert ventilasjon (avtrekks- og tilluftventiler)
- Annet
- Vet ikke

15) Hvilken type oppvarming hadde du i forrige bolig? (flere kryss mulig)

- Vedovn i stue
- Panelovner i stue/soverom
- Radiator (vannbåren) i stue/soverom
- Gulvvarme på bad
- Gulvvarme i stue
- Luft til luft-varmepumpe
- Annet
- Vet ikke

16) Har du i løpet av de siste 3 måneder vært plaget av noen av følgende faktorene i boligen?

	Ja, ofte (hver uke)	Ja, iblant	Nei, aldri
Trekk			
For høy temperatur			
Varierende romtemperatur			
For lav romtemperatur			
Innestengt ("dårlig") luft			
Tørr luft			

Ubehagelig lukt	◯	◯	◯
Statisk elektrisitet med småstøt	◯	◯	◯
Tobakksrøyk fra andre	◯	◯	◯
Støy	◯	◯	◯
Støv og smuss	◯	◯	◯

17) Hvordan opplever du boligen stort sett når det gjelder:

	meget dårlig	dårlig	akseptabelt	bra	meget bra
størrelse	◯	◯	◯	◯	◯
planløsning	◯	◯	◯	◯	◯
dagslys	◯	◯	◯	◯	◯
generell standard	◯	◯	◯	◯	◯

18) Hva synes du om følgende forhold?

	meget dårlig	dårlig	akseptabelt	bra	meget bra
Temperaturforhold i boligen	◯	◯	◯	◯	◯
Støyforhold i boligen	◯	◯	◯	◯	◯
Luftkvalitet i boligen	◯	◯	◯	◯	◯
Boligområde generelt	◯	◯	◯	◯	◯

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
    - Hvis "Temperaturforhold i boligen" *er lik* "dårlig"
    - eller
    - Hvis "Temperaturforhold i boligen" *er lik* "meget dårlig"
-)

19) Hva er årsak til misnøye med temperaturforholdene? (flere kryss mulig)

- ☐ alt for kalt om vinterhalvåret
- ☐ alt for varmt i sommerhalvåret
- ☐ alt for varmt hele året
- ☐ varierer med utetemperaturen
- ☐ kalde gulv i vinterhalvåret
- ☐ trekk fra vinduer
- ☐ trekk fra ytterdør
- ☐ kan ikke påvirke temperaturen
- ☐ Annet ____________

20) Hvilken form for solskjerming har boligen på solutsatte vinduer?

- ☐ Innvendige persienner/rullegardiner/gardiner
- ☐ Utvendige persienner/screen
- ☐ Utvendige markiser
- ☐ Ingen skjerming
- ☐ Annet

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Støyforhold i boligen" *er lik* "dårlig"
  - eller
  - Hvis "Støyforhold i boligen" *er lik* "meget dårlig"
-)

21) Hva er årsak til misnøye med støy? (flere kryss mulig)

- ☐ støy fra ledninger og rør
- ☐ støy fra ventilasjon
- ☐ støy fra svalgang, trappehus eller heis
- ☐ støy utenfra (trafikk, industri, lekende barn)
- ☐ Annet

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Luftkvalitet i boligen" *er lik* "dårlig"
  - eller
  - Hvis "Luftkvalitet i boligen" *er lik* "meget dårlig"
-)

22) Hva er årsak til misnøye med luftkvaliteten? (flere kryss mulig)

- ☐ luften føles innestengt
- ☐ luften føles støvholdig
- ☐ irriterende lukter
- ☐ egen matos spres i boligen
- ☐ matos fra naboer
- ☐ tobakksrøyk eller annen lukt fra naboer
- ☐ lukter utenfra (trafikk e.l.)

- ☐ fuktig luft på badet
- ☐ rim på innsiden av vinduer vinterstid
- ☐ rim på innsiden av vinduer ved matlaging
- ☐ små muligheter for lufting pga. støybelastning
- ☐ små muligheter å påvirke ventilasjonen
- ☐ Annet

---

23) Har boligen vært utsatt for fuktskader?

- ○ Ja
- ○ Nei
- ○ Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Har boligen vært utsatt for fuktskader?" *er lik* "Ja"
-)

24) Hvor har det vært fuktskader?

- ☐ på badet
- ☐ på kjøkkenet
- ☐ i taket/himling
- ☐ kondens på yttervegg/tak/gulv
- ☐ annen plass
- ☐ Vet ikke

---

25) Har du i perioder hatt plager/symptom som du antar skyldes inneklima i boligen?

- ○ Ja
- ○ Nei
- ○ Vet ikke

---

26) Har barn i husholdningen i perioder hatt plager/symptom som du antar skyldes inneklima i bolig?

- ○ Ja
- ○ Nei
- ○ Vet ikke

---

27) Har du i løpet av de siste 3 måneder hatt noen av følgende

plager?

	Ja, ofte (hver uke)	Ja, iblant	Nei, aldri
Trøtthet	○	○	○
Tung i hodet	○	○	○
Hodepine	○	○	○
Kløe/svie/irritasjon i øynene	○	○	○
Irritert, tett eller rennende nese	○	○	○
Heshet, tørrhet i halsen	○	○	○
Hoste	○	○	○
Tørr eller irritert hud i ansiktet	○	○	○

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Trøtthet" *er lik* "Ja, iblant"
  - eller
  - Hvis "Trøtthet" *er lik* "Ja, ofte (hver uke)"
-)

28) Tror du at plager med trøtthet skyldes inneklima?

○ Ja
○ Nei
○ Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Tung i hodet" *er lik* "Ja, iblant"
  - eller
  - Hvis "Tung i hodet" *er lik* "Ja, ofte (hver uke)"
-)

29) Tror du at plager med tunghetsfølelse i hodet skyldes inneklima?

○ Ja
○ Nei
○ Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Hodepine" *er lik* "Ja, iblant"
  - eller
  - Hvis "Hodepine" *er lik* "Ja, ofte (hver uke)"
-)

30) Tror du at plager med hodepine skyldes inneklima?

- Ja
- Nei
- Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Kløe/svie/irritasjon i øynene" *er lik* "Ja, iblant"
  - eller
  - Hvis "Kløe/svie/irritasjon i øynene" *er lik* "Ja, ofte (hver uke)"
-)

31) Tror du at plager med kløe/svie/irritasjon i øynene skyldes inneklima?

- Ja
- Nei
- Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Irritert, tett eller rennende nese" *er lik* "Ja, ofte (hver uke)"
  - eller
  - Hvis "Irritert, tett eller rennende nese" *er lik* "Ja, iblant"
-)

32) Tror du at plager med irritert, tett eller rennende nese skyldes inneklima?

- Ja
- Nei
- Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
    - Hvis "Heshet, tørrhet i halsen" *er lik* "Ja, iblant"
    - eller
    - Hvis "Heshet, tørrhet i halsen" *er lik* "Ja, ofte (hver uke)"
-)

33) Tror du at plager med heshet eller tørr hals skyldes inneklima?

○ Ja
○ Nei
○ Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
    - Hvis "Hoste" *er lik* "Ja, iblant"
    - eller
    - Hvis "Hoste" *er lik* "Ja, ofte (hver uke)"
-)

34) Tror du at plager med hoste skyldes inneklima?

○ Ja
○ Nei
○ Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
    - Hvis "Tørr eller irritert hud i ansiktet" *er lik* "Ja, iblant"
    - eller
    - Hvis "Tørr eller irritert hud i ansiktet" *er lik* "Ja, ofte (hver uke)"
-)

35) Tror du at plager med tørr eller irritert hud i ansiktet skyldes inneklima?

○ Ja
○ Nei
○ Vet ikke

36) Har du eller har du hatt følgende plager/symptom?

	Ja	Nei
Astma	○	○
Høysnue	○	○
Eksem	○	○

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Astma" *er lik* "Ja"
-)

37) Har du vært plaget med astma det siste året?

- Ja
- Nei

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Høysnue" *er lik* "Ja"
-)

38) Har du vært plaget med høysnue det siste året?

- Ja
- Nei

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Eksem" *er lik* "Ja"
-)

39) Har du vært plaget med eksem det siste året?

- Ja
- Nei

40) I hvor stor grad har noen i husholdningen registrert en endring i inneklimarelaterte plager etter at du/dere flyttet til Løvåshagen?

- mye mindre plager
- mindre plager
- ingen endring
- mer plager
- mye mer plager

På en skala fra 1 til 6, der 1 er svært lite tilfreds og 6 er svært tilfreds.

41) Hvor tilfreds eller utilfreds er du med ventilasjonsanlegget?

○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Hvor tilfreds eller utilfreds er du med ventilasjonsanlegget?" *er lik* "1"
  - eller
  - Hvis "Hvor tilfreds eller utilfreds er du med ventilasjonsanlegget?" *er lik* "3"
  - eller
  - Hvis "Hvor tilfreds eller utilfreds er du med ventilasjonsanlegget?" *er lik* "2"
-)

42) Hva er årsak til misnøye med ventilasjonsanlegget? (flere kryss mulig)

☐ Støy

☐ Trekk

☐ Tørr luft

☐ Gir ikke nok friskluft

☐ Foretrekker friskluft gjennom vinduer/ventiler i yttervegg

☐ Vanskelig kontrollpanel for innregulering av luftmengde/temperatur

☐ Vanskelig/brysom filterskift

☐ Annet

På en skala fra 1 til 6, der 1 er svært vanskelig og 6 er svært enkelt.

43) Hvor vanskelig var det å sette seg inn i bruken av ventilasjonsanlegget ved innflytting?

○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6

44) Hvordan styres luftmengder i ventilasjonsanlegget?

○ Luftmengder står stort sett på trinn I

○ Luftmengder står stort sett på trinn II

○ Luftmengder står stort sett på trinn III

○ Luftmengder justeres etter behov

○ Vet ikke

45) Hvordan styres temperatur i ventilasjonsanlegget?

45) Hvordan styres temperatur i ventilasjonsanlegget?

- ◯ Temperatur står alltid på trinn 1 eller 2 (laveste trinn)
- ◯ Temperatur står alltid på trinn 3 eller 4
- ◯ Temperatur står alltid på trinn 5 eller 6 (høyeste trinn)
- ◯ Temperatur justeres etter behov
- ◯ Vet ikke

På en skala fra 1 til 6, der 1 er svært lite tilfreds og 6 er svært tilfreds.

46) Hvor tilfreds eller utilfreds er du med oppvarmingsløsningen i følgende rom?

	1	2	3	4	5	6
Stue/spisestue	◯	◯	◯	◯	◯	◯
Bad	◯	◯	◯	◯	◯	◯
Soverom	◯	◯	◯	◯	◯	◯

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Stue/spisestue" *er lik* "3"
  - eller
  - Hvis "Stue/spisestue" *er lik* "2"
  - eller
  - Hvis "Stue/spisestue" *er lik* "1"
-)

47) Hva er årsak til misnøye med oppvarmingsløsningen i stuen/spisestuen? (flere kryss mulig)

- ☐ Vanskelig innregulering til ønsket temperatur
- ☐ Savner vedovn
- ☐ Ville heller hatt gulvvarme
- ☐ Annet ____________

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Bad" *er lik* "2"
  - eller
  - Hvis "Bad" *er lik* "1"
  - eller
  - Hvis "Bad" *er lik* "3"
-)

48) Hva er årsak til misnøye med oppvarmingsløsningen på

badet? (flere kryss mulig)

- ☐ Vanskelig innregulering til ønsket temperatur
- ☐ Annet

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Soverom" *er lik* "1"
  - eller
  - Hvis "Soverom" *er lik* "3"
  - eller
  - Hvis "Soverom" *er lik* "2"
-)

49) Hva er årsak til misnøye med oppvarmingsløsningen på soverommet? (flere kryss mulig)

- ☐ Vanskelig innregulering til ønsket temperatur
- ☐ Savner oppvarmingskilde (radiator/ovn)
- ☐ Ventilasjonsluften skulle vært kjøligere
- ☐ Annet

50) Omtrent hvor mange timer er vinduet på soverommet åpent/på gløtt ved forskjellige årstider?

	0	0,5	1	2	4	8	16	24
Om sommeren	○	○	○	○	○	○	○	○
I overgangsperioder vår og høst	○	○	○	○	○	○	○	○
Om vinteren	○	○	○	○	○	○	○	○
De kaldeste dagene	○	○	○	○	○	○	○	○

51) Dersom vinduet holdes lukket på soverommet om natten til tider, hva er årsaken? (flere kryss kan settes)

- ☐ Støy utenfra
- ☐ Kald luft utenfra
- ☐ Støv/pollen utenfra
- ☐ Ventilasjonsanlegget gir nok friskluft
- ☐ Reduksjon varmetap (energikostnader)
- ☐ Annet

52) Dersom vinduet holdes åpent på soverommet om natten til tider, hva er årsaken? (flere kryss kan settes)

- ☐ Av gammel vane
- ☐ Ventilasjonsanlegget gir ikke nok friskluft

☐ Ønsker det kjølig

☐ Annet

---

53) Hvordan er dine vaner når det gjelder gulvvarme på badet?

○ Gulvvarme står på stort sett hele året

○ Gulvvarme står på kun i vinterhalvåret

○ Gulvvarme er avslått hele året

○ Vet ikke

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Hvordan er dine vaner når det gjelder gulvvarme på badet?" *er lik* "Gulvvarme står på stort sett hele året"
-)

Du har krysset av at gulvvarme på badet står på hele året, antageligvis fordi det er gulvkaldt med fliser også i sommerhalvåret.

54) Kunne du tenke deg å ha et varmere material på baderomsgulvet (moderne vinyl, vannfast parkett, kork), slik at gulvvarmen ikke trengte å stå på hele året?

○ Ja

○ Nei

På en skala fra 1 til 6, der 1 er "*Ikke av betydning*" og 6 er "*Avgjørende*".

55) Hvilken betydning har følgende forhold for kjøp/leie av bolig i Løvåshagen?

	1	2	3	4	5	6
Reduserte energikostnader	○	○	○	○	○	○
Redusert miljøbelastning	○	○	○	○	○	○
Beliggenhet	○	○	○	○	○	○
Forventning til økt termisk komfort	○	○	○	○	○	○
Forventning til bedre luftkvalitet gjennom ventilasjonsanlegget	○	○	○	○	○	○
Forventet økt verdi ved fremtidig salg pga. bedre energiklasse	○	○	○	○	○	○
Arkitektonisk utforming	○	○	○	○	○	○
Innovativt byggekonsept	○	○	○	○	○	○

---

56) Hvor bevisst eller ubevisst er du på følgende forhold med hensyn til energibruk?

Ikke Litt Meget

	bevisst	bevisst	bevisst
Romtemperaturer holdes på et moderat nivå	○	○	○
Vinduer holdes stort sett lukket i vinterhalvåret	○	○	○
Det kjøpes energieffektive belysningskilder (sparepærer/LED)	○	○	○
Det kjøpes energieffektivt utstyr (f.eks. A-merkede hvitevarer)	○	○	○
Det spares på varmtvannet	○	○	○
Oppvarming slås av ved lengre fravær, f.eks. ferie	○	○	○
Luftmengder for ventilasjonsanlegget reduseres til trinn I ved fravær	○	○	○
Inne-ute-bryteren ved ytterdør brukes aktivt	○	○	○

På en skal fra 1 til 6, der 1 er "*Svært lite tilfreds*" og 6 er "*Svært tilfreds*".

57) Hvor tilfreds eller utilfreds er du generelt med å bo i et lavenergi-/passivhus?

○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Hvor tilfreds eller utilfreds er du generelt med å bo i et lavenergi-/passivhus?" *er lik* "2"
  - eller
  - Hvis "Hvor tilfreds eller utilfreds er du generelt med å bo i et lavenergi-/passivhus?" *er lik* "1"
  - eller
  - Hvis "Hvor tilfreds eller utilfreds er du generelt med å bo i et lavenergi-/passivhus?" *er lik* "3"
-)

58) Hva er årsaken til misnøye med å bo i et lavenergi-/passivhus? (flere kryss mulig)

☐ Forventningene til lavt energibruk ikke innfridd

☐ Forventinger til termisk komfort ikke innfridd

☐ Forventninger til luftkvalitet ikke innfridd

☐ Annet

59) Er du interessert i å lære mer om energibruk og inneklima i din bolig?

○ Ja

○ Nei

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Er du interessert i å lære mer om energibruk og inneklima i din bolig?" *er lik* "Ja "
-)

60) I hvilken form ønsker du å lære mer om energibruk og inneklima i din bolig? (flere kryss mulig)

☐ Kort brukermanual/flyer

☐ Personlig veiledning

☐ Eget kveldsseminar (1-2 timer) for borettslaget

☐ Kort informasjon (20 minutter) under allmøte

☐ Informasjon på hjemmeside

☐ Applikasjon for telefon med informasjon

☐ Annet

Vi ønsker å gjennomføre en detaljert måling av energibruk og inneklimaparameter i noen leiligheter for å få økt kunnskap om hvor energien brukes og hvordan brukeradferd påvirker energibruk og inneklima. Målinger vil foregå i en 1-2 års periode ved at det plasseres utstyr forskjellige steder i leiligheten.

Målinger vil gi oss nyttig kunnskap og vil i tillegg kunne bidra til å redusere energibruken og forbedre inneklima.

61) Er du åpen for å vurdere å stille din leilighet til disposisjon for en detaljert måling av energibruk og innklimaparameter?

○ Ja

○ Nei

Denne informasjonen vises kun i forhåndsvisningen

Følgende kriterier må være oppfylt for at spørsmålet skal vises for respondenten:

- (
  - Hvis "Er du åpen for å vurdere å stille din leilighet til disposisjon for en detaljert måling av energibruk og innklimaparameter?" *er lik* "Ja"
-)

62) Du har vist interesse for måling av energibruk i din boenhet. Vi ber deg om å oppgi en e-postadresse som kan brukes for å opprette dialog

63) Generelle kommentarer om hva som er bra med Løvåshagen borettslag:

64) Generelle kommentarer om hva som er mindre bra/dårlig med Løvåshagen borettslag:

Appendix 7

Questionnaire Granåsen (in Norwegian)

Evaluering av Boliger med Lavt Energibehov

Forespørsel om å delta i spørreundersøkelse.

Undersøkelsen gjennomføres innenfor SINTEF prosjekt EBLE – "Evaluering av Boliger med Lavt Energibehov" og NTNU prosjekt "Energianalyse og erfaring fra det første passivhus boligområde i Norge". Boligen som skal er ditt nye hjem er et passivhus. Det er en type bygg som vi ennå ikke har så mange av i Norge. Prosjektene er et støttet av Norges Forskningsråd, NTNU og utbyggerfirmaet som har bygget din bolig.

Vi vil hermed invitere deg til å delta i undersøkelsen ved å svare på spørreskjemaet. Målet med undersøkelsen er at vi vil gjerne vite mer om dine/ deres erfaringer med å bo i passivhus. Hvordan du/dere opplever å bo i ditt nye hus? Hva synes du/dere om komfort, brukbarhet, og utforming?

Benytt lenken for å svare:
[SURVEYLINK]

Vi ber om at du svarer innen 30. april 2014

Forskningsprosjektenes overordnet mål er å bidra til etablering av nye, robuste og funksjonelle boligbygg på passivhus- eller nesten nullenerginivå i Norge. Med utgangspunkt i evalueringen ønsker vi å finne fram til løsninger som fungerer godt med hensyn til norsk klima, byggetradisjon og levemåte.

Det er frivillig å være med i prosjektet. Svarene vil bli behandlet konfidensielt og anonymiseres. Ingen enkeltpersoner vil kunne gjenkjennes rapporten om resultatene. SINTEF prosjektet avsluttes 30.06.2016, NTNU prosjektet avsluttes 31. januar 2015.

Undersøkelsen utføres av SINTEF Byggforsk ved Judith Thomsen og NTNU ved Natasa Nord ved NTNU. Hvis det er noe du lurer på kan du ringe eller sende epost:

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Prosjektet er meldt til Personvernombudet for forskning, Norsk samfunnsvitenskapelig datatjeneste (NSD).

Med vennlig hilsen
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1. Hvor fornøyd eller misfornøyd er du med følgende forhold når det gjelder din bolig?

	Svært misfornøyd	Misfor nøyd	Verken eller	Fornø yd	Svært fornøyd
Lydisolering mot uteområder	❑	❑	❑	❑	❑
Lydisolering mot naboleiligheter (dersom finnes)	❑	❑	❑	❑	❑
Dagslystilgang i boligen	❑	❑	❑	❑	❑
Luftkvalitet ift. lukter, støv, pollen etc.	❑	❑	❑	❑	❑
Planløsning og arkitektonisk utforming	❑	❑	❑	❑	❑
Boligområdet generelt	❑	❑	❑	❑	❑

2. Hvordan opplever du luftfuktigheten innendørs om vinteren?

❑ Alt for lav luftfuktighet
❑ Noe for lav luftfuktighet
❑ Verken eller
❑ Noe for høy luftfuktighet
❑ Alt for høy luftfuktighet

3. Hva er årsak til misnøye med luftkvaliteten?

Flere kryss mulig

❑ Luften føles innestengt
❑ Luften føles støvholdig
❑ Irriterende lukter
❑ Egen matos spres i boligen
❑ Matos fra naboer
❑ Tobakksrøyk eller annen lukt fra naboer
❑ Fuktig luft på badet
❑ Små muligheter for å påvirke ventilasjonen
❑ Annet: ____________

4. Benyttes det tiltak for å øke luftfuktigheten i vinterhalvåret?

❑ Nei, ingen tiltak
❑ Luftfukter
❑ Tørking av tøy innendørs
❑ Planter
❑ Annet: ____________

5. Hvordan opplever du romtemperaturene om vinteren?

	Hett	Varm t	Noe varmt	Akkurat passe	Noe kjølig	Kjølig	Kaldt
Stue/spisestu e	❑	❑	❑	❑	❑	❑	❑
Soverom	❑	❑	❑	❑	❑	❑	❑
Bad	❑	❑	❑	❑	❑	❑	❑

6. Har du opplevd følgende ubehag/plager når det gjelder romtemperaturer om vinteren?

	Nei, aldri	Ja, iblant	Ja, ofte
Varierende romtemperatur	❑	❑	❑
Kaldt gulv i stuen	❑	❑	❑
Kaldt gulv på badet	❑	❑	❑
Trekk fra vinduer/ytterdør	❑	❑	❑
Trekk fra ventilasjonsanlegget	❑	❑	❑

7. Hvordan opplever du romtemperaturene om sommeren?

	Hett	Varm t	Noe varmt	Akkurat passe	Noe kjølig	Kjølig	Kaldt
Stue/spisestu e	❑	❑	❑	❑	❑	❑	❑
Soverom	❑	❑	❑	❑	❑	❑	❑
Bad	❑	❑	❑	❑	❑	❑	❑

8. Hvilken form for solskjerming har boligen på solutsatte vinduer?

❑ Innvendige persienner/rullegardiner/gardiner
❑ Utvendige persienner/screen
❑ Utvendige markiser
❑ Ingen skjerming
❑ Annet ____________

9. Hvor fornøyd eller misfornøyd er du med ventilasjonsanlegget når det gjelder følgende forhold?

	Svært misfornøyd	Misfor nøyd	Verken eller	Fornø yd	Svært fornøyd
Informasjon/opplæring om bruk og vedlikehold ved innflytting	❑	❑	❑	❑	❑
Brukervennlighet kontrollpanel	❑	❑	❑	❑	❑
Arbeidsmengde og vanskelighetsgrad filterskift	❑	❑	❑	❑	❑
Mengde på tilluften i stue/spisestue	❑	❑	❑	❑	❑
Mengde på tilluften i soverom	❑	❑	❑	❑	❑
Temperatur på tilluften i stue/spisestue	❑	❑	❑	❑	❑
Temperatur på tilluften i soverom	❑	❑	❑	❑	❑
Fjerning av fukt	❑	❑	❑	❑	❑
Fjerning av lukt	❑	❑	❑	❑	❑
Filtrering støv/pollen fra uteluften	❑	❑	❑	❑	❑
Lydnivået fra ventilasjonsanlegget (under normal drift)	❑	❑	❑	❑	❑

10. Hvordan opplever du inneklimaet sammenlignet med forrige bolig?

	Mye dårligere	Dårligere	Ingen endring	Bedre	Mye bedre
Luftkvalitet	❑	❑	❑	❑	❑
Romtemperaturer om vinteren	❑	❑	❑	❑	❑
Romtemperaturer om sommeren	❑	❑	❑	❑	❑
Dagslys	❑	❑	❑	❑	❑

11. Hvordan opplever du at din helse påvirkes av inneklimaet i din bolig?

❑ Meget bra for helsen
❑ Bra for helsen
❑ Ingen påvirkning
❑ Dårlig for helsen
❑ Meget dårlig for helsen
❑ Vet ikke

12. Hvor fornøyd eller misfornøyd er du med oppvarmingsløsningen i følgende rom?

	Svært misfornøyd	Misfornøyd	Verken eller	Fornøyd	Svært fornøyd
Stue/spisestue	❑	❑	❑	❑	❑
Bad	❑	❑	❑	❑	❑
Soverom	❑	❑	❑	❑	❑

13. Hva er årsak til misnøye med oppvarmingsløsningen i stuen/spisestuen?

Flere kryss mulig

❑ Vanskelig innregulering til ønsket temperatur
❑ Ujevn varme i rommet
❑ Savner vedovn
❑ Ville heller hatt gulvvarme
❑ Annet: ____________

14. Hva er årsak til misnøye med oppvarmingsløsningen på badet?

Flere kryss mulig

❑ Vanskelig innregulering til ønsket temperatur
❑ Ujevn varme i rommet
❑ Skulle heller hatt radiator
❑ Annet: ____________

15. Hva er årsak til misnøye med oppvarmingsløsningen på soverommet?

Flere kryss mulig

❑ Vanskelig innregulering til ønsket temperatur
❑ Savner oppvarmingskilde (radiator/ovn)
❑ Ventilasjonsluften skulle vært kjøligere
❑ Annet: ____________

16. I hvor stor grad er dine forventninger til din bolig oppfylt når det gjelder følgende forhold?

	Langt under forventning	Noe under forventning	Som forventet	Noe over forventning	Langt over forventning
Energibesparelse	❑	❑	❑	❑	❑
Luftkvalitet	❑	❑	❑	❑	❑
Romtemperatur om vinteren	❑	❑	❑	❑	❑
Romtemperatur om sommeren	❑	❑	❑	❑	❑
Dagslys i boligen	❑	❑	❑	❑	❑

17. Generelle kommentarer om hva som er bra med din bolig:

18. Generelle kommentarer om hva som er mindre bra eller dårlig med din bolig:

19. Hvor lenge er vanligvis vinduet på soverommet åpent eller på gløtt i løpet av et døgn ved forskjellige årstider?

	Ikke i det hele tatt	Noen minutter	Noen timer	Hele natten	Hele døgnet
Om sommeren	❑	❑	❑	❑	❑
Vår og høst	❑	❑	❑	❑	❑
Om vinteren	❑	❑	❑	❑	❑
De kaldeste dagene	❑	❑	❑	❑	❑

20. Dersom vinduet holdes lukket på soverommet om natten til tider, hva er årsaken?

Flere kryss mulig

- ❑ Støy utenfra
- ❑ Kald luft utenfra
- ❑ Støv/pollen utenfra
- ❑ Ventilasjonsanlegget gir nok friskluft
- ❑ For ikke å slippe ut varmen
- ❑ Annet: ____________

21. Dersom vinduet holdes åpent på soverommet om natten til tider, hva er årsaken?

Flere kryss mulig

- ❑ Av gammel vane
- ❑ Ventilasjonsanlegget gir ikke nok friskluft
- ❑ Ønsker det kjøligere
- ❑ Annet: ____________

22. Hvordan opplever du behovet for å lufte ved å åpne vindu i din nåværende bolig sammenlignet med din forrige bolig?

- ❑ Mye mindre
- ❑ Mindre
- ❑ Ingen endring
- ❑ Større
- ❑ Mye større
- ❑ Vet ikke

23. Hvilken viftehastighet/luftmengde for ventilasjonsanlegget er vanligvis innstilt?

	MIN	NORMAL	MAX	Anlegget er avslått, dvs. koblet fra strømmen	Vet ikke
Om natten	❑	❑	❑	❑	❑
Ved tilstedeværelse om dagen	❑	❑	❑	❑	❑
Ved fravær om dagen (jobb/skole)	❑	❑	❑	❑	❑
Ved lengre fravær (ferie)	❑	❑	❑	❑	❑

24. Hvilken temperatur på luften fra ventilasjonsanlegget er vanligvis innstilt?

	Tillegsvarme er avslått	10-15 grader	16-20 grader	21-25 grader	26-30 grader	Vet ikke
Om natten	❑	❑	❑	❑	❑	❑
Ved tilstedeværelse om dagen	❑	❑	❑	❑	❑	❑
Ved fravær om dagen (jobb/skole)	❑	❑	❑	❑	❑	❑
Ved lengre fravær (ferie)	❑	❑	❑	❑	❑	❑

25. Hvilket styringspanel for ventilasjonsanlegget har du/dere?

CI 60 (uten display) CI 600 (med display)

- ❑ Styringspanel uten display/skjerm
- ❑ Styringspanel med display/skjerm
- ❑ Vet ikke

26. Oppgi årsaken til at du ikke vet innstilling av luftmengde/temperatur for ventilasjonsanlegget.

- ❑ Annen person gjør dette
- ❑ Innstilling er ikke endret siden innflytting
- ❑ Annet: ___________

27. Opplever du et behov for en automatisk tidsstyring av luftmengde og temperatur?

Du har krysset av at du/dere har et styringspanel uten display/skjerm, dvs. ingen muligheten for automatisk tidsstyring av luftmengder og temperaturer for forskjellige tidsintervaller.

- ❑ Ingen behov
- ❑ Noe behov
- ❑ Sterkt behov
- ❑ Vet ikke

28. Hvordan benyttes muligheten for en automatisk tidsstyring av luftmengde og temperatur?

Du har krysset av at du/dere har et styringspanel med display/skjerm. Dette gir muligheten for automatisk tidsstyring av luftmengder og temperaturer for forskjellige tidsintervaller.

- ❑ Benyttes ikke
- ❑ Temperaturen senkes om natten
- ❑ Temperaturen senkes ved fravær
- ❑ Luftmengden senkes ved fravær
- ❑ Annet: ____________
- ❑ Vet ikke

29. I hvilke tidsperioder er følgende varmekilder slått på slik at de avgir varme?

	Hele året	Hele vinterhalvåret	Kun de kaldeste dagene	Er avslått hele året	Har ikke	Vet ikke
Radiator i 1. etasje	❑	❑	❑	❑	❑	❑
Radiator i 2. etasje (dersom finnes)	❑	❑	❑	❑	❑	❑
Gulvvarme i gang (dersom finnes)	❑	❑	❑	❑	❑	❑
Gulvvarme i bad	❑	❑	❑	❑	❑	❑

30. Benyttes andre varmekilder i tillegg til de som var installert ved innflytting? I så fall, hvilke?

- ❑ Nei, ingen andre varmekilder benyttes
- ❑ Vifteovn
- ❑ Panelovn
- ❑ Oljeovn
- ❑ Annet: ____________

31. Oppgi typiske romtemperaturer i vinterhalvåret.

	Mindre enn 16 grader	16-18 grader	19-21 grader	22-24 grader	Mer enn 24 grader	Vet ikke
Stue/spises tue	❑	❑	❑	❑	❑	❑
Soverom	❑	❑	❑	❑	❑	❑
Bad	❑	❑	❑	❑	❑	❑

32. Er oppgitte temperaturer målt eller stipulert/gjettet?

❑ Målt
❑ Stipulert/gjettet

33. Hva er din typiske bekledning innendørs om vinteren?

❑ Lett bekledning (shorts/kortermet skjorte)
❑ Normal bekledning (langbukse/skjorte)
❑ Varm bekledning (langbukse/genser/innesko/tøfler)

34. Skrur du/dere temperaturen ned om natten?

	Nei, aldri	Av og til	Ja, stort sett	Har ikke	Vet ikke
Radiator 1. etasje	❑	❑	❑	❑	❑
Radiator 2. etasje (dersom finnes)	❑	❑	❑	❑	❑
Gulvvarme gang (dersom finnes)	❑	❑	❑	❑	❑
Gulvvarme bad	❑	❑	❑	❑	❑

35. Kunne du tenke deg å ha et varmere material på baderomsgulvet, f.eks. vannfast parkett eller vinyl, slik at gulvvarmen ikke trengte å stå på hele året?

Du har krysset av at gulvvarme på badet står på hele året, antageligvis fordi det er gulvkaldt med fliser også i sommerhalvåret.

❑ Ja
❑ Nei

36. Hvilken energiklasse har følgende elektrisk utstyr?

	A++	A+	A	B	C eller lavere	Har ikke dette utstyret	Vet ikke
TV	❑	❑	❑	❑	❑	❑	❑
TV nummer to	❑	❑	❑	❑	❑	❑	❑
Stereo-/hjemmekinoanlegg	❑	❑	❑	❑	❑	❑	❑
Stereo-/hjemmekinoanlegg nummer to	❑	❑	❑	❑	❑	❑	❑
Mikrobølgeovn	❑	❑	❑	❑	❑	❑	❑
Tørketrommel	❑	❑	❑	❑	❑	❑	❑

37. Oppgi antall datamaskiner som brukes i boligen

	0	1	2	3	Annet	
Stasjonær PC/MAC	❑	❑	❑	❑	❑	____________
Bærbar PC/MAC	❑	❑	❑	❑	❑	____________

38. Oppgi annet elektrisk utstyr som brukes jevnlig i boligen.

Flere kryss mulig

- ❑ Kaffetrakter
- ❑ Espressomaskin
- ❑ Vannkoker
- ❑ Brødrister
- ❑ Vaffeljern
- ❑ Elektrisk grill
- ❑ Luftfukter
- ❑ Ekstra fryser
- ❑ Annet: ____________

39. Hvordan er dine typiske vaner når det gjelder utstyr som ikke er i bruk?

	Slås helt av	Står i "stand-by modus"	Står på	Vet ikke
PC/MAC	❑	❑	❑	❑
TV	❑	❑	❑	❑
Stereoanlegg	❑	❑	❑	❑

40. Er følgende utstyr koblet til strøm selv om de ikke er i bruk?

	Ja, alltid	Av og til	Nei, aldri	Ikke relevant (har ikke)	Vet ikke
PC/MAC-skjerm	❑	❑	❑	❑	❑
Bærbar PC/MAC	❑	❑	❑	❑	❑

41. Hvilken type teknologi er belysningen i følgende rom i hovesak basert på?

Flere kryss per rom mulig

	LED	Sparepære	Halogenpærer	Lysrør	Glødepærer	Vet ikke
Inngang	❑	❑	❑	❑	❑	❑
Stue	❑	❑	❑	❑	❑	❑
Soverom	❑	❑	❑	❑	❑	❑
Bad	❑	❑	❑	❑	❑	❑
Utelys	❑	❑	❑	❑	❑	❑

42. Hva er typisk antall dusjer per uke for hele familien?

	0	1-5	6-10	11-15	16-20	21-25	Mer enn 25
Antall dusjer med lengre varighet (mer enn 10 min)	❑	❑	❑	❑	❑	❑	❑
Antall dusjer med moderat varighet (5-10 min)	❑	❑	❑	❑	❑	❑	❑
Antall dusjer med kort varighet (mindre enn 5 min)	❑	❑	❑	❑	❑	❑	❑

43. Dersom du/dere har badekar, omtrent hvor ofte benyttes dette?

❑ Har ikke badekar
❑ Aldri
❑ Noen ganger i året
❑ En gang per måned
❑ En gang per uke
❑ Flere ganger per uke

44. Hvordan er dusjvanene i forhold til årstid?

❑ Det dusjes mer om sommeren enn om vinteren
❑ Det dusjes mer om vinteren enn om sommeren
❑ Det dusjes like mye sommer og vinter

45. Hvilken type dusjutstyr har du/dere?

	Hånd dusj	Hånddusj med vannsparing (sparedusj)	Overdusj (regndusj) og hånddusj	Har ikke	Vet ikke	Annet	
Bad 1	❑	❑	❑	❑	❑	❑	______ ______ _
Bad 2 (dersom finnes)	❑	❑	❑	❑	❑	❑	______ ______ _

46. Hvordan er vanene i forhold til varmtvannsforbruk?

	Alltid	Delvis	Aldri
Varmtvannet slås av ved innsåping i dusjen	❑	❑	❑
Det spares bevisst på varmtvann når en vasker hender	❑	❑	❑
Det spares bevisst på varmtvann når en vasker opp	❑	❑	❑

47. Ditt kjønn

❑ Kvinne
❑ Mann

48. Hvor gammel er du?

❑ Under 20 år
❑ 20 - 40 år
❑ 41 - 65 år
❑ Over 65 år

49. Oppgi alder og antall på beboere i boligen?

	0	1	2	3	4 eller flere
Under 12 år	❑	❑	❑	❑	❑
12 - 20 år	❑	❑	❑	❑	❑
21 - 65 år	❑	❑	❑	❑	❑
Over 65 år	❑	❑	❑	❑	❑

50. Oppgi antall personer som vanligvis er hjemme på hverdager ved forskjellige tidspunkt.

	0	1	2	3	4 eller flere
Om dagen (kl. 8 - 16)	❑	❑	❑	❑	❑
Om ettermiddagen (kl. 16 - 24)	❑	❑	❑	❑	❑
Om natten (kl. 24 - 8)	❑	❑	❑	❑	❑

51. Hvor lenge har du bodd i boligen?

- ❑ Mindre enn 3 måneder
- ❑ 3-6 måneder
- ❑ 6-12 måneder
- ❑ 1-2 år
- ❑ Mer enn 2 år

52. Hvilken boligtype bodde du i før du flyttet til din nåværende bolig?

- ❑ Leilighet
- ❑ Rekkehus/tomannsbolig
- ❑ Enebolig
- ❑ Annet ____________

53. I hvilken tidsperiode ble din forrige bolig bygget eller omfattende rehabilitert?

- ❑ før 1940
- ❑ 1940-1955
- ❑ 1956-1970
- ❑ 1971-1980
- ❑ 1981-1990
- ❑ 1991-2000
- ❑ 2001-2007
- ❑ Etter 2007

54. Hvilken type ventilasjon hadde du i din forrige bolig?

- ❑ Kun naturlig ventilasjon (vinduslufting/ventiler i yttervegg)
- ❑ Periodisk mekanisk avtrekk fra bad/kjøkken (manuelt eller fuktstyrt)
- ❑ Kontinuerlig mekanisk avtrekk fra bad/kjøkken
- ❑ Balansert ventilasjon (avtrekks- og tilluftventiler)
- ❑ Annet ____________
- ❑ Vet ikke

55. Hvilken type oppvarming hadde du i forrige bolig?

Flere kryss mulig

- ❑ Vedovn i stue
- ❑ Panelovner
- ❑ Radiator (vannbåren)
- ❑ Gulvvarme på bad
- ❑ Glødeovn under taket
- ❑ Gulvvarme i stue
- ❑ Takvarme i stue
- ❑ Luft til luft-varmepumpe
- ❑ Annet ____________
- ❑ Vet ikke