ZEB Project report 39– 2017

Laurent Georges, Maria Justo Alonso, Ruth Woods, Kang Wen,
Fredrik Håheim, Peng Liu, Magnar Berge and Martin Thalfeldt

Evaluation of Simplified Space-Heating Hydronic Distribution for Norwegian Passive Houses

The Research Centre on
Zero Emission Buildings

SINTEF Academic Press

Laurent Georges, Maria Justo Alonso, Ruth Woods , Kang Wen,
Fredrik Håheim, Peng Liu and Magnar Berge

Evaluation of Simplified Space-Heating Hydronic Distribution for Norwegian Passive Houses

ZEB Project report 39 – 2017

ZEB Project report no 39

Laurent Georges (LG), Associate Professor, Energy and Process Engineering Department (EPT), NTNU[1)]
Maria Justo Alonso (MJA), Research Scientist, SINTEF Building and Infrastructure [2)]
Ruth Woods (RW), Senior Scientist, SINTEF Building and Infrastructure[2)]
Kang Wen (KW), Student, joint Master degree NTNU[1)] and Shanghai Jiao Tong University (SJTU)
Fredrik Håheim (FH), Student, Master in Energy and Environment at NTNU[1)]
Peng Liu (PL), postdoctoral fellow at the Energy and Process Engineering Department (EPT), NTNU[1)]
Magnar Berge (MB), Associate professor, Department of Civil Engineering, Western Norway University of Applied Sciences (HVL)[3)]
Martin Thalfeldt (MT), postdoctoral fellow at the Energy and Process Engineering Department (EPT), NTNU[1)]

Evaluation of Simplified Space-Heating Hydronic Distribution for Norwegian Passive Houses

Keywords:
simplification, radiator, passive house, thermal comfort, temperature zoning

Photo on front page: Maren Adgestein (EPT/NTNU)

ISSN 1893-157X (online)
ISSN 1893-1561
ISBN 978-82-536-1558-5 (pdf)

Norwegian University of Science and Technology [1)]
N-7491 Trondheim
Tel: +47 73 59 50 00
www.ntnu.no
www.zeb.no

Western Norway University of Applied Sciences [3)]
Høgskulen på Vestlandet, Postbox 7030, 5020 Bergen, Norway
Tel: +47 55 58 58 00
www.hvl.no

SINTEF Building and Infrastructure Trondheim [2)]
Høgskoleringen 7 b, Postbox 4760 Sluppen, N-7465 Trondheim
Tel: +47 73 59 30 00
www.sintef.no/byggforsk
www.zeb.no

SINTEF Academic Press
c/o SINTEF Building and Infrastructure Oslo
Forskningsveien 3 B, Postbox 124 Blindern, N-0314 Oslo
Tel: +47 73 59 30 00, Fax: +47 22 69 94 38
www.sintef.no/byggforsk
www.sintefbok.no

Acknowledgement

This report has been written within the *Research Centre on Zero Emission Buildings* (ZEB). The authors gratefully acknowledge the support from the Research Council of Norway, BNL – Federation of construction industries, Brødrene Dahl, ByBo, DiBK – Norwegian Building Authority, Caverion Norge AS, DuPont, Entra, Forsvarsbygg, Glava, Husbanken, Isola, Multiconsult, NorDan, Norsk Teknologi, Protan, SAPA Building Systems, Skanska, Snøhetta, Statsbygg, Sør-Trøndelag Fylkeskommune, and Weber.

Husbanken partly funded this research through a competence project for sustainable buildings and building quality entitled *evaluation of the simplified hydronic heating system in Norwegian passive houses*.

Abstract

This technical report combines research results from the Norwegian Research Center on Zero Emission Buildings (ZEB) and a competence project about simplified hydronic distribution funded by Husbanken.

In the Norwegian definition of the passive house standard (NS3700), the current building code TEK10 or existing concepts of ZEB residential buildings, building envelopes are so-called *super-insulated* in order to drastically reduce the space-heating needs. Given this high level of insulation, it is theoretically possible to simplify the space-heating distribution inside the building by reducing the number of heat emitters. There is currently a lack of theoretical knowledge about the design of simplified distribution systems and lack of evidence-based feedbacks about their actual performance during real operation. The present work investigates the performance of simplified space-heating distribution in super-insulated residential buildings using one radiator per floor. The case with less than one heat emitter per floor is not considered here. In all investigated cases, the building was equipped with balanced mechanical ventilation with one centralized heat recovery and one set-point temperature for the supply ventilation air (sometimes called one-zone mechanical ventilation). In other words, all the supply ventilation air is preheated at the same temperature, without distinction between rooms.

The research methodology is based on field and laboratory measurements, calibrated detailed dynamic simulations (using IDA-ICE) as well as user's interviews. The main research question was to investigate the real, desired and perceived thermal environment in heated areas (like the living room) and in the rooms without radiators (like bedrooms). In this context, the question of window openings in bedrooms was also addressed. The research also investigated the user behavior, such as the way users operate the heating system in reality. In addition, the energy efficiency of the hydronic distribution was also analyzed in the context of super-insulated buildings: it is indeed often claimed (with limited evidence) that thermal losses from pipes would be too important.

In this report, we distinguished between conclusions that are specific to the simplified space-heating distribution with radiators (and would not be found with other standard distribution strategies, like floor heating) to conclusions that are specific to super-insulated buildings with one-zone mechanical ventilation (and that would be found whatever the space-heating distribution system used). In line with the work of Magnar Berge *et al.*, results confirm that the thermal environment in heated rooms with one radiator is experienced as satisfactory, with limited horizontal and vertical temperature differences (stratification). Even though bedrooms are not equipped with heat emitters, no case has been reported where bedrooms have been experienced as too cold. On the contrary, many users still experience bedrooms as too warm (above ~16°C) and use window opening to regulate their temperature. Different control strategies have been investigated to check whether a proper control can provide low temperature in bedrooms without increasing space-heating needs significantly. None of the investigated controls managed to reach temperatures of ~16°C (or below) without large increase of the space-heating needs. Therefore, the research rather suggests that the building concept should be reconsidered, especially the one-zone mechanical ventilation that tends to homogenize temperature inside the building and prevent temperature zoning. The research also showed that the energy efficiency using hydronic distribution in super-insulated buildings can be kept high if state-of-the-art techniques are correctly applied (meaning a weather-compensated heating curve, a low temperature for the water in the distribution system and, obviously, shutting down the system outside the heating season).

This report presents the research methodology and results exhaustively. For the reader that has limited time or no interest in technical details, it is recommended to only read the introduction (Chapter 1) and the conclusion chapter (Chapter 8).

Contents

1. INTRODUCTION 7
1.1 CONCEPT OF SPACE-HEATING SIMPLIFICATION IN SUPER-INSULATED BUILDINGS 7
1.2 RESEARCH QUESTIONS 7
1.3 RESEARCH METHODS 9
1.4 BUILDING INVESTIGATED 10
1.5 SHORT LITERATURE REVIEW 11
1.6 HOW TO READ THIS DOCUMENT? 13
2. EVALUATION OF SPACE HEATING SYSTEMS: USER BEHAVIOUR 14
2.1 PREVIOUS THERMAL EXPERIENCES 15
2.2 THE MAIN LIVING AREAS 17
2.2.1 Miljøbyen Granåsen 17
2.2.2 Living Lab 18
2.3 BEDROOMS TEMPERATURES 20
2.3.1 Miljøbyen Granåsen 21
2.3.2 Living Lab 22
2.4 UNDERSTANDING THE SYSTEM 22
2.4.1 Miljøbyen Granåsen 22
2.4.2 Living Lab 23
2.5 SAVING ENERGY 24
2.6 TENDENCIES FOUND IN THE RESPONSE OF THE TWELVE HOUSEHOLDS 25
3. MEASUREMENTS 27
3.1 DESCRIPTION OF MEASUREMENTS 27
3.1.1 Apartments 27
3.1.2 Terraced houses 29
3.2 FIELD MEASUREMENT RESULTS FOR THE APARTMENTS 33
3.2.1 Apartment 1 33
3.2.2 Apartment 2 37
3.3 FIELD MEASUREMENTS RESULTS IN THE TERRACED HOUSES 41
3.3.1 House 1 41
3.3.2 House 2 47
3.4 DISCUSSION AND CONCLUSIONS OF THIS CHAPTER 52
4. IMPROVING CONTROL STRATEGIES FOR THE APARTMENT BUILDINGS 54
4.1 MODEL DEVELOPMENT AND CALIBRATION 54
4.1.1 Model development and assumptions 54
4.1.2 Model calibration 55
4.2 ALTERNATIVE SCENARIOS 56
4.2.1 Thermal comfort analysis 57
4.2.2 Energy efficiency analysis 58
4.3 DISCUSSION AND CONCLUSIONS 59
5. IMPROVING CONTROL STRATEGIES FOR THE ROW HOUSES 61
5.1 MODEL DEVELOPMENT AND CALIBRATION 61
5.1.1 Model development and assumptions 61
5.1.2 Model calibration 62
5.2 ALTERNATIVE SCENARIOS 65
5.2.1 Row house in the middle of the block 66
5.2.2 Row house in the corner of the block 67
5.2.3 TEK10 row house in the middle of the block 68
5.3 DISCUSSION AND CONCLUSIONS 70

6. ENERGY EFFICIENCY OF HYDRONIC DISTRIBUTION SYSTEMS IN SUPER-INSULATED RESIDENTIAL BUILDINGS 72
6.1 INTRODUCTION 72
6.2 METHODOLOGY 73
6.2.1 Building test case 73
6.2.2 Definition of the SH distribution loop 74
6.2.3 Modelling of the building and the SH distribution 75
6.2.4 Performance indicators 76
6.3 ANALYSIS AND DISCUSSION OF RESULTS 76
6.3.1 Distribution efficiency 77
6.3.2 Simplified versus detailed modelling 78
6.3.3 Overall energy efficiency 80
6.3.4 Discussion 82
6.4 CONCLUSION 83
7. MEASUREMENTS IN THE ZEB LIVING LAB 85
7.1 THE ZEB LIVING LAB 85
7.1.1 Plan of the Living Lab and envelope properties 86
7.1.2 Ventilation and heating systems 87
7.2 MEASUREMENT SETUP 88
7.2.1 Test cases and matrix 88
7.2.2 Internal heat gains 89
7.2.3 Sensor arrangement 89
7.3 RESULTS AND DISCUSSION 91
7.3.1 Floor heating with all Tset,SH at 21 °C and internal door closed (case 1) 91
7.3.2 Floor heating with bedroom set-point at 16 °C and internal doors closed (case 2) 92
7.3.3 Radiator with set-point at 21 °C, no night setback, internal doors closed (case 3) and open (case 4) 93
7.3.4 Radiator heating with night setback, open (case 5) and closed doors (case 6) 97
7.4 CONCLUSIONS 98
8. OVERALL CONCLUSIONS 100
8.1 WHAT ARE THE RESULTING TEMPERATURE DIFFERENCES BETWEEN HEATED AND NON-HEATED ROOMS FOUND DURING REAL OPERATION? 100
8.2 HOW TO GET WARM BEDROOMS? 101
8.3 HOW TO GET COLD BEDROOMS? 102
8.3.1 Can we get cold bedrooms without window opening by a proper control? 103
8.3.2 What is the increase of the space-needs induced by window opening or a reduction of the set-point temperature of the supply ventilation air? 103
8.3.3 Is there energy efficient ways to control the building to create temperature zoning, or more drastic technical measures should be taken? 104
8.4 IS THE THERMAL ENVIRONMENT IN HEATED LIVING AREAS COMFORTABLE? 105
8.5 IS THE BUILDING ENOUGH "*RESPONSIVE*" IN A CHANGE OF SET-POINT TEMPERATURE? 106
8.6 DOES THE SIMPLIFICATION OF THE SPACE-HEATING DISTRIBUTION INCREASE THE ENERGY EFFICIENCY COMPARED TO A TRADITIONAL DISTRIBUTION IN EACH ROOM? 107
8.7 DO THE BUILDING USERS HAVE A GOOD UNDERSTANDING OF THE WAY THEY SHOULD OPERATE THE BUILDING? 109
8.8 SIMPLIFIED SPACE-HEATING DISTRIBUTION, KEEP IT OR LEAVE IT? 109
9. REFERENCES 111

APPENDIX

1. Introduction

This introduction aims at giving the background of this research. It describes the need for research along with the research objectives, the methodology used as well as the buildings and households investigated. This research work has been performed using different research methods to answer this multi-disciplinary problem. The chapter ends with instructions for readers to find information in this report (the final section entitled “How to read this document?”).

1.1 Concept of space-heating simplification in super-insulated buildings

The necessity to drastically reduce the space-heating (SH) needs of residential buildings in Europe has prompted the emergence of building concepts based on a *super-insulated building envelope*, such as the passive house (PH) standard [1]. Developed for central Europe (e.g. Germany), the PH concept has been extended to Nordic countries. In particular, Norway has elaborated a national definition with the NS 3700 standard [2]. The current Norwegian building regulation, TEK10, requires comparable energy performance for the building envelope. Besides, the proposed concepts for Zero Emission Buildings (ZEB) are most often based on super-insulated building envelopes [3, 4].

While the construction of super-insulated envelopes is more challenging, these envelopes also offer opportunities. Given the level of insulation and the use of high-performance windows (typically triple-glazed windows), the SH distribution system can be simplified because it is theoretically not necessary anymore to place a heat emitter in each room, or in front of windows. This simplification is at the basis of the German definition of the PH [1], the primary motivation for simplification being the reduction of investments. A well-known simplified distribution approach is the so-called centralized air heating [1, 5] but one could also consider one wood stove [6-8] or a limited number of low-temperature radiators. Typically, the number of radiators is limited to one per floor; except for bathrooms equipped with their own heat emission system (most often floor heating). In addition, in Nordic conditions, the air handling unit (AHU) usually has a small heating battery after the heat recovery unit to ensure that the fresh air supplied to the building does not generate cold draft.

1.2 Research questions

The present work focuses on simplified distribution using a limited number of radiators in residential buildings. Conclusions from the current work are not meant to be directly applied to office buildings [9]. The study investigates the configuration with one radiator per floor. Cases with less than one heat emitter per floor are thus not covered by this study.

In general, there is a lack of knowledge to support the simplification of the SH distribution system in PH. A very limited amount of these studies focuses on the simplified SH distribution using a limited number of radiators in residential buildings. In the Norwegian context, an exception is the work of Wigenstad [10], essentially focusing on the concept and design of simplified radiator distribution. **To date, there is a lack of detailed analyses proving that this concept works in real conditions, is robust and leads to user satisfaction**.

In our work, the primary research scope of the simplified SH is extended to integrate more general questions about the heat distribution in super-insulated buildings. The performance of SH systems reported during our investigations is also influenced by the thermal properties of super-insulated building envelopes (which significantly differ from traditional less insulated buildings) and not exclusively by the simplified SH distribution system. In order not to attribute conclusions to the simplified SH distribution which are in fact shared by all types of SH distributions in super-insulated buildings, research questions (and discussions) are adapted to distinguish both aspects and avoid confusion.

The research questions are interconnected and defined here below:

1. On the one hand, using simplification, limiting the number of the heat emitters to a couple of rooms inevitably leads to temperature differences with the other "non-heated" rooms. A priori, one may think that the temperature in rooms not equipped with a radiator will be experienced as too cold, typically bedrooms. On the other hand, super-insulation tends to homogenize the temperature inside the building envelope. A first reason is the insulation of external walls and high-performance windows but also as a result of the balanced mechanical ventilation with a high-efficiency heat recovery unit. The heat from the air extracted from the building is mainly recovered to preheat the supply air; this supply air is blown in the occupancy rooms (living room) and bedrooms. Furthermore, internal gains play a major role to counterbalance thermal losses from super-insulated envelopes. Internal gains depend on the activity from occupants inside the building (metabolic activity, use of artificial lighting or household appliances). Finally, the temperature difference between rooms will also be dependent on the way users operate the building. The set-point temperature for the radiators or for the air-heating battery is a critical parameter. It is also known that the opening of interior doorways is an efficient physical process to homogenize temperature in super-insulated buildings [1, 11]. This factor is also important and depends a lot on the user behavior. Summing up all these aspects, **the resulting temperature differences between rooms inside the building is not known and needs to be clarified.** The answer is not trivial and deserves a detailed analysis as the temperature distribution inside the building is the combined result of a complex building thermal dynamics and user behavior. This question is also a good example where the simplified SH cannot be investigated alone but needs to be combined with the thermal properties of super-insulated buildings. **A corollary interrogation to this first question is to know how these temperature differences between rooms can be influenced by users. How they can adjust it to meet their expectations using control?**
2. A second aspect is related to the relatively slower thermal dynamics of super-insulated buildings. In simple words, if the SH emission system is stopped during a period of time, the resulting temperature decrease is significantly slower than in a traditional less insulated building (with a comparable thermal mass). It may alter the perception of thermal comfort for users. This slower dynamics affects the ability to quickly decrease the temperature inside the envelope, for instance, to apply a different temperature during daytime and night time. In addition, if some rooms need to be re-heated after a period with a lower set-point temperature but have no heat emitter installed, these rooms will be heated up only by the heat transferred from the neighbouring rooms and the mechanical ventilation. This dynamic is also slower than using one heat emitter directly in the room. Consequently, **the slower dynamics of super-insulated buildings needs to be investigated, along with the user's acceptance**. **Combining points (1) and (2), it is important to determine whether users can technically create low temperatures in bedrooms if they would like to.**
3. A third aspect is related to thermal losses from pipes of the SH distribution using radiators. In a traditional less insulated building, standard hydronic systems have at least one radiator in each room, resulting in a long pipework. If these pipes are located inside the protected volume of the building and with proper control, the effect of thermal losses of pipes over the SH system overall efficiency is limited. The so-called distribution efficiency is kept above ~95% for these less insulated buildings. If a standard distribution loop is kept in a super-insulated building, the thermal losses from pipes would not be small anymore compared to the space-heating needs of the building (or the pipe losses compared to the heat emitted by the radiators). This high share of thermal losses could lead to a major drop in the SH distribution efficiency. **The energy efficiency of the SH distribution should then be investigated in the context of super-insulated buildings. It will be also checked whether a simplified SH distribution could be a way to reduce the total length of pipes, reduce the pipe thermal losses and then keep the distribution energy efficiency high**. This aspect has never been investigated in detail in the technical literature (according to authors 'opinion).
4. Last but not least, the heating system is built to satisfy occupant's expectations/wish and is controlled by them. **The user acceptance of simplified space-heating should be investigated. The actual way they control/use the heating system should be highlighted. Users either change set-point**

temperatures (for the thermostatic valves or the air-heating supply temperature) or open internal doors and windows to control their thermal environment. Opening windows during the SH season (mostly winter time) may have a strong adverse effect on the SH needs. Finally, it is important to determine whether users got sufficient and clear explanations (instructions) on the way to operate the building according to their expectations concerning indoor temperature and indoor air quality (IAQ).

1.3 Research methods

These research questions can only be answered if all the aspects are combined in a multi-disciplinary analysis: building thermal dynamics along with the space-heating system, control, building occupants (as internal gains, people to satisfy and operator). The following research methods have thus been applied:

1. **Detailed measurements in a real occupied building.** Sensors were placed in each room in passive houses during a relatively short period (i.e. two weeks) of the space-heating season to measure air temperature. Some critical rooms, such as the living room, were equipped with more temperature sensors to monitor the air temperature distribution (such as the vertical temperature stratification). The openings of internal doors and windows have also been recorded using contact sensors. Also, the set-point temperatures for the space-heating (position of thermostatic valves and air-heating temperature) and the set-point for ventilation airflow rates have been registered manually by users using a diary. These measurements have been combined with an interview to determine the indoor temperatures users were perceiving and expecting. This enables to compare the expected and perceived indoor temperatures to the set-point temperatures applied in the control and to the temperatures measured in reality. It also enables to monitor the temperature differences between rooms that are found during real operation, to highlight the way users actually control the building, and if they control it coherently to their expectations.
2. **Detailed measurements in a real non-occupied building.** This method enables to remove the user behaviour from the analysis and to leave the physical aspects alone. Especially, it enables to study the thermal dynamics of super-insulated building envelopes combined with the heating system. Internal gains are introduced artificially and are strictly controlled by the experimenter. Internal doors are kept constantly closed or open during experiments. As for method (1), a detailed measurement of the indoor temperatures is performed.
3. **Calibrated detailed dynamic simulations.** Building performance simulation (BPS) and more specifically detailed dynamic simulations (using IDA-ICE [12]) have been performed. The building models have been calibrated against field measurements when available. In this case, some assumptions had to be made about user behaviour and their interactions with the building. The problem is thus intrinsically simplified. Nevertheless, BPS is a powerful tool. It enables to extrapolate the performance of the building from a short measurement period to the entire space-heating season, for instance, to evaluate the yearly space-heating needs. It also enables to investigate the effect of different control strategies on the temperature distribution inside the building and their respective influence on the space-heating needs. In addition, the energy efficiency of the space-heating distribution can be investigated, an aspect that is very difficult to measure directly. The effect of different layouts of the SH distribution loop (simplified vs. standard), the temperature control for the water distribution, as well as the pipe insulation can be investigated.
4. **Semi-structured interviews**. This interview form includes a sequence of themes, as well as a set of questions. It is open to changes of sequence and questions. The interview style encourages the follow-up of answers given. The purpose of an interview is to obtain qualitative descriptions of the "lifeworld" of an informant. It is a conversation with structure and purpose, which the researcher defines and directs by introducing the topic and following up answers with predefined questions [13]. In this case, interviews were performed to highlight the user behaviour regarding building operation, technology acceptance and expectations. User behaviour is expected to play a role in the actual performance of the simplified SH

distribution in super-insulated buildings. Building performance is understood concerning physical quantities, for instance, the resulting indoor temperature or the space-heating needs. However new technology is implemented in contexts that have pre-established behavioural patterns or cultural expectations. In the Norwegian context, householders are dealing with cold winters, and often have space heaters in all rooms and wood stoves in the main living areas. In other words, the use and understanding of simplified heating systems may be influenced by the user's previous experience of space-heating. Performance is therefore understood within a context which includes aspects such as identity, security and privacy [14]. Thermal comfort is also considered and understood in a larger context than just indoor temperatures [15].

1.4 Building investigated

Research is based on one housing estate, Miljøbyen Granåsen, and one ZEB pilot building, the ZEB Living Lab, both located in the centre of Trondheim. Trondheim is located in Norway (63°30' N, 10°22' E) and has a subarctic climate with severe winters (Köppen-Geiger classification Dfc). The SH design outdoor temperature (DOT) is -19°C, the yearly-averaged outdoor temperature 5.1°C and the yearly-averaged horizontal solar irradiation is 101.6 W/m².

1. **Miljøbyen Granåsen (acronym MB)** is the largest passive house (PH) project in Nordic countries. The whole complex will consist of 430 dwelling units corresponding to 34.000 m², 17 single-family houses, 67 row houses and 341 apartments. Miljøbyen Granåsen is developed by Heimdal Bolig and was also part of the EBLE, Concerto and Eco-city research projects. In this project, measurements during occupancy have been performed in two apartments and two detached houses along with calibrated detailed dynamic simulations. Construction details of these buildings are given in Chapter 3. Semi-structured interviews have been done using six households living in apartments. For measurements, additional interviews have been performed with the households of the four buildings analysed. All the houses investigated have a simplified SH distribution using one radiator per floor, an electric heating coil after the heat recovery unit as well as electric floor heating in the bathroom(s).

Figure 1.1 Picture of the apartment block investigated in Miljøbyen Granåsen (image Interiørfoto AS).

2. **ZEB Living Lab (acronym LL)** is one of nine pilot buildings designed and built by the Norwegian Research Centre on Zero Emission buildings (ZEB) [16, 17]. The ZEB Living Lab is a detached house located on the NTNU Gløshaugen campus in Trondheim, with a gross volume of about 500 m^3 and a heated floor space of approximately 100 m^2 that aims to demonstrate how a CO_2 neutral building can be

realised in the Norwegian climate. The house was designed to perform experimental investigations, for example on air conditioning and ventilation strategies, or research on the interaction between users and low-energy buildings. The Living Lab has overlapping heat emission systems: the house can either be heated using air-heating, a single radiator or floor heating. Every system is sized to cover the entire space-heating load independently. Measurements have been done in the Living Lab without occupants using either floor heating or a single radiator. On the contrary, semi-structured interviews have been performed with six different households. Each of them temporarily lived during about one month in the building using exclusively floor heating.

Figure 1.2 Picture of the ZEB Living Lab on the Gløshaugen campus, NTNU (image by ZEB).

1.5 Short literature review

As already explained, it is hard to distinguish challenges using simplified space-heating systems from general problems related to the space-heating of super-insulated buildings. This last aspect is more general as these challenges would be found for all types of heat emission system. The question of the space-heating of a super-insulated building has already been addressed in the literature. Instead of an exhaustive review of this question, we rather focus in this short review on simplified distribution and Norwegian studies. The work of Berge *et al*. [18, 19] published in 2016 is particularly relevant. Even though they did not mention the terminology "*simplified space-heating distribution*", these works investigated buildings equipped with simplified distribution (using one radiator per floor combined with pre-heating of the ventilation air). Only the conclusions of these works related to simplified space-heating distribution are reported here. Nevertheless, these studies cover other aspects, such as the ventilation system or the relative humidity. The reader is invited to read these articles for more information and extended explanations.

In their study [19], Berge *et al.* also investigated Miljøbyen Granåsen but using questionnaires distributed to the residents of 62 detached and terraced houses. This widespread survey was not used in the present research project, but some of the questions used in Berge's work are introduced in the guide for the interview in our project. Their questionnaires enable to investigate a larger set of households, making the study more "statistically" representative. Their key findings are:

- Regarding bedrooms, 50% of occupants experience their temperature as too warm, 46% as appropriate and about 4% as too cold. About half of the residents reported their dissatisfaction with the temperature of the ventilation air (too warm). The authors suggest developing systems where the supply air temperature to the bedrooms can be controlled independently from the other rooms. A very limited number of occupants stated they would like a supplementary heat source in bedrooms.
- Regarding the living room, 89% of occupants stated that the room temperature was appropriate. There is, in general, a high degree of satisfaction with the heating solution in the living room.
- During winter, approximately half of the respondents keep the bedroom window open at least a few hours per day. Their motivation to keep the bedroom window open was determined by a multiple-choice question. Nearly all respondents (96%) specify the need for cooled air as a reason for maintaining the window in the bedroom open at times. About 35% stated that the window is kept open because the ventilation system does not provide sufficient fresh air. A few (13%) maintain the window open out of habit. All respondents who have the window open all day and most of the respondents who keep the window open all night perceive the bedroom temperature as being too warm. In contrast, no significant correlation was found between the perceived IAQ and window ventilation behaviour. Consequently, these findings support the hypothesis that the dominant driver of bedroom window ventilation is temperature control.
- 65% of the respondents who keep the bedroom window open all night, or all day, have pre-set the supply air temperature to a level which requires post-heating during a significant portion of the winter season. They do not operate the system coherently according to their desired indoor temperature**.** The authors also recommend investigating the influence of an appropriate control on the temperature zoning inside the building, especially on bedroom temperatures.
- Occupants expressed a small degree of satisfaction with the information and training provided at move-in regarding the use and maintenance of the ventilation system.

In their study [18], Berge *et al*. investigated apartments of the Løvåshagen project in Bergen using user survey and indoor climate measurements. Apartments built according to the Norwegian passive house and low-energy houses standard levels [2] have been analysed. Again, even though the article does not use the term "*simplified space-heating*", both types of apartments are heated using one single radiator, floor heating in the bathroom and pre-heating of supply ventilation air. 34 households answered to the occupant survey (14 lived in a PH apartment and 20 in a low-energy apartment). Long-term measurements (about one year) of the indoor climate, opening duration of windows and external doors were conducted in four apartments with measurement intervals of twenty seconds. These measurements have been performed on a much longer period than in our project (see Chapter 3). Their survey combined with measurements enabled to compare the actual, expected and perceived indoor climate. The main conclusions are:

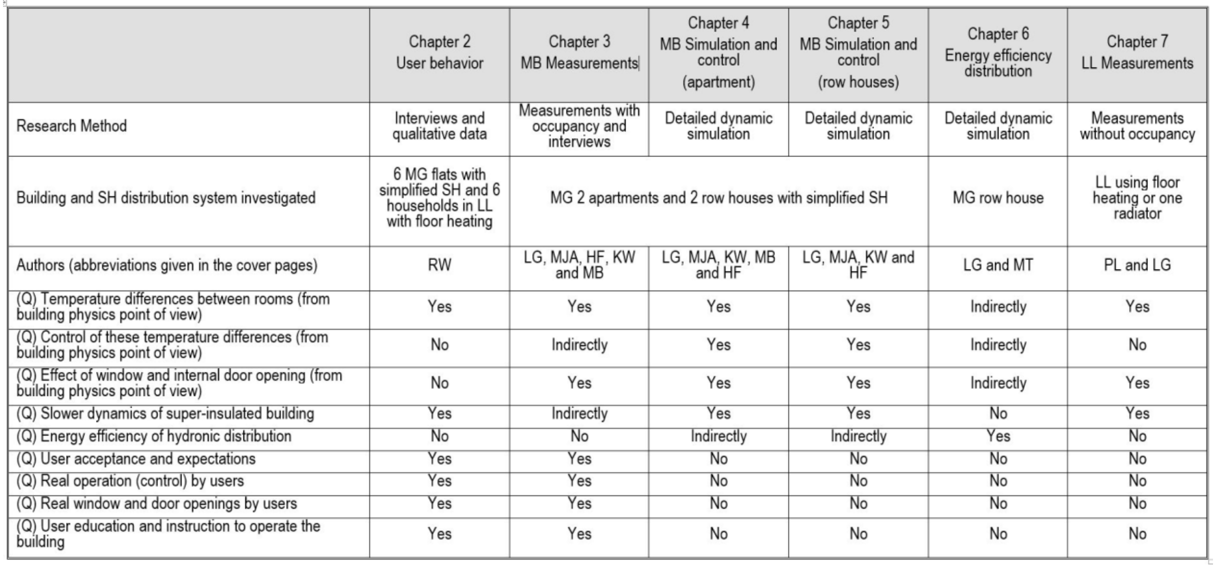
- The user survey indicates a generally high degree of satisfaction with the overall thermal environment, and no indication for an aggravation in comparison with older building standards was found.
- Results clearly demonstrate the need for temperature zoning in residential buildings: higher bathroom temperatures and lower bedroom temperatures are preferred compared to the temperature in the other parts of the dwelling. As for the previous study, the survey confirmed that occupants open bedroom windows in average 4h per day in winter time. Again, the primary motivation for window opening is temperature control in bedrooms. This is also confirmed by the measurements of CO_2 concentrations, air temperature and window opening in bedrooms. Measurements showed that opening the bedroom window is an effective way to decrease bedroom temperatures (to 14-16°C). Nevertheless, one case shows a bedroom with a high temperature of ~19°C while its window stayed opened the major part of the time. The potential explanation given was a problem in the ventilation system, high air supply temperatures or high temperature of adjacent rooms.

- The authors suggest developing systems where the supply air temperature to the bedrooms can be controlled independently from the other rooms.
- Measurements showed that the highest bedroom temperatures could be found when the supply air temperature is the lowest. This demonstrates that other factors than supply air temperature contribute more significantly to the heat balance in bedrooms, such as the heat loss to the outside and heat gain from the neighbouring rooms and internal heat gains.
- A high level of satisfaction with the heating system in the living room and bathroom was reported. In contrast, the mean degree of satisfaction for bedrooms is lower. The following reasons were specified regarding the discomfort with the heating system in bedrooms: the supply air should be cooler (29% response), the difficulty of adjusting the temperature (12% response) and the lack of local heat source (6% response).
- During the space-heating season, the mean temperature in the three monitored living rooms is 23.2°C.

1.6 How to read this document?

Different studies have been performed in the framework of our project. They are divided into chapters, describing the research methodology, presenting and discussing results in detail. The relation between these different studies, the research questions they aimed to answer and the research methodology they applied are summarized in Table 1.1.

Table 1.1 Summary of the research methodologies and questions (Q) for the different studies divided into chapters.



	Chapter 2 User behavior	Chapter 3 MB Measurements	Chapter 4 MB Simulation and control (apartment)	Chapter 5 MB Simulation and control (row houses)	Chapter 6 Energy efficiency distribution	Chapter 7 LL Measurements
Research Method	Interviews and qualitative data	Measurements with occupancy and interviews	Detailed dynamic simulation	Detailed dynamic simulation	Detailed dynamic simulation	Measurements without occupancy
Building and SH distribution system investigated	6 MG flats with simplified SH and 6 households in LL with floor heating	MG 2 apartments and 2 row houses with simplified SH			MG row house	LL using floor heating or one radiator
Authors (abbreviations given in the cover pages)	RW	LG, MJA, HF, KW and MB	LG, MJA, KW, MB and HF	LG, MJA, KW and HF	LG and MT	PL and LG
(Q) Temperature differences between rooms (from building physics point of view)	Yes	Yes	Yes	Yes	Indirectly	Yes
(Q) Control of these temperature differences (from building physics point of view)	No	Indirectly	Yes	Yes	Indirectly	No
(Q) Effect of window and internal door opening (from building physics point of view)	No	Yes	Yes	Yes	Indirectly	Yes
(Q) Slower dynamics of super-insulated building	Yes	Indirectly	Yes	Yes	No	Yes
(Q) Energy efficiency of hydronic distribution	No	No	Indirectly	Indirectly	Yes	No
(Q) User acceptance and expectations	Yes	Yes	No	No	No	No
(Q) Real operation (control) by users	Yes	Yes	No	No	No	No
(Q) Real window and door openings by users	Yes	Yes	No	No	No	No
(Q) User education and instruction to operate the building	Yes	Yes	No	No	No	No

Each chapter can be read independently, except for Chapters 4 and 5 investigating alternative control strategies which should be read along with Chapter 3. A summary of the different answers to the research questions is given in the conclusion chapter, Chapter 8. For the reader that has limited time or not interested in technical details, it is recommended to read the introduction (Chapter1) and the conclusion (Chapter 8).

2. Evaluation of Space Heating Systems: User Behaviour

This chapter focuses on user experiences about space heating systems in passive houses and zero emission dwellings. It combines interviews from two housing projects in Trondheim: Miljøbyen Granåsen, a housing estate with dwellings built to the Norwegian passive house standard and ZEB Living Lab, a zero emission detached house that also serves as a research laboratory.

The qualitative interview data was collected during two different research projects between 2012 and 2016 and is presented here together to give a "*thick description*" [20] of householder's response to heating systems. Data from a total of twelve interviews is included. Each of the two projects provides interview data from six households. The interviews were semi-structured. Each project had its interview guide, but the interview guides were developed in an inter-project collaboration and had overlapping questions and fields of interest. Questions can be found in the appendix. The interview data from both projects is anonymous. Each household group has been given a pseudonym (a common British surname), which follows the initials LL (Living Lab) or MG (Miljøbyen Granåsen).

The MG dwellings used for interviews were completed in 2014. Six apartments with different household constellations, ranging from single to two people were part of the project. All these apartments are equipped with a simplified SH distribution using radiators, where bedrooms have no radiator.

Table 2.1 A presentation of households from Miljøbyen Granåsen

Pseudonym	Household	Miljøbyen Granåsen	Moved from
Baker MG	Elderly couple	Apartment 103m^2	Detached house from 1971
Peters MG	Elderly couple	Apartment 80m^2	Detached house from 1960's rehabilitated 1993
Lewis MG	Man aged 50	Apartment 80m^2	Detached house 200m^2 from 1997
Harris MG	Elderly couple	Apartment 80m^2	Row house from 1985
Evans MG	Woman & child	Apartment 80m^2	Upgraded row house from 1960's
Moore MG	Woman	Apartment 80m^2	3 story row house from 1986

Table 2.2 A presentation of households participating in the experiment in Living Lab

Pseudonym	Date of interview	Household	Own home
Smith LL	04.11.2015	Couple, man 22, woman 22	Student apartment 52 m^2 from 1964
Jones LL	03.12.2015	Friends, woman 20, woman 21	Apartment from 1905 shared with 3 other women
Brown LL	27.01.2016	Family, woman 31, man 36, son 6 & daughter 2	Row house 185 m^2 from 2007
Wilson LL	22.02.2016	Couple, man 81, woman 68	Detached house 170m^2 from 1980's
Clarke LL	18.03.2016	Family, man 37, woman 31, daughters 3 & 2	Detached house 135m^2 from 1980's
Parker LL	22.04.2016	Couple, man 61, woman 56	Semi-detached house ca. 120m^2 from 1959

The LL experiments presented here include six different households who lived in the Living Lab for 25 days each, starting in October 2015 and ending in April 2016. Occupants were only able to use floor heating, so results cannot always be directly translated to simplified SH distribution. Some qualitative methods were used to gather data: interviews, participant observation, film and photography. The interviews considering the heating system and indoor climate took place during the last week of each residential period.

Based on feedback from the twelve households, five main areas are presented in five different sections in this chapter. Firstly, a first section deals with previous experiences. It provides a general background to understand householder's response to the heating systems. The second section focuses on main living areas, on the experience related to these rooms concerning temperatures and heating systems. The third section investigates bedrooms, meaning the user experience related to bedrooms in terms of temperatures, indoor climate and the heating system. The next section deals with the user understanding of the system, with the potential challenges for users regarding the control and operation of the heating and ventilation systems. The fifth section describes the occupant's interest in reducing energy consumption. This chapter present tendencies, preferences and results in a relatively detailed manner. The mains trends and conclusions from this study are therefore summarised in the concluding section, and which provides the reader with the short version of the chapter.

2.1 Previous thermal experiences

The analysis of this section primarily considers the user response to the heating system in the apartments in Miljøbyen Granåsen and ZZEB Living Lab based on the experience they have from the previous housing. Past experiences provide useful context to understand their behaviour in the dwellings which are the focus of this study. Householders in Living Lab were only living there temporarily and were therefore asked to describe both their response to Living Lab and how they would behave in a similar situation in their own home. Householders in Miljøbyen Granåsen were not required to give such a detailed description but did on occasions explain their reasons for approval or frustration by giving examples from previous homes or friend's homes.

The Living Lab is the primary focus of this section because there is access to more information about the householder's residential experience. The six households before participating in the residential experiment in ZEB Living Lab lived in houses of different age (1905-2007), size (52 m^2 to 185 m^2) and form (apartments, row houses and detached houses). This suggests a variety of experiences, challenges and preferences.

The LL Jones household usually lives in a large apartment in a multifamily apartment building built in 1905, with high ceilings, an old fuse box and inefficient heating system. They share this apartment with three other women. LL Jones told us that they had a thermometer in the kitchen, but had no idea about the actual indoor temperature. They said: "*19 degrees perhaps? It is often really cold but the fuse box cannot cope with us turning the heating on in all the rooms*." Their problem was getting the apartment warm enough. This was an issue in all the rooms, including the bedrooms. Their heating expectations were, therefore, different to the LL Wilson household who lived in a 1980s detached house equipped with a wood burning stove, heat pump, panel heaters and underfloor basement heating. The LL Wilson household told us: "*If we light the wood burning stove at home it gets hot. John (the husband) uses too much wood! We turn the heating down at night, and if it is cold during the day, we turn it up using the wood burning stove and the heat pump. We would have perhaps turned the temperature down in Living Lab, but we have experienced that it takes a long time to get the temperature up*" in Living Lab. The LL Wilson household did not struggle to warm their detached house and they aimed for different day and night-time temperatures. **This heating practice suggests a desire for immediate heat, meaning the ability to quickly change the indoor temperature if desired**. None of the six households was interested in waiting for any house to warm up (both in Living Lab and in their own homes) and wanted personal control over the temperature indoors.

Five of six households stated that they aimed for different temperature zones in their homes, closing and opening doors to regulate the temperature. The LL Brown household seeks to create temperature zones by closing the bedroom doors, although it is unclear whether they achieved this. The doors are open during the night to allow audio contact with their children (proving, that the decision for door opening is not only motivated by physical reasons, such as the temperature or indoor air quality).

In Living Lab, the 23 degrees was the set-point temperature in the main living areas most of the households applied for their residency, although LL Smith did on one occasion adjust the temperature at 21 degrees, and at the end of their residency, LL Wilson set the temperature at 26 degrees. All the households had the bedroom temperature set at 16 degrees. It varied between households whether the temperatures in their houses were due to preference or technical difficulties (with the heating system or the building thermal dynamics). **All six households had lower day and night-time temperatures in their own houses than they had in ZEB Living Lab**. Four of the households had a lower set temperature than in the Living Lab due to preference. Two of the households LL Smith and LL Jones struggled to achieve higher temperatures in their living areas, complaining that it was often cold in these areas. Their lower temperature was not because of personal choice. LL Wilson and LL Clarke both chose lower day and night time set-point temperatures in their own homes, and when they desired a higher indoor temperature, they use both wood stoves and heat pumps. Draughts and thermal bridges affect the temperature in the main living areas for LL Brown and LL Clarke. In their detached house from 1985, the LL Parker household, have the heat pump set at 23 degrees, but they say that this temperature is not achieved. They use panel heaters in the living room when it is very cold, and there is underfloor heating in the bathroom. They do not use the fireplace.

The group of households from the residential experiment in Living Lab is small, but there is a tendency towards a difference in heating preferences between different age groups and family types. Households LL Brown and LL Clarke both have two small children, and apart from bedrooms, they both aim for higher temperatures, 24 hours a day. Neither of these household uses wood stoves to regulate the heat. On the contrary, LL Wilson and LL Parker households are both older couples with no children living at home. Both couples raise and lower indoor temperatures at different times during the day and are very fond of using wood stoves.

The LL Parker household showed a strong enthusiasm for wood stoves; they liked the act of chopping wood and the kind of heat that stoves provide. They had great faith in the future of wood stoves. They told us: "*At home, the temperature is usually lower (than in Living Lab), around 21 degrees. We have a heat pump and supplement it with a wood-burning stove. Bob (i.e. the husband) relaxes when chopping wood. Fireside pleasure ("peiskosen" in Norwegian) is important, visually and physically, it is a wonderful heat. It is becoming more popular again; it will be mandatory with wood stoves one day. I am not sure it is a good idea just to heat with electricity. What if the electricity supply was cut off for some time? When we grew up the power was shut off quite often, and for some time. It is more stable now and is rarely gone for more than a couple of hours. Heat emitted by wood stoves, right clothes and insulation all help, but when you see natural disasters on the television, then you realise that the electricity could be gone for a long time*." This preference for wood stoves is reflected in Scandinavian society in general, although it is unclear if there is a difference in preference between generations, as suggested by the Living Lab example [21].

The analysis of previous experiences among the residential groups who lived in Living Lab points towards three main factors:

1. There is a desire to control the heating system. Whether this means simply achieving a high enough temperature, quickly changing the indoor temperature in time or being able to create different temperature zones throughout a house. P. Personal control is a central factor for all six households.

2. The need for different temperature zones, particularly in bedrooms, is something all the households prefer, and are willing to do manually, when able, by opening and closing doors.
3. Finally, individual choices will always play a role. Preferences are based on experience and may be expected to change. It is also a function of age group and family type. For example, households LL Wilson and LL Parker are from older age group and show a strong preference for heating based on the use of wood burning stoves.

2.2 The main living areas

Different zones in the dwellings are presented separately. This is to highlight the different expectations and preferences concerning various areas in the house. The main living areas refer primarily to the lounge and kitchen. Because the dwellings investigated have open plans, the living areas also include corridors, hallways and zones between rooms. The two building complexes are presented separately, although occasional comparisons are made. Nevertheless, the discussion at the end of the section takes into account factors from both examples.

2.2.1 Miljøbyen Granåsen

The dwellings in Miljøbyen Granåsen were completed in 2014, at the time of the interviews households had lived in their apartments for approximately one year. Initial start-up issues (or "teething problems") with the heating, therefore, play an important part in the feedback received from households during interviews. The focus of the analysis in this section is the householder's response to perceived problems and solutions, not technical issues associated with the building. The causes of the problems experienced and the final solutions to fix them were not known at the time of the interviews.

All six households in Miljøbyen Granåsen desired the temperature to be between 22-24 degrees in the main living areas. This value is higher than the set-point indoor temperature usually proposed in standards and building regulations (typically 21°C). They all stated that their apartments were too warm during the summer. Nevertheless, residents disliked the cold more than the heat. They expressed more frustration about not being able to achieve 22-24 degrees than having to manually air their apartments by opening veranda doors during the summer. This could be connected to the climate in Trondheim, the winter, often starting in October and ending in March, is long, dark and cold with temperatures often below zero. The summer is shorter, June to August, with relatively few days over 20 degrees. Consequently, there are more days during the year when a home is potentially cold than days when it is too warm indoors. Also, Lisa Heschong, in a description of natural strategies by mammals and other living forms for dealing with different thermal qualities, suggests that an animal's metabolism spends more energy dealing with cold environments than they do with dealing with warm conditions [22]. In conclusion, the cold is a "natural" preoccupation. It is not just the households interviewed that emphasised upon keeping their homes warm.

Of the six MG households, only MG Baker was happy with the temperature during the first year. After adjustments had been made, MG households Peters, Harris and Evans were all satisfied with the heating systems during the second winter. Because of complaints previous to the interview, some of the apartments in this study had larger radiators installed. Nevertheless, MG Lewis and MG Moore remained critical and appeared frustrated with both the airflow from the ventilation system and the heat from radiators.

The initial problems within the dwellings in Miljøbyen Granåsen indicate the general importance of achieving the expected indoor temperature. Not being able to achieve it can potentially affect the long-term relationship with the house. For instance, MG Moore plans to move out from the apartment. The temperature and heating system were not given as the reasons for the move-out, rather a frustration over how sound travels through the building, from stairwells and between apartments. However, a continuing general dissatisfaction with the apartment was present during the interview.

Two main factors had an impact on the response from the residents' in Miljøbyen Granåsen: (1) not being in control of the temperature in their homes and (2) their expectations about comfort in a new dwelling.

MG Lewis was not satisfied with the temperature during the first winter. It was too cold inside and difficult to reach 22 degrees in the living room. He said: "*This should be possible in a new house?*" After winter number two, he still believed that the heat source does not have the capacity to achieve 22 degrees during the winter. MG Lewis stated that: "*It is important for him to be able to sit inside wearing just a t-shirt in the winter*." He was not the only householder to want to wear a t-shirt indoors all year round. MG Evans stated that she prefers the temperature to be about 24 degrees and that she likes to wear a t-shirt indoors during winter. She also noted that the housing developer "*created high expectations about comfort*." MG Moore said: "*A friend of mine also bought a new house and it is warm there all the time, it is not a passive house. And I sit in a passive house and freeze all the time?!*" Passive houses are advertised as comfortable houses without further definition. Household knowledge about passive houses is based on the information they were given when buying the apartment. None of the householders interviewed was looking for a passive house when they chose to purchase the apartment. Their criticism of passive houses is therefore based on their limited experience with living in them, and not on a broader technical understanding of how other passive houses should function. They have, however, become critical of the whole idea of what a passive house is based on this limited experience. None of the residents had challenged their own knowledge about the technical system works by attempting to learn more about passive houses. In other words, they criticized the concept of passive house first before checking if they properly operate the building according to their expected thermal environment, or if there was any technical fault in the building or technical installation.

The householders from Miljøbyen Granåsen understood indoor temperature to be an important part of comfort, the thermal comfort from a physical point of view mentioned in the introduction chapter. When they did not achieve expected temperatures, they were disappointed. This is highlighted by their comments about how they dress indoors. In Miljøbyen Granåsen, two of the householders wanted to wear t-shirts all year round. Wearing socks and slippers was given as examples of system failure. MG Moore told us: "*I used to live in a house where you always had to wear slippers. I expected to have it warm enough in every room here. That is comfort!*" Wearing woollen socks and slippers by two of the household groups in Living Lab, was described by them as, habit and part of what they did when they wanted to be cosy. In that case, it did not have negative connotations. Householders in Miljøbyen Granåsen did not feel that they were being given a choice about what they could wear indoors. Socks and slippers were therefore regarded as a negative factor.

2.2.2 Living Lab

Living Lab was also a new building with start-up problems. Apart from some bad experiences during their first week of residence by the LL Brown family, initial faults with the heating did not characterise feedback during interviews. The residential experiment in Living Lab took place from October to April. There were few comments about the house being too warm when it was sunny outside.

The LL Parker household who lived in Living Lab in April told us: "*When the sun shines, it gets warm in Living Lab. We have used the sun shading on the outside, it works well, and we have used it to protect the plants*." LL Clarke household also experienced it getting warm during the spring. Nevertheless, they blamed the temperature on them forgetting to use the sun shading. These two comments confirm that sun shading can help to keep the temperature down in highly insulated houses, at least during the spring.

Three main factors characterise the response to the heating system in the Living Lab: (1) the pleasure in the underfloor heating, (2) the temperature in each zone and (3) the delay to the indoor temperature to adjust to a new set-point.

All six households gave positive feedbacks about the underfloor heating in ZEB Living Lab. The LL Smith household told us that the floors are cold in their own apartment: "*It is much nicer in Living Lab*". They can sit and read, feel that it is warm under their feet. They said: "*the warmth from the floor is just right. Not too hot and not too cold*." In their apartment, only the bathroom has floor heating. The LL Wilson household was also pleased with the floor heating, as were their visitors who commented on it. Households used examples related to the floor heating in ZEB Living Lab to highlight issues that exist in their own homes. For example, the LL Clarke household told us that: "*There are some thermal bridges at home along the floor. The wind barrier in the walls is not very efficient, and the floor is cold at least up to one meter into the room*." This was very different to the Living Lab, which was described as having "*a very pleasant floor temperature*". The mother in the household said: "*At home, we use thick socks*." She also used woollen socks in Living Lab, but she said that it was out of habit: "*In Living Lab, we can walk barefoot*." The four children who lived in Living Lab were observed playing barefoot indoors. This happened even when it was minus degrees outside. The children who were all under the age of seven were "responding" to the thermal quality in Living Lab, a response that was not based on predefined habits or expectations.

Figure 2.1 Living areas in the ZEB Living Lab on the Gløshaugen campus, NTNU (image by ZEB).

The floor plan in ZEB Living Lab is open: the entrance hall, kitchen, living room and studio area, are all part of one large space. This space can be made even more open using the bedroom doors which cover a whole wall and may be completely opened. This turns the bedroom and studio areas into one large room. The temperature in Living Lab is set using a digital interface (a screen) in the entrance hall. Although installed, the radiator was not in use in Living Lab during these experiments. The only heat source was the floor heating that may be controlled differently by users for each zone. All six households stated that they liked that it was possible to set different set-point temperatures for the underfloor heating in the different zones of the house. Although LL Smith household did say that the temperature differences between zones were not as clear as in their own apartment (where they created different zones manually by opening and closing doors). The LL Brown household, although they were more critical about the house than the other five households to for example the open plan design, kitchen design, inbuilt furniture, said that they liked the different temperature zones in Living Lab, and being able to set different temperatures in different rooms. This household was more temperature conscious than the other five households; they were the only one to bring a thermometer into Living Lab. They stated that they had not needed to turn the temperature down or air the house in Living Lab. They had only opened the windows once because they were curious about how the windows worked.

The LL Brown household also stated that they had greater freedom to adjust the temperature in Living Lab than at home in their own row house.

The other five households were more critical about the space-heating system ability to adjust to the desired temperature. LL Smith household was warned when they moved in that it would take up to six hours for the temperature to adjust to a new set-point in ZEB Living Lab. Therefore, they never attempted to change the temperature. The research team learned from this experience. They did not warn the other groups of residents about the relatively slower heat dynamics before they moved in. **The LL Clarke household told us that it took a while for the temperature to change in the living room and bedroom**. The LL Parker household said that it takes time to get the indoor temperature warm: "*Lowering the temperature was not the natural thing to do because it takes a long time to stabilise*."

During these experiments, Living Lab residents were only able to use floor heating. They appreciated some aspects associated with the heating system and were critical of others. Aspects that encouraged more control such as the ability to create temperature zoning were appreciated by all six households. The relatively slow temperature changes suggested a loss of control and they were critical about this. Achieving immediate temperature increase when they experienced the house as too cool was important to all six households. However, when the house was warm enough, and the heating system was functioning, as they wanted it to, they all expressed pleasure in the floor heating.

2.3 Bedrooms temperatures

Residents from both examples stated that they would have liked lower temperatures in the bedrooms, although they did not state what these lower temperatures should be. The 15-16 degrees proposed by the thermostats in Miljøbyen Granåsen and Living Lab told not to be low enough and not what they would have chosen if they had more freedom to choose.

Some households talked about preferring to sleep with the bedroom windows open. Some households in Miljøbyen Granåsen still slept with the windows open even though a balanced ventilation system exists in the dwellings (that should have been providing good IAQ in bedrooms). It suggests that people opened windows for other reasons than IAQ. **The most common reason stated for opening bedroom windows in Miljøbyen Granåsen, ZEB Living Lab and their own homes was that it was warm in the bedroom**. Other households established strategies to deal with higher bedroom temperatures and, in one example, even expressed changes in preference. In Miljøbyen Granåsen two households were uncertain if opening the window was the correct thing to do in their apartments. This suggests a need for more information about the ventilation and heating system. Not just information about how to turn it on and off or changing filters, but also what influences the performance of the system and implications are for energy use. In Living Lab, sliding doors are installed in both bedrooms instead of windows. This has influenced resident behaviour. None of the six households who took part in the residential experiment in Living Lab slept with open windows during their stay there. All the adults in Living Lab stated that they preferred to sleep in cold bedrooms and five of the six Living Lab households opened windows during the night in their own homes. However, they all stated that they slept well in Living Lab (if noise from outside and lights from the traffic did not disturb them). Three households developed strategies for dealing with the warmer bedroom temperature.

These results are in good agreement with the work of Berge et al. [19]. They performed a questionnaire distributed to the residents of 62 houses from Miljøbyen Granåsen. Detached and terraced houses were investigated but no apartments. Even though the building types are different from the present work, conclusions are interesting as the number of persons questioned is larger and thus the results more representative. Also, a same SH distribution strategy is applied (i.e. air-heating battery, simplified hydronic distribution with no radiator in the bedroom, floor heating in the bathroom). Their questionnaire revealed that occupants are mostly satisfied with the thermal comfort in the living room and bathroom. On the contrary, the level of satisfaction is significantly lower in bedrooms where a lower temperature than the rest of the building is preferred. In fact, 50% of occupants experience the bedroom temperature as too warm. Quite surprisingly, most of these dissatisfied occupants apply a high set-point temperature for the air-heating that requires the heating battery to be active for a large part of the winter period. About 50% of occupants open the bedroom window in the winter for a least a few hours. **The main reported motive for people to open the bedroom window is the temperature control (not IAQ)**.

2.3.1 Miljøbyen Granåsen

Households MG Baker, MG Peters and MG Lewis all stated that they slept with the bedroom window open. The MG Baker household had the window open all day, and had also started to use summer duvets all year round. The MG Peters household opened the window even though they stated that there was good air quality in the bedroom, but it is unclear whether the good air quality was because they opened the bedroom window or because of the ventilation system. They also told us that the bathroom which is attached to the bedroom heats the room and that the bedroom is too hot if they do not open the window.

The MG Evans household lowers the temperature of the supply air from the ventilation system when it gets too hot in the summer, but says that: "*The downside is that it gets cooler in the whole apartment and not just in the bedroom where it matters most*." The temperature in the bedroom is regulated by keeping the door closed. **When she wants a higher temperature in the bedroom, she opens the door to the rest of the apartment**.

MG Moore told us that she does not use down duvets anymore. She also stated that she used to prefer a very cold bedroom. Bow she has almost become accustomed to a warmer bedroom. She is slightly unsure whether she should open the window in the bedroom: "*If you are going to sleep with the window open, it ruins the temperature in the living room due to the crack under the door*." She would like to have better control over the temperature in the bedroom "*but the air never feels stuffy, not even at night-time. Otherwise, it would not have been possible to sleep with the window closed*."

Figure 2.2 Bedroom in the ZEB Living Lab on the Gløshaugen campus, NTNU (image by ZEB).

2.3.2 Living Lab

The bedrooms in Living Lab both have sliding doors instead of windows, influencing the behaviour of the six households. None of the six households chose to sleep with the sliding doors open. The LL Smith household told us that they could not sleep with these external doors open: "*We could open it, a very narrow crack, but it is creepy, just the thought of it*." This is in part due to the location of the Living Lab: it is in a busy area of town, on the edge of the university campus. This affects the noise level and feelings of security at night-time. The LL Parker household told us that they were afraid that spiders and mice would crawl into the bedroom if the external doors were open even a little bit. The physical structure of the building affected household behaviour, but the main preference among five of the households in their own home was to sleep with bedroom windows open. The LL Wilson household told us that they sleep with the window open at home whatever the weather: "*We only close the window if it is windy*." The woman in the household sleeps with a headband ("pannebånd" in Norwegian) if it is very cold.

In the households with children, the parents slept with windows open in their own home, but the children slept with the windows closed. The LL Brown household stated that the youngest child was restless in her sleep and often (in whatever house she was sleeping in) ended up sleeping without a duvet. In their home, she became cold if the window was open and this disturbed her even more. The older child slept with the window open in their own row house if the weather was warm. **All six households agreed that the bedroom was supposed to be a cold room**. The LL Jones household said, "*At home, we usually close the door to the bedroom; it is supposed to be a cold room*."

During their twenty-five days stay in Living Lab, three of the households established strategies to deal with the bedroom temperature. One strategy was summer duvets, a solution applied by LL Wilson and LL Parker households. LL Smith household told us that they would probably use a thinner duvet if they lived in ZEB Living Lab all the time.

All six households stated that they slept well in ZEB Living Lab and five indicated that the air quality was good in the bedroom, even in the mornings. However, the LL Parker family told us that, although they slept as well in Living Lab as they do at home, the air was "*a bit stuffy in the mornings*." The wife in the LL Parker household established what might be understood as a second strategy to deal with the temperature, airing before sleep: "*I have a better night if I ventilate the bedroom before I go to bed. It gets warmer at night. When I was ill (while living in Living Lab), I really noticed that it was warmer*."

Despite stating that they preferred a colder sleeping environment and sleeping with the windows open, all six households accepted sleeping with the windows closed and experienced a good night's sleep. However, they did turn the set-point temperature down as low as possible and used (or considered using) different strategies to improve experienced comfort.

2.4 Understanding the system

Being able to use a SH system requires that the user understands how it works and is able to use it properly to achieve required levels of comfort. This also applies to wood burning stove (appropriate use of drafts, ignition, amount of wood and vents) and it applies to the SH systems in Miljøbyen Granåsen and Living Lab. In both examples, residents were given a short introduction to how to use the SH system.

2.4.1 Miljøbyen Granåsen

Nevertheless, one household in Miljøbyen Granåsen, MG Lewis told us that he thought the introduction went a little too quickly. The majority of households stated that they had been given sufficient information to be able to regulate the heat. Only one household stated that the information had been insufficient[1]. This does not necessarily mean that residents had enough knowledge about how the system worked. However, residents themselves did not regard the understanding and drifting the operation of the heating and ventilation system as main challenges in Miljøbyen Granåsen. They were critical of the difficulties associated with achieving expected temperatures. This was their primary challenge during the first year of residence. It is possible that a better understanding of the system could improve the chances of achieving the expected temperature, but residents themselves did not connect the problems they were having with reaching the expected temperature, to their own knowledge of how the system works. This aspect is investigated in Chapters 4 and 5 where the impact of different control strategies on the indoor thermal environment of the building was studied (such as the bedroom temperatures).

Understanding a SH system does not only rely on information provided to households at the start of residence. Personal experience and information that is gathered in other social contexts also play a role. Residents in Miljøbyen Granåsen placed the heating systems within a wider social understanding of technical systems. The man in the MG Peters household told us that he had worked with heating and ventilation in nursing homes and that he knew how the heating system in his new apartment worked. The MG Harris household told us that they had mechanical ventilation from 2008 in a previous residence. MG Lewis, although he complained that the information exchange went too quickly during the takeover of the apartment, solved problems by talking to his neighbours. Householders are not blank pages when they move into a home; they often have technical experience that they can adapt to a new system and they can apply other strategies if a problem arises. However, householders may be making mistakes that they are not aware of, which potentially reduce system efficiency and increase energy use. For example, an informant from Miljøbyen Granåsen told us that he did not have enough information about how the system worked and that he was learning to use it through trial and error. During the interview, it was discovered that he was closing the ventilation to reduce draughts in his apartment and that this was causing a severe imbalance in the ventilation.

2.4.2 Living Lab

In the Living Lab, households had a touch screen control panel mounted in the entrance hall[2]. Residents used the control panel to adjust the temperature and to position the external sun shading. The panel also gave them insight into the energy use and the resulting CO_{2eq} production. They had access to the technical room, but this was only to give them access to the fuse box. They were not given a technical introduction to in operating the systems included in the technical, or the ventilation system. They were given general information about the systems included in Living Lab and how a zero emission building works. There was no question of them changing filters.

The LL Smith household would have liked to have more control over ZEB Living Lab, but were unsure about what they wanted more control over. The use of the touch screen was something they were used to (referring to touch screens on phones and tablets). They would have liked to be able to do more through this screen. Although they stated that they were glad that the house was not all automatic. The LL Jones household felt that they had more control in the Living Lab than they have at home. This statement was based on being able to regulate the temperature using the touch screen. Their own home is difficult to heat and is often cold which provides background to understand what they mean by control. The LL Jones household also stated that they turned off the lights when they left the Living Lab and they would have liked to also be able to turn down the space-heating when they left the house.

---

[1] Miljøbyen Granåsen has been a source of data in other research projects. In one of these projects, informants from row houses were given an information booklet. None of the informants spoken to was happy with the booklet.

[2] Householders never criticized the information, possibly because the researchers who gave them the information were the same ones who were them asking questions about how the system worked.

They suggested installing a timer or a function on their mobile phones: "*This ought to be possible in such a technical house*." Although they liked the technical solutions and wanted more of them, they were at the same time worried about what would have happen if anything went wrong: "*We would not be able to fix it. We are more dependent on an electrician. When the heating stopped working (*in the Living Lab*) we could not do anything about it ourselves*."

The LL Wilson household told us that they had "*mastered the system*". However, they showed some frustration with what the system delivered. For example, they said: "*If we knew what the temperature was in a room, we would have perhaps turned the temperature down*." The touch screen only showed the set-point temperature in the different rooms and not the actual temperature. They did not bring their own thermometer into Living Lab (only the LL Brown household did that), but they did not trust the temperature that was shown on the screen was found in reality in the room: "*It takes a long time for it to change (to a new set-point temperature)*." The LL Wilson household told us that: “At home, *we can change the temperature much more quickly, there is a quicker response*."

The LL Clarke household told us they would have like to have more control and more information coming out of the screen: "*With more information, we could have made more choices. Information would have influenced energy use*." They suggested that the information could be made available on their telephone. They would also have liked to be able to change the heating source and to turn the temperature up and down.

Households LL Smith, LL Jones and LL Clarke all liked the idea of using mobile phones to control the heating system. Nevertheless, two of these households are sceptical to the consequences of too much technical steering in a home. Being able to turn the temperature down when they leave the house was something three households felt should have been part of the system, partly because they did this in their own homes and partly because they expected that kind of technology in a house as technical as the Living Lab. However, from a pure technical point of view, it is not necessarily a good strategy to apply intermittent heating in super-insulated buildings such as passive houses or zero emission houses. In super-insulated buildings, reducing indoor temperature during night-time leads to a limited reduction of the energy use for SH. On the contrary, it requires the installation of some additional SH power which is relatively more important in a super-insulated buildings than in older less insulated ones. There is thus a risk of so-called power oversizing, resulting into poorer performance of the SH system during operation. Given the limited benefit on energy use and technical problems it may generate, heating with a constant indoor temperature is often promoted in super-insulated buildings. A general comment based on the feedback from Living Lab is that households want more control over the SH system. Not knowing what the actual indoor temperature was and not being able change the indoor temperature quickly when needed, are examples of not being in control. Both were understood as negative.

2.5 Saving Energy

Super-insulated houses aim to reduce energy use and to improve user comfort. **Interviews with residents in Miljøbyen Granåsen and Living Lab showed them to be more interested in comfort that energy savings and the resulting reduction in costs which this could imply**.

A factor that influenced the experience of comfort in Living Lab is social quality. When asked if Living Lab was a comfortable home, householders included social qualities in their descriptions. This included visits received from friends and family, how the house enabled interaction within the household. For example, the LL Clarke household which has two small daughters told us: "*The location of rooms is comfortable. It means that we are close to each other all the time and have more control over each other*." Much of the analysis focuses on descriptions of temperature and air quality, because it allows us to assess how well a system works. Nevertheless, as mentioned in the introductory section, the heating should be understood in its wider context. Householders suggest that comfort is made up of more than one factor.

The MG Peters household wondered if they might be able to save some electricity. MG Lewis and MG Moore households both stated that their energy bills were lower than in their previous residences. None of the Miljøbyen Granåsen residents interviewed had bought their apartments because they wanted to live in a passive house. This factor came in addition to other qualities such as size and location. Their focus was not on environmental or energy saving issues.

Residents of the ZEB Living Lab did not have to pay energy bills incurred during their residential period. When advertising for residents to live in Living Lab, we did not ask for households who were particularly interested in the environment or energy issues. During interviews, questions were asked that aimed to uncover whether they were interested in energy saving or not: "*Do you watch your electricity consumption at home/in Living Lab daily, weekly, other?*" However, while all households were interested in the size of their energy bills (particularly student households), only one the LL Brown household told us that they tracked the energy use in their own home.

Energy prices would appear to influence the attitude towards energy use. The billing system affects how residents follow up energy use. For example, this is implied by the LL Parker household, who told us: "*We do not really follow how much electricity we use at home. We have automatic billing, so it happens by itself. The electricity price is low so it is not a problem. A few years ago, there was a greater difference in price during the winter*." The general lack of interest in how much energy is used by a household has implications for how a space-heating system is used. Households are, as mentioned earlier, interested in temperatures from 22-24 degrees. Saving energy by lowering the indoor temperature was not an issue in the households interviewed in Living Lab and Miljøbyen Granåsen. When the system in Miljøbyen Granåsen did not work, householders did not worry about how much energy was being used to produce heat. They were concerned with not being able to achieve required temperature. The space-heating needs increase significantly if the windows are kept closed (see Chapter 4). Nevertheless, assuming that users understand that opening windows leads to increase energy consumption, it means comfort was considered more important than the question of increasing energy use by window opening. Residents in Living Lab were more concerned with turning temperatures down in their own homes than they were in Living Lab. Households LL Smith and LL Jones are students. Keeping down the price of energy bills was more of an issue for them in their own homes. **For the other households from both examples, lowering temperatures was about creating different temperature zones in the living and sleeping areas. It was primarily a comfort issue, rather than an energy issue.**

2.6 Tendencies found in the response of the twelve households

This section combines the response of the twelve households and suggests five main points which are important to household use and preference with regard to heating. The dwellings considered in this analysis are very different. In Miljøbyen Granåsen, the six householders were living apartments built to passive house standard. All are equipped with simplified SH distribution. These apartments were their permanent home. In the ZEB Living Lab, the six households were only living temporarily (25 days each) in a detached zero emission house. The Living Lab was exclusively heated using floor heating. Users had nonetheless the possibility to apply a different set-point temperature in each room. Although dwellings and experiments are different, the combined response of the twelve households about heating does provide a set of tendencies. These tendencies are not presented in order of importance and are interrelated. The twelve households' expressed:

- **A desire to be in control of the heating system**. Individual preferences, which are often based on previous experiences, will always play a role. Householders want to choose for themselves. This applies to the temperature in the different rooms (temperature control in space), to being able to quickly change the temperature to warmer or colder when they wish to (temperature control in time), and to what they wear indoors. Wearing woollen socks is positive only when it is by choice and not because the temperature is too low because the heating system is not providing enough heat. Super-insulated buildings react more slowly to a change of temperature set-point than older less insulated buildings. The slower dynamics was considered as a negative factor by householders. The heating system in ZEB Living Lab provides the opportunity to set different temperature set-points in the different rooms. This does not mean that the selected temperature was reached in reality in each room, but that selecting the set-point temperature was proposed (see following comments about temperature zoning). This is an example of improved household control which was appreciated by householders.
- **A preference for different temperature zones (control in space): cold bedrooms (less than 15-16 degrees) and warm living areas (22-24 degrees).** The need for different temperature zoning in a dwelling is supported by other studies in Nordic countries [19]. Closing the door of bedrooms is a common way to regulate bedroom temperatures and create temperature zones in houses that are not super-insulated. It is not sufficient in super-insulated buildings, as confirmed in measurements (Chapter 3) and simulations (Chapters 4 and 5). Berge and Thomsen's questionnaire [19] also suggested that the highest degree of thermal discomfort in super-insulated residential buildings is essentially found in bedrooms that are experienced as too warm. Householders expressed a preference for sleeping with windows open to achieve cold bedrooms and provide air quality. For super-insulated buildings, the work of Berge and Thomsen showed that the main motivation for window opening in bedrooms was to control temperature. This was also confirmed by measurements during the project where window openings have been recorded along with indoor temperatures (see Chapter 3). This expectation for cold bedrooms is not always found, especially in families with small children. This is because children are found to be more restless if the bedroom is too cold and because doors between rooms are kept open at night to allow for audio contact with the children.
- **Householders expect to be able to apply intermittent space-heating (control in time)**. Householders expect to be able to quickly change the indoor temperature. On the one hand, super-insulation prevents the indoor temperature to decrease quickly. On the other hand, the heating system in super-insulated buildings is usually dimensioned to keep a constant indoor temperature to prevent power oversizing. The additional power to quickly increase the indoor temperature is thus limited.
- **High expectations about comfort in a new dwelling**. Passive houses and the next generation of houses, such as zero emission houses, are advertised as comfortable and energy efficient. Comfort was for all the households more important than energy use. Residents had high expectations about comfort when they moved in. The desire to have control over the heating system in the dwelling was not about achieving energy savings, it was about achieving expected levels of comfort which was often related to required temperature levels.
- **Residents were willing to change habits or develop new strategies for living with temperatures provided by the heating system**. For example, they started using summer duvets during the winter. Household behaviour can change. Previous experience and existing preferences are not set in stone.

Finally it should be mentioned that some of the householder's comments are based on initial start-up problems in their dwellings. This coloured their attitude towards the heating system installed, and in the case of Miljøbyen Granåsen, to the idea of passive houses in general. It is interesting to notice that some users criticized the whole passive house concept if they did not get the expected comfort, without checking beforehand whether the building could have initial start-up problems or that the control could be improved. It was however deemed relevant to take these into account because the comments highlight user preference and their response when their expectations are not met.

3. Measurements

Detailed measurements were performed in two apartments and two row houses of Miljøbyen Granåsen in Trondheim (Norway). Measurements were combined with an interview during the sensors installation before the initial measurements. Note that these interviews are not to be confused with the interviews reported in Chapter 2, although they partly focus on the same buildings (i.e. the two apartments). Buildings have been measured during two periods of two weeks. The first period, in November 2015, aimed at enhancing our understanding of the problem and optimising the experimental setup. Only the results from the second period, in spring 2016, with improved measurements, are presented thereafter. The main results and figures are taken from the Master theses authored by Kang Wen [23] and Frederic Håheim [24] along with two conference publications [25, 26].

3.1 Description of measurements

3.1.1 Apartments

The first measurement campaign took place in November 2015. This campaign aimed at developing the experimental setup and mapping the challenging areas to improve measurements in the second campaign. This second measurement campaign took place during March and April 2016. The two apartments were measured sequentially. The first measurements indicated that not only temperatures shall be measured. Thus, in the second campaign, window and internal door openings were measured and the set-points for the radiators temperature and the ventilation system were manually registered using diaries.

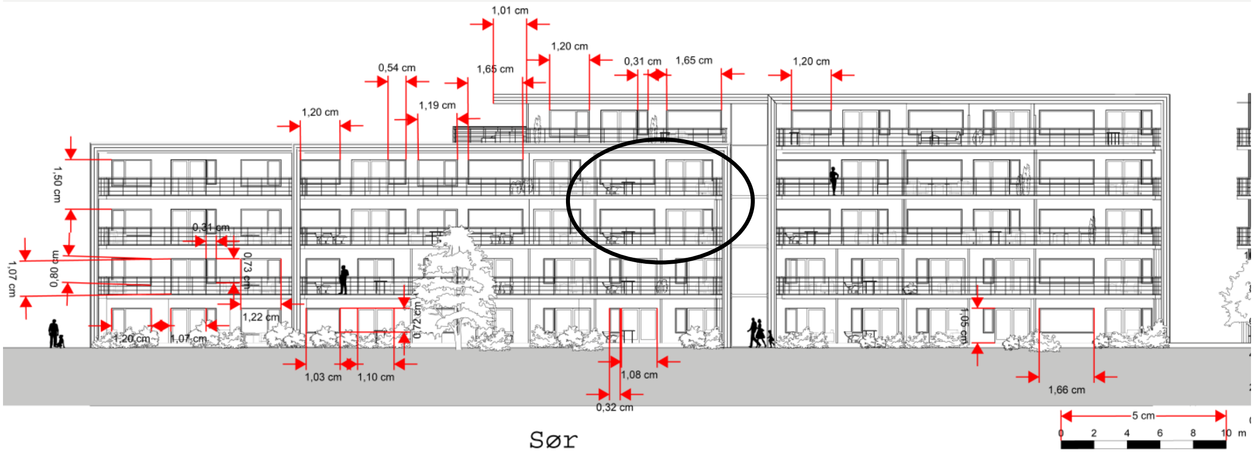


Figure 3.1 South façade of the building block B4.

Both measured flats have the same area. They are placed in the centre of the block in two adjacent floors (second and third floor), see Figure 3.1. Each flat has a heated area of 80 m². These flats are designed as apartments for three persons consisting of two sleeping rooms, for one and two persons, respectively. The living room facing south is an open landscape with the kitchen and the corridor. A radiator placed in the corridor is the only heat emitter in the flat, except for the bathroom which is equipped with floor heating. The door of the bathroom is nonetheless almost always closed so that the floor heating influence over the entire flat is limited. The balcony is a closed and glazed volume using sliding windows to enable ventilation. The entrance from the kitchen to the balcony is allowed by a sliding door.

The building is constructed of wood frame and insulated with mineral wool. External walls have a U-value of 0.17 W/m².K, the gable wall to the atrium 0.16 W/m².K. The U-value of the internal floors and inter-flat walls is estimated to be 0.25 W/m².K. The building thermal mass is lightweight. The internal partition walls between rooms are insulated with 7 cm mineral wool with a U-value estimated to be 0.49 W/m^2.K. The normalised thermal bridges are 0.02 W/m^2.K. These were measured only for one apartment of the whole block. Unfortunately, the flat is not one of the followed up during measurements. Infiltrations and air leakages have not been measured for this specific flat. The designed value is 0.6 ach at 50 Pa [25].

The balanced mechanical ventilation generates a cascade flow: fresh air is supplied in occupancy rooms, both sleeping rooms and the living room (41.5 m^3/h), transferred using the corridor and extracted in the bathroom and kitchen. The supply air in bedrooms is designed depending on the number of occupants. Each occupant is supplied 26 m^3/h. This means 52 and 26 m^3/h for the double and single sleeping room, respectively. The design air supply rate (Vn) is 1.5 m^3/h per m^2 or 0.6 ach. The air handling unit is a Systemair Villavent 200 equipped with a heat recovery wheel with a rated efficiency of 85% (EN308). A 1 kW electric heating battery is placed after the heat exchanger, where the set-point (Tset,AH) is defined by the occupant using a panel located in the living room. The ventilation can be operated at three different speeds, where speed two is the nominal one (Vn) [25].

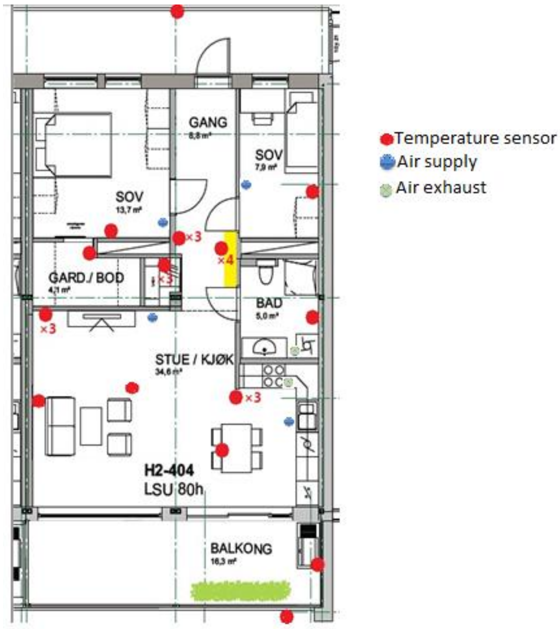


Figure 3.2 Flat layout along with the description of the sensor location: temperature sensors are marked in red, the main radiator in the entrance hall marked in yellow and supply air inlets in blue, extraction of air in green.

In both campaigns, air temperature was measured by means of temperature sensors iButton DS1922L-F5. These sensors have an accuracy of ±0.5°C. All the sensors were placed in such a way to avoid direct solar radiation. They were positioned according to the locations marked in Figure 3.2. Table 3.1 summarizes the positioning of sensors and the goal of their installation.

Table 3.1 Summary of placement and goal of the sensors placed in the flats

Room	Positioning	Measurements goal
Balcony	Given that balconies were closed with glass, one sensor is placed outside the glass to measure outdoors conditions (not shaded) and one inside (shaded)	1 Outdoors temperature 2 Balcony temperature
Living room	Five sensors: three are placed vertically (next to the television and away from the ventilation air supply) to determine stratification; one next to the sitting area close to the wall; one in the centre of the living room, in line with the entrance door	1-3 Stratification 4 Sitting area temperature 5 Living room temp.
Kitchen	Four measurements: three are placed vertically next to the kitchen exhaust and one in the chair closest to the sliding door	1-3 stratification 4 temp. sitting area kitchen
Storage room	One measurement to better represent the temperature boundaries of the bedroom	Room temp.
Bathroom	One sensor to measure the temperature in the extracted air	Extract air temp.
Heat wheel	Three sensors to measure the heat wheel's temperatures	To be better understand how the heat wheel operates
Entrance hall	Seven sensors: two in the inlet and outlet of the warm water to and from the radiator; one on the surface of the radiator; one on the bulb of the thermostatic valve control valve of the radiator; three vertically placed to measure air stratification	1-2 water supply temp. 3 superficial radiator temp 4 thermostatic valve 5-7 stratification
Main bedroom	One sensor is placed to measure room temperature	Room temp.
Secondary bedroom	One sensor is placed to measure room air temperature.	Room temp.
Entrance, outdoors	Two sensors are placed to measure the outdoors temperature on the north facade (shaded from the sun).	North outdoor temp.

Additional sensors were installed in all the air terminal devices (ATD). Occupants were asked to register in a diary the set-point of the supply air temperature (Tset,AH) and for the airflow rates controlled as “min”, “normal” and “max” as well as the position of the radiator thermostatic valve (Tset,SH) from 1 to 5. The manufacturer data of thermostatic valves enabled to map a corresponding set-point temperature to the thermostatic valve position. Both flats were normally occupied by a single person, but both get visitors that sometimes sleep over. Both occupants usually reduce the ventilation flow rate to level one (i.e. one-half of the nominal value, Vn) because they have been instructed to do so in winter time when they are the only inhabitants of the apartment. They have been recommended as well to increase the airflow rates during shower times. Therefore, they manually force the ventilation to a higher level (when they remember to do so).

In the second measurement campaign, the openings of all windows and internal doors were monitored using contact sensors. They deliver a binary signal (open/closed) but do not measure the degree of opening.

3.1.2 Terraced houses

The first measurement campaign happened in the second quarter of November 2015. This campaign had the goal to develop the experimental setup and to improve it for the second campaign. The second campaign happened during April 2016. Both houses were measured sequentially.

The major conclusions from preliminary measurements were equal between the row houses and the flats. It appeared necessary to measure other parameters than air temperatures. For the second campaign, temperatures, window and internal door openings were measured. The position of the radiators thermostatic valves was logged in a diary. In addition, users were asked to register changes in the ventilation settings (set-point temperature for the ventilation supply air and the airflow rate).

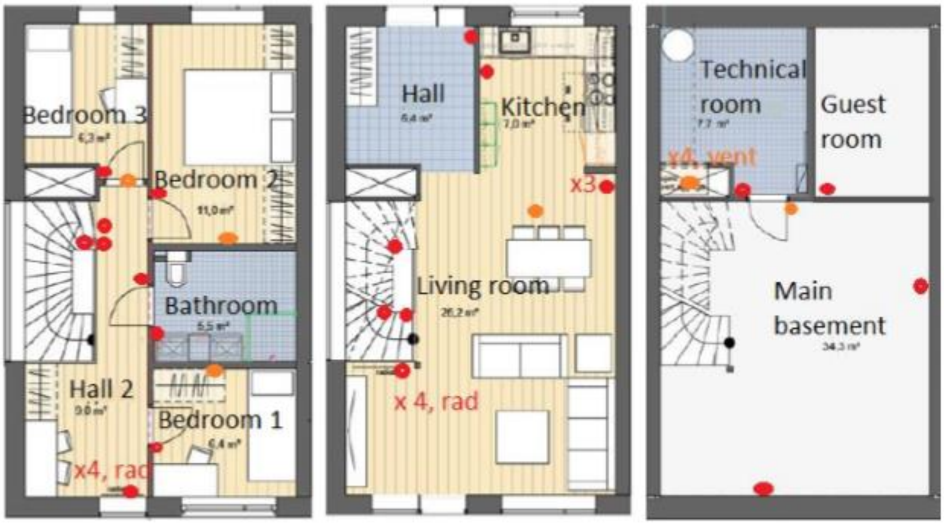


Figure 3.3 Layout House 1: first floor (left), ground floor (centre) and basement (right) with north pointing upwards [24]; orange points show the positioning of air temperature sensors placed in the ventilation terminal devices and the red points inside the rooms.

Figure 3.4 Picture (image Interiørfoto AS) and layout of House 2: first floor (left), ground floor (centre) and basement (right) with north pointing upwards [24]; orange points show the positioning of air temperature sensors in the ventilation terminal devices and the red inside the rooms.

Both terrace houses have the same area 142.5 m^2. The houses are designed for four persons, consisting of one bedroom for two persons and two bedrooms for one person, all located on the first floor. The layout of both houses is similar but slightly different. In House 1, the entrance is on the ground floor. The open landscape on the ground floor combines the living room 1 (facing south) with the kitchen 1 (facing north). This living room has a sliding door towards the garden. Its radiator is placed near the open staircase. In House 2, the entrance is in the basement where one radiator is placed near the staircase. There is no heat emitter in the living room of House 2. Both houses have a radiator in the corridor of the first floor and floor heating in the bathroom. Nevertheless, floor heating has a limited effect on the rest of the house as the bathroom door is closed most of the time.

Table 3.2 Summary of placement and goal of temperature sensors in House 1.

Room	Positioning	Measurements goal
Main basement	Two sensors and one sensor to measure supplied air temperature	Room temperature
Technical room	Four temperature sensors to measure the wheel's temperatures, one to measure air temperature of the room	1-4 Temperature of airflows around -heat wheel 5 Room temperature
Guest room	One sensor to measure air temperature	Room temperature
Living room	Three sensors were placed in a vertical line at 0.1 m, 1.5 m and 2.4 m height. One sensor in the supplied air duct. Two in the inlet and outlet pipe to and from the radiator. One on the surface of the radiator. One on the bulb of the thermostatic control valve of the radiator.	1-3 Stratification 4 Supplied air temperature 5-6 Water temperature to and from radiator 7 Superficial radiator temperature 8 Thermostatic valve
Kitchen	One sensor to measure air temperature	Room temperature
Entrance hall	One sensor by the entrance door	Room temperature
Bedroom 1 (small bedroom)	One sensor is placed to measure room temperature and one sensor in the supplied air	1 Room temperature 2 Supply air temperature
Bathroom	One sensor to measure the bathroom's temperature	Room temperature
Bedroom 2 (large bedroom):	One sensor is placed to measure room air temperature and one sensor in the supplied air	1 Room temperature 2 Supply air temperature
Bedroom 3 (medium bedroom)	One sensor is placed to measure room air temperature and one sensor in the supplied air	1 Room temperature 2 Supply air temperature
Hall 2	Two in the inlet and outlet pipe to and from the radiator. One on the surface of the radiator. One on the bulb of the thermostatic valve of the radiator. One sensor in the middle of the corridor to measure its temperature.	1-2 Water temperature to and from radiator 3 Superficial radiator temperature 4 Supplied air temperature 5 Thermostatic valve
Stairway	Six sensors to measure stratification temperatures in the stairway throughout the three floors	1-6 Stratification

The building is constructed in timber and insulated with mineral wool. External and partition walls between houses have a U-value of 0.15 W/m².K. The U-value for the two types of internal partition walls (also insulated with mineral wool) is estimated to be 0.4 and 0.64 W/m².K. Partition ceilings and floors between floors have a U-value of 0.12 W/m².K. The normalised thermal bridges (Ψ”) are estimated at 0.03 W/m²K. These were measured in only one of the row houses and not in the entire building block. This house is unfortunately not the one investigated in our measurements. Infiltrations and air leakages have not been measured for these specific row houses but the design value is 0.6 ach at 50 Pa [25].

The balanced mechanical ventilation generates a cascade flow: fresh air is supplied to rooms with long occupancy (both sleeping room, the living room with 41.5 m^3/h) and in the basement. The air is then extracted in the kitchen and in the bathroom. The design supply air in bedrooms depends on the number of occupants. Each occupant is supplied 26 m^3/h. This means 52 and 26 m^3/h for the double and single bedroom, respectively. The design air supply rate (Vn) is 1.4 $m^3/h.m^2$ or 0.52 ach. The air handling unit is a Flexit Uni 4 equipped with a heat recovery wheel with a rated efficiency of 88% (EN308). A 1 kW electric heating battery is placed after the heat exchanger, where the set-point (Tset,AH) is defined by the occupant using a panel located in the living room. The ventilation can be operated at three different speeds, where speed two is the nominal one (Vn) [25].

As for the apartments, air temperature was measured using iButton DS1922L-F5. These sensors have an accuracy of ±0.5°C. They registered temperature every 6 minutes. At least one sensor was placed in each room at the height of about 1 meter above the floor. All the sensors were placed to be protected from the direct solar radiation. Sensors in House 1 (Figure 3.3) were placed in the positions specified in Table 3.2 [24]. Sensors in House 2 (Figure 3.4) were placed in slightly different positions specified in Table 3.3 due to the different layout of House 2 compared to House 1 [24].

Table 3.3 Summary of placement and goal of temperature sensors in House 2.

Room	Positioning	Measurements goal
Storage room	One sensor	Room temperature
Bathroom basement	One sensor	Room temperature
Technical room	One sensor to measure the room's temperature	Room temperature
Guest room	One sensor to measure air temperature, one sensor to measure the supply air temperature	1 Room temperature 2 Supply air temperature
Entrance hall	One sensor by the entrance door. Two in the inlet and outlet pipe to and from the radiator. One on the surface of the radiator. One on the bulb of the thermostatic valve of the radiator. Three temperature sensors to monitor the air handling unit.	- 1 Room temperature - 2-3 Water temp to/(from radiator - 4 Superficial radiator temp. - 5 Thermostatic valve - 6-8 Temperature around heat wheel
Kitchen	One sensor	Room temperature
Living room	Three sensors were placed in a vertical line at 0.1 m, 1.5 m and 2.4 m height. One sensor in the supplied air duct.	1-3 Stratification 4 Supplied air temperature
Bedroom 1 (small bedroom)	One sensor is placed to measure room temperature and one sensor in the supplied air	1 Room temperature 2 Supply air temperature
Bathroom	One sensor to measure the bathroom temperature	Room temperature
Bedroom 2 (large bedroom)	One sensor is placed to measure room air temperature and one sensor in the supplied air	1 Room temperature 2 Supply air temperature
Bedroom 3 (medium bedroom)	One sensor is placed to measure room air temperature and one sensor in the supplied air	1 Room temperature 2 Supply air temperature

Room	Positioning	Measurements goal
Hall 2	Two in the inlet and outlet pipe to and from the radiator. One on the surface of the radiator. One on the bulb of the thermostatic valve of the radiator. One sensor in the middle of the corridor to measure its temperature	1 Room temperature 2-3 Water temp to/from radiator 4 Superficial radiator temp. 5 Thermostatic valve 6 Supplied air temperature
Stairway	Six sensors to measure stratification temperatures in the stairway throughout the three floors	1-6 Stratification

In the second campaign, additional sensors were installed at all the air terminal devices (ATD) to investigate heat losses of the ventilation ducts. Occupants were asked to register in a diary the position of the set-point temperature of the supply ventilation air (Tset,AH) and the regime for airflow rates controlled as “min”, “normal” and “max” as well as the position of the radiator thermostatic valves between 1 and 5 (Tset,SH). The manufacturer data of thermostatic valves enabled to map a corresponding set-point temperature to the thermostatic valve position.

The opening of all windows and internal doors were monitored using contact sensors from Fibaro®. These are magnetic sensors that send a signal each time the movable part of the window (or door) is less than 5 mm away the frame. They deliver a binary signal (open/closed) but do not measure the degree of opening.

House 1 has solar shading for two of four windows on the south façade. As these are controlled manually, occupants were asked to register any change in position. On the contrary, House 2 has automatic controlled solar shading on three of the four windows facing south.

3.2 Field measurement results for the apartments

3.2.1 Apartment 1

The general trend of indoor temperatures in Apartment 1 is shown in Figure 3.5. These temperatures are fairly constant despite the fluctuating outdoors temperatures and the time of the day. The living room has a higher temperature of about 22-25 ºC, with some peaks due to solar radiation. The temperature difference between the living room and bedrooms is also very constant in time, with ~2°C for the large bedroom (bedroom 1) and ~1°C for single bedroom (bedroom 2).

The case of Apartment 1 is particular. A cold draft has been discovered in the sliding door towards the balcony in the living room. This phenomenon has been confirmed in the second measurement campaign. It most probably explains the thermal environment measured in this living room, a behaviour that was not found for the other buildings measured.

The *living room* has a temperature that seems more affected by solar radiation. The interview revealed that the desired temperature in the living room is somewhere between 24 and 26ºC. This is confirmed by the set-point temperature of the radiator that is mostly at 24ºC, see Figure 3.9. The temperature distribution in the living room is shown in Figure 3.6. The corridor has a temperature that is about 1°C higher than the living room and kitchen. Such a large temperature difference over a short distance is not found in the other buildings investigated. This could be due to the problem of air leakage of the sliding door in the kitchen that could generate non negligible infiltrations. This hypothesis needs further research to be corroborated. Regarding stratification, it is very limited in the living room. Both the kitchen and the living room show a maximum stratification of ~1ºC. In the corridor, there is a larger stratification of about 2ºC, most probably due to the effect of the heat source.

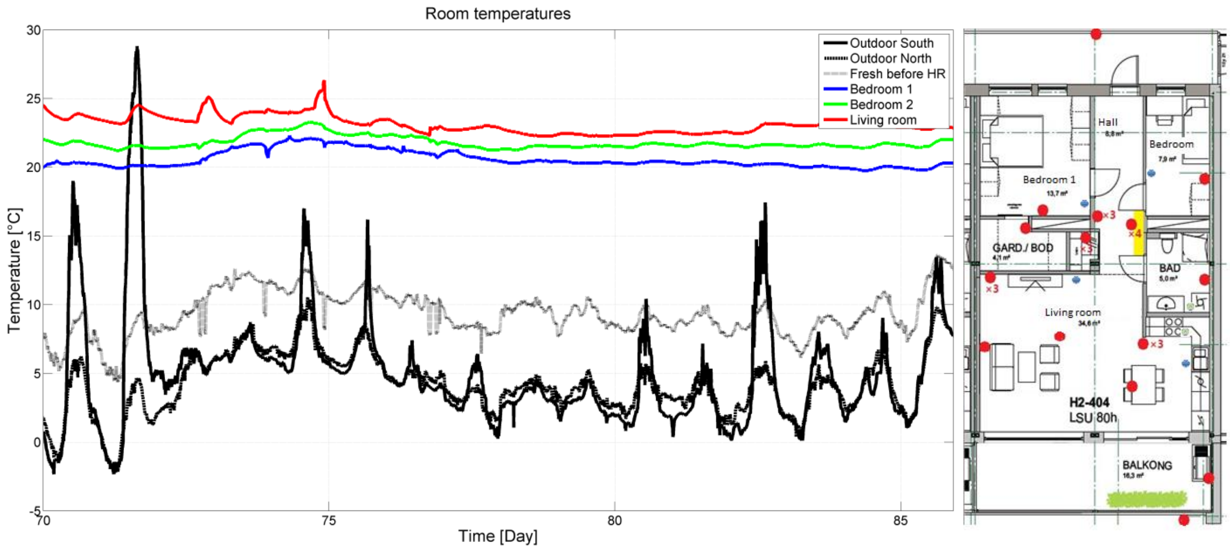


Figure 3.5 Temperature measurements in Apartment 1 (left) and layout of the apartment (right).

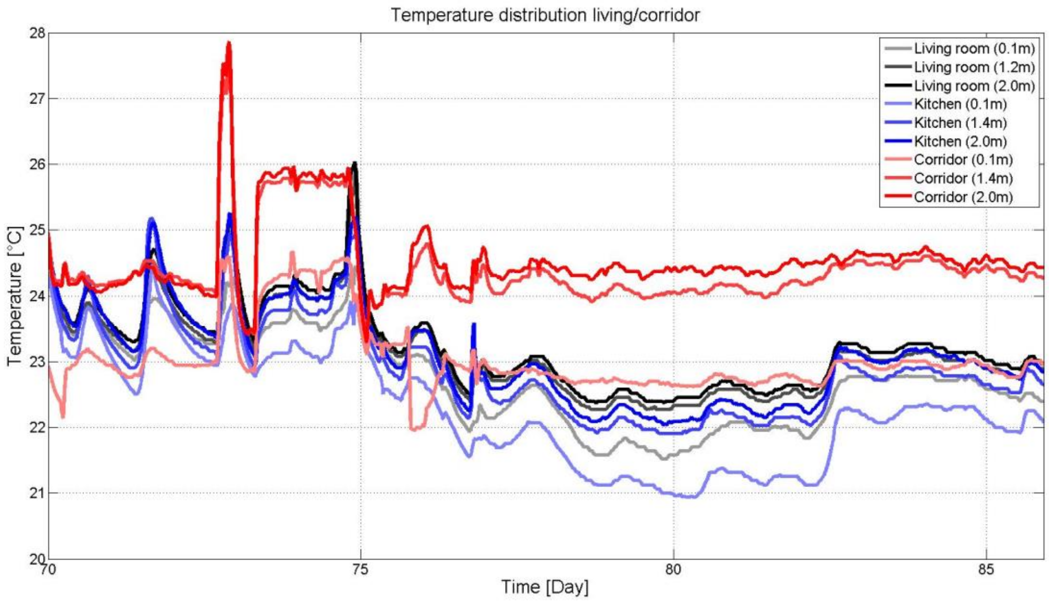


Figure 3.6 Air temperatures in living room, kitchen and corridor of Apartment 1.

Bedroom 1 is the largest bedroom. It is the only one used on an everyday basis. Figure 3.7 shows that the temperature difference between the heated zone and bedroom 1 ranges between 2 and 4°C. This temperature difference is achieved without window opening and keeping the bedroom door closed: the bedroom door is seldom open and the window is almost always closed except for one night. The expected temperature reported in the interview for this room is somewhere between 16-18ºC while the measured temperature is over 20ºC. These measurements suggest that the closing of internal doors as the only strategy to get cold bedrooms is not enough to comply with the expectations of many occupants regarding low bedroom temperatures (with a temperature of ~16°C or lower). Nevertheless, the user said to get use to sleep at this temperature. For instance, the user has changed the winter blanket to a summer blanket. The user would like to open the bedroom window to decrease the temperature, but does not due to the outside noise and because the user has been instructed not to do so. Nevertheless, the occupant sometimes opens the window before going to bed during a short period of time.

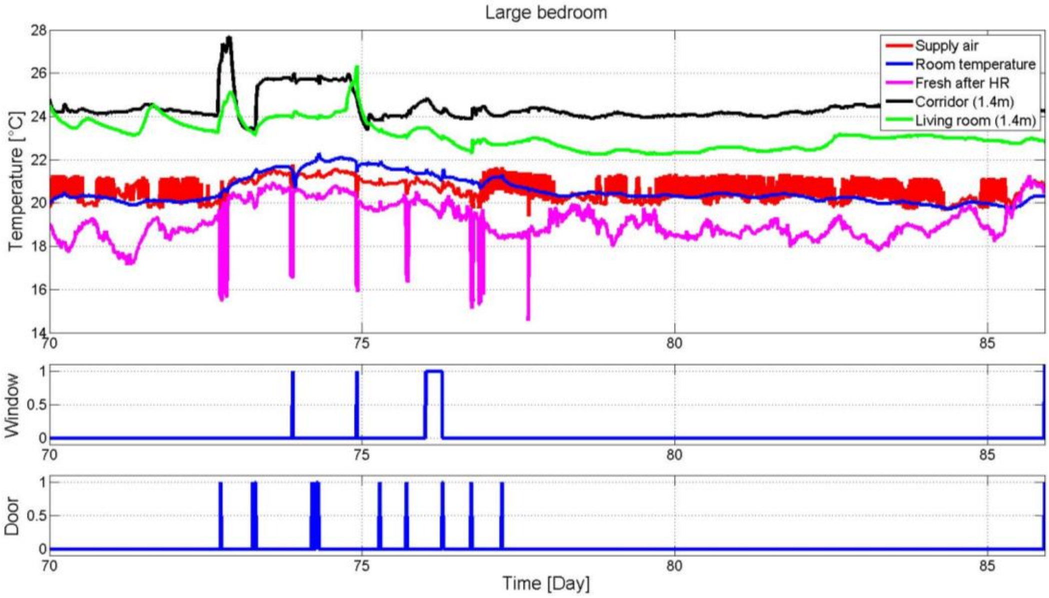


Figure 3.7 Temperatures in bedroom 1 and adjacent rooms in Apartment 1.

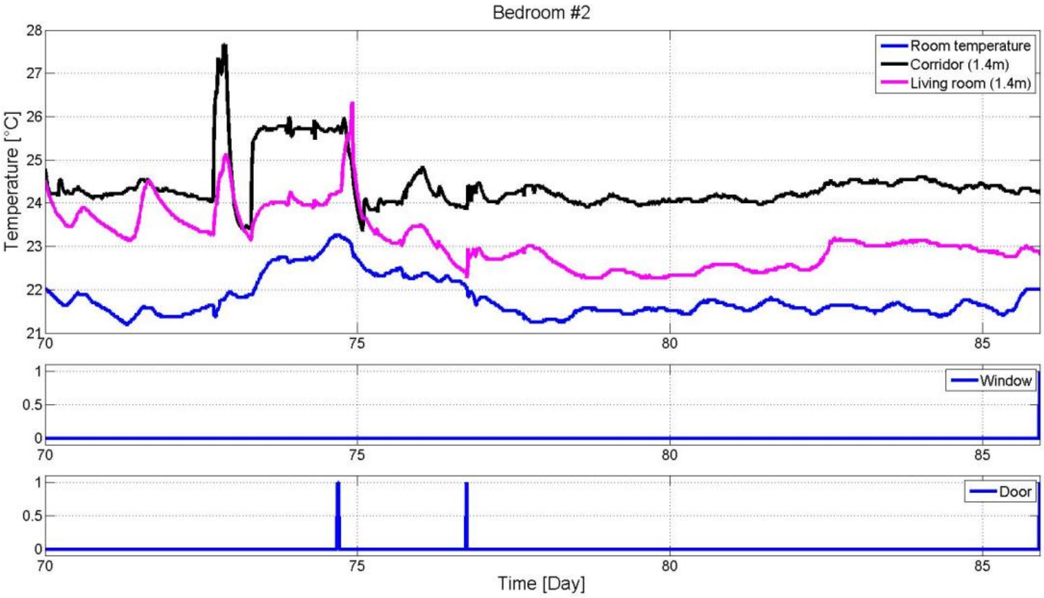


Figure 3.8 Temperatures in bedroom 2, the corridor and the living room in Apartment 1.

Bedroom 2 is only used by guests. It is not often used during the period of measurements. Figure 3.8 shows that both the window and the door of this bedroom are kept closed almost all the time. The time profile of the bedroom temperature follows closely the profiles of the adjacent rooms, especially the corridor: when the temperature in the corridor increased, the temperature in bedroom 2 increases accordingly even though the bedroom door is closed. The temperature difference between the corridor and the bedroom is in the range of ~2°C. The measurement period is relatively short and outdoor temperatures were mild. This temperature difference is expected to increase with decreasing outdoor temperatures.

The *radiator* seems to operate correctly, see Figure 3.9. It can provide the expected temperature in the corridor: the temperature measured by the thermostatic valve in the corridor (TRV bulb) corresponds to thermostatic valve set-point (TRV set-point). When the set-point temperature is 24°C, the corridor has a temperature of 24°C. Nevertheless, when the set-point temperature has been temporarily increased to 28°C, the temperature in the corridor did not exceed 26°C while the radiator in this apartment is significantly oversized (but numbers for this oversizing are not given here). This limitation to ~26°C may again be explained by the sliding door infiltrations that may increase the space-heating power significantly and may prevent the radiator to increase the indoor temperature up to 28°C. Regarding measurements on the radiator pipes and its surface, their accuracy is significantly lower than for the air temperature measurements. Those measurements were indeed done by attaching the sensors to the pipes or radiator surface with a limited contact area. This limitation known, results can be better interpreted. There is about 10°C between supply and outlet flow, each time there is a heat demand (meaning than TRV bulb is lower than TRV set-point).

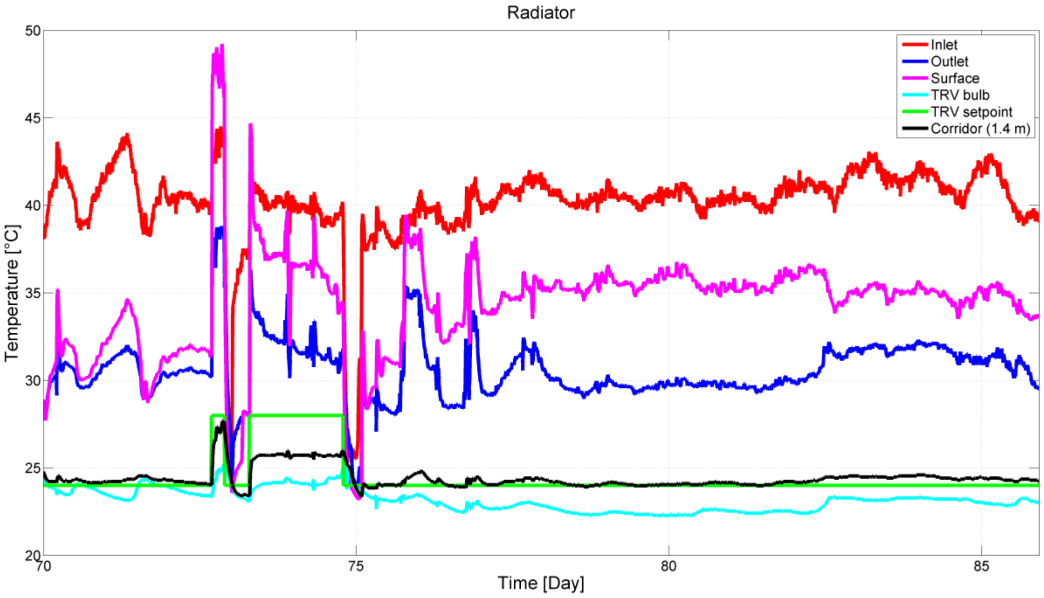


Figure 3.9 Temperatures related to the radiator in Apartment 1.

The performance of the heat recovery unit is now analysed. The airflow rates were not measured in detail in this apartment. In addition, the air temperature measurements on each side of the heat recovery are based on a single point. Therefore, no accurate assessment of the temperature effectiveness can be performed, only a first indication can be obtained. Assuming that airflow rates were balanced, the temperature effectiveness is evaluated to be 73% using these basic temperature measurements.

Regarding the heating battery of the air handling unit, the set-point temperature was set at 20ºC. From Figure 3.10, one can see that this temperature is achieved. However, as discussed before, this temperature is not optimal as regards the desired bedroom temperature. Using the supply air temperature over 20°C is indeed not coherent to achieve the desired bedroom temperature (16-18°C) but it is reasonable to get a warm living room (desired temperature of 24-26°C).

During the interview, the occupant told us that it was recommended to use the ventilation as a heating “booster”. During coldest periods, it was advised to increase the ventilation temperature to get a warmer apartment. This occupant was not present the day of move in of the apartment and has only the information from the brochure. The advice regarding the temperature is from a company that came to the apartment to check the functioning of the ventilation. In practice, the occupant increases the supply temperature during winter and reduces it during summer. When asked, the occupant claims to need *"additional heating from the ventilation*". It supports the hypothesis that this apartment lacks space-heating power due to the spurious infiltrations from the sliding door.

In this apartment, due to the high level of insulation, the ventilation seems to have a homogenization role making all the rooms with a similar temperature. However, in this study, **we have learned that**

most of the occupants want to have a different temperature in bedrooms than in living areas. Having a ventilation system with a supply temperature over the expected temperate in bedrooms does not help achieving the desired lower temperature in these bedrooms.

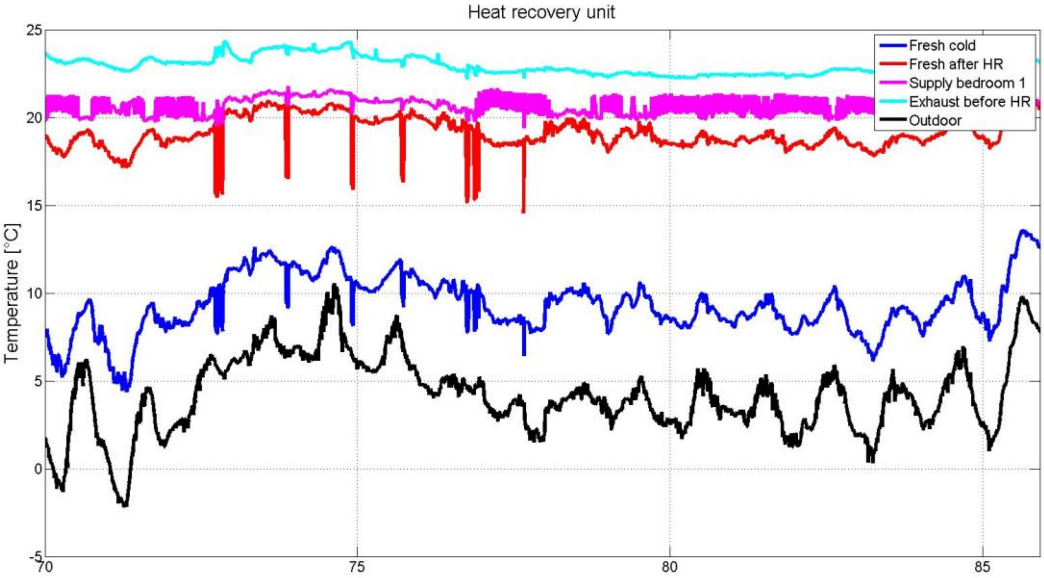


Figure 3.10 Temperatures related to the heat wheel operation in Apartment 1.

The general conclusion for Apartment 1 is that the user is not satisfied with the indoor environment:

- The occupant wanted to have temperatures in winter of 24-26°C in living areas and 16-18°C in the large bedroom. This is not achieved.
- Regarding the living room, the occupant initially thought that the installed space-heating power was too low, but the problem persists even though the radiator size has been increased. Measurements showed that the temperature in the corridor is higher than the temperature in the living room and kitchen. This points towards air infiltration (or lack of air tightness), but more detailed investigations are needed to confirm this hypothesis.
- The occupant uses the air heating to boost the temperature in the living room but this affects negatively the temperature in the sleeping room. The occupant was also advised against opening any window. The outside noise was also reported as another reason for not opening the bedroom window. In order to reduce the temperature in the bedroom, the only acceptable solution for the user was to close the bedroom door. It did not enable to reach the expected bedroom temperature and the user had to adapt to this situation.

3.2.2 Apartment 2

Apartment 2 is characterised by larger temperature differences between rooms. The living room is almost constantly over 20ºC. By means of bedroom window opening, the temperature in bedroom 1 is kept at about 16ºC, while bedroom 2 has almost the same temperature as the living room. Figure 3.11 shows that, in this apartment, it is feasible to create temperature zoning. However, as the simulations in Chapter 4 will show, this is done at the expense of larger energy use for space-heating.

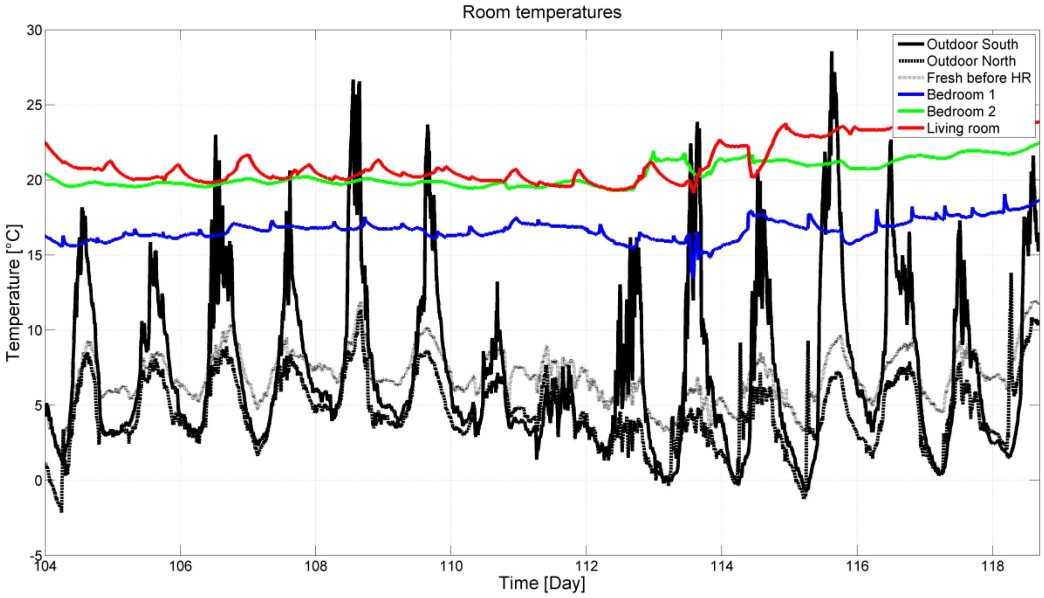


Figure 3.11 Temperature measurements in Apartment 2.

Bedroom 1 has its window constantly open and its door is normally closed except for some punctual moments. The user confirmed in the interview having the window always open and claimed that has learnt to keep the door closed (was not doing it at the beginning). **In this apartment, it is made clear that the opening of the bedroom window with internal door closed creates a larger difference between heated rooms and the main bedroom (between 4 and 6°C difference).** The temperature reached in the large bedroom is ~16°C, but the occupant said he would like even colder temperatures.

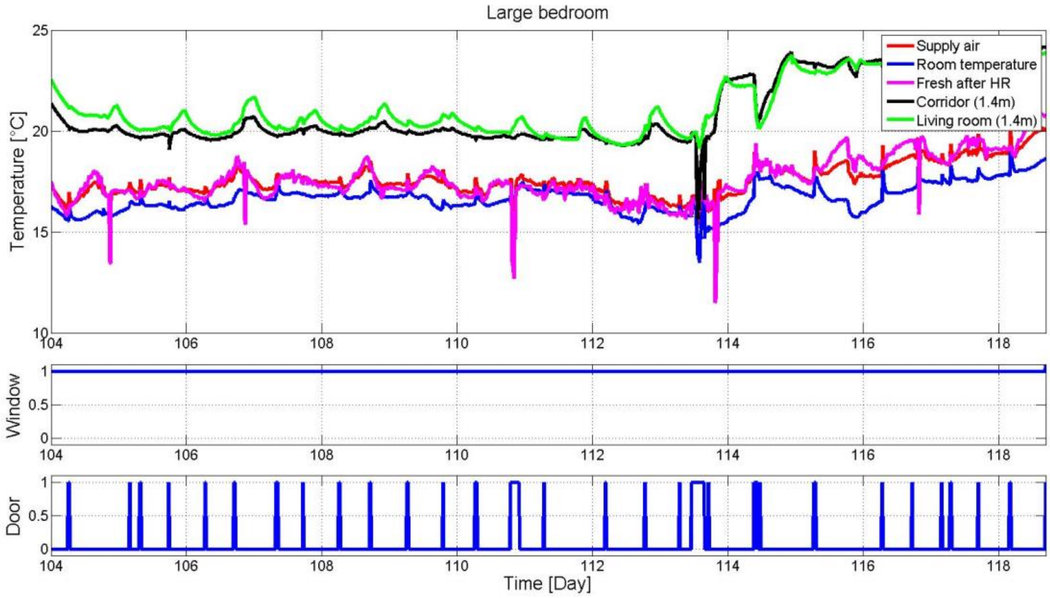


Figure 3.12 Temperatures in bedroom 1 and adjacent rooms in Apartment 2.

Bedroom 2 is seldom used, only when the owner has visitors. During the measured period, both its door and window were closed. This room temperature is relatively constant. After day 113, there is an increase in the set-point temperature of the radiator (see Figure 3.15). This temperature increase is not followed by the air temperature in bedroom 2.

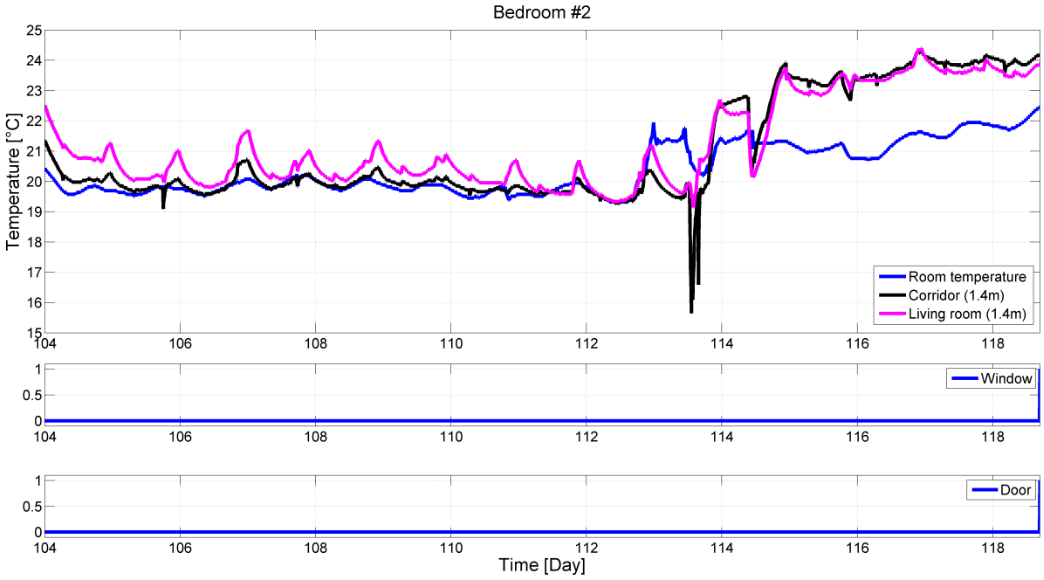


Figure 3.13 Temperatures in bedroom 2 and adjacent rooms in Apartment 2.

The *living room* has a temperature affected by solar radiations. Every day, there is a peak of temperature corresponding to the hours with higher solar radiation. As Figure 3.14 shows, there is no significant stratification: the maximum vertical temperature difference measured is ~0.5 ºC.

Regarding the stratification in the corridor, up to 4ºC difference is measured (between the floor and 2 m high) when the radiator emits power. We also see a limited stratification in all the measured points and a small temperature difference between the kitchen, the living room and the corridor, showing that the heat from the single heat source is distributed efficiently.

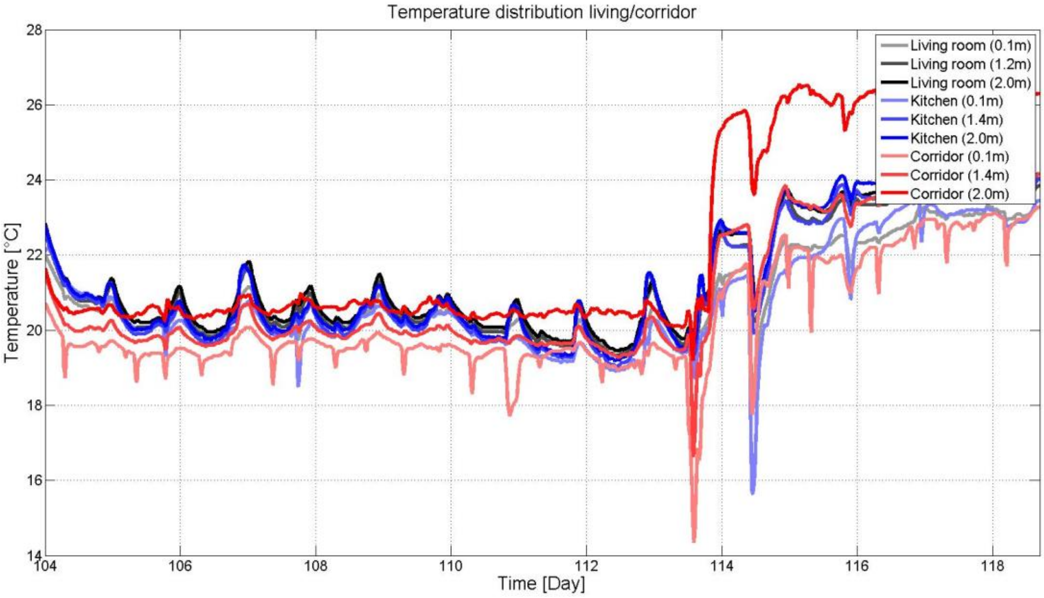


Figure 3.14 Air temperatures in the living room, kitchen and corridor of Apartment 2.

During the first days (from 104 to 113), the radiator thermostatic valve is set to 20 ºC, see Figure 3.15. During this period, the temperature measured by the thermostatic valve is slightly higher than this set-point temperature. Therefore, a limited amount of heat is emitted by the radiator, its surface temperature being equal to its outlet temperature also very similar to the corridor temperature. For the following days (after the 113), the set-point temperature is increased to 26 ºC leading to a need for space-heating. As already mentioned, temperature measurements of the inlet and outlet pipes as well as the radiator surface are less accurate because of the simple measurement setup used. Nevertheless, it can be seen that the need for space-heating power leads to high temperature for the radiator outlet and a high surface temperature. The corridor temperature increases progressively to the set-point temperature. The measurement period is too short to determine whether this temperature would have been reached, or an offset error would have remained (as expected from a P-control). Combining previous results, the space-heating distribution appears to perform as expected. For instance, there is no evidence showing that the radiator has not enough power (such as in Apartment 1).

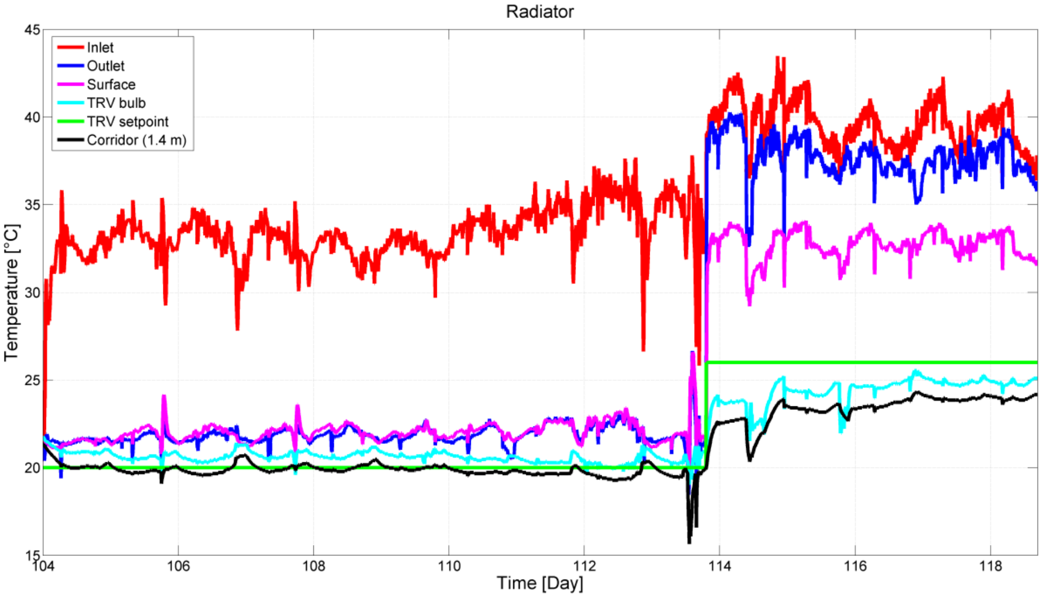


Figure 3.15 Temperatures related to the radiator in Apartment 2.

The analysis of the heat wheel shown in Figure 3.16 shows that the user does not use the ventilation as a heating system, which is coherent with the wish for cold bedrooms. Nevertheless, it can be concluded that the heat recovery of the mechanical ventilation in this super-insulated building equalize room temperatures in the apartment. For example, on day 105, we can see temperatures of 21, 19 and 16ºC in the living room, bedroom 2 and bedroom 1, respectively. The temperature of the extract air before the heat wheel is already 21ºC, but the supplied temperature from the heat wheel to the whole apartment is 18ºC, meaning it will increase the temperature in the bedroom and cool down the temperature in the living room. The use of the heat wheel is very positive for reducing the ventilation losses. However, regarding comfort, it seems that the use of the centralized mechanical ventilation with heat recovery providing for a single temperature for the supply ventilation air is negative as it does not help to achieve the wished temperatures in neither the living room nor the sleeping room. It shows that the usual concept of the mechanical ventilation system (based on one centralized heat recovery and one set-point temperature for the supply air) should be changed to enable temperature zoning and to prevent homogenizing temperature inside the building.

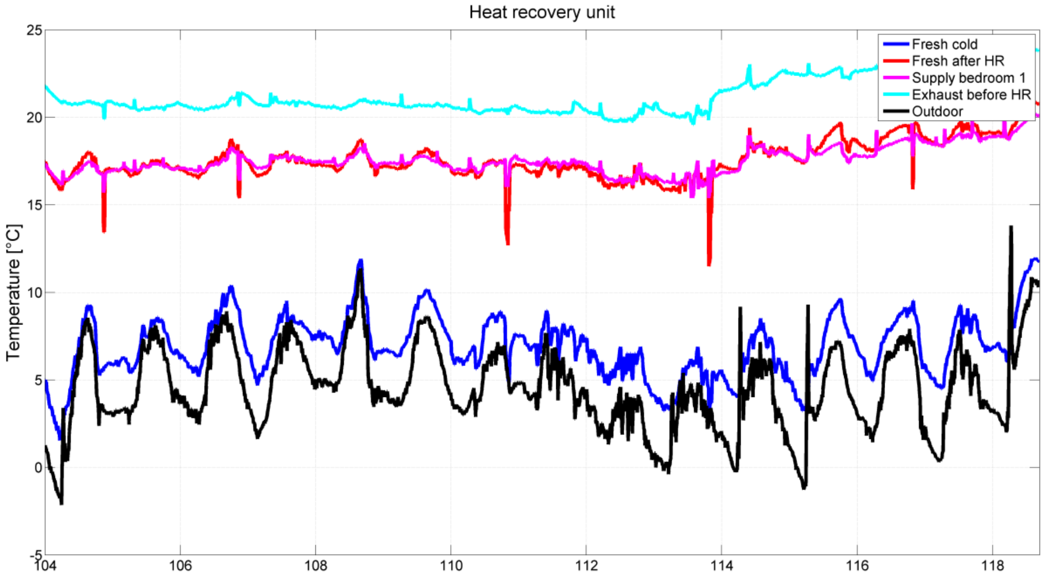


Figure 3.16 Temperatures related to the heat wheel in Apartment 2.

The conclusion for Apartment 2 is that the user is generally satisfied with the indoor temperatures:

- During the measurement campaign with relatively mild outdoor temperatures, the radiator in the corridor was able to provide for a uniform thermal environment in the corridor, living room and kitchen, with limited thermal stratification. In future work, this conclusion should be confirmed for colder outdoor temperatures.
- The occupant creates lower temperatures in his bedroom (about 16°C) by constantly closing the door and opening the window. However, he would like to have even lower temperatures in this bedroom.
- The user operates the ventilation system correctly to achieve the desired indoor temperature in the bedroom. Surprisingly, he didn’t get information that it was possible to change the set-point temperature for the supply ventilation air.
- The user was given some general recommendations when moving in the house but he thinks that he has learnt more using trial-error.

3.3 Field measurements results in the terraced houses

The households living in the two terraced houses had very different expectations regarding bedroom temperatures. Since the measurements were done sequentially, and the houses had different layouts, the results are not fully comparable.

3.3.1 House 1

The household in House 1 is satisfied with temperatures of ~22°C in the living room, however, they describe 20°C as the ideal temperature in the bedroom. They report having the windows in the bedroom almost always closed (due to outdoor noise), but sometimes they open them to provide fresh air or control the indoor temperature. They normally have the internal doors open to keep the sleeping room warm, but sometimes, due to privacy needs, they close them. There was a folder with information, but the user has mostly learnt by trying.

The general trend of the indoor air temperatures in the first floor of House 1 is shown in Figure 3.17. Most of the rooms have similar temperatures, though the south-facing rooms are more affected by the solar radiation. The room with the highest temperatures is the bedroom 3 that fluctuate between 21-28°C mostly due to the solar radiation.

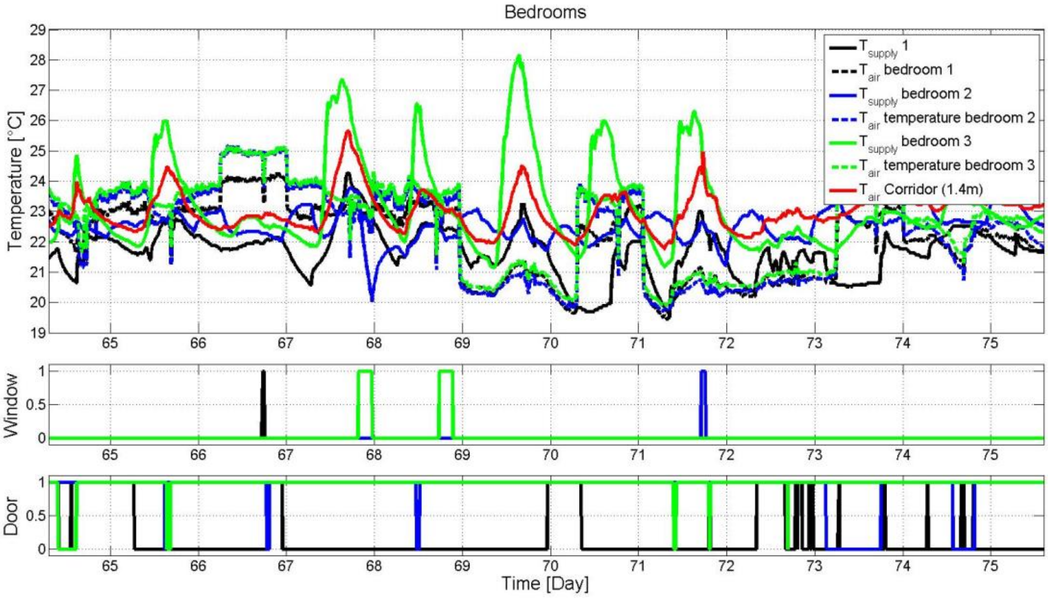


Figure 3.17 Temperature measurements, doors and windows status in the first floor of House 1.

Bedroom 1 is the children's room whose window is very seldom open (only once during the two weeks of measurements). Bedroom 1 has temperatures in the range 19 to 24ºC and the average temperature measured during the two weeks is 21.6ºC. This temperature is slightly lower than in the adjacent rooms. This room is generally affected by the temperatures in the corridor since the door is kept mostly open. In the interview, the users said that the room is used as a playing room during the day and a sleeping room during the night.

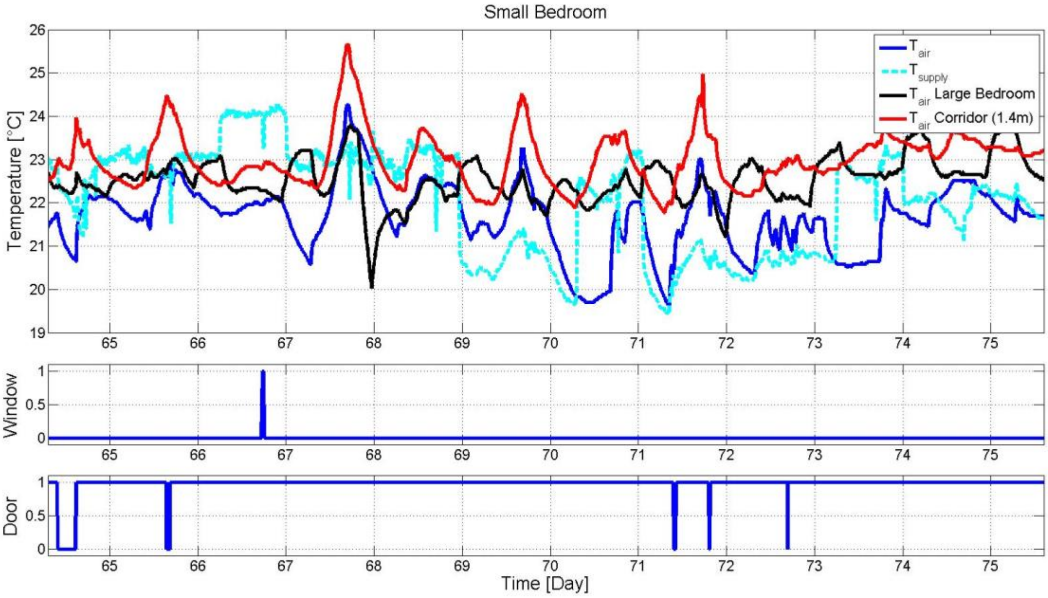


Figure 3.18 Air temperatures, door and windows status of the small bedroom 1 in House 1.

Bedroom 2 has the internal door mostly open and its window is mostly closed, see Figure 3.19.When the window is open, the room temperature drops from 23.7 ºC to 20 ºC.

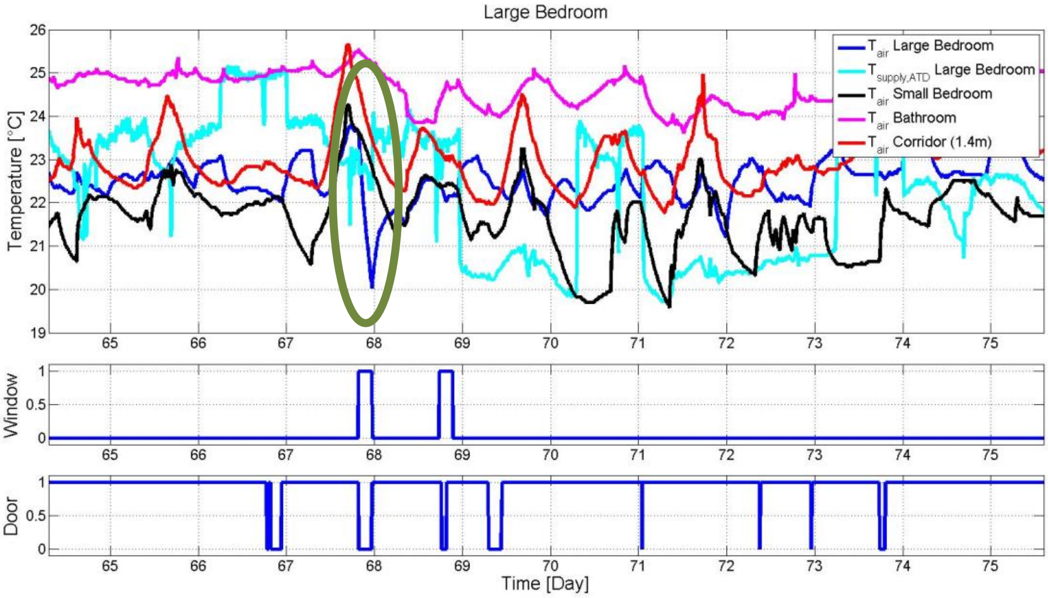


Figure 3.19 Air temperatures, door and windows status of the large bedroom 2 in House 1.

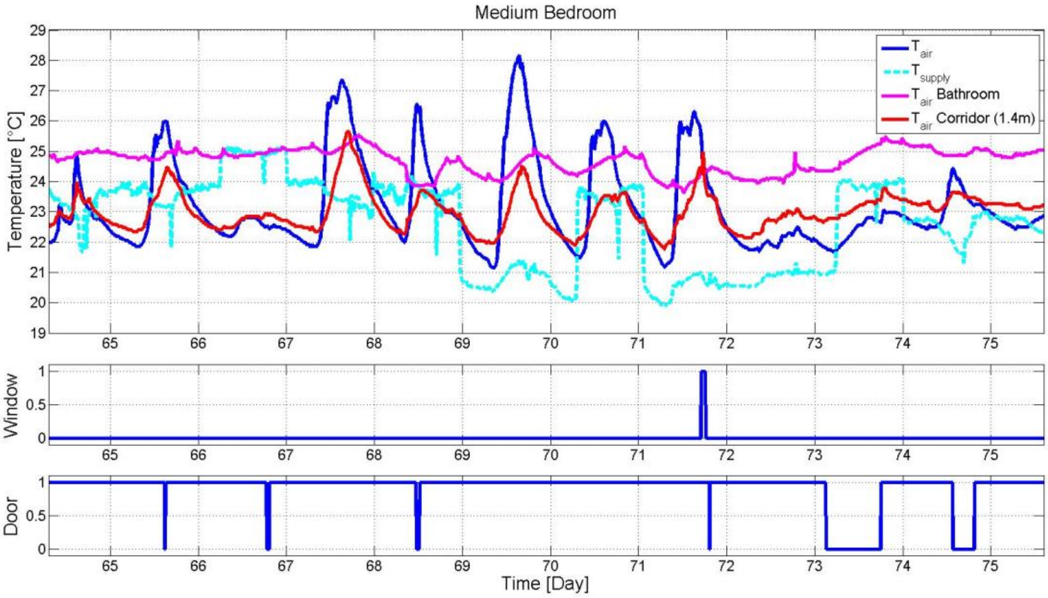


Figure 3.20 Air temperatures, door and windows status in the medium bedroom 3 in House 1.

In general, the temperature in bedroom 2 oscillates between 21 and 23°C, a range which is slightly higher than the desired temperature of 20°C. Except for periods with high solar gains, this temperature is similar to the corridor temperature, the bedroom door being most of the time open. Bedroom 2 presents both periods with temperatures higher and lower than the corridor. In periods with higher temperatures than the corridor, the bedroom should get additional heat source(s) which could be internal gains, the supply ventilation air (that oscillates between 20°C and 24°C) or the heat transfer through the partition wall with the bathroom kept at a higher temperature. Measurements in Figure 3.19 do not show a clear correlation between periods where bedrooms temperatures are above the corridor temperature and the temperature of the supply ventilation air or the temperature in the bathroom. **The resulting temperature is thus a complex heat balance between many contributions. This short measurement campaign along with a limited set of sensors does not allow to analyze this heat balance in more detail. Detailed dynamic simulation tools would be of great assistance to**

investigate this complex balance. It is almost impossible to predict the resulting bedroom temperature based on simple analytical or qualitative approaches.

In *bedroom 3,* the door is kept almost always open and the windows are open only in punctual moments. In this bedroom oriented to the south, there is a clear synchronization with solar gains. With solar gains, the bedroom temperature is higher than the corridor (where the radiator is placed). On the contrary, without solar gains, the bedroom is slightly colder than the corridor (up to ~1°C).

The *living room* on the ground floor is an open layout integrating the kitchen and connected to the entrance hall. Air temperatures measured are reported on Figure 3.21. The vertical stratification in the living room is very small, most often below 1ºC. The average measured temperature in this room is 22.7ºC which is very close to the desired set-point temperature and to the occupant's perception of thermal comfort. The living room temperature oscillates between 22 and 23ºC. The temperature difference with the corridor in the ground floor and the kitchen connected to the living room is limited. During this short measurement period, the single radiator is able to provide for the space-heating in the entire floor.

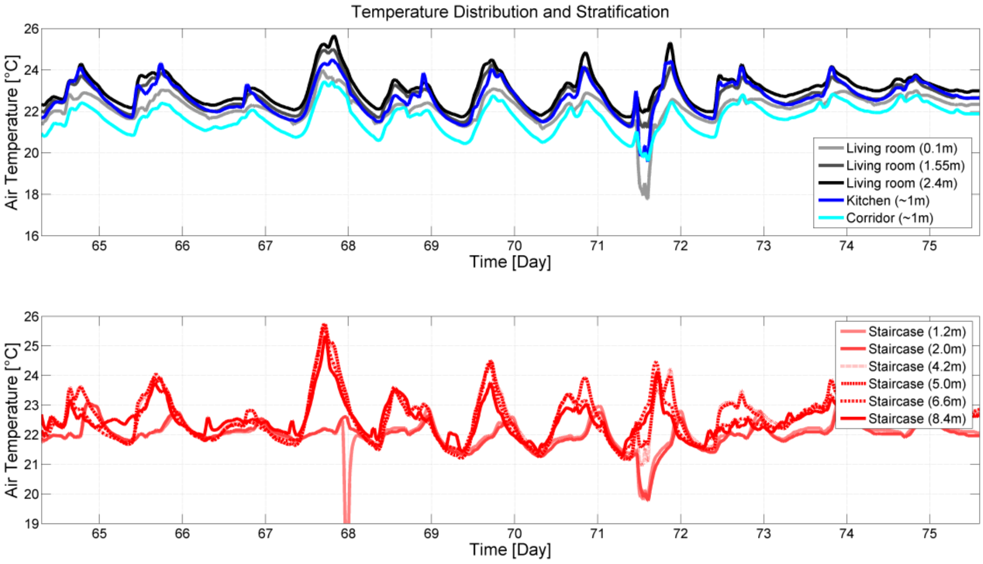


Figure 3.21 Temperatures in the living room and the open staircase of House 1.

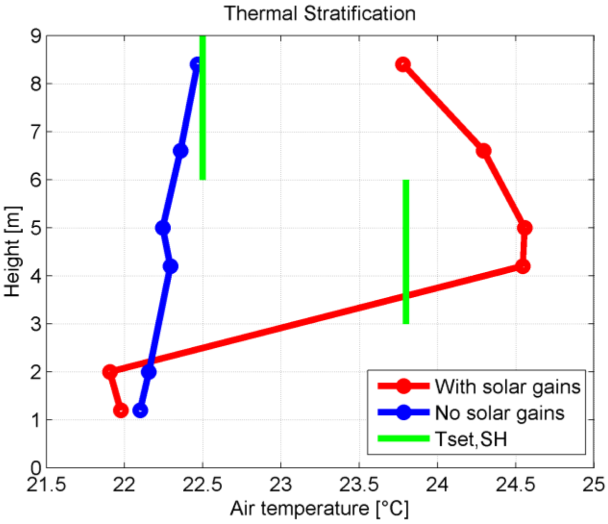


Figure 3.22 Example of temperature stratification in the staircase of House 1 during a period with and without solar gains (the set-point temperature applied to the radiator is shown in green).

Thermal stratification takes place in the stairs characterized by increasing air temperatures with increasing height. Although the number of measurement points is limited, it does not seem that the heat delivered by the radiator in the living room flowed to the first floor: the two floors are independent from a space-heating point of view. However, with large solar gains, the temperature in the living room can be higher than the first floor and a temperature inversion occur in the staircase, see Figure 3.22.

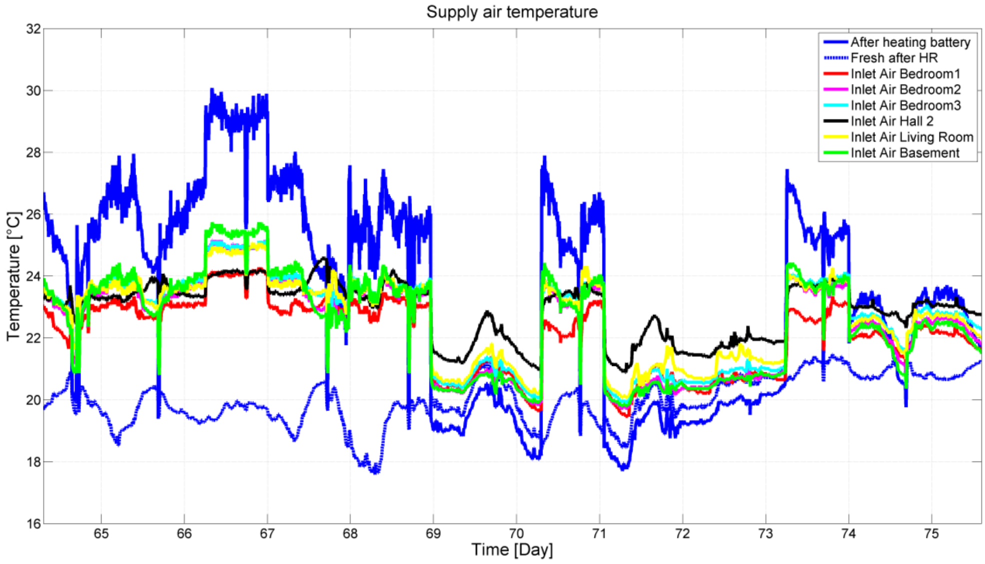


Figure 3.23 Temperatures of the supplied air by the ventilation system in House 1.

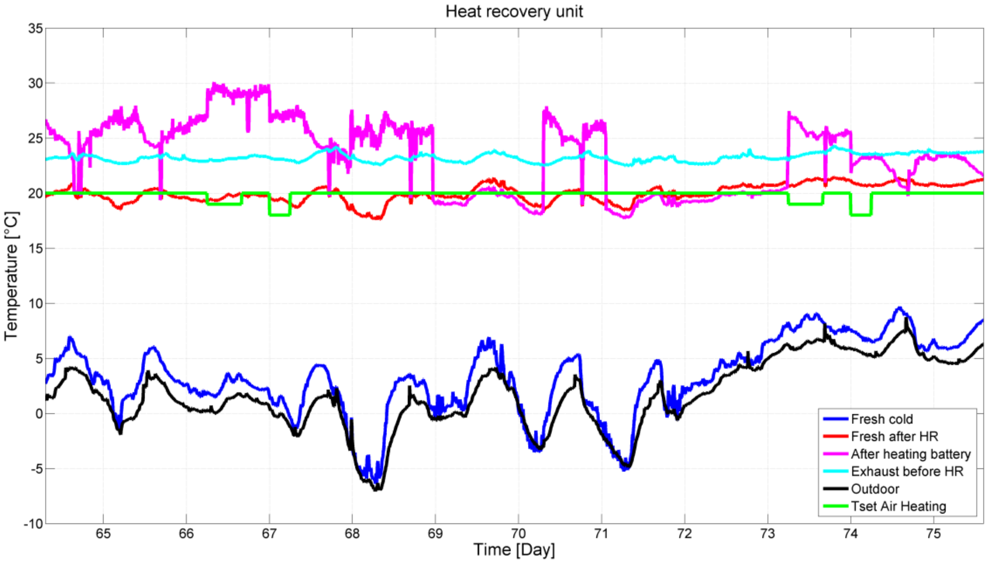


Figure 3.24 Air temperatures around the heat wheel in House 1.

Air temperature throughout the ventilation distribution system is now analysed. The temperature sensor for the supply air right after the AHU may have been placed too close to the heating battery. The sensor has most probably been influenced by the thermal radiation from the coil, leading to a measured temperature significantly higher than the air temperature supplied by the ATDs. This measurement would need to be verified since its quality is questionable. The air supply in the basement is the closest to the air handling unit. The temperature at the ATD in the basement is thus taken as a good approximation of the air temperature after the heating battery. Based on this assumption the temperature differences between air inlets are estimated to range between 1 to 2ºC. They vary with distance and the temperature difference with the ambient air in the room.

The performance of the heat recovery unit is now analysed. As for other buildings investigated, the airflow rates were not measured in detail in House 1. In addition, the air temperature measurements on each side of the heat recovery are based on a single point. Therefore, no accurate assessment of the temperature effectiveness can be performed, only a first indication can be obtained. Assuming that airflow rates were balanced, the temperature effectiveness is evaluated to be 85-90% using these basic temperature measurements. The family seems to use ventilation air for heating, which is coherent with the relatively high temperatures they want in bedrooms.

Radiator 1 placed on the ground floor works as expected and is able to provide for enough space-heating power to the room. Each time the air temperature measured by the TRV bulb is higher than the set-point temperature, the radiator emits heat to the room. The temperature between the inlet and outlet water pipes is then large (7-10°C). If the air temperature measured at TRV bulb is higher than the set-point temperature, the radiator stops to emit heat and cools down progressively. The temperature measured by the TRV bulb is very close to the living room temperature.

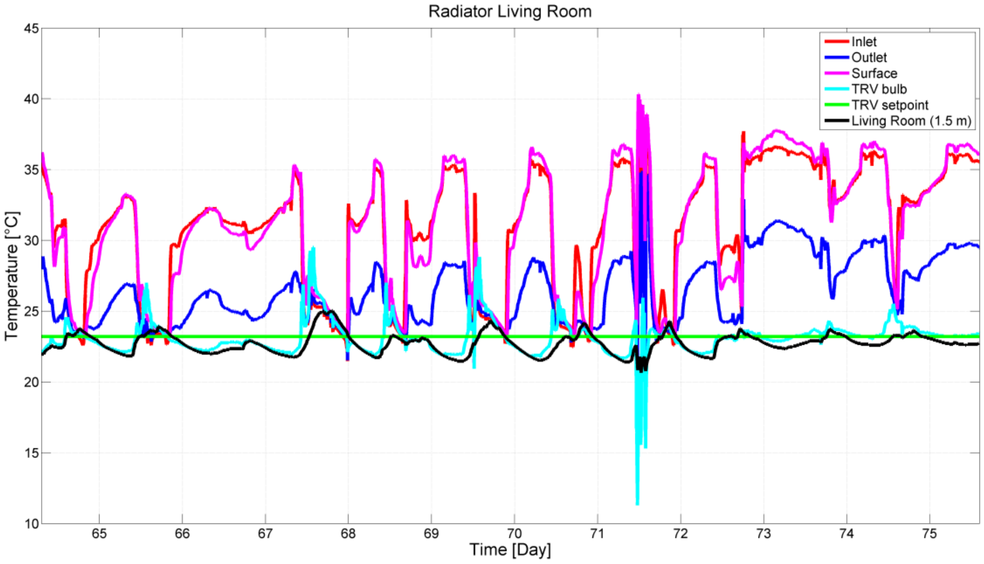


Figure 3.25 Temperatures related to radiator 1 in the living room of House 1..

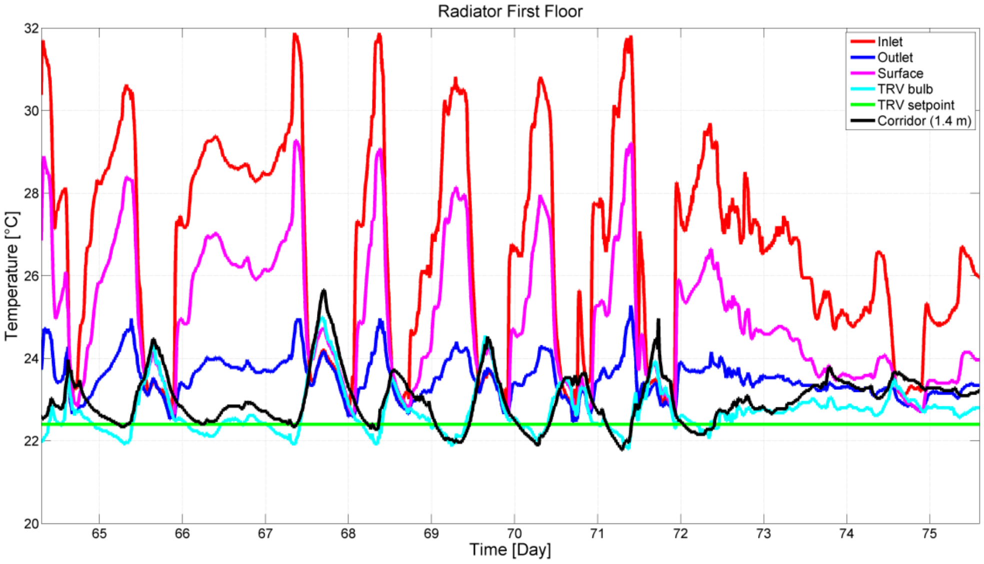


Figure 3.26 Temperatures related to radiator 2 in the first floor of House 1.

Radiator 2 in the first floor is shown in Figure 3.26. Similar comments done to radiator 1 can be applied for radiator 2.

The conclusion for House 1 is that the users are generally satisfied with the indoor thermal environment:

- During this short period of measurements with outdoor temperatures ranging from -5 to +5°C, one radiator enables to create a uniform temperature on the ground floor with limited temperature stratification. The measured temperature in the living room complies with the desired temperature reported by users during the interview and the set-point temperature they applied to the radiator TRV during measurements.
- The users of this building would like relatively warm bedrooms (~20°C). Measurements show that they reach this temperature level even though bedrooms are not equipped with a radiator. To get warm bedroom, users accept to keep bedroom doors open most of the time and bedroom windows close. In addition, they use the ventilation system coherently by applying a relatively high set-point temperature for the supply ventilation air (~20°C).
- Both radiators operate correctly and obtain the desired temperatures both in the living room and the corridor on the first floor.
- In addition, they received only a short instruction about the control of the house when they moved in. Eventually, they contacted the ventilation supplier to get further information.

3.3.2 House 2

The household of House 2 is satisfied with temperatures of ~23°C. Let us remember that House 2 has no heat emitter in the ground floor. However, they wish to have much lower temperatures in the bedroom, ~15°C. To achieve this, they normally have the windows opened 6-7h per night, except during the coldest nights in winter. They normally have the internal doors closed to keep the low temperatures and due to privacy needs.

The general trend of the room temperatures in House 2 is shown in Figure 3.27. They are similar for all the measured rooms during the two weeks of measurements. The bedrooms display a lower temperature, and the rooms with radiator achieve higher temperatures.

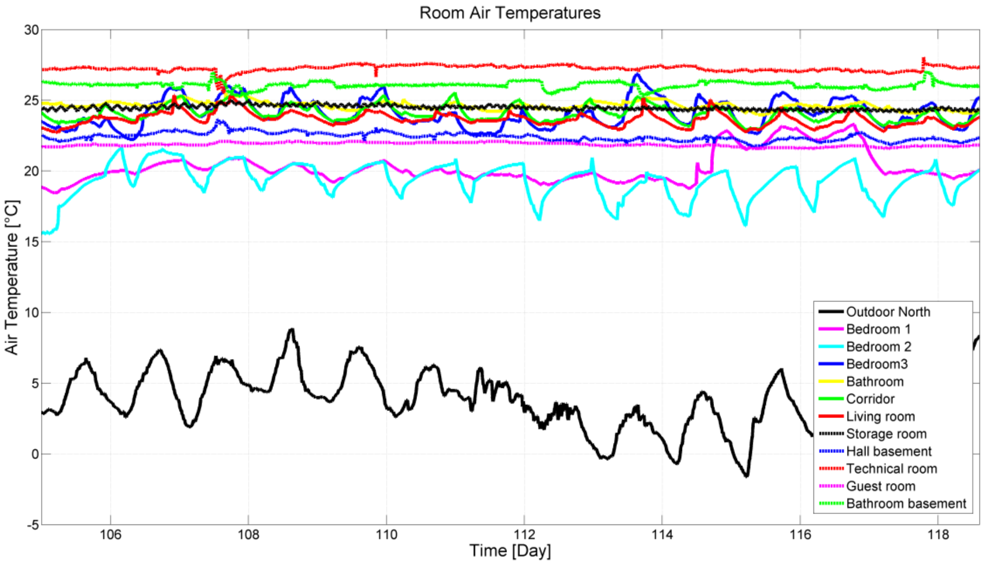


Figure 3.27 Temperature measurements, doors and windows status in House 2.

Bedroom 1 has no permanent occupation as it is used as guest room. The bedroom temperature oscillates between 22 and 26°C, following closely temperature in the corridor. The bedroom has a temperature that is sometimes higher, sometimes lower than the corridor. This cannot be correlated with the door opening status or the temperature of the supply ventilation air. However, the bedroom temperature decreases each time the temperature in the neighbouring large bedroom decreases suddenly (as it will be shown, due to window opening). Again, the resulting bedroom temperature is the result of a complex heat balance that is difficult to predict using simple analytical or qualitative evaluation methods.

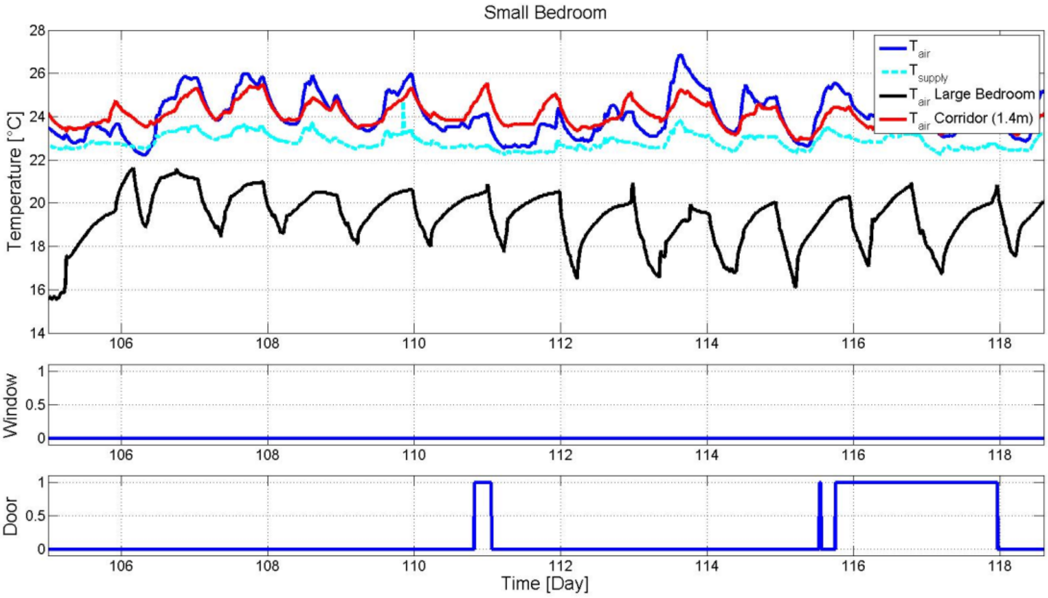


Figure 3.28 Air temperatures, door and windows status of the small bedroom1 in House 2.

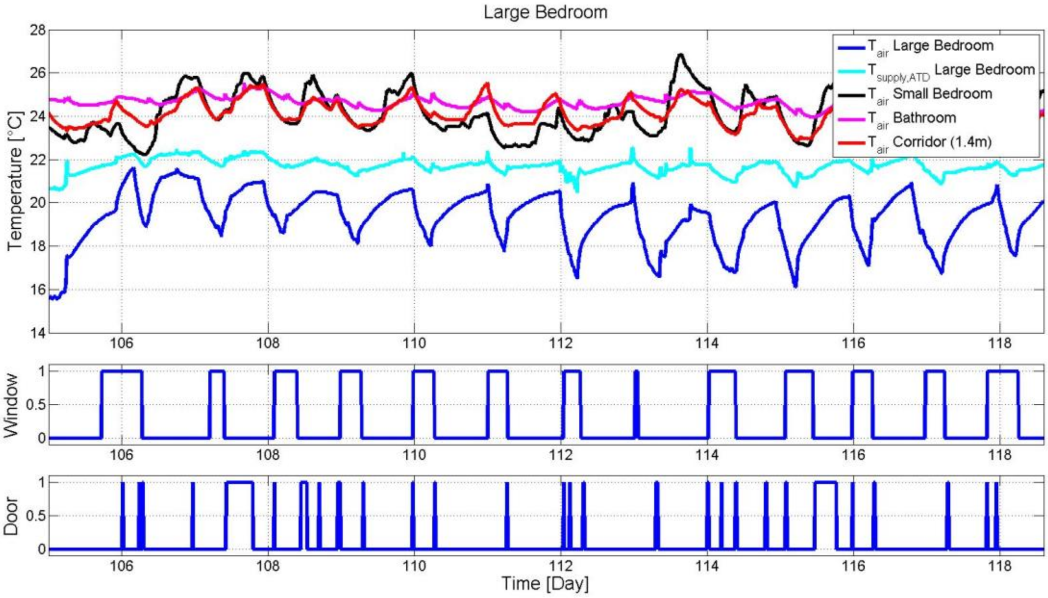


Figure 3.29 Air temperatures, door and windows status of the large bedroom 2 in House 2.

Bedroom 2 has its window open every night from midnight to 7 am during week days and from midnight to 10 am during weekends. During open window periods, the door to the hall is normally closed. Users leave the window open to get a colder bedroom, while they have learnt that having the door to the hall open helps warming up the bedroom. The users expect temperatures in this bedroom between 14 and

16ºC, however the measured temperature ranges from 15 to 19ºC. Despite the cooling from the open window, they do not manage to achieve the desired temperature. In conclusion, users nearly achieve the expected temperature. Nevertheless, it is done at the cost of increasing space-heating needs and, as shown for the small bedroom, it impacts the temperature of in neighbouring rooms. It is also interesting to see that the temperature slope when opening the window (during cooling) is steeper than the temperature slope when closing the window (during heating). *Bedroom 3* is mostly used as an office. In this room, the door is mostly open and the windows are mostly closed. Equipped with automatic window shading, this room is much less affected by the solar radiation than the corridor

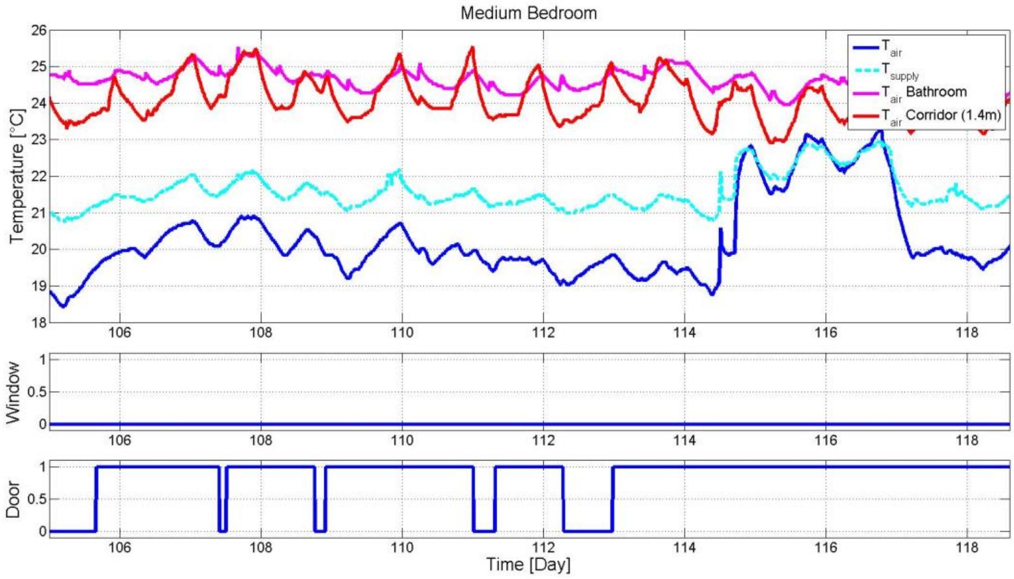


Figure 3.30 Air temperatures, door and windows status of the medium bedroom 3 in House 2.

The ground floor is an open layout combining the living room and the kitchen. It does not have a radiator. In the living room, the temperature fluctuates from 23 to 25ºC with average 24ºC. The stratification is limited to ~1.5ºC in the worst case, and is 0.5 to 1ºC on average. As it will be shown, even though users expect lower temperatures in the bedroom, the set-point temperature of the supply ventilation air is taken at 22 ºC because they wish to keep a high temperature in the living room. Measurements during the first campaign had additional temperature sensors in the ground floor. The temperature appeared to be uniform in both the living room and kitchen.

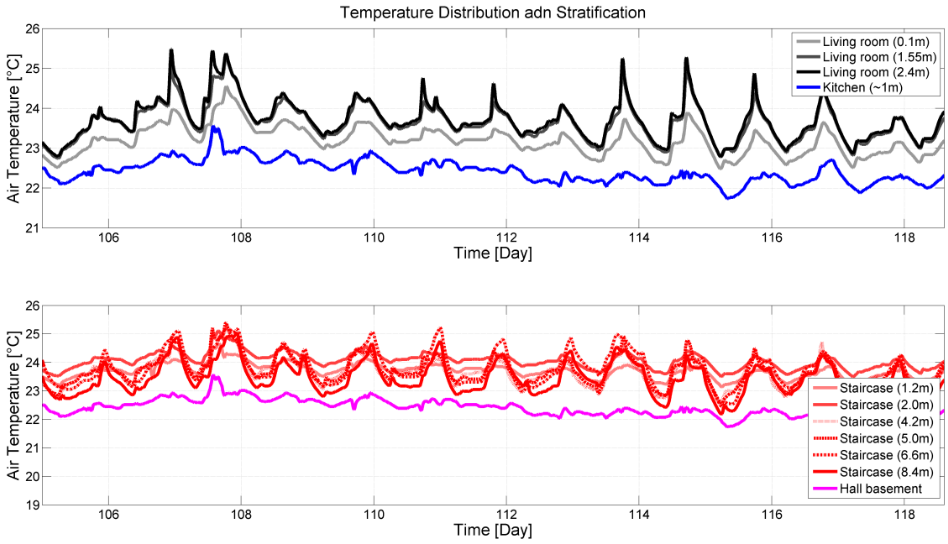


Figure 3.31 Temperatures in the ground floor and the open stairway in House 2.

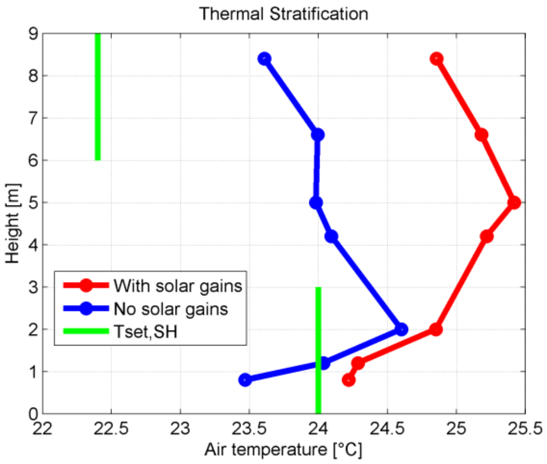


Figure 3.32 Example of temperature stratification in the staircase of House 2 during a period with and without solar gains (the set-point temperature applied to the radiator is shown in green).

Regarding the temperature stratification in the open stairway, a temperature inversion can be seen over the three floors: the temperatures in the lower levels are higher than at higher levels. This is due to the heat delivered by the radiator located in the basement. The stratification can be better understood when analysed along with the performance of the radiators.

Radiator 1 is placed in the entrance hall, in the basement floor. The radiator provides heat without interruption to the room as the TRV bulb is always lower than the TRV set-point temperature of 24 ºC, see Figure 3.33. This temperature difference is large (0.8°C) and comparable to the P-band of the valve (estimated at ~1°C by the manufacturer). It looks like this valve is often widely open and the power emitted by the radiator close to its maximum. However, the measured room temperature is even lower than TRV bulb temperature, with an average temperature of 22.4 ºC. Combined with the measurements in the open staircase and the living room, it is seems like a large convection cells takes place between the corridor in the basement and upper floors. For instance, a significant part of the radiator heat moves directly from the basement to the ground floor (providing comfortable temperatures in the living room area). The space-heating power left for the corridor in the basement appears too small to reach the set-point temperature. The radiator looks thus undersized but it has most probably not been dimensioned to provide heat for the upper floors. The present work focuses on the simplified space-heating distribution using one radiator per floor. The present configuration with less than one radiator per floor has thus not been investigated exhaustively. More research is needed to conclude about this space-heating distribution strategy.

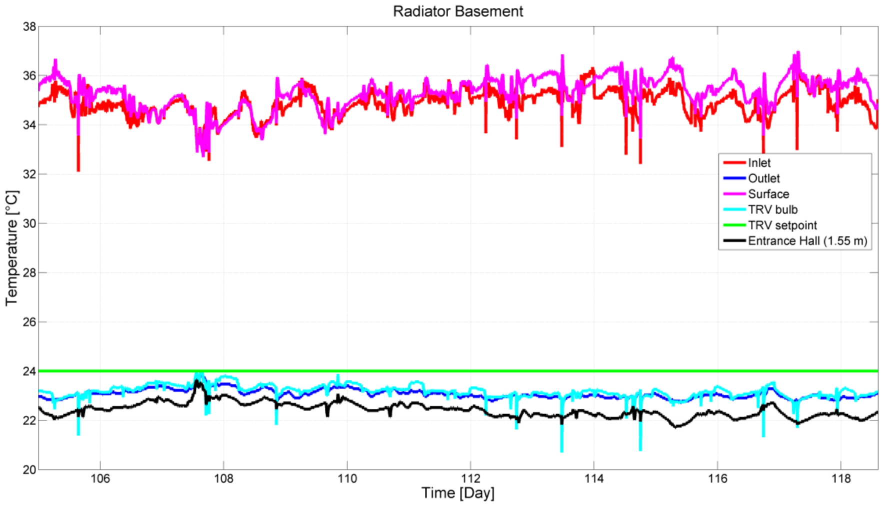


Figure 3.33 Temperatures related to radiator 1 in the basement of House 2.

Radiator 2 in the first floor did not have to function during the measurement period. The TRV bulb temperature is always higher than the set-point temperature. With a TRV closed, the temperatures related to the radiator are thus close to the room temperature. In Figures 3.31 and 3.32, the thermal stratification shows frequent temperature inversions between the basement, the ground floor and the first floor. The first floor gets a significant amount of heat by convection from the other floors below. In practice, one may strongly suspect that the radiator in the basement to provide heat for both the ground and first floors (meaning almost the entire building). The measurement campaign was too short to confirm if this space-heating distribution approach would provide for enough heat in the coldest days of the winter. Nevertheless, the radiator in the first floor is expected to enter into action during these coldest days.

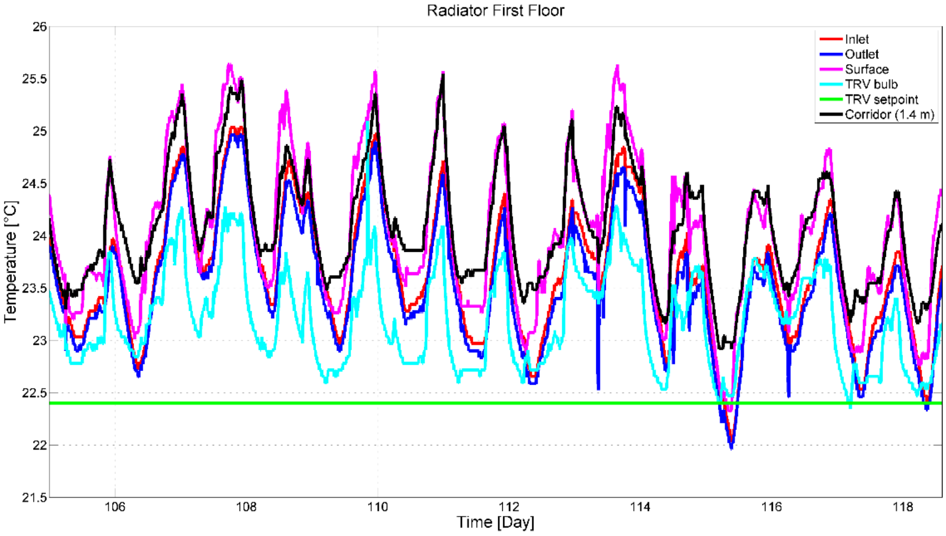


Figure 3.34 Temperatures related to radiator 2 in the first floor of House 2.

The performance of the heat recovery unit of House 2 is now analysed. Again, no accurate assessment of the temperature effectiveness can be performed, only a first indication can be obtained. Assuming that airflow rates were balanced, the temperature effectiveness is evaluated to be about 80%. However, due to the lack of information about airflows, we cannot conclude further about the effectiveness. Most of the time, the supply temperature before the heating battery is very close to the supply temperature, suggesting that the heating battery may not be working very often.

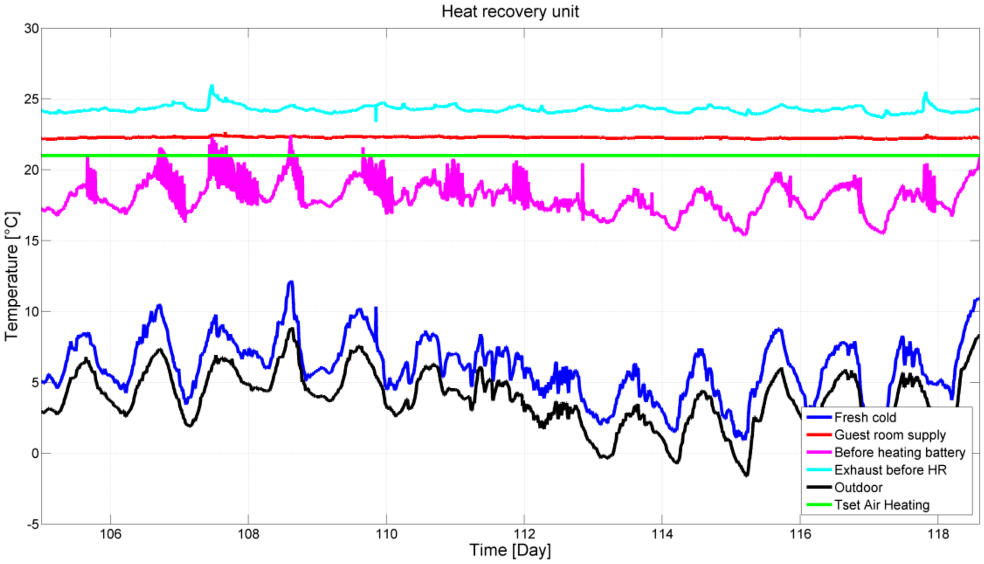


Figure 3.35 Temperatures in the air handling unit of House 2.

The users of House 2 are in general moderately satisfied with the indoor thermal environment:

- Measurements were done during a short period with mild outdoor temperatures (from -2 to 5°C). The radiator in the basement seems to provide for the heat in the entire building through the open staircase (i.e. both the ground and first floor). In general, the temperature in the living room is kept close to the expected 24°C, even if this floor does not have a heat emitter. The first floor getting enough heat from the lower floors to reach the set-point temperature, the radiator in the first floor did not even have to function. This space-heating strategy with a single heat emitter may have adverse effects. Firstly, the space-heating power left for the basement seems limited (or not sufficient to reach the set-point temperature). Secondly, one may suspect this space-heating power to be too low for the coldest periods of the winter, leading to insufficient heating in the building. The set-point temperature of both radiators in the basement and the first floors should then be coordinated to avoid large temperature inversion in the open staircase and provide for enough space-heating power for each floor. A condition that (most probably) the occupants may not be aware of.
- Users would rather have colder bedroom (~15°C). Despite sleeping with the window open during night-time, they do not manage to achieve temperatures as low as expected.

3.4 Discussion and conclusions of this chapter

This chapter presents the measurements conducted during two weeks in two flats and two row houses in Miljøbyen Granåsen. The responses to the interview have been compared to measurement results to connect the users perception of thermal comfort (what they think is good for them), the real thermal environment and the actions they do to achieve it.

The temperature in each room, especially when the space-heating distribution has been simplified, is the result of a complex heat balance involving building physics (e.g. thermal properties of the building, solar gains and shading), the HVAC systems and the user behaviour (e.g. the way to control the building, HVAC systems, open window and doors, as well as internal gains). As this balance is difficult to predict, the measurements showed room temperatures found in reality in an occupied building (meaning with in real operation). This measurement campaign was short with relatively mild outdoor temperatures. Therefore, these results should be ideally complemented with measurements over a longer period of time. Although imperfect, the main conclusions of these measurements combined with the interviews are listed below.

About bedrooms:

- Although most of the occupants would like different temperatures in bedroom and living room, results showed that creating this temperature zoning is difficult in a super-insulated building (with cascade ventilation, heat recovery and a single temperature for the supply ventilation air temperature).
- We had no complaint about bedrooms that were experienced as too cold, even if they are not equipped with a heat emitter. This was confirmed by temperature measurements.
- On the contrary, interviews show that many occupants want even colder bedrooms (16°C or even colder). It is here confirmed that, when they want cold bedrooms, occupants open windows during many hours per day to control temperature (almost on an everyday basis). We have not measured cold bedrooms (< 18°C) without window opening. When opening windows, most of the occupants close the bedroom door simultaneously.
- One occupant (i.e. Apartment 1) could not open the bedroom window due to outside noise and gets a bedroom temperature warmer than expected. This occupant got used to this situation by adapting “clothing” (using thinner blankets).

- It has been confirmed that users do not always operate the ventilation system coherently to get cold bedrooms. They typically still apply relatively high set-point temperatures for the supply ventilation air (~20°C. However, this is not consistent with having cold bedrooms, since the ventilation air will eventually contribute to rise the bedroom temperature. In some cases, it is done to support the space-heating in the heated living areas.

About the living room (or heated areas):

- Measurements showed that a single radiator per floor provided a comfortable indoor thermal environment in the living room. Measured indoor temperatures were comparable to the set-point temperature applied to the radiators and to the desired temperature reported during interviews. In addition, measurements showed an almost uniform thermal environment with no large temperature differences in the horizontal and vertical directions (i.e. limited temperature stratification). An exception is Apartment 1 where initial problems with sliding doors may most probably have altered the envelope performance and significantly increased the required space-heating power.
- In House 2, the living room in the ground floor had no heat emitter. The living room was heated by the radiator in the basement through the open staircase. Again, the thermal environment in the living room turned out to be comfortable. Nevertheless, this strategy may lead to adverse effects, such a lack of space-heating power for the basement itself. Let us remember that the present work focused on the distribution using one radiator per floor.
- Again, these measurements were performed during a relatively mild period of the space-heating season. Results should be ideally complemented with measurements during the coldest periods of the winter.
- In addition, many users would like the temperature in the living rooms to be slightly higher than considered in usual assumptions: households responded in interviews that their expectation is to have ~22 or 24°C but not 21°C as usually assumed in design, energy or thermal comfort evaluations.

About users (in addition to previous comments):

- Interviews with the four households showed that the education of users to operate the building according to their needs was not optimal. Most of the households were given a booklet with all the information that shows how to vary set-point temperatures and airflow rates. All users said that the knowledge transfer was good but it went too fast and they had wished to have more. Most of them claim to have tips from other occupants about how to change control parameters. However, there is a real lack of understanding of how these changes they apply will affect the indoor environment. For instance, we would advise that users are informed in the following way:
    - 1) Opening windows in bedrooms will reduce bedroom temperature but will also yield increased energy use.
    - 2) Increase temperature of the ventilation supply air will increase the living room temperature but will simultaneously also increase bedroom temperatures.

4. Improving control strategies for the apartment buildings

Measurement data is influenced by user behavior. As already shown, the way occupants operate the building using its control is not always optimal. It can even be in contradiction with the desired indoor environment. This is particularly true for bedrooms where some occupants want cold temperatures but keep the set-point temperature for the supply ventilation air high. The present chapter investigates control strategies to determine whether a proper control could generate the desired thermal environment without increasing the space-heating needs significantly. As a first step, it is indeed important to check if a right control could lead to higher energy efficiency and user satisfaction without modification of the building construction (for example, insulation of the internal partition walls) or the ventilation system (e.g. a ventilation system with two temperature levels could have been considered [27, 28]). Cases with a major modification of the building or the ventilation system are not investigated in this project. As most occupants are satisfied with the temperature in the living room, the focus is on bedrooms. Investigations are done using detailed dynamic simulations using IDA-ICE [12]. The model is firstly validated against the two-week measurement data to confirm that the model is reliable. Secondly, using this calibrated model, different control strategies are compared in terms of thermal comfort and space-heating needs. Main results and graphs are taken from the Master thesis of Kang Wen [23] and reference [25].

4.1 Model development and calibration

4.1.1 Model development and assumptions

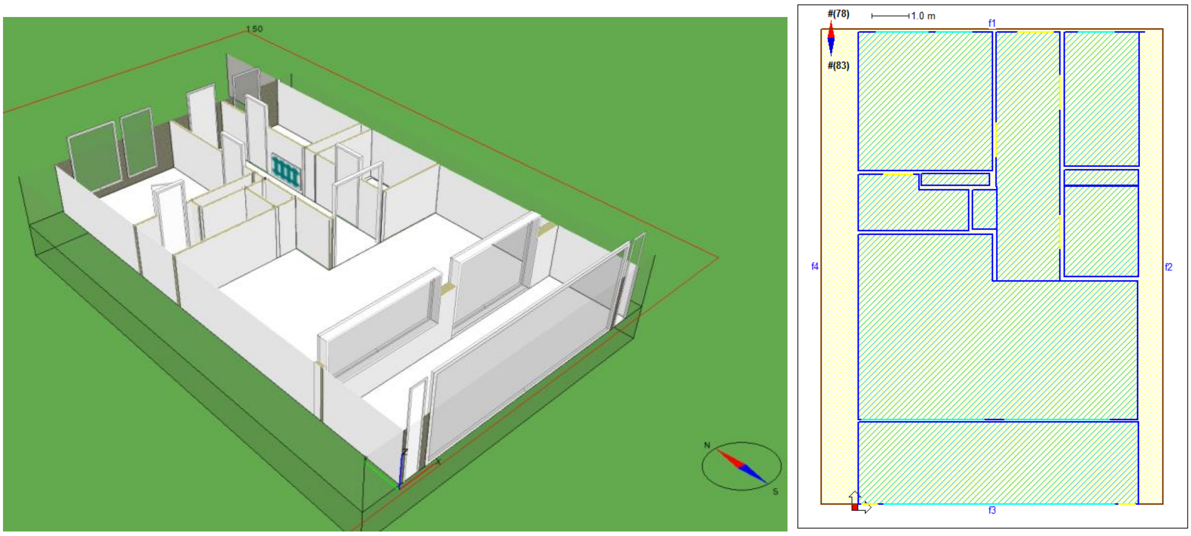


Figure 4.1 Virtual 3D model of the apartment (left) and floor layout with the division into thermal zones (right).

As both apartments are similar, a single building model is used for both cases. The apartment is divided into ten thermal zones, see Figure 4.1. It has been decided to create separated zones for the technical rooms and shafts. This level of detail is probably not necessary but does not generate significant complexity to the model. The partition walls and ceilings between flats have been assumed adiabatic, which is in general a major simplification. In the present case, these partition walls are well-insulated (0.25 W/m².K) so that rooms are less sensitive to the indoor temperature of the neighboring flats. The corridor and living room have been modeled with two different thermal zones. Internal gains of the Norwegian passive house standard NS3700 [2] have been applied.

One should be careful in the expected outcome of detailed building performance simulation (BPS) applied to this problem. This model has the following limitations. Firstly, standard room models in BPS consider an isothermal zone (fully-mixed assumption), such as in IDA-ICE. Therefore, thermal stratification cannot be investigated. Secondly, the bidirectional flow in large openings, such as between the corridor and the living room, is modeled assuming a bulk flow [29]. In this case, the flow is driven by the difference of hydrostatic pressure in both rooms connected by the opening. This assumption is not necessary correct, especially in the context of a narrow zone like a corridor [30, 31]. Finally, a large part of the heat emitted by the radiator is in form of thermal radiation. Given the complex room geometry (i.e. concave enclosure) and assuming that the corridor and the living room will be modeled by two distinct zones, it is not clear whether thermal radiation will be treated properly. Consequently, BPS is probably not the right tool to investigate the temperature difference between the corridor and the living room. On the contrary, this tool can be useful to investigate the thermal environment in bedrooms.

4.1.2 Model calibration

The first step is to calibrate the IDA-ICE model based on measurements. Boundary conditions are adapted accordingly. Firstly, the measured outdoor temperature on the north façade and the horizontal total shortwave radiation measured 3 km away from the building are applied in the simulation weather file. The set-point for the radiator (Tset,SH) and the ventilation levels (between 0 and 3) reported by occupants in the diary are imposed to the building model. The measured bathroom and air-heating temperature (Tset,AH) are also applied to simulations. Doors and windows openings are set equivalent to measurements. Important boundary conditions that are left unknown are internal gains and real nominal ventilation flow rate. Internal gains are taken equivalent to the NS3700, except in periods when it was obvious that occupants were not present. Real nominal ventilation flow rates are assumed equal to design values (Vn).

Results of the calibration are reported on Figures 4.2 and 4.3. It is clear that BPS manages to reproduce the temperature difference between rooms in a satisfactory manner. It is not perfect but it is in the range of accuracy expected by a building simulation, especially when internal gains are not known. For instance, the temperature in the large bedroom is well reproduced meaning that BPS can be used to investigate different control strategies and their impact on the bedroom temperature and the net space-heating needs. In addition, the window of the second flat (Figure 4.3) is almost always open. The fraction of the window opening has been calibrated to reach the right temperature in the bedroom. The calibrated value is 20% opening of the total window area which is compatible with real window geometry.

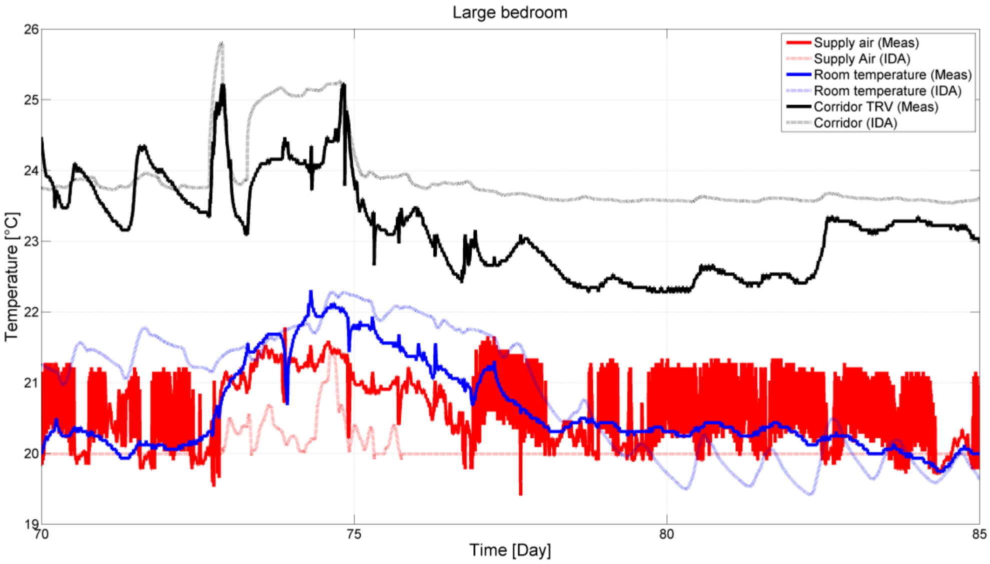


Figure 4.2 Calibration of the IDA-ICE model for Apartment 1.

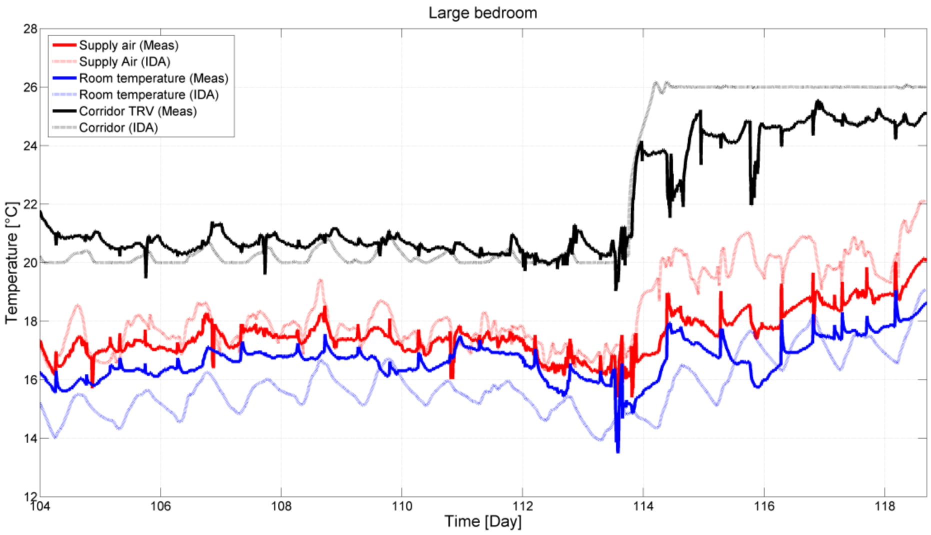


Figure 4.3 Calibration of the IDA-ICE model for Apartment 2.

Table 4.1 Summary of the investigated control strategies for the apartment.

Control	Tset,HR	Tset,AH	Tset,SH	Window	Door
0, baseline	No	20°C	Exp. Data (24°C)	Closed	Closed
1	No	16°C	Exp. Data (24°C)	Closed	Closed
2	16°C	16°C	Exp. Data (24°C)	Closed	Closed
2b	16°C	16°C	+Night-setback (16°C)	Closed	Closed
2c	16°C	16°C	Constant 20°C	Closed	Closed
3	14°C	14°C	Exp. Data (24°C)	Closed	Closed
4	16°C	16°C	Exp. Data (24°C)	Open if T>16°C and nighttime	Closed
4b	16°C	16°C	Exp. Data (24°C)	Open if T>16°C and nighttime	Open in daytime (window closed)
5	16°C	16°C	Exp. Data (24°C)	Open	Closed

4.2 Alternative scenarios

With a calibrated building simulation model, it is possible to investigate how the temperature in the bedroom could have been improved with a better control, see Table 4.1. Apartment 1 is here taken as test case. The different controls are defined in the following way:

- Control 0 (baseline): The baseline control corresponds to real measurements in Apartment 1.
- Control 1: The set-point of the heating battery (Tset,AH) is lowered to 16°C, the heat recovery efficiency is constant.
- Control 2: The set-point of the heating battery (Tset,AH) and heat recovery set-point temperature (Tset,HR) is lowered to 16°C.
- Control 2b: the same control as Control 2 is applied but the set-point temperature of the radiator (Tset,SH) is reduced to 16°C during night (8 PM to 7AM). Intermittent heating is in general not recommended for passive buildings. It could nonetheless be investigated as the building construction is light.
- Control 2c: the same control as Control 2 is applied but a constant temperature (Tset,SH) of 20°C is applied in the corridor, instead of the ~24°C recorded during measurements.

- Control 3: The set-point of the heating battery and heat recovery is lowered to 14°C. This case can generate a cold draft but such a cold draft will be also present if the occupant would like to open a window in bedrooms. On the contrary, it may alter local comfort in the heated living areas. This effect cannot be investigated using detailed dynamic simulations.
- Control 4: A same control than Control 2 is applied but with open window when the occupant is present (during nighttime) and when the bedroom air temperature is higher than 16°C. The window opening is controlled by a PI action and the total opening area is limited to 20% of the total window area (this last value is taken from calibration).
- Control 4b: A same control than Control 4 but the bedroom door is open during the day to warm up the bedroom for daytime activities. The bedroom window is closed when the door is open.
- Control 5: A same control than Control 2 is applied but with the bedroom window always open with 20% of the total window area.

4.2.1 Thermal comfort analysis

A first type of analysis simulates the exact same period as measurements but applying the alternative control strategies. As the model has been validated for this specific period, the accuracy of results should be high. In practice, the same boundary conditions (outdoor temperature and solar irradiation) are applied for each case, only the control differs.

From Figure 4.4, the relative influence of each control strategy can be compared. Starting from the baseline scenario, reducing the heating battery set-point (Tset,AH) to 16°C (Control 1) has a limited impact on the bedroom temperature. By reducing the heat recovery efficiency in order not to exceed 16°C (Control 2), the bedroom temperature is reduced by two degrees, ranging from 18-20°C. It is worth noticing that a night setback did not improve the situation either (Control 2b). Only a constant reduction of the corridor temperature gives a significant decrease on the bedroom temperature (Control 2c). Further limiting the recovered heat to a temperature of 14°C (Control 3), the bedroom temperature is reduced from an additional 1°C compare to Control 2, reaching a temperature level of ~19°C when the occupant is present (i.e. before day 78). At this stage, all the possible strategies have been used to reduce the bedroom temperature without resorting to window opening. A temperature level of 16°C has not yet been reached which is representative for the ideal bedroom temperature for many occupants.

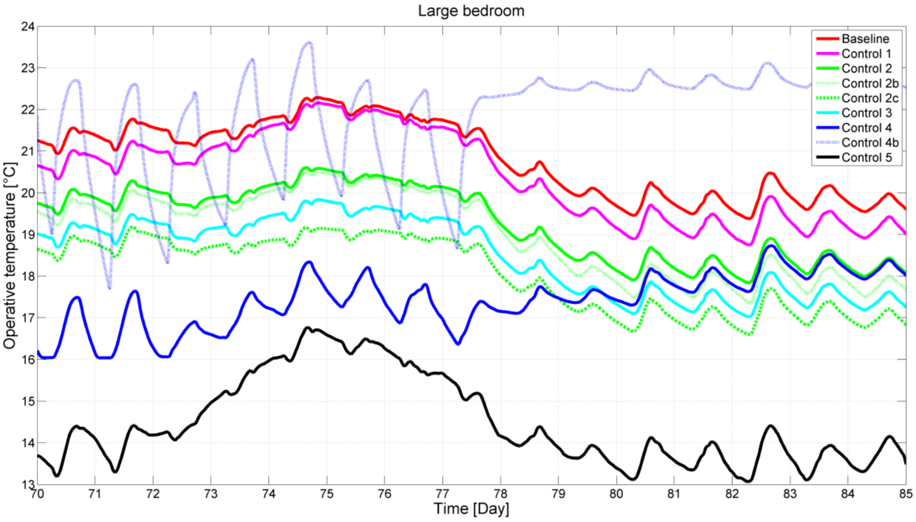


Figure 4.4 Influence of control strategies over thermal comfort in the large bedroom in Apartment 1.

As expected, the opening of the window enables to decrease the bedroom temperature. Ideally, this opening does not need to be constant and can be dynamically controlled as a function of the indoor temperature (Control 4). Then, the bedroom temperature is kept in the range of 16°C. The case 4b has been designed to investigate the possibility to switch from a higher temperature during daytime to a lower nighttime temperature. Due to the simplification of the space-heating distribution, the room is only heated during daytime by the airflow through the open doorway. The corresponding heating power is therefore limited so that several hours are needed for the temperature to rise from lower nighttime temperatures to higher daytime temperatures (above 20°C). The same situation happens with the open window during night time. The temperature decreases progressively, never reaching a steady-state within the night. In practice, the window opening could be more widely opened than 20%, so that the heat stored in the bedroom could be flushed quicker. This case 4b illustrates a limitation of the simplified space-heating distribution when a room not equipped with a local heat emitter (such as a bedroom) has to adjust to a changing set-point temperature within a short period of time (within a day).

4.2.2 Energy efficiency analysis

Except for the baseline and Control 1, all the investigated strategies result in an increased energy use, either by limiting the outlet temperature of the heat recovery unit (Tset,HR) or by opening the bedroom window which significantly increases ventilation losses (i.e. creating a local heat sink). The performance of Control 0 to 4 is thus compared. The Control 2c is not compared in this section as it proposes a different temperature in the corridor and the living room than the other cases. Its space-heating needs cannot be compared directly. The Control 5 is also not taken into account as it would potentially lead to unacceptable low temperatures in the bedroom during the coldest periods during the winter.

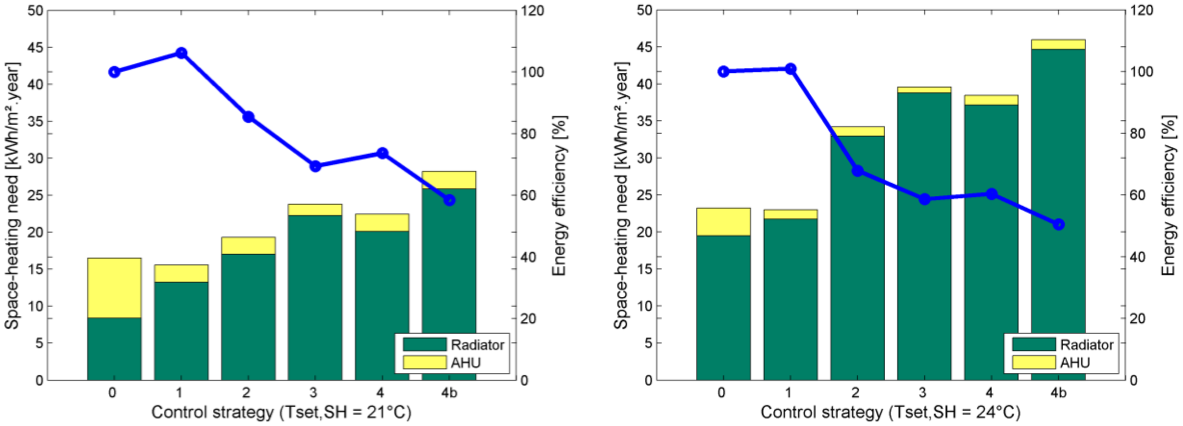


Figure 4.5 Yearly net space-heating needs for five control strategies and a set-point temperature (Tset,SH) of 21°C (left) and 24°C (right): the efficiency in “blue” is evaluated by taking the baseline control 0 as a reference.

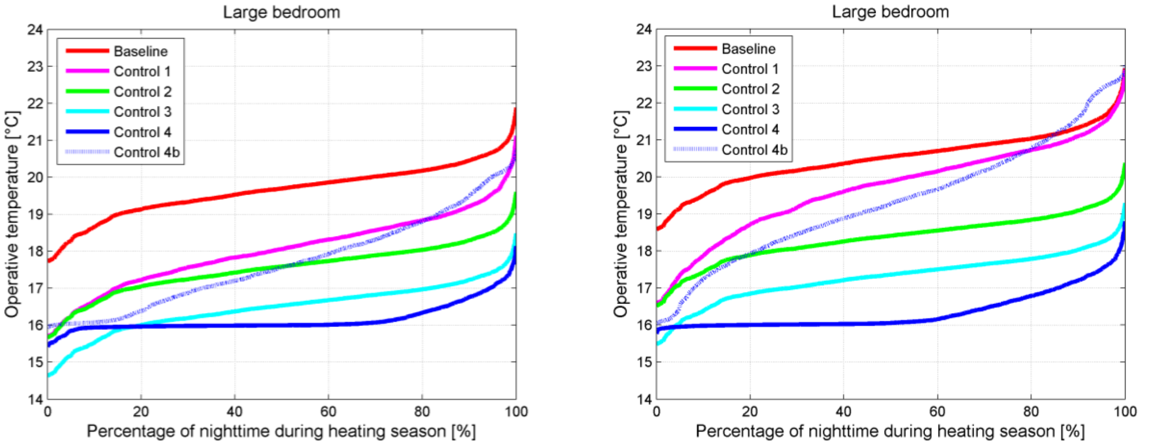


Figure 4.6 Duration curve for the operative temperature in the large bedroom (during nighttime and the heating season): case with a corridor constant set-point temperature Tset,SH of 21°C (left) and 24°C (right).

Yearly space-heating needs are compared in Figure 4.5. For this comparison, the building is simulated outside the calibration period using the validated model. These confidence in results is in theory lower than for the previous analysis about thermal comfort as some assumptions had to be made. A Typical Meteorological Year (TMY) for Trondheim is applied as boundary condition. Ventilation airflow rates are considered constant and equal to the nominal values. Internal gains comply with the NS3700. Two different set-point temperatures for space-heating (Tset,SH) have been taken for the radiator and the bathroom: constant 21°C and constant 24°C.

From Figure 4.5, one clearly notices that the baseline control is a mix of water (radiator) and air-heating, especially with a Tset,SH of 21°C. When lowering the heating battery set-point (Control 1), the space-heating supply (radiator) becomes dominant. In both cases, the space-heating needs with Tset,SH of 21°C are typical for passive houses, i.e. about 15 kWh/(m².year). In terms of thermal comfort, Control 1 is able to reduce the bedroom temperature. This potential increases with lower outdoor temperatures but remains limited for milder outdoor temperature, see Figure 4.6. By progressively reducing the set-point for the AHU with Controls 2 and 3, the temperature in the bedroom can be further decreased but at the cost of higher space-heating needs. This effect is particularly important if the Tset,SH is 24°C. This shows that the increase on energy use induced by window opening or reduced heat recovery efficiency is more important with higher space-heating set-point temperatures (Tset,SH).

An important question is to determine which strategy reaches low bedroom temperatures at the lowest energy cost. Control 3 consumes as much energy as the Control 4 where the window opening is controlled continuously during nighttime. Compared to the baseline case, they both use roughly 50% more space-heating energy. The worst case scenario is when the bedroom needs to be cyclically heated by the door opening and cooled down by window opening every day (Control 4b). This daily flushing of the bedroom thermal mass is more energy demanding than keeping the bedroom cold during daytime by keeping closed internal doors (Control 4). In addition, Control 4b cannot generate low bedroom temperatures (at least if the window is not opened more than 20%). Finally, energy needs reported in Figure 4.5 illustrate the influence of the user behavior over the performance of passive houses. The worst case, yet realistic, has space-heating needs of 45 kWh/(m².year), three times higher than the value computed using normative conditions, ~15 kWh/(m².year). Conclusions about space-heating needs will be further consolidated when the measured energy consumption of both flats will be available.

4.3 Discussion and conclusions

The thermal comfort in bedroom is critical. Many occupants, especially Norwegians, would like cold bedrooms while the super-insulated envelope tends to homogenize temperature in the entire apartment. It prevents temperature zoning. This occurs even if no heat emitter is placed in bedrooms. Consequently, occupants tend to reduce the bedroom temperature using window opening which has an adverse effect on space-heating needs and potentially on the indoor environment (e.g. noise, introduction of unfiltered air).

Different control strategies have been compared in terms of bedroom temperature and increased space-heating needs using detailed dynamic simulations. The performance of each control strategy is a function of the outdoor air temperature that changes throughout the heating season and are discussed for different set-point temperatures applied to the radiator (Tset,SH):

- With a Tset,SH of 21°C, bedroom temperatures of ~18°C can be reached without a drastic increase of the space-heating needs (+20%). Further decreasing the bedroom temperature below 18°C requires more radical measures, such as a significant reduction of the heat recovery efficiency (Tset,HR to 14°C) or frequent window opening during several hours, resulting to a large increase in energy use.

- The situation is more critical if a Tset,SH of 24°C is applied to the radiator. There is no easy way to significantly reduce the bedroom temperature without increasing the space-heating needs above 50%. For instance, adjusting the window opening during nighttime to keep 16°C is the bedroom would result in energy needs increase of about 65%.
- The most critical case is when the bedroom is cyclically heated up and cooled down every day. The energy stored during the day is systematically flushed outside the building during nighttime. This aspect is not specific to simplified space-heating distribution. It holds also true if a traditional distribution is applied. Nevertheless, using simplified distribution, the airflow through the open doorway is the main heat source when bedroom needs to be (re)heated. The heating power corresponding to door opening is limited (a couple of hundreds Watts [11, 29]), so that several hours are needed to reach higher daytime temperatures (above ~20°C). The slower dynamics can be seen as a limitation of simplified space-heating.

In conclusion, getting the desired indoor environment in bedrooms with acceptable energy efficiency is not just a question of proper control and appropriate user behavior. Extra measures should be taken to provide for the flexibility that the user expects:

- A priori, it looks intuitive to place the only radiator in a central location within the flat in order to ensure enough space-heating power for each room. The present investigations suggest that the radiator could have been placed directly in the living room to increase the distance between the radiator and bedrooms. For the present plan layout, installing the radiator in the living room could have improved thermal comfort in this room. Simultaneously this would reduce the temperature of the corridor which is the main thermal zone in contact with bedrooms and this could be beneficial to get colder bedrooms. It has already been discussed that detailed dynamic simulations are not best suited to investigate this strategy. This problem requires the correct evaluation of the heat transfer between the corridor and the living room (by convection and thermal radiation). Such physics are not supported by default by standard building models. Experiments would be more reliable and easier to realize in order to investigate the efficiency of this measure.
- With the radiator placed in the living room, a door could have been placed between the corridor and the living room. The corridor would be a buffer zone where an intermediate temperature between the living room and bedrooms could be created. Preliminary simulations (not reported here) have shown that this strategy is efficient to reduce bedroom temperatures without increasing significantly space-heating needs. Nevertheless, given the corridor area and prices of the real estate, it is not likely that occupants would like to sacrifice their corridor with an intermediate temperature to ensure lower temperatures in bedrooms.
- Other strategies regarding changes in insulation levels and ventilation layout would be more invasive and are not reported in this report. Preliminary simulations have shown that further insulating internal walls would not improve the temperature zoning. In fact, lightweight partition walls are already insulated for acoustic reasons (0.5 W/m².K). Most of the thermal zoning effect is already created by this default amount of insulation. The ventilation strategy could be changed, for instance the concept of cascade ventilation with a centralized heat recovery and a single set-point temperature for the supply ventilation air could be reconsidered as it is a major process that homogenizes temperature in the building. For instance, a two-zone ventilation has been investigated in the article of Berge et al. [28].

5. Improving control strategies for the row houses

Following the same approach used for apartment buildings, the present chapter investigates control strategies for the row houses. The goal of this chapter is to determine whether a proper control may generate the desired thermal environment without increasing the space-heating needs significantly. As most occupants are satisfied with the temperature in the living room, the focus is again on bedrooms and window opening. Investigations are also done using detailed dynamic simulations in IDA-ICE [12]. The model is firstly validated against the two-week measurement data to confirm that the model is reliable. Secondly, different control strategies are compared in terms of thermal comfort and space-heating needs. Thirdly, the influence of the insulation level of the building on the bedroom temperature is investigated. Part of the results have been taken from the Master thesis of Fredrik Håheim [24].

5.1 Model development and calibration

5.1.1 Model development and assumptions

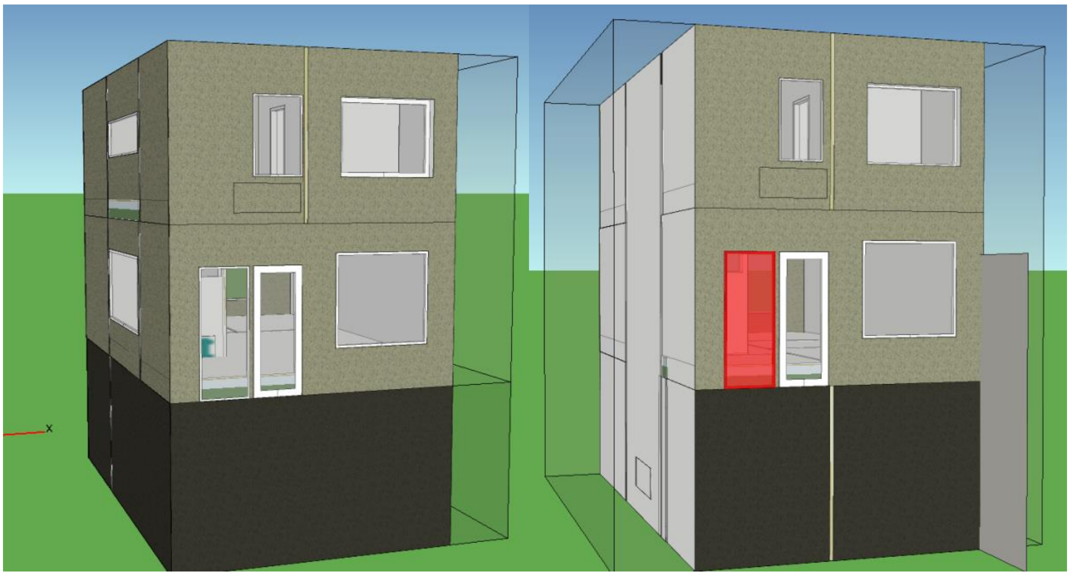


Figure 5.1 Virtual 3D model of the row House 1 (left) and 2 (right).

Two row houses have been investigated. House 1 is located at the west corner of a block, while House 2 is located in the middle of a block. The total area of external walls is thus different between both houses giving large differences in space-heating needs. In addition, the two houses have different floor plan; see Figures 3.3 and 3.4 in Chapter 3. The basement of House 1 consists of a main large room with electric floor heating, a technical room and a guest (or storage) room. The basement of House 2 is composed of a corridor equipped with a radiator and connected to a guest room, a bathroom, a storage room and a technical room. The entrance of House 1 is at the ground floor while it is in the basement of House 2. The partition walls between neighboring houses have been considered adiabatic. This approximation is realistic for the timber frame walls above the ground with a U-value of 0.15 W/m².K but less reliable for the non-insulated concrete walls in the basement (U-value of 3 W/m².K). As the artificial lighting, electric appliances and detailed occupancy have not been measured, internal gains of the Norwegian passive house standard NS3700 [2] have been applied to the building model.

House 2 has no radiator in the living room. Measurements and interviews have nonetheless shown that the temperature is the living room was kept at ~23.5°C in good accordance with the desired indoor temperature. The heat is provided by the radiator in the basement. Measurements have shown a temperature inversion in the open staircase (typically 0.5°C higher temperature in the basement corridor and staircase than in the living room). This generates a large airflow by natural convection.

Unfortunately, the airflow through large horizontal openings is not modelled in a reliable way in detailed dynamic simulation tools. They are often modeled as an extension of the vertical opening case, or using pure correlations. This inversion does not appear in House 1 where the first floor is most often warmer than the ground floor and ground floor always warmer than the basement. This case is compatible with the modeling approximation of horizontal opening in IDA-ICE. In conclusion, the configuration of House 1 better suits the modeling approximations in BPS. In House 1, the open staircase is split into 3 different zones (one per floor) connected by a large horizontal opening, see Figure 5.2. In House 2, the open staircase is modeled as a single zone with the objective to better reproduce the strong convective heat flow from the basement to the upper floors, see Figure 5.3.

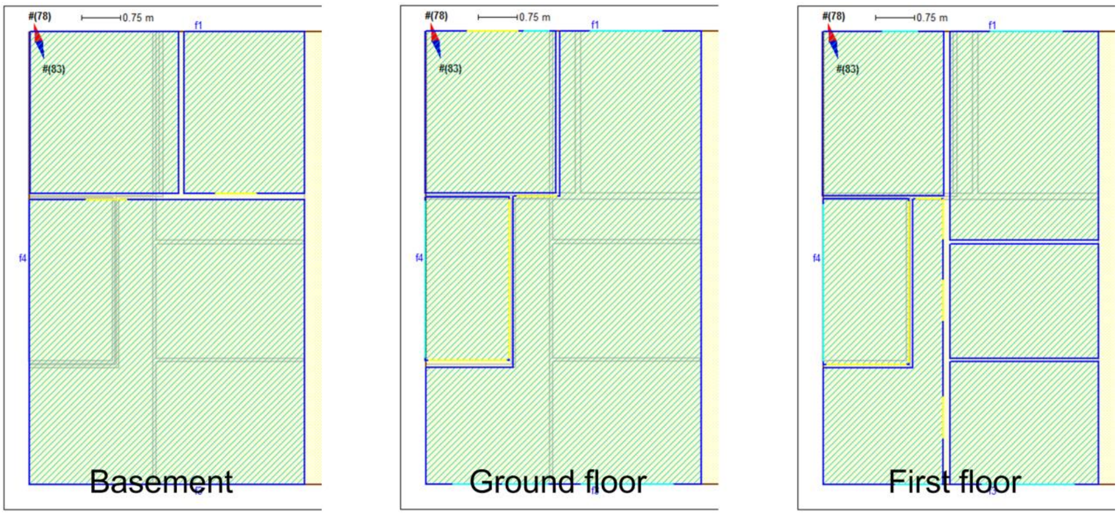


Figure 5.2 Floor layout of row House 1 and division into thermal zones.

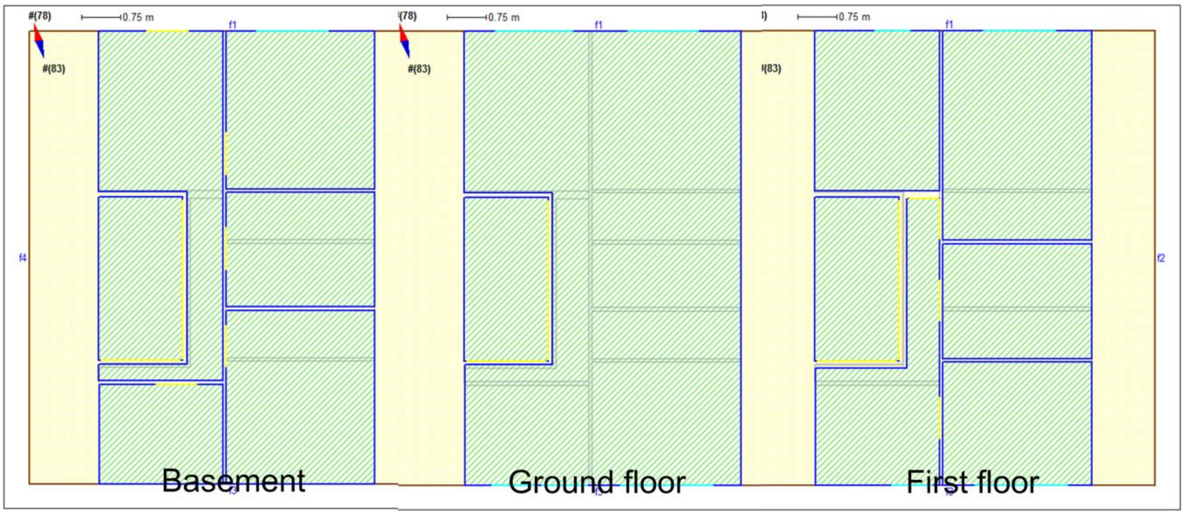


Figure 5.3 Floor layout of row House 2 and division into thermal zones.

As already explained, standard room models in BPS such in IDA-ICE consider an isothermal zone (fully-mixed assumption). Therefore, thermal stratification cannot be investigated by such tools.

5.1.2 Model calibration

The first step is to calibrate the IDA-ICE model based on measurements. Boundary conditions are adapted accordingly. Firstly, the measured outdoor temperature on the north façade and the horizontal total shortwave radiation measured 3 km away from the building are applied in the simulation weather file. The set-point for the radiator (Tset,SH) and the ventilation levels (between 0 and 3) reported by occupants in the diary are imposed to the building model. The measured bathroom and air-temperature

(Tset,AH) are also applied to simulations. Doors and windows openings are set equivalent to measurements (with the limitation that the opening was measured binary, the percentage of window opening was calibrated using parametric runs). Important boundary conditions that are left unknown are internal gains and real nominal ventilation flow rate. Internal gains are taken equivalent to the NS3700. Real nominal ventilation flow rates (meaning level 2) are assumed equal to design values (Vn).

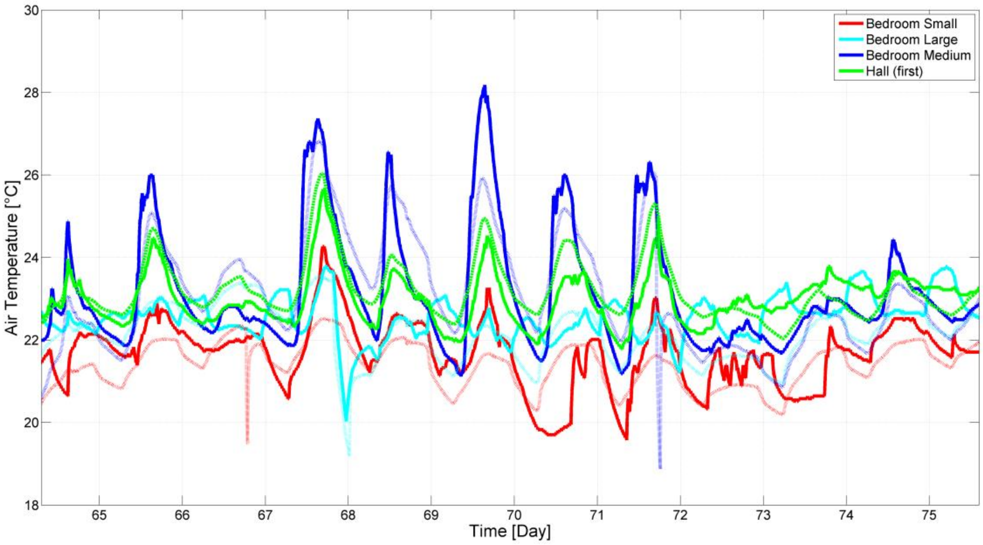


Figure 5.4 Measured (solid line) and simulated (dotted line) air temperature in first floor of House 1.

Calibration results for House 1 are shown in Figures 5.4 and 5.5. Occupants made very little use of window opening during the measurement period. Consequently, this case cannot be used to calibrate the model for the airflow through open windows. On the contrary, internal doors are most of the time open. The default discharge coefficient (Cd) of 0.65 for doorways has been kept unchanged. Even though internal gains are not known, simulation results show that the building model is able to well reproduce the air temperature in the corridor and bedrooms of the first floor, see Figure 5.4. More specifically, the difference of temperature between rooms is well reproduced.

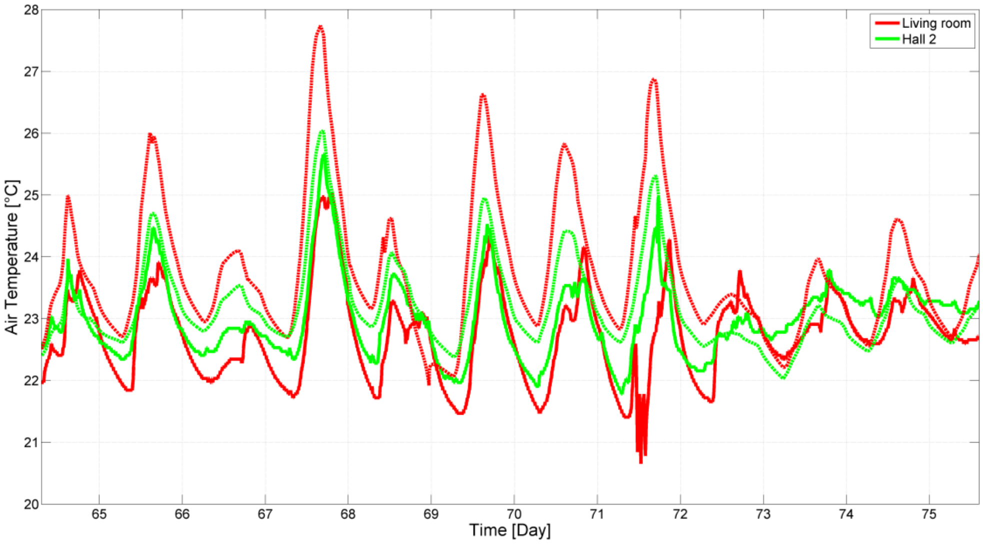


Figure 5.5 Measured (solid line) and simulated (dotted line) air temperature in House 1.

Figure 5.5 also reports on the air temperature in the living room. In general, simulation tends to overestimate the living room temperature (about 1°C), especially in periods of high solar gains (with up to 3°C differences). This room is particularly exposed to solar gains as it a large glazing area facing south. Only the total solar irradiation on a horizontal plane was measured 3 km away from the building. The split between direct and diffuse radiation is thus not known and has been reconstructed artificially. In addition, the thermal mass of the furniture and internal gains are also undefined and can play a role. As the purpose of simulation is mainly to focus on bedrooms which are correctly simulated, it let us to conclude that the model is enough accurate for the purpose of the study (as long as window openings are not considered).

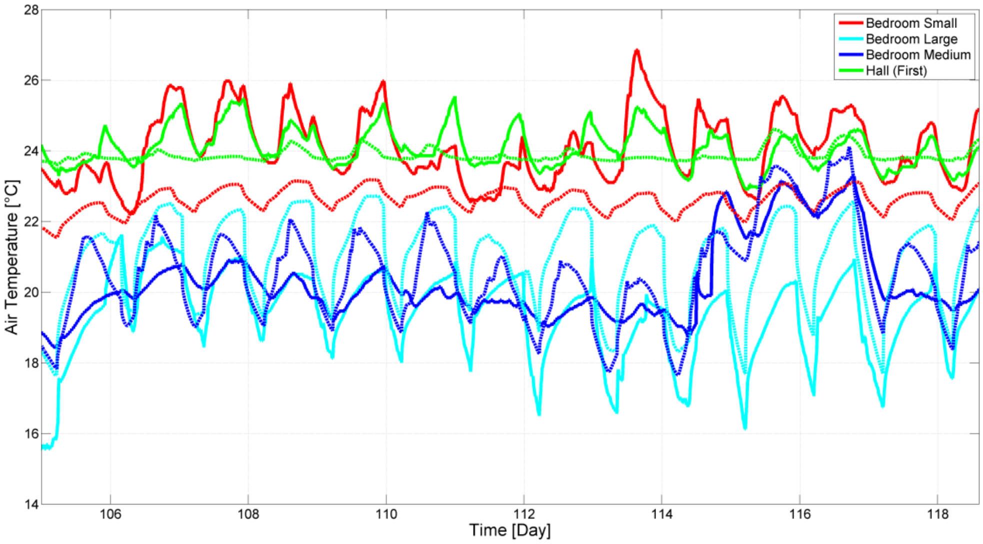


Figure 5.6 Measured (solid line) and simulated (dotted line) air temperature for first floor of House 2.

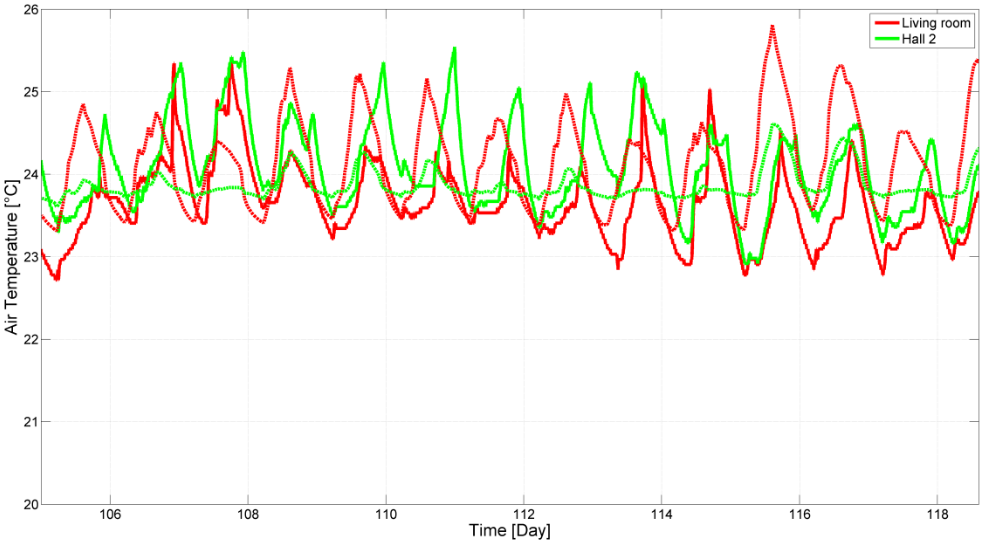


Figure 5.7 Measured (solid line) and simulated (dotted line) air temperature in House 2.

The calibration of House 2 is shown in Figures 5.6 and 5.7. Occupants of House 2 resorted to window opening frequently, especially in the medium and large bedrooms. In the large bedroom, the opening is done on a daily basis while the window opening of the medium bedroom is constant over a long period of time (e.g. between day 105 to day 114). The fraction of window opening has been calibrated for these two bedrooms to match the measured amplitude of temperature change when the window is closed or opened. Using parametric analysis, it gives 5% of the total area for the medium bedroom and 4% for the large bedroom. Internal doors are most of the time closed. In House 2, windows facing south are equipped with automatic solar shading. The exact control applied to these shading devices is not known. This lack of knowledge about shading and internal gains explains that the temperature fluctuations are different between measurements and simulations. Nevertheless, time-averaged values are similar. Especially the temperature differences between rooms are well reproduced which is a major interest for the present investigations. Figure 5.7 shows the air temperature in the living room. Again the average level is well reproduced by simulations but, as for the apartment building, simulations exhibit large fluctuations (overshoot) in presence of solar gains. Reasons for these deviations have already been discussed.

In conclusion, calibration enabled to tune the model and check its accuracy, particularly in the active use of window (case of House 2) or door (case of House 1) opening in bedrooms. Simulations proved to be able to reproduce the temperature differences between rooms in a reliable way, at least in the expected range of accuracy given that internal gains are unknown and values for solar irradiation inaccurate.

5.2 Alternative scenarios

With a calibrated building simulation model, it is possible to investigate how the temperature in the bedroom could have been improved with a better control, see Table 5.1. House 1 with a radiator in the living room is here taken as test case, as it better fits the modeling assumption than House 2 (as explained the previous section). Nevertheless, cases with the house located in a corner and the center of the block are both considered.

Table 5.1 Summary of the investigated control strategies for the row house.

Control	Tset,HR	Tset,AH	Tset,SH	Window	Door
0, baseline	No	20°C	21°C (or 24°C)	Closed	Closed
0b	No	24°C	21°C (or 24°C)	Closed	Closed
1	No	16°C	21°C (or 24°C)	Closed	Closed
2	16°C	16°C	21°C (or 24°C)	Closed	Closed
3	14°C	14°C	21°C (or 24°C)	Closed	Closed
4	16°C	16°C	21°C (or 24°C)	Open if T>16°C and nighttime	Closed
4b	16°C	16°C	21°C (or 24°C)	Open if T>16°C and nighttime	Open in daytime (window closed)

The different controls are defined in the following way:

- Control 0 (baseline): The baseline control corresponds to real measurements in House 1, except for set-point temperature for the radiators that is fixed (21 or 24°C) and kept constant.
- Control 0b: The set-point of the heating battery (Tset,AH) is increased to 24°C, the heat recovery efficiency is constant. This increased contribution of air-heating aims at increasing the temperature in bedrooms above 20°C, a hypothetical situation that may be required by some users.
- Control 1: The set-point of the heating battery (Tset,AH) is lowered to 16°C, the heat recovery effectiveness is kept constant.
- Control 2: The set-point of the heating battery (Tset,AH) and heat recovery (Tset,HR) is lowered to 16°C.
- Control 3: The set-point of the heating battery and heat recovery is lowered to 14°C. This case can generate a cold draft. Such a cold draft will be also present in bedrooms if the occupant would like to open a window, but low supply air temperature can be experienced as uncomfortable in the living room.
- Control 4: A same control than Control 2 is applied but with open window *for all bedrooms* when the occupant is present (during nighttime) and when the bedroom air temperature is higher than 16°C. The

window is controlled by a PI action and the total opening area is limited to 10% of the total window area (this last value is taken from the calibration procedure of the building simulation model).

- Control 4b: The same control than Control 4 but the bedroom door is open during the day to warm up the bedroom for daytime activities. The bedroom window is closed when the door is open.

5.2.1 Row house in the middle of the block

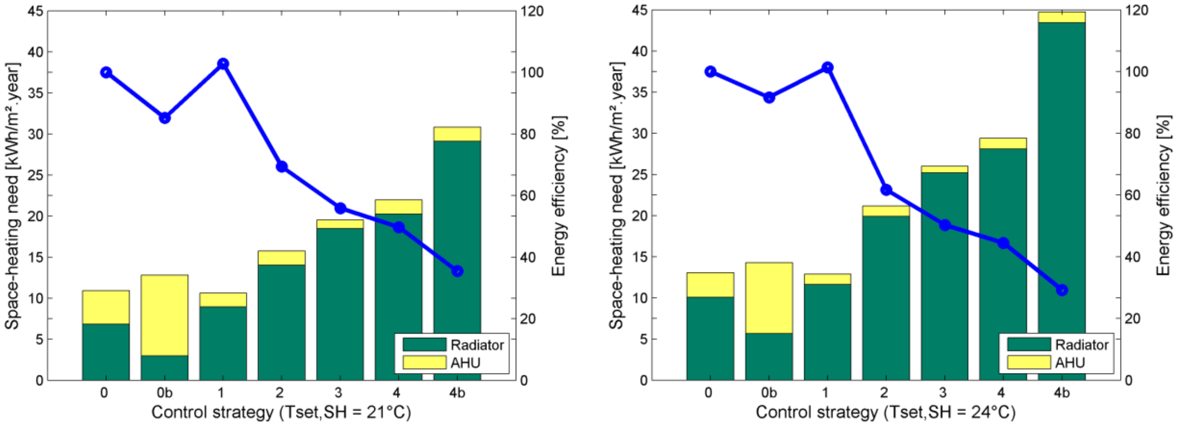


Figure 5.8 Yearly net space-heating needs for house in central position in the block and a set-point temperature (Tset,SH) of 21°C (left) and 24°C (right): the efficiency in “blue” is evaluated by taking the baseline control 0 as a reference.

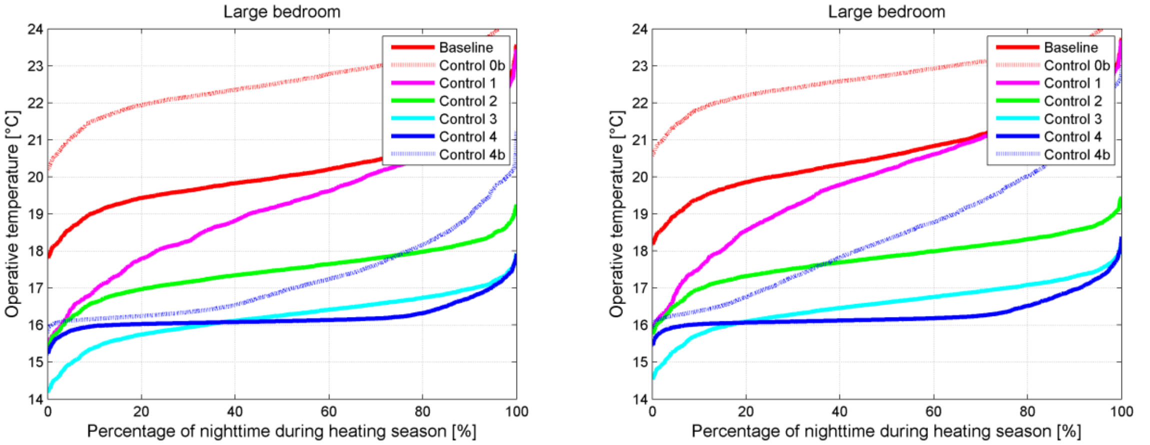


Figure 5.9 Duration curve for the operative temperature in the large bedroom for the house in a central position in the block (during nighttime and the heating season): case with a corridor constant set-point temperature Tset,SH of 21°C (left) and 24°C (right).

The house located in a central position in the building block is here analyzed. Results present very similar trends as for the apartment simulations. With a constant set-point temperature of 21°C, the largest bedroom temperature with the baseline control has a temperature between 18 and 22°C. If users would like higher temperature in bedrooms, the air-heating temperature can be increased such as in case 0b. A temperature above 20°C is then found during all the space-heating season by increasing the Tset,AH to 24°C. In that case, Figure 5.8 shows that air-heating dominates over radiator heating. If users would like colder bedrooms than the baseline control, the set-point temperature of the heating battery (Tset,AH) can be reduced to 16°C (control 1) without decreasing the heat recovery effectiveness. It would lead to colder bedrooms, especially in colder period of the space-heating season. During a large part of this heating season, the bedroom temperature is still above 18°C. With a Tset,HR and Tset,AH both limited to 16°C (control 2), the bedroom temperature is most of the time between 17 and 19°C. This is done at the cost of increased space-heating needs of about 5 kWh/(m².year). Further limiting Tset,HR and Tset,AH to 14°C (control 3), the temperature in the bedroom ranges between 14 and 17°C which is a temperature range that many occupants that would like. Unfortunately, the space-heating needs have almost doubled compared to the baseline case. Control 4 gives approximately the same results as control 3, although the temperature is better controlled at 16°C using the PI-action than in the control 3. The worst case is when the bedroom is heated during daytime and cooled down during nighttime with window opening. The space-heating needs have tripled. In addition, due to the dynamics of the building, it takes long time for the intensive ventilation using the window opening to cool down the bedroom from daytime temperature to nighttime temperatures. It could give a temperature that is not fully satisfactory for users asking for cold bedroom (T < 16°C). Increasing the set-point temperature for radiators (Tset,SH) from 21 to 24°C, does not influence on the bedroom temperature significantly but has a large influence on the space-heating needs.

5.2.2 Row house in the corner of the block

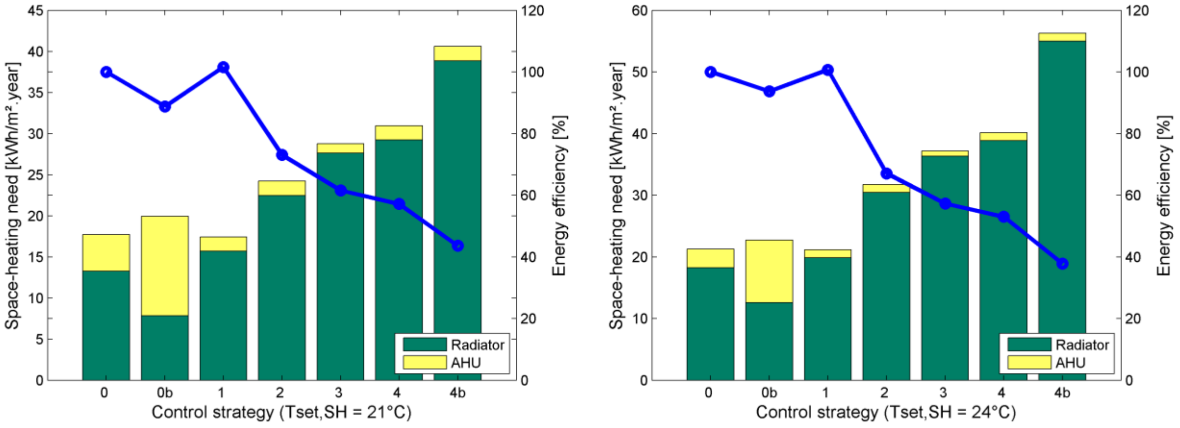


Figure 5.10 Yearly net space-heating needs for house in side position in the block and a set-point temperature (Tset,SH) of 21°C (left) and 24°C (right): the efficiency in "blue" is evaluated by taking the baseline control 0 as a reference.

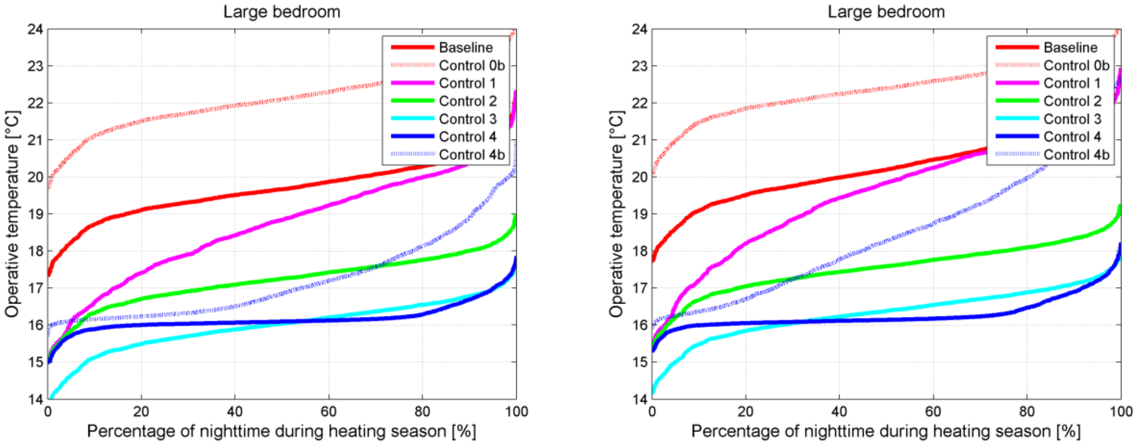


Figure 5.11 Duration curve for the operative temperature in the large bedroom for house in side position in the block (during nighttime and the heating season): case with a corridor constant set-point temperature Tset,SH of 21°C (left) and 24°C (right).

Compared to the case with the house located in the center of the block, the house on one side of the block presents similar results, especially regarding the temperature in bedrooms. For the baseline case, space-heating needs are about 17 kWh/m².year, well above the value for the central location. Most building buyers are most probably not aware of this difference. The *relative* differences in space-heating needs between control strategies are very similar between both cases, but are not in *absolute* value.

These results illustrate how much the user behavior or the position of the house in a block influence significantly the space-heating needs.

5.2.3 TEK10 row house in the middle of the block

It is commonly understood that variations in space-heating needs due to the different user behaviors do not change in *absolute value* with increasing building insulation levels. On the contrary, with increasing insulation levels, these differences in space-heating needs become *relatively* more important compared to the normalized space-heating needs assuming a standardized user behavior (often considered in standards such as NS3031). As the influence of users becomes relatively more important with increasing insulation level, it draws more attention in highly-insulated buildings (also with the current trend towards super-insulated buildings). To study this effect, an alternative building model has been defined which complies with the minimal requirements of the TEK10 building regulation, see Table 5.2. In addition, two additional controls are considered, control 0s and 4s in Table 5.3. In the TEK10 house, the space-heating distribution system cannot be simplified. Additional heat emitters are placed in bedrooms. With control 0s and 4s, these heat emitters in bedroom are activated during daytime to ensure 21°C. If occupants do not use them, it corresponds to the previous controls already introduced in Table 2.1.

Table 5.2. Thermal properties of the NS3700 and TEK10 building cases.

Component	PH	TEK10
Extern. wall U-value [W/m².K]	0.15	0.22
Roof U-value [W/m².K]	0.06	0.18
Basement U-value [W/m².K]	0.10	0.18
Infiltration n50 [1/h]	0.60	2.50
Windows U-value [W/m².K]	0.80	1.20
Doors U-value [W/m².K]	0.80	1.20
Norm. cold bridges [W/m².K]	0.03	0.03
Heat recovery rated temperature efficiency (EN 308)	88%	70%

Table 5.3. Complementary control strategies for the row house.

Control	Tset,HR	Tset,AH	Tset,SH (corridor-living)	Tset,SH (bedrooms)	Window	Door
0s	No	20°C	21°C (or 24°C)	21°C in daytime	Closed	Closed
4s	16°C	16°C	21°C (or 24°C)	21°C in daytime	Open if T>16°C and nighttime	Closed

Comparing the NS3700 and TEK10 houses in Figure 5.12, the magnitude of the space-heating needs is different. Nevertheless, the *absolute* value of the changes (i.e. given in kWh/m².year) generated by the different controls is similar between both insulation levels. This supports the previous statement that the influence of the user behavior does not increase in absolute value with increasing insulated buildings. On the contrary, the efficiency curve in “blue” translates the relative performance between the different controls (i.e. given in %). Comparing both insulation levels, the influence of the user behavior is thus relatively more important with higher insulation. Nevertheless, the analysis of the temperature in the bedroom in Figure 5.13 offers nuances to these conclusions. In fact, the control 1 (i.e. meaning reducing the air-heating temperature Tset,AH to 16°C) and 2 (i.e. also reducing the heat recovery efficiency Tset,HR to 16°C) are efficient in the TEK 10 house to keep the temperature in the bedroom in the range of ~16°C, while they were not for the passive house. It is means that in the TEK10 house, occupants do not need to open windows (meaning strategies 4, 4b and 4s) to reach cold bedrooms with a temperature of ~16°C. In the TEK10 house, the condition to get a constant low temperature in the bedroom is to keep the bedrooms unheated and the internal doors closed, which is a common habit to control temperature as shown in Chapter 2.

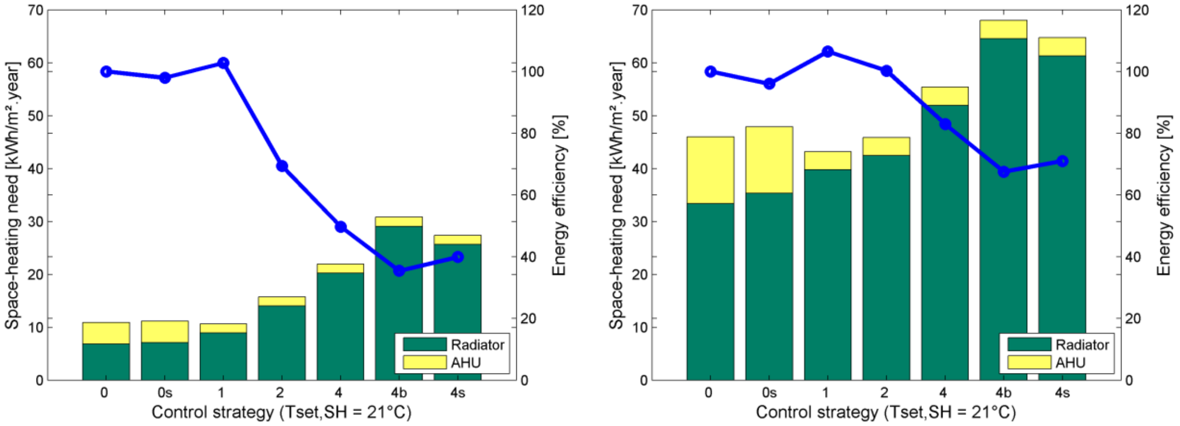


Figure 5.12 Yearly net space-heating needs for the NS3700 (left) and TEK10 (right) houses: the efficiency in “blue” is evaluated by taking the baseline control 0 as a reference.

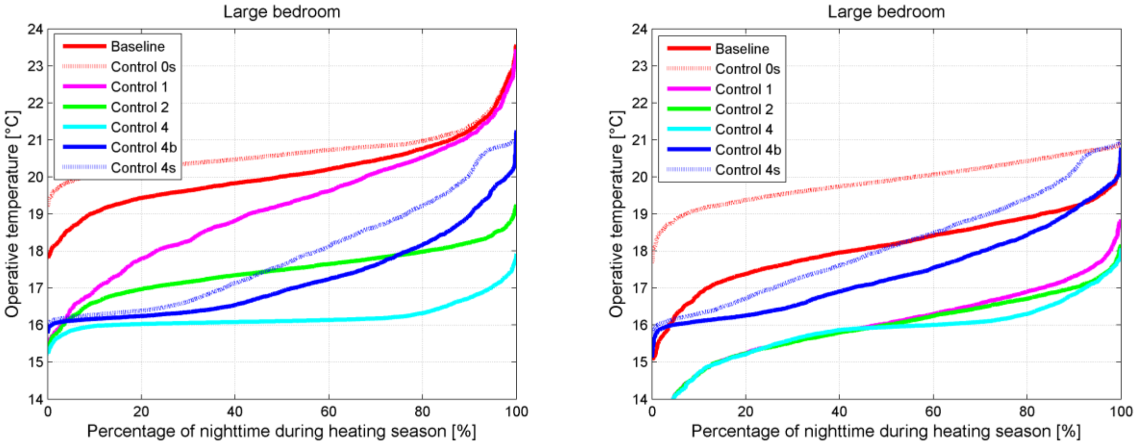


Figure 5.13 Duration curve for the operative temperature in the large bedroom for house (during nighttime and the heating season): NS3700 (left) and TEK10 (right) houses.

If, on the contrary, occupants in the TEK10 house would like to heat bedrooms during daytime (control 0s), they will not get low temperatures in bedrooms during nighttime. If they would like cold bedrooms during nighttime, they also need to open the window (case 4s). The resulting absolute increase of space-heating needs (meaning the difference between the space-heating needs for case 4s and 0s) is then similar in TEK10 and passive houses. From a building physics point of view, a decrease of temperature between daytime (21°C) and nighttime (~16°C) is a question of flushing the heat accumulated in a room which is in fact independent of the insulation level but rather dependent of the thermal mass.

In summary, a same control (or a same user behavior) gives a comparable increase (or decrease) of the space-heating needs compared to the standardized operation for both building insulation levels. So, it is in line with the idea that changes in energy use due to users are relative and not absolute with increasing building performance. Nevertheless, if the user would like cold bedrooms all the time (with a temperature of about 16°C), closing the bedroom doors with ventilation supply air at 16°C is enough in the TEK10 house. The bedroom window does not need to be opened to regulate the bedroom temperature in the TEK10 house, unlike the passive house. The effect of the user is thus more important in absolute value in the passive house because its building physics most likely requires a different behavior to get cold bedrooms. If the bedroom is expected to be heated up during daytime and to be cold during nighttime, this last effect disappears and the absolute changes due to user behavior are the same for both insulation levels. The conclusions are thus case dependent but there is a risk that the user behavior is more important in absolute value (i.e. kWh/m².year) with increasing insulation levels (because their behavior changes with increasing insulation levels) and that extra attention should be paid to users in such buildings.

5.3 Discussion and conclusions

The thermal comfort in bedrooms is critical. Many Norwegian householders would like cold bedrooms while the super-insulated envelope tends to homogenize temperature in the entire building envelope, even if no heat emitter is placed in bedrooms. Consequently, occupants tend to adjust the bedroom temperature by opening windows, which has an adverse effect on space-heating needs and potentially on the indoor environment (e.g. noise).

Different control strategies have been compared in terms of bedroom temperature and increased space-heating needs using detailed dynamic simulations. The performance of each control strategy is a function of the outdoor air temperature that changes throughout the heating season and should be discussing for different set-point temperature applied to the radiators (Tset,SH). The results about row houses are very similar to those of the apartments. The location of the row house within the block, either in the center or one side of the block, does not influence the temperature distribution inside the building or the relative performance of the different controls in a significant way but it affects the energy use. The additional external wall with the house located on the block side is mainly connected to rooms equipped with a heat emitter. However, the location influences the absolute value of the space-heating needs (which are significantly different between the central and lateral location). As for the flat case, occupants of the passive row house have to open bedrooms windows if they would like cold bedrooms with a temperature of ~16°C. Simulations with the same building but insulated at the TEK10 level show that cold bedrooms can be obtained without opening their windows. Internal doors should be kept closed and bedrooms unheated, which is a typical way to control bedrooms. This suggests that there is a higher risk of increased space-heating needs by window opening in passive houses than in TEK10 houses.

These results do not constitute an absolute proof as they are based on building simulations calibrated on a two-week measurement period. Measurement of the energy use over a longer period of time (one year or more) combined with detailed measurements of the user behaviors (registering set-points for the space-heating, ventilation as well as windows and doors opening) would constitute a more reliable and definitive evidence.

In conclusion, getting the desired indoor environment in bedrooms of passive row houses with acceptable energy efficiency is not just a question of proper control and correct user behavior. Extra measures should be taken to provide for the required flexibility for the user:

Without an open staircase between the ground and first floors, it would be possible to create a buffer zone with the corridor of the first floor. Again, it is not sure that occupants will accept to sacrifice this corridor with an intermediate temperature, a corridor which can be used as a room with frequent occupancy (some of them are used an office).

Other strategies would be more invasive. Preliminary simulations with flats have shown that further insulating internal walls would not improve the temperature zoning. In fact, lightweight partition walls are already insulated for acoustic reasons (0.5 W/m².K). Most of the thermal zoning effect is already created by this default amount of insulation. The ventilation strategy could be changed, such as the concept of cascade ventilation with a centralized heat recovery and a single supply air temperature could be reconsidered as it is a major process that homogenizes temperature in the building. For instance, a two-zone ventilation concept has been investigated in the article of Berge et al. [28].

6. Energy efficiency of hydronic distribution systems in super-insulated residential buildings

In space-heating (SH) dominated climates, super-insulated building envelopes, such as passive houses (PH), are often promoted to drastically reduce SH needs. Using hydronic SH distribution in PH, thermal losses from pipes become a relatively large source of internal gains. Nevertheless, buildings with super-insulated envelopes have high utilization factors of heat gains so that the resulting SH distribution energy efficiency is currently unknown. The chapter investigates this efficiency with dynamic simulations (here using IDA-ICE) including a detailed modelling of the SH distribution system. Such studies with detailed modelling of the SH distribution are rarely found in the scientific or technical literature. Generally the physics of the SH distribution is modelled in an oversimplified way. The performance of standard and simplified SH distribution loops are also compared and discussed. It is confirmed that the fraction of uncontrolled thermal losses from the SH distribution system is large. Up to 50% of the heat delivered to the distribution system can be emitted by pipes: in that case, the remaining 50% are emitted by the radiators. Nevertheless, the distribution efficiency is nonetheless kept high (above 90%). Compared to other forms of energy losses in super-insulated buildings such as bedroom window openings, the present work suggests that the increase of energy use caused by thermal losses from the hydronic SH distribution remains a secondary problem in super-insulated buildings.

6.1 Introduction

In space-heating (SH) dominated climates, such as Scandinavia, building regulations and standards promote highly-insulated buildings to drastically reduce SH needs. A good example is the passive house (PH) standard, which requires for so-called *super-insulated* building envelopes. This standard has been adapted to many locations, such as Norway with the NS3700 standard [2]. Most existing concepts and pilot buildings for Norwegian Zero Emission Buildings (ZEB) are also based on super-insulated building envelopes [3, 4].

Compared to older buildings with a significantly lower insulation level, super-insulated building envelopes introduce new challenges and opportunities for the SH distribution system:

- Firstly, **internal gains** play a major role to counterbalance the limited amount of thermal losses of the building envelope. Thermal losses from the water-based distribution system become relatively more important so that their contribution as internal gains should be properly evaluated.
- Secondly, the SH distribution system can in principle be **simplified** in PH [1] without leading to thermal discomfort. As the building is super-insulated, it is indeed not necessary to place a heat emitter in front of each window to prevent cold draft, or even in each room. This simplification of the SH distribution forms the basis of the German definition of the PH standard [1], where the initial motivation for the simplification is reduction of investment costs. Typically, this can be done by reducing the number of heat emitters inside the building. In the present study, the case of one radiator per floor is investigated while the cases of air-heating or wood stoves have been already studied in other Norwegian research [5, 7].
- Thirdly, super-insulated building envelopes offer **better heat storage**, characterized by higher time constants and thus higher utilization factors of gains [32].

Combining these three elements, calculating the resulting energy efficiency becomes less evident. Keeping the SH distribution network unchanged (i.e. without simplification), heat losses from the distribution system are relatively more important in super-insulated buildings but these buildings have a better capability of utilizing these losses for SH. In addition, the SH distribution loop can be simplified to reduce the heat gains for the SH distribution system. The objective of the chapter is to investigate the influence of the distribution system design on the energy efficiency in the context of super-insulated buildings. To the authors' knowledge, this question has never been addressed from the perspective of super-insulated buildings in previous works.

In general, few studies investigating SH distribution efficiency in detail have been conducted. The reason might be the complicated dynamic phenomena of distribution losses. Until now, building performance simulation (BPS) tools typically have not supported the detailed modelling of the heating system with pipework, thermostatic valves and radiators, which have continuously changing flow rates and temperatures. The work of Maivel *et al*. [33] is an exception, where the emission and distribution efficiency of low-temperature radiators has been investigated for nearly zero-energy buildings using detailed dynamic simulations (IDA-ICE). In practice, SH distribution losses are generally evaluated in a simplified way, typically using tabulated distribution efficiencies. In Europe, these tabulated values are usually given in national standards, see e.g. NS3031 [34], while the overarching EN 15316 standard [35] provides guidelines to establish these tabulated distribution efficiencies. Detailed evaluation methods are nonetheless already introduced in standards, each of them having different levels of modelling simplification, such as the EN 15316 [35, 36], prEN 15316 [37] or TS3031 [38]. These detailed evaluations are most often not applied and not supported by default in building simulation packages per today.

Following the work of Maivel *et al*., the present contribution also investigates distribution losses using dynamic simulation (in IDA-ICE) with a detailed modelling of the SH distribution system. Compared to the previous work, the present contribution rather focuses on the influence of the building insulation level and on the design of the SH distribution system. The need for BPS tools to model in detail the SH distribution system in super-insulated buildings is questioned. The work mainly focuses on the energy efficiency of the SH distribution. The ability of a simplified SH loop to provide for the required thermal comfort in each zone is covered in previous chapters. This chapter is mainly taken from the conference paper [39]. The technical terminology is taken from EN 13790 [32] for building physics and EN 15316 [35, 37] for the energy efficiency of the space-heating distribution.

Figure 6.1 Sketch of the basement, ground and first floor of the investigated row house.

6.2 Methodology

6.2.1 Building test case

The test case is the terraced house from the Miljøbyen Granåsen project. The terraced house (based in House 1 of Chapter 5) with heated area of 142.5 m² consists of three stories as shown in Figure 6.1. It is a timber frame construction except for the basement, which was built with concrete. In that respect, the building thermal mass is characterized as light [32]. The balanced mechanical ventilation has a heat recovery unit and provides for a nominal air change rate (ach) of 0.52/h. If necessary, the electric resistance further preheats ventilation air to a set-point temperature of 16°C. Standard internal gains for persons, lighting and equipment have an average value of 4.0 W/m² [34].

To investigate the influence of the building thermal insulation on the performance of the SH distribution system, two alternative cases are considered, see Table 6.1. One corresponds to the minimal requirements of the current Norwegian building regulation, TEK10 [40], and the second to the requirements of 1985, TEK87 [41]. Typically, natural ventilation was used in TEK87 buildings. For the sake of the simplicity, it was modelled as balanced mechanical ventilation with a heat recovery efficiency of 0% and no air pre-heating.

Table 6.1. Thermal properties of the NS3700, TEK and TEK87 building cases.

Component	PH	TEK10	TEK87
Extern. wall U-value [W/m².K]	0.15	0.22	0.35
Roof U-value [W/m².K]	0.06	0.18	0.23
Basement U-value [W/m².K]	0.10	0.18	0.30
Infiltration n50 [1/h]	0.60	2.50	3.00
Windows U-value [W/m².K]	0.80	1.20	2.10
Doors U-value [W/m².K]	0.80	1.20	2.00
Norm. cold bridges [W/m².K]	0.03	0.03	-
Heat recovery rated temperature efficiency (EN 308)	88%	70%	-

Trondheim is located in Norway (63°30’ N, 10°22’ E) and has a subarctic climate with severe winters (Köppen-Geiger classification Dfc). The SH design outdoor temperature (DOT) is -19°C, the yearly-averaged outdoor temperature 5.1°C and the yearly-averaged horizontal solar irradiation is 101.6 W/m².

6.2.2 Definition of the SH distribution loop

The nominal SH power (P_n) for each room has been computed using the detailed building model. Following the standard design procedure in Norway [42], the power is evaluated during steady-state regime with a constant DOT without solar or internal gains.

Based on nominal power, three SH distribution loops have been designed using two-pipe connections.

- The ***standard loop*** has one radiator in each room except for the technical room.
- Two ***simplified loops*** have only one radiator per floor (i.e. the basement, the living room and the corridor in the first floor). One version has pipes mainly crossing non-heated rooms (**Type 1**), meaning the corridor on the ground floor and the technical room, while the second version has pipes crossing heated rooms only (**Type 2**). The total length of pipes for the standard loop is 38.55 m and 18.8 m for both simplified loops. This is comparable to the default pipe length for standard and simplified loops proposed in the TS3031 [38]. By definition, simplified loops are only applied to the test case at PH insulation level.

Two design distribution temperatures (T_{dist}) are considered: 60°C/40°C and 40°C/30°C. Nevertheless, the TEK87 house can only accommodate a 60°C/40°C distribution loop, as 40°C/30°C would lead to radiators with prohibitive dimensions. During operation, a weather-compensated heating curve is applied. For each case, the diameter of each pipe segment is evaluated in detail using standard design criteria, including linear and singular pressure losses. The smallest pipe diameter that simultaneously generates a pressure drop lower than 100 Pa/m and a water velocity below 0.5 m/s is selected, with an additional constraint that the pipe should have a minimal internal diameter of 8 mm. The influence of pipe thermal insulation is investigated by comparing cases without insulation and with 19 mm Armaflex® insulation (thermal conductivity λ = 0.037 W/m.K).

6.2.3 Modelling of the building and the SH distribution

Multi-zone building simulations have been performed using the BPS software IDA-ICE version 4.7.1 [12]. Parameters for the building envelope and ventilation system have been defined in IDA-ICE using as-built documents. The discharge coefficient (C_d) for the bidirectional airflow in open doorways is taken at 0.65. SH needs have been validated against the value computed using SIMIEN [43]. SIMIEN is the BPS software that has been used during construction to prove that the building complies with the Norwegian building regulation. In previous chapter, comparison with measurements has shown that this IDA-ICE model is able to reproduce the temperature differences between rooms during the SH season. Even though this comparison has not been done using standard calibration indexes, such as the NMBE and RMSE [44], the building model is considered validated enough for the purpose of the study.

The standard IDA-ICE interface already includes a detailed radiator model, which considers both thermal and hydraulic aspects. As emission efficiency is not the subject of the work, thermostatic valves (TRV) are modelled using a PI control directly adapting the mass flow through the radiator (which is in practice equivalent to a perfect control with a valve authority of 1.0). Consequently, the mass flow through each radiator changes continuously during simulation as a function of the room instantaneous SH needs. The radiator geometry is embedded in the 3D virtual model of the building. This enables the radiator model to account for the enhanced thermal losses through the wall at the back of the radiator. Stratification losses are not modelled.

Each pipe segment of the distribution network was created manually in the advanced interface of IDA-ICE (so-called “schematic”) where users can combine components into a system in an equation-based environment, see Figure 6.2. Each time a distribution pipe crosses another zone or connects a pipe junction, a new pipe segment (or component) was created in the network model. The implementation of each network (i.e. standard and simplified loops) in IDA-ICE has been validated by comparing the water temperature and mass flows at each node of the network with an equivalent implementation in Matlab®.

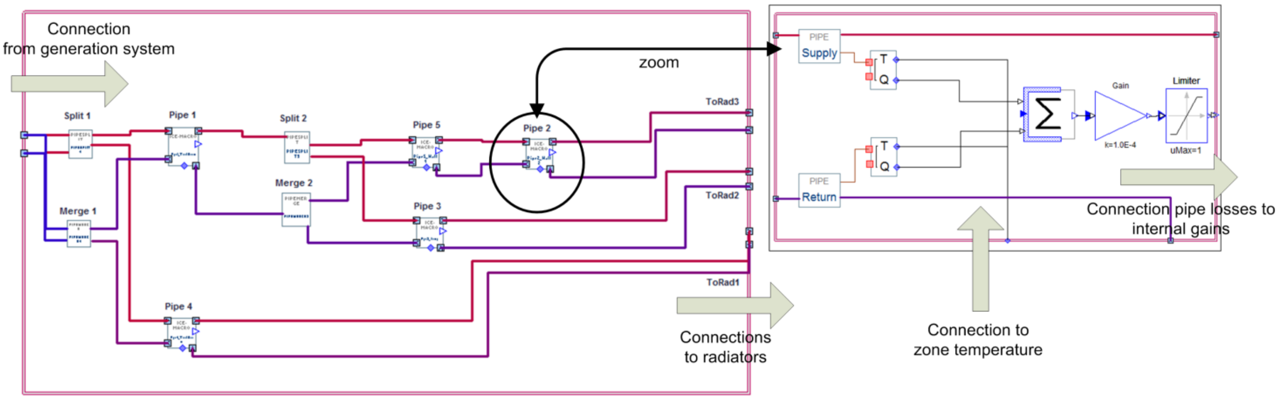


Figure 6.2 Example of IDA-ICE macro developed to model the simplified SH distribution system: a first layer combines a supply and a return pipe segment (right), the second layer (left) combines these two-pipe components into a network.

Thermal losses from each pipe segment are evaluated using the ISO12241 standard [45] assuming a steady-state heat exchanger model and a mean logarithmic temperature difference (LMTD). The overall heat transfer coefficient (U_w) between the water in the pipe and the pipe environment is assumed constant. Two different U_w have been evaluated for the two design distribution temperatures (60°/40°C and 40°C/30°C). U_w combines both the convection and the thermal radiation towards the room. Defined in terms of inside pipe area, U_w is evaluated using

$$U_w = \frac{1}{\frac{1}{h_{c,in}} + \frac{r_{in}}{\lambda} ln\left(\frac{r_{out}}{r_{in}}\right) + \frac{r_{in}}{r_{out}} \frac{1}{h_{tot,out}}} \tag{1}$$

where r_{in} and r_{out} are the internal and external pipe radius, respectively. The convection coefficient ($h_{c,in}$) for a fully turbulent developed flow within a circular pipe is evaluated using the Dittus and Boelter correlation [46]. For the external airflow, the convection coefficient ($h_{c,out}$) is estimated using the Churchill and Chu correlation [47] for a free convection around a long horizontal cylinder. The heat transfer coefficient for radiation ($h_{r,out}$) to the room is evaluated analytically assuming that the dimension of the pipe is small compared to the room geometry. The radiation transfer rate is then only dependent on the area of the pipe external surface, its emissivity (ε) as well as the wall and duct surface temperatures [48]. The external heat transfer coefficient ($h_{tot,out}$) in Eq. (1) combines $h_{c,out}$ and $h_{r,out}$. Consequently, it is accurate when the difference between the room air and the wall temperatures is small (compared to the pipe external temperature). The heat emitted by the pipe segment Q_w to the room is evaluated using

$$Q_w = U_w(2\pi r_{in} L)\ LMTD(T_w, T_a) \tag{2}$$

where L is the pipe length, T_w the water temperature and T_a the room air temperature. The heat Q_w is injected into the room model as an internal gain both in form of convection and radiation according to the ratio between $h_{c,out}$ and $h_{r,out}$. Pipes have no physical location in the 3D virtual model of the room in IDA-ICE so that radiative gains are distributed between surfaces in an area-weighted manner. The overall heat transfer coefficients (U_w) computed using this method give values comparable to the default values of prEN15316-3:2014 [37]. The linear heat losses (Q_w/L) are also comparable to values reported in the standard.

6.2.4 Performance indicators

The performance of SH distribution systems is mainly compared using two monthly (or yearly) indicators:

1. The **fraction of thermal losses (ξ)** is the ratio between monthly (yearly) thermal losses emitted from the distribution system (Q_{loss}) and the monthly (yearly) energy delivered to the distribution loop by the heat generation system (Q_d). Q_d will be here termed “energy use”, a terminology that is only correct if the generation efficiency is assumed to be 100% [49].
2. The **distribution efficiency (η_d)** is by definition the ratio between Q_d computed without pipe losses and Q_d computed with pipe losses. This last indicator also translates the amount of thermal losses that has been usefully recovered for SH.

For the sake of the simplicity, a constant indoor temperature set-point of 21°C is applied for all cases. This assumption is not expected to have a major influence on results and conclusions.

6.3 Analysis and discussion of results

The performance of the different SH distribution systems is firstly compared in terms of distribution efficiency (η_d), using a same set-point temperature for each radiator. In that case, the temperature in free-floating rooms without radiator is different between the different SH distribution systems investigated. This effect is accounted for in a second step where a minimal temperature is imposed in all rooms.

6.3.1 Distribution efficiency

The distribution efficiency is investigated in successive steps.

Firstly, the case of the 60°C/40°C standard loop without pipe insulation is shown in Figure 6.3 for the three performance levels of the building envelope. The share of pipe losses (ξ) has a moderate value of 20% for the TEK87 house. This value increases progressively to 30% for the TEK10 house. When the building performance is further improved to PH, ξ increases to 50%. As the utilization factor of gains is high in PH, a significant amount of these losses is recovered usefully. Nevertheless, from the TEK87 to the PH building, the distribution efficiency (η_d) is decreased from 97% to 88%. This decrease is significant but rather limited compared to the increased share of pipe losses (ξ).

Secondly, some measures can be taken to improve η_d, such as the pipe insulation or the reduction of the distribution temperature. Results are reported in Table 6.2. A distinction is made between closed and open internal doors. With open internal doors, internal gains, such as pipe losses, will lead to a lower temperature increase in rooms than the case with closed doors because of the large bidirectional flow in open doorways. In other words, there is a better mixing and less zoning with internal doors open. The resulting distribution efficiency (η_d) is then higher for the case with open doors. This effect is more important with a higher share of internal gains, typically with high ξ. In Figure 6.4, a good correlation is found between ξ and the change of η_d between closed and open doors, regardless of the insulation level or distribution loop. It also gives an idea about the sensitivity of η_d to the user behavior.

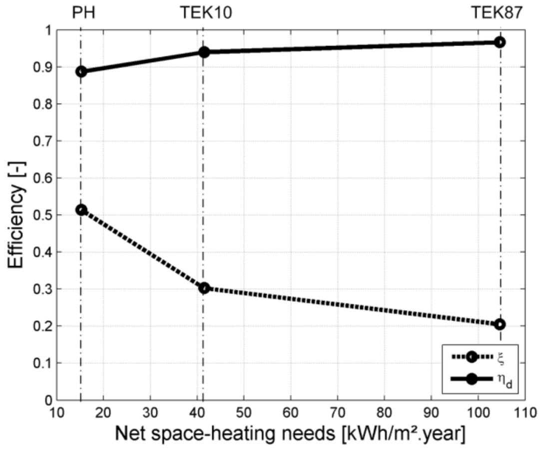


Figure 6.3 Yearly performance of the 60°C/40°C standard distribution loop without pipe insulation for the three buildings (with internal doors closed).

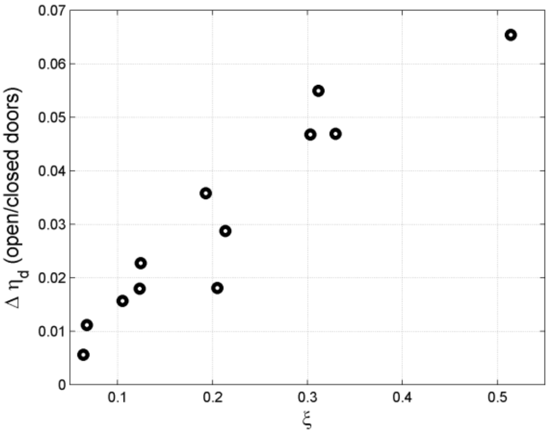


Figure 6.4 Correlation between the fraction of losses (ξ) and the variation of distribution efficiency (ηd) between open and closed doors.

Compared to the baseline case with a 60°C/40°C loop without insulation, the standard loop has a better distribution efficiency using 40°C/30°C. Nonetheless, the pipe insulation has a more drastic influence on losses. Combining both effects, the η_d of a standard loop may reach 97-99% in a PH. This leads to the original conclusion than standard distribution loops can still be implemented in PH if measures are taken to limit losses from pipes.

Regarding the performance of the simplified distribution loop, cases with distribution pipes crossing non-heated zone (Type 1) and only crossing heated zones should be distinguished (Type 2). It is here assumed that the set-point temperature of 21°C is only applied to the zones equipped with a radiator. The temperature in the rooms without radiator is “free-floating”. With loop of Type 1, the share of losses (ξ) is reduced compared to the standard loop and kept at a level equivalent to the TEK10 building. In the PH case, the distribution efficiency (η_d) of the Type 1 loop is only slightly better than the standard loop because it is here considered that the temperature increase generated by losses emitted in non-heated zones does not add any value. This effect is obviously reduced if internal doors are open. Regarding the loop of Type 2, thermal losses from pipes are emitted in heated zones, a solution that gives very high efficiency (> 99%) whatever the distribution temperature level, the opening of internal doors, or the pipe insulation level. In other words, **the simplified loop has very high distribution efficiency and is more robust to design parameters than the standard loop, if location of pipes is selected carefully.**

Table 6.2. Performance of the SH distribution system with closed and open internal doors (21°C set-point temperature only applied in rooms equipped with a radiator).

				Internal doors closed		Internal doors open	
House	**Loop type**	**Temperature**	**Pipe insulation**	**ξ**	**η_d**	**ξ**	**η_d**
TEK87	Standard	60°C/40°C	No	0.205	0.967	0.202	0.985
			Yes	0.064	0.989	0.061	0.994
TEK10	Standard	60°C/40°C	No	0.303	0.940	0.278	0.987
			Yes	0.105	0.980	0.092	0.996
		40°C/30°C	No	0.193	0.957	0.167	0.992
			Yes	0.067	0.986	0.056	0.998
PH	Standard	60°C/40°C	No	0.514	0.887	0.495	0.953
			Yes	0.213	0.957	0.196	0.985
		40°C/30°C	No	0.330	0.929	0.308	0.975
			Yes	0.123	0.975	0.111	0.993
	Simplified (Type 1)	60°C/40°C	No	0.311	0.906	0.279	0.961
			Yes	0.124	0.968	0.096	0.990
		40°C/30°C	No	0.200	0.941	0.165	0.983
			Yes	0.083	0.980	0.055	0.996
	Simplified (Type 2)	60°C/40°C	No	0.382	0.992	0.228	0.992
			Yes	0.137	0.999	0.107	0.996
		40°C/30°C	No	0.237	0.992	0.194	0.995
			Yes	0.088	0.999	0.062	0.999

6.3.2 Simplified versus detailed modelling

Two common simplified approaches to account for the SH distribution losses are now introduced and compared to the detailed model: tabulated data of NS3031 and using a fixed fraction of thermal losses (ξ).

The Norwegian standard NS3031 [34] evaluates the energy use of buildings and resorts to tabulated distribution efficiencies. They are given as a function of the building type, the insulation level of pipes, as well as the distribution temperature, but regardless of the insulation level of the building. Table 6.3 reports on the value that should be taken from tables for the present application. These tabulated efficiencies are very close to the TEK10 values computed using the detailed model, with a maximum difference of 0.02. Nevertheless, these values are not representative for the other cases (TEK87 and PH) as well as for the simplified distributions.

Table 6.3. Tabulated distribution efficiency of NS3031.

Temperature	Pipe insulation	η_d
60°/40°C	No	0.92
	Yes	0.96
40°C/30°C	No	0.94
	Yes	0.97

By default, IDA-ICE enables to account for the SH distribution losses by introducing the yearly fraction of thermal losses (ξ) as an input parameter. The instantaneous heat delivered to the radiators is then increased by this factor to calculate the instantaneous energy use. The corresponding losses are introduced as internal gains distributed uniformly in all zones. Assuming ξ known, this method is here compared to the detailed evaluation. For the case of the standard distribution loop with a weather-compensated distribution temperature, the distribution efficiency (η_d) computed by both approaches shows a good agreement, even on a monthly basis, see e.g. Figure 6.5. In that case, the knowledge of the yearly fraction of thermal losses (ξ) is enough to determine the η_d. As ξ is rather constant throughout the SH season, its value could be pre-evaluated with a dedicated software in a decoupled way. Alternatively, a sensitivity analysis to the input parameter ξ could be done in IDA-ICE.

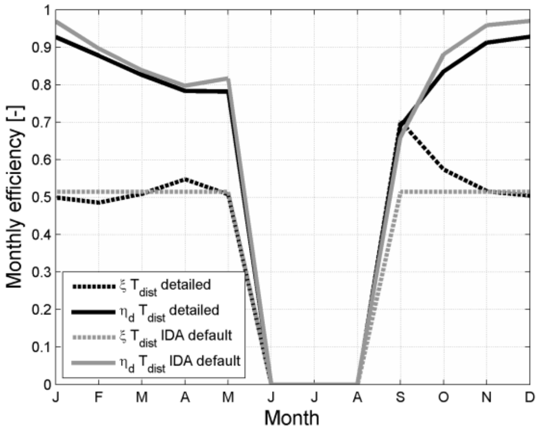


Figure 6.5 Monthly performance of the 60°C/40°C standard distribution loop in the PH without pipe insulation, detailed modelling versus default IDA-ICE modelling (with internal doors closed).

Nevertheless, the accuracy of the simplified method decreases when the hypotheses behind the simplification are no longer valid. For instance, a constant water distribution temperature would lead to larger variations of ξ during the SH season, or the simplified distribution generates by definition thermal losses that are not distributed uniformly inside the building, see Table 6.4.

Table 6.4. Default IDA-ICE model compared to the detailed model for the 60°C/40°C distribution loop without pipe insulation in the PH.

Loop type	Temperature	η_d (detailed method)	η_d (default method)
Standard	Variable	0.89	0.92
Standard	Constant	0.80	0.87
Simplified (Type1)	Variable	0.90	0.94
Simplified (Type 2)	Variable	0.99	0.92

6.3.3 Overall energy efficiency

The previous section only focused on the distribution efficiency (η_d), by applying a constant set-point of 21°C in rooms equipped with radiators. Nevertheless, standard and simplified loops lead to different temperature differences between rooms inside the building. To investigate the overall energy efficiency, the energy use of the different distribution systems should be compared for a same thermal comfort. One should distinguish between two scenarios:

1. Firstly, the user wants 21°C in each room, equipped with radiator or not. With a simplified SH distribution, the set-point temperature in rooms equipped with radiator should be increased above 21°C in order to ensure 21°C in rooms not equipped with radiator. With simplified distribution, users should accept to open internal doors. This requirement may lead to privacy problems and is a major limitation of the simplified SH distribution. The increase of set-point temperature above 21°C leads to higher SH needs, which should theoretically be considered as a type of SH emission losses. This first scenario complies with standards as they compare the energy use of different SH systems for a uniform set-point temperature in all rooms.
2. Secondly, users are satisfied with a lower temperature in rooms not equipped with radiator. This situation may arise when users want lower temperatures in specific rooms. As explained in previous chapters many Norwegians desire lower temperatures in bedrooms, typically ~16°C or below [18, 19, 25]. People that would like colder bedrooms should typically keep internal doors closed. The set-point temperature for radiators is kept at 21°C only in the basement, the living room and the corridor of the first floor, for both the simplified and the standard loops (i.e. the thermostatic valve in other rooms are fully closed). The temperature in bedroom is free-floating. In this second scenario, the increase of temperature due to pipe losses in non-heated zone is assumed to have no value.

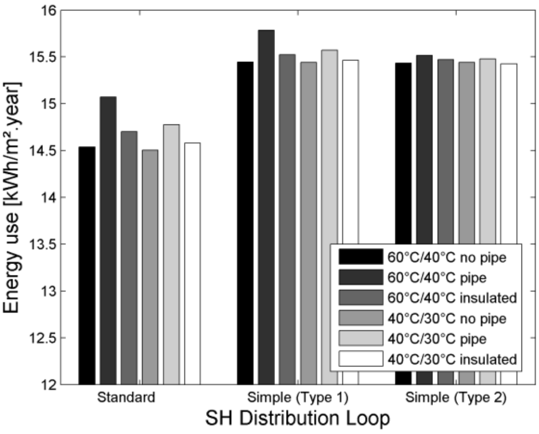


Figure 6.6 Energy use (Q_d) for the different loops with a minimum temperature of 21°C in each room (with open internal doors).

Both scenarios have been simulated in IDA-ICE for the three types of loops. Other possible scenarios can be seen as intermediate cases between these two extreme scenarios. The scenario (1) of a minimum temperature of 21°C in each room is shown in Figure 6.6. Starting with the idealized case without pipe losses, the simplified loops need a higher temperature in the rooms equipped with radiator (see e.g. Figure 6.7) leading to a higher energy use by ~1 kWh/m². Again, it translates a loss of emission efficiency. Taking pipe losses into account, the higher distribution efficiency (η_d) of simplified loops does not compensate for the initial increase of ~1 kWh (due to emission efficiency). For instance, the standard loop at 60°C/40°C without insulation has an energy use of 15.1 kWh/m².year while the equivalent simplified loop (Type 2) uses 15.5 kWh/m².year. The simplified distribution is thus less energy-efficient than the standard distribution.

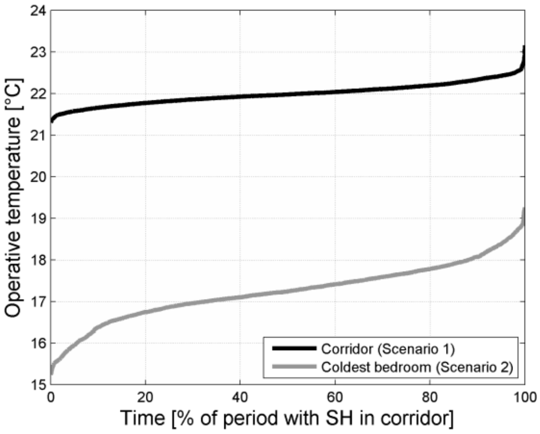


Figure 6.7 Duration curve of the corridor of the first floor temperature in scenario 1 and the double bedroom temperature in scenario 2 (case with 60°C/40°C distribution without insulation).

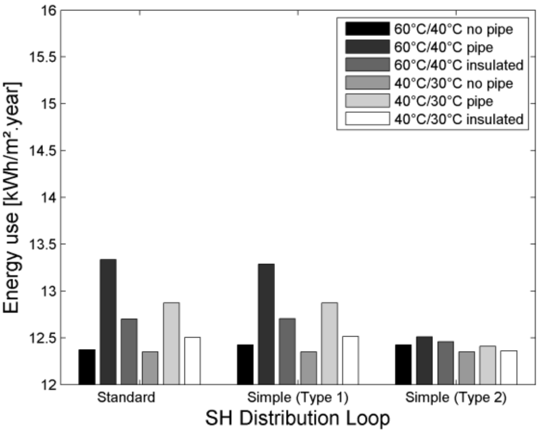


Figure 6.8 Energy use (Q_d) for different loops with a temperature of 21°C only imposed in the basement, living room and hall (with closed internal doors).

The scenario (2) with a set-point temperature of 21°C only applied in the basement, living room and corridor of the first floor, is shown in Figure 6.8. Starting with cases without pipe losses, the energy delivered to the distribution system (Q_d) is equal for each case. The temperature zoning (i.e. lower temperature in bedrooms such as in Figure 6.7) reduces the yearly energy to ~2 kWh/m².year compared to the previous scenario (1). When pipes losses are considered, results for the three distribution layouts are mixed. The simplified loop with pipes crossing non-heated zones (Type 1) does not outperform the standard loop. In fact, the fraction of losses (ξ) is comparable for both cases. The simplified loop has fewer pipes but with higher mass flows than the standard loop. On the contrary, the simplified loop with pipes only crossing heated zones (Type 2) always has higher distribution efficiency leading to yearly energy uses 0.25 to 1 kWh/m².year lower than the standard loop.

6.3.4 Discussion

Both temperature levels (60°C/40°C and 40°C/30°C) are used in practice, but pipe insulation inside the building protected volume is almost never applied. In this context, it can be concluded that the energy performance of the standard loop compared to the simplified loop (Type 2) depends on the desired temperature differences between rooms, with a difference of 0.5-1.0 kWh/m².year between both scenarios. These variations are non-negligible for super-insulated buildings with SH needs of ~15 kWh/m².year. Nevertheless, they are small compared to the influence of users over the SH energy use, for instance by adjusting the set-point SH temperature, by opening the windows frequently during winter time, or the user influence over the domestic hot water (DHW) needs [25, 50]. For these cases, variations higher than ~5 kWh/m².year are frequently reported. In general, it is well known that users have relatively more influence over the energy use for heating when the building is more insulated. It can then be concluded that the question of the SH distribution efficiency is secondary. This confirms that the first reason for simplification of the SH distribution is the reduction of investment costs [1]. To the authors' knowledge, the reduction in embodied energy and CO_{2eq} emissions from a lifecycle perspective (LCA) resulting from the reduced amount of pipes and radiators has not been investigated yet in the scientific literature.

The present investigation applied state-of-the-art control techniques, meaning a weather-compensated heating curve and a shutdown of the SH distribution outside the heating season. Due to higher shares of losses (ξ), super-insulated buildings are more vulnerable to distribution losses if these control techniques are not applied, or if pipes are located outside the heated volume. Examples are given in Figures 6.9 and 6.10 for a constant distribution temperature (T_{dist}) compared to a weather-compensated distribution temperature. Figure 6.9 shows that the fraction of losses (ξ) increases by ~10% for each of three building insulation level. While it only decreases the yearly distribution efficiency (ηd) by 2% for the TEK87 house, it decreases this efficiency by 10% for the PH case. Figure 6.10 only focuses on the PH case and shows how the monthly ηd is lower during the shoulder months of the SH season. These months are characterized by lower SH needs so that the utilization factor of internal gains is lower [32].

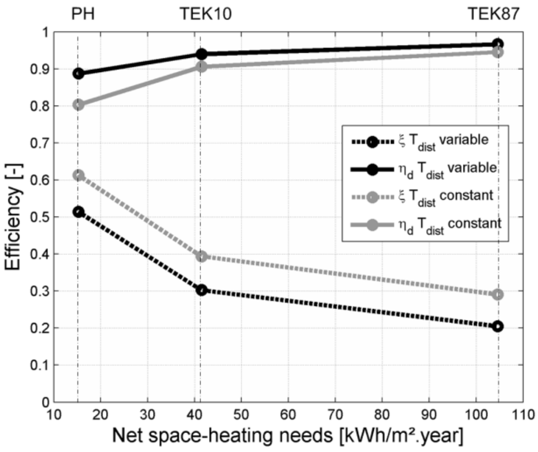


Figure 6.9 Yearly performance of the 60°C/40°C standard distribution loop without pipe insulation for the three buildings, with and without weather-compensated heating curve (with internal doors closed).

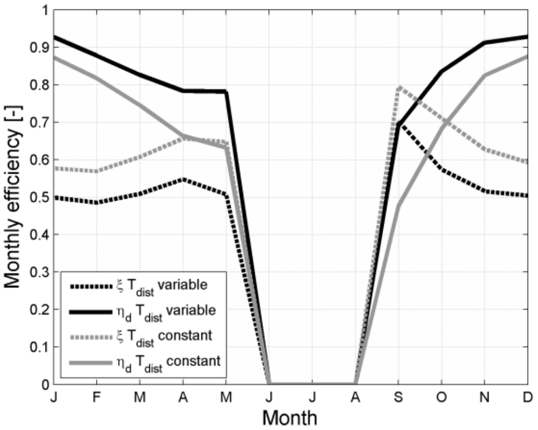


Figure 6.10 Monthly performance of the 60°C/40°C standard distribution loop in the PH without pipe insulation, with and without weather-compensated heating curve (with internal doors closed).

A limitation of the present study is the constant heat transfer coefficient of pipes U_w. The thermal inertia of pipes is also not accounted for. This is inherent to the current implementation of the pipe model available in IDA-ICE. This is nonetheless not specific to IDA-ICE. For instance, the pipe model of TRNSYS (*Type 31*) also presents the same limitation [51]. These models should be extended to variable U_w and thermal inertia. Finally, the thermostatic valve control has been assumed perfect while in reality the closing time is not instantaneous as assumed in the model.

6.4 Conclusion

To date, the energy efficiency of hydronic SH distribution in super-insulated buildings has not been investigated in detail. Compared to less insulated buildings, the fraction of losses from the SH distribution system (ξ) is expected to increase significantly. Nevertheless, super-insulated building envelopes are better heat storages, so that the utilization factor of internal gains is higher. The resulting energy efficiency of the SH distribution is unknown. In addition, simplifying the SH distribution could be an option to reduce these losses, essentially by reducing the piping length.

Detailed dynamic simulations (here using IDA-ICE) are ideal to investigate this problem as instantaneous mass flow and temperature of pipes are evaluated, but it requires the detailed modeling of the SH distribution network. By default, this detailed modeling is not implemented in building simulation packages where simplified approaches are rather proposed.

Simulations showed that uncontrolled thermal losses from pipes can cover up to ~50% of the annual SH energy use (i.e. ξ < 50%). Nevertheless, the study showed that the building can recover most of these losses usefully, and keep the distribution efficiency (η_d) above ~90%, for all the distribution loops investigated. In super-insulated buildings, high ξ would advocate that the SH distribution system should be properly taken into account during design and modelled in details. It is a “false alert”. The present study suggests on the contrary that the error is limited if the SH distribution system is not analyzed in detail (as η_d remains high). This is also an important conclusion for developers of BPS software.

The simplified distribution system showed better distribution efficiency (η_d) than the standard distribution loop. It is especially true if the distribution pipes of the simplified loop cross heated zones only. Then the η_d is almost perfect (~99%). Nevertheless, for users that would like the same temperature in all rooms, the set-point temperature in rooms equipped with radiator should be increased to ensure the minimal temperature in rooms without heat emitter. This effect can be considered as SH emission losses. Simulations show that the resulting increase in SH energy use would prevail over the improved η_d using simplified SH distribution. In the end, the relative energy performance between the simplified and standard SH distribution systems depends on the desired temperature differences between rooms. The computed differences in annual energy use have been here evaluated to be between 0.5-1.0 kWh/(m^2.year). These differences are not negligible for super-insulated building (with typical SH needs of ~15 kWh/m^2.year). Nevertheless, these numbers are small compared to variations in energy use generated by occupant behavior, such as a change of the indoor set-point temperature, frequent opening of windows during the SH season or the variability of DHW energy use. Consequently, the present investigations suggest that the energy efficiency of SH distribution system in super-insulated buildings is a secondary problem (if the SH distribution temperature is controlled in a proper way). The main motivation for the simplification of SH distribution system thus remains the reduction of investment costs.

7. Measurements in the ZEB Living Lab

This chapter aims to evaluate the performance of the space-heating distribution in the ZEB Living Lab without occupancy using detailed measurements. The simplified space-heating distribution using a single radiator is compared to a conventional floor heating. The floor heating and the radiator distribution were separately applied to heat the ZEB Living Lab, meaning that no combination of these two SH distribution systems was used in the present measurements. The performance of both distributions is analyzed in terms of air temperature differences between rooms (especially to investigate thermal zoning between bedrooms and living areas), vertical temperature stratification and operative temperature in each room. Cases of closed and open bedroom doors were considered. In addition, the slower thermal dynamics resulting from the super-insulation of the Living Lab was also investigated, as it is a main factor to enable a quick change of indoor set-point temperature and to create a temperature zoning between rooms. The absence of occupants enabled to create controlled conditions for experiments and to highlight the building physics rather than the user-behavior. Therefore, these experiments do not give a full picture of the problem but enable to show how the building reacts from a physical point of view. Nevertheless, users have a significant influence on the energy balance of the building through internal gains (metabolic, or the use of artificial lighting and household appliances). For the physics to be properly captured, it has been decided to implement controlled internal gains inside the building envelope.

7.1 The ZEB Living Lab

Before presenting the experimental setup specific to the present investigations, some general background is given about the ZEB Living Lab. This summarized information is extracted from the conference paper of Goia et al. [17].

Figure 7.1 Picture of the ZEB Living Lab located on the NTNU campus (image by ZEB).

The ZEB Living Lab is a multipurpose experimental facility that was designed to carry out investigations at different levels, ranging from envelope to technical systems, from ventilation strategies to research on lifestyles and technologies (where the way users interact with the building with state-of-the-art technologies is studied). In general, people are expected to live (for shorter or longer periods) in the Living Lab even though this option has not been taken for the results presented in this chapter. Example of users experiences in the Living Lab can be found in Chapter 2.

The ZEB Living Lab is a single-family detached house and should be representative for the most common typology in the Norwegian residential building stock. Its primary aim is to demonstrate how a CO_{2eq} neutral construction can be realized in Norway. The Living Lab is designed to have high indoor environmental quality, lower the energy needs for space-heating and cooling using passive techniques and integrate energy-efficient thermal systems as well as solar energy (both solar thermal and photovoltaic panels).

7.1.1 Plan of the Living Lab and envelope properties

The ZEB Living Lab is a single-family house with a gross volume area of ~500 m^3 and heated surface of ~100 m^2. The flexibility of the plan was particularly addressed towards the possibility of allocating many different programs within the building surface (i.e. young or old couples, families, housing for students). The plan is organized in two main zones, see Figure 7.2: a living area facing south and a working and sleeping area towards the north. The entrance is located in the south west corner. Users access the living room through a hall space with a wardrobe. The kitchen is located at the opposite of the living room. At the center of the north zone, there is a shared studio area (also called north living room), equipped with a long office desk. Two bedrooms are located at the two sides of the studio room, both designed for two persons. A sliding door (larger than 2m) separates bedrooms of the studio but can be opened to create a larger space. The technical room (accessible only from the outside), the bathroom and the kitchen have been placed along the central spine of the building in order to optimize the distribution of technical equipment.

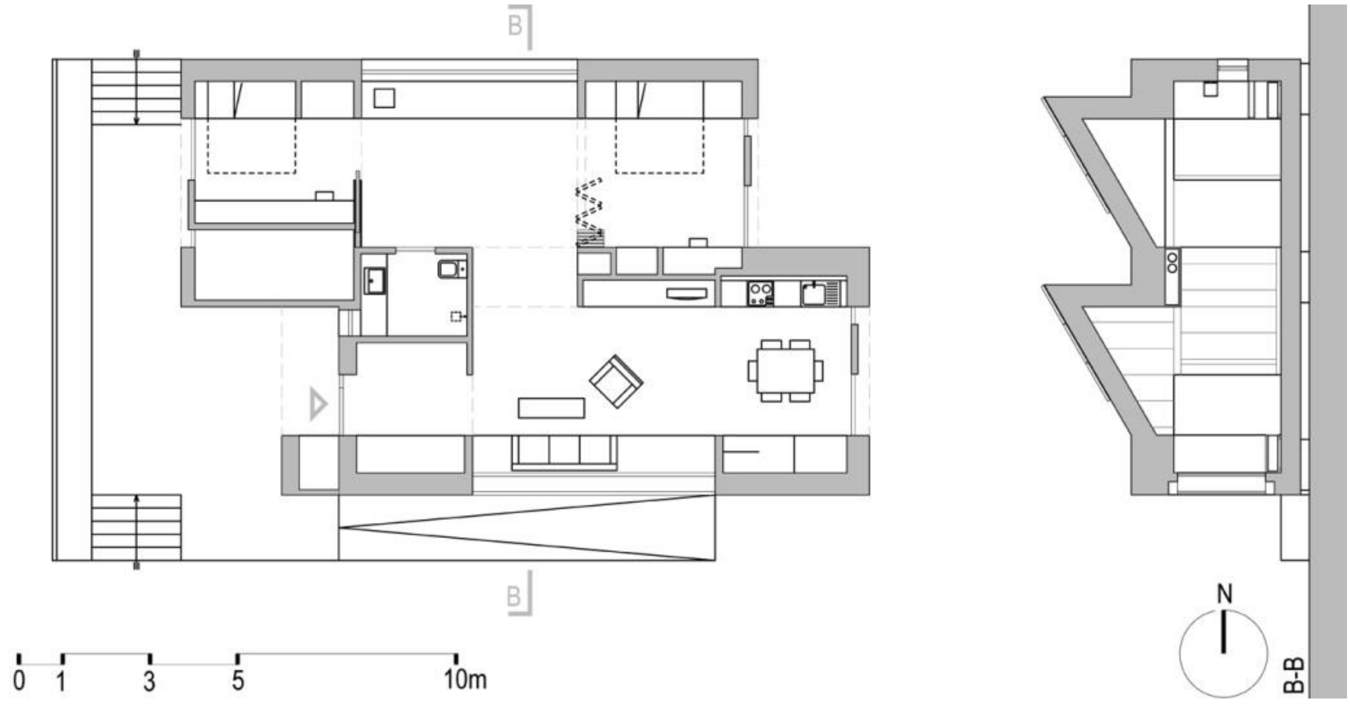


Figure 7.2 Plan and vertical section of the ZEB Living Lab [17].

Walls, floors and roofs are made out of a conventional wooden-frame structure insulated by a double layer of rock wool, with 40, 40 and 45 cm respectively. The corresponding U-values for these components are 0.11, 0.10 and 0.11 W/m^2.K. 90 m^2 of PCM boards have been placed at the indoor surface of the sloped roof (just behind the finishing wooden cladding) to minimize the risk of overheating due to the lightweight construction feature of the building. For the present application during the space-heating season, these PCM boards are not expected to have a significant influence on results. The envelope is characterized by a glass ratio of around 20%. Windows are characterized by low U-values (from 0.65 to 1.0 W/m^2.K). The south facing window is constructed with a double skin and can be ventilated. This feature has not been activated during our experiments.

7.1.2 Ventilation and heating systems

The ZEB Living Lab is equipped with balanced mechanical ventilation with a high-efficiency rotary heat recovery. The heat wheel has a nominal efficiency of 85% for a flow rate of 250 m^3/h. Cascade ventilation is applied. The supply air is delivered to the two sleeping rooms (52 m^3/h per bedroom) and the living room (26 m^3/h). The extractions are located in the bathroom (78 m^3/h) and kitchen (52 m^3/h). The air handling unit (AHU) is equipped with an electric heating coil of 1.2 kW to preheat the supply air to up to 40°C. An additional water-based heating battery of 2 kW is placed to investigate air-heating strategies.

The building is heated using a ground-source heat pump (GSHP) connected to a horizontal surface collector field and solar thermal collectors positioned vertically on the south façade. Both heat generation systems are connected to an integrated water storage tank for both space-heating (160 liters) and domestic hot water, DHW (240 liters). This dual tank is equipped with two electric resistances that act as peak-load systems. The ZEB Living Lab has three different types of water-based heat emitters: (1) independent floor heating in each room, (2) a single radiator located in the passage between the living room and the studio, and (3) air-heating. Each heat emission system has been dimensioned to cover alone the nominal space-heating power of the building. Unfortunately, floor heating was the only heat emission system operational during investigations (as well as during experiments with users analyzed in Chapter 2). The control for the radiator and the air-heating was not already available in the Living Lab. To circumvent this limitation, two electric radiators of 800 W (Dimplex Classic 2NW5 082 4L), located side by side, have been used in our experiments to mimic the waterborne radiator, see Figure 7.3. These electric radiators are airtight (meaning they are not convectors) which should lead to a ratio between convection and radiation comparable to the original radiator. Nevertheless, both electric radiators have an "on-off" control (i.e. thermostat) while the waterborne radiator is controlled using a continuous proportional (P) action (representative for a thermostatic valve) or proportional-integral (PI) action, which would minimize control losses. Air-heating has not been investigated during our work.

Figure 7.3 Twin electric radiators and the original waterborne radiator.

7.2 Measurement setup

7.2.1 Test cases and matrix

For all cases, the floor heating is always turned on in the bathroom with a set-point of 21 °C. The bathroom door is kept closed during all measurements. Therefore, the influence of the floor heating in the bathroom is expected to have a limited influence over the rest of the building. The set-point for the supply air temperature (Tset,AH) is taken at 18 °C. Nominal airflows are applied constantly (CAV) during the whole period of measurements. To avoid the effect of direct solar radiation on sensors, all windows have been shaded using internal screens except for the skylight.

Figure 7.4 Sliding door between the studio area and bedrooms the ZEB Living Lab (image by ZEB).

Table 7.1 Test matrix for the measurements in the ZEB Living Lab (bathroom set to 21°C in all cases).

Case	Night setback	Door status	Tset,SH living (°C)	Tset,AH (°C)	Tset,SH bedroom (°C)	Case No.
Floor heating (no night-setback)	No	Closed	21	18	21	1
			21	18	16	2
Radiator (with/without night-setback)	No	Closed	21	18	-	3
		Open	21	18	-	4
	Yes	Open	21-off (setback)	18	-	5
		closed	21-off (setback)	18	-	6

To limit time for experiments, only a limited set of test cases has been investigated from 3rd of February to 25th of March 2017. In these experiments, both the building behavior during the transitions between two test cases (such as a change of control strategies) and the resulting new “steady-state” thermal regime were of interest. Using floor heating, different set-point temperatures for space heating (Tset,SH) can be applied in the different rooms. Two cases with a constant Tset,SH of 16°C and 21°C in bedrooms have been investigated. 21°C is always applied with floor heating in the living areas. As temperature can be controlled for each room, it has been assumed that it would be the main method used to control indoor temperature rather than opening internal doors. Therefore, only the case of closed internal doors was considered. Floor heating is expected to be a slow-reacting heat emission system and the installed heating power in the Living Lab is relatively low to perform an intermittent heating (meaning night setback). Therefore, only constant Tset,SH were applied for floor heating (i.e. no night setback). The test matrix was made more comprehensive for the radiator case. With only one heat emitter, it is expected that users will use door opening to create temperature zoning (see Chapter 2). The cases of open and closed internal doors have thus been investigated, see Figure 7.4. Radiators having a low thermal inertia (i.e. a fast reaction time), the cases of constant and intermittent heating have been analyzed. Nevertheless, the total power of 1600 W from radiators is relatively low to perform intermittent heating. The test matrix for measurement is reported in Tabke 7.1.

7.2.2 Internal heat gains

As already explained, user behavior has been removed from investigations. Nevertheless, to mimic the thermal balance of the building correctly during operation, artificial internal gains are introduced in the building. They have been calibrated on the standardized internal gains of NS 3700 [2] that distinguishes between artificial lighting, household appliances (equipment) and gains from human metabolism, see Table 7.2. Internal gains are generated using cylindrical dummies equipped with a lamp (an incandescent bulb) and a programmable plug timer, see Figure 7.6. The heat gains generated from artificial lighting and equipment are also simulated with the thermal dummies throughout the test in the Living Lab. The number of dummies, the power of the lamp and the on-off schedule is designed to give internal gains equivalent to NS 3700 (Table 7.3). Internal gains of persons are introduced using dummies of 60 and 75 W activated using a defined schedule. Internal gains from appliances and artificial lighting are aggregated and implemented in the Living Lab using two dummies of 100 W (in the living room and in the studio area) and 1 dummy of 50 W in the entrance. These last three dummies are continuously running.

Table 7.2 Internal gains of NS 3700 [2] and the corresponding value in the ZEB Living Lab.

Heat gains	Daily-averaged value (NS 3700)	Heat gains in the LL (102 m²)
Lighting	1.3 W/m^2	133 W
Equipment	1.2 W/m^2	122 W
Person	1.5 W/m^2	153 W
Sum	4.0 W/m^2	Sum 408 W

Table 7.3 Artificial internal gains schedule in the Living Lab.

Time	Activity represented	Activity duration (h)	Nb of dummies	Occupancy location	Heat source power (W)	Heat gains from person (W)	Heat gains from lighting and equipment (W)
7-8	Cooking	1	4	Living room	75	300	253
8-18	Working	10	0			0	253
18-20	Cooking	2	4	Living room	75	300	253
20-23	Relaxing	3	4	Living room	75	300	253
23-7	Sleeping	8	4	Bedroom	60	240	253
Average						155	253

7.2.3 Sensor arrangement

The ZEB Living Lab is equipped with a large number of built-in temperature sensors in each room. However, in order to get results with a better accuracy, a temporary measurement setup with PT100 probes has been used instead (with an accuracy of 0.1°C). The air temperature and the mean radiant temperature are measured in each room by these PT100 probes. Mean radiant temperature is measured using a black globe. The operative temperature on a certain location is computed as the arithmetic mean between the local air temperature and the mean radiant temperature [52]. Measurement data is acquired using the WiSensys® system, where sensors are equipped with a wireless emitter and information sent to a so-called “base station” that collects data from all sensors with a sampling time set to 1 minute.

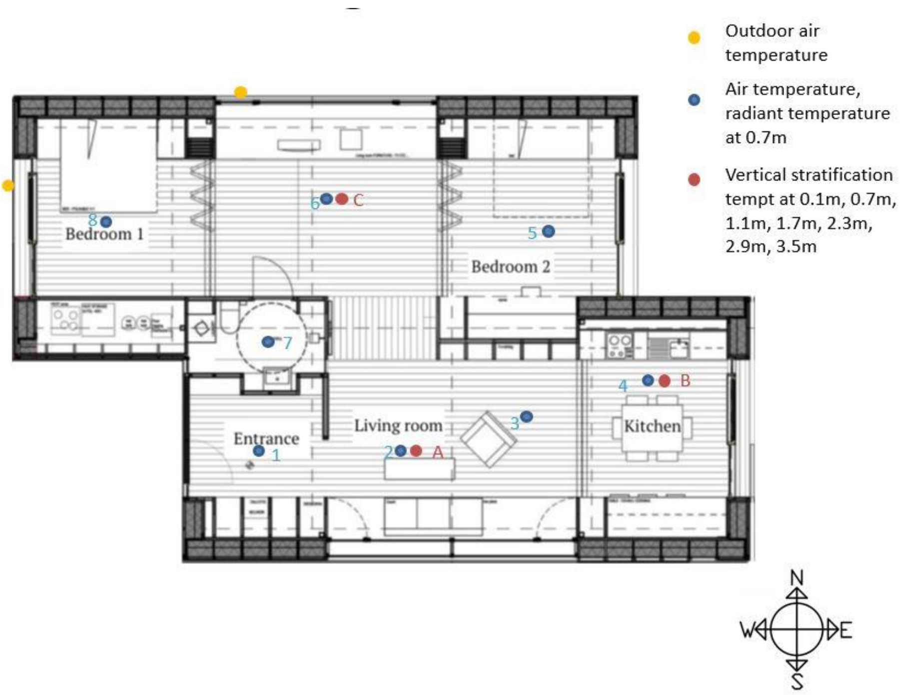


Figure 7.5 Sensor location in the ZEB Living Lab.

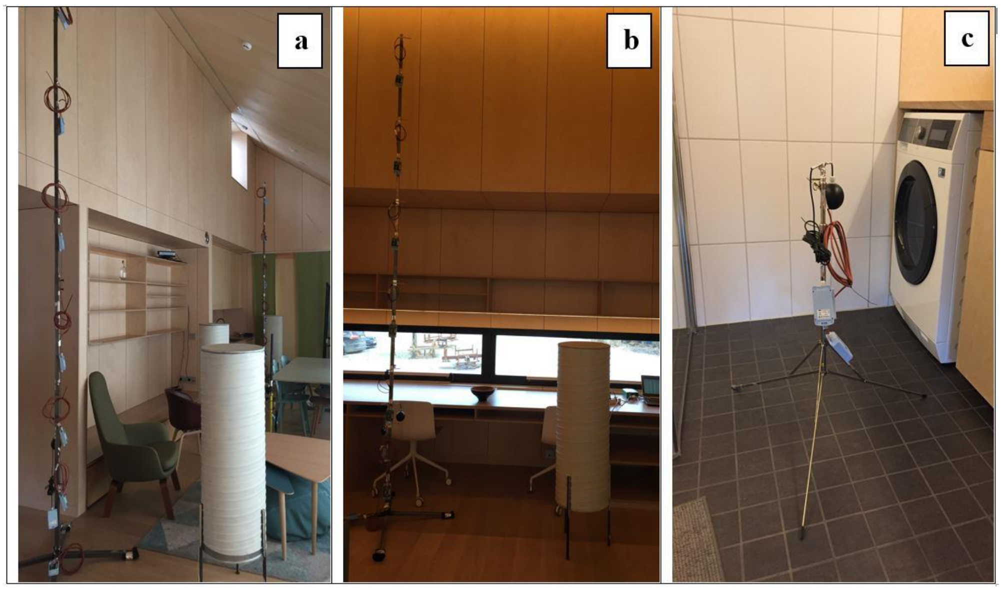


Figure 7.6 Sensors and their placement in the ZEB Living Lab: (a) thermal dummies (white cylinder) and temperature sensors placed on a pole in the kitchen, (b) temperature sensors in the studio and (c) mean radiant and air temperature sensors in the bathroom.

A total of 41 temperature sensors are used in the measurements. Their placement in the ZEB Living Lab is shown in Figure 7.5. The blue points represent the location for one air temperature and one mean radiant temperature sensor at 0.7 m height above the floor. The red points refer to several air temperature measurements placed on a same vertical pole, meaning at a same horizontal location, at different heights in order to investigate the air temperature stratification. For each pole, the vertical temperature was recorded at 0.1, 0.7, 1.1, 1.7, 2.3, 2.9 and 3.5 m above the floor. The outdoor air temperature, its relative humidity and solar radiation are monitored by the built-in weather station in the Living Lab. In addition, two PT100 probes are mounted at the north and west façades to verify the outdoor air temperature reported by the weather station (see yellow point in Figure 7.5). Figures 7.5 and 7.6 show the sensor placement in the laboratory.

7.3 Results and discussion

Cases will be analyzed following the order of Table 7.1. Cases using floor heating as a heat emission system with closed internal doors closed are discussed first. Again, the floor-heating control enables to set a different set-point temperature for each room.

7.3.1 Floor heating with all Tset,SH at 21 °C and internal door closed (case 1)

The case with a constant set-point temperature of 21 °C applied uniformly (meaning in the living room, the studio and bedrooms) is analyzed. Difference of temperatures between rooms is reported on Figure 7.7, where the air and mean radiant temperatures have been averaged over a 6-hour period (from 12PM to 18PM on the 14th of February 2017). The bars on either side of the temperature points represent the measurement uncertainties, which include bias and precision error with 95 % confidence interval.

.

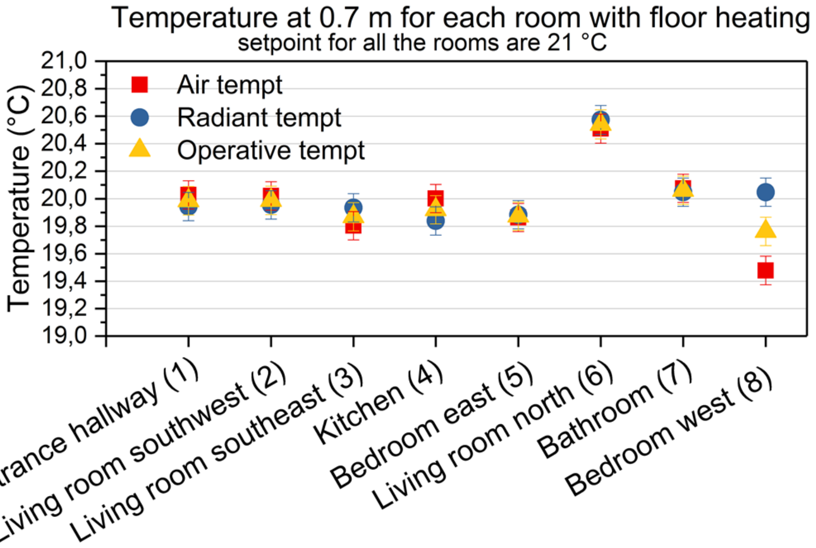


Figure 7.7 Temperature difference between rooms for uniform floor heating with internal door closed (case 1).

The range of magnitude of the temperature was about 20°C which was lower than the set-point temperature of 21°C. A reason can be given to this phenomenon. The floor heating is controlled using the built-in temperature sensors of the Living Lab that have a lower accuracy. Comparison with PT100 sensors confirmed that temperature sensors of the Living Lab show systematically a lower temperature of about 1°C. PT100 sensors have been recently calibrated. Nevertheless, measurements suggest a good homogeneity of the indoor temperature, with an air temperature very close to the mean radiant temperature and with a relatively uniform temperature between rooms. The only exception is the west bedroom showing a lower air temperature.

Figure 7.8 shows the vertical temperature stratification at 7 vertical locations in the kitchen, north and south living rooms. The mean radiant temperature at 0.7 m above the floor was also measured. The air temperature differences between the ankle level (0.1 m) and head level (1.7 m) were 0.7, 0.1 and 0.5 °C for the kitchen, north living room and south living room, respectively. The local thermal discomfort caused by vertical temperature stratification was imperceptible. The typical minimum vertical temperature difference leading to local thermal discomfort ranges from 2 to 3 degrees as indicated by the literature [52].

Results can be compared with interviews of occupants in Chapter 2 that used floor heating during their short stay in the Living Lab. With a good homogeneity of temperatures and no significant temperature stratification, it is not astonishing that occupants reported a very pleasant thermal environment using floor heating (at least during daytime).

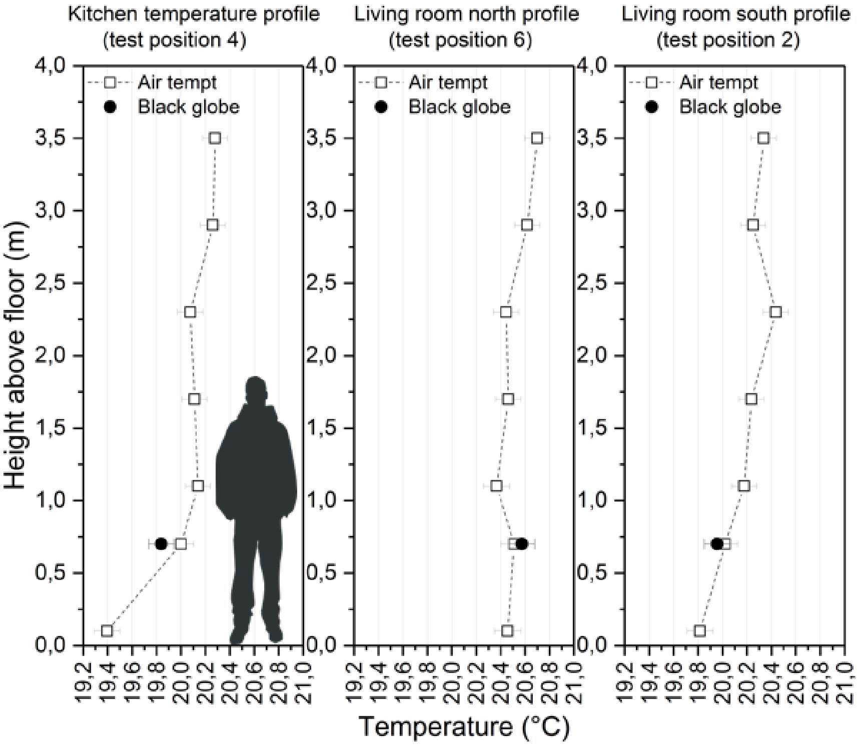


Figure 7.8 Vertical temperature stratification in the living rooms and kitchen for case 1.

7.3.2 Floor heating with bedroom set-point at 16 °C and internal doors closed (case 2)

According to the results presented before and the recent research [18, 19, 28], Norwegians tend to prefer cold bedrooms, which a temperature of 16 °C (or even lower). The possibility of temperature zoning (with living areas warmer than bedrooms) was therefore investigated with floor heating. Starting with the uniform temperature distribution of case 1, the time evolution of the air temperature is shown after a sudden decrease of the bedroom set-point temperature from 21 to 16°C, see Figure 7.9. The occupancy schedule is presented on the lower part of the figure. The set-points of the two bedrooms were changed at 9AM on the 6th of February (switch from case 1 to case 2). It took 38 hours for the bedroom temperature to decay and reach the new set-point. Meanwhile, the living areas remained at about 20 °C. This experiment clearly shows the slower dynamics of these super-insulated buildings. The dynamics of the building does not enable to heat up bedrooms during daytime and get low bedrooms temperatures during nighttime by only reducing the set-point temperature of bedrooms. The experiment was done when the outdoor temperature ranged between 0 and -8°C so that the slower reaction time cannot be explained by a mild outdoor temperature. In other words, with milder conditions, this temperature zoning is expected to take even longer to reach. Both Figures 7.9 and 7.10 show that after a sufficiently long period of time, a temperature difference of ~5°C was found between the living areas and the bedrooms. The air and mean radiant temperatures in Figure 7.10 are averaged over a 6-hour period (from 00AM to 06AM on the 9th of February 2017). This temperature difference is relatively larger than those found in other field measurements in this report. This could be explained by the fact that doors are constantly closed or constantly open. As for case 1, the stratification does not lead to local discomfort (figure not reported).

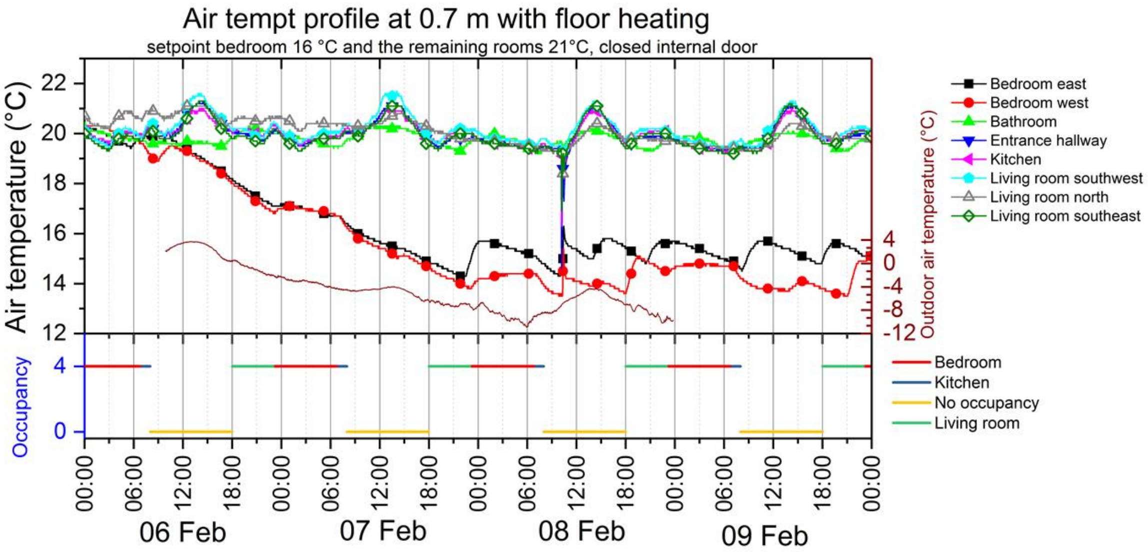


Figure 7.9 Indoor air temperature evolution after a sudden decrease of the bedroom set-point temperature from 21°C to 16 °C (case 2)

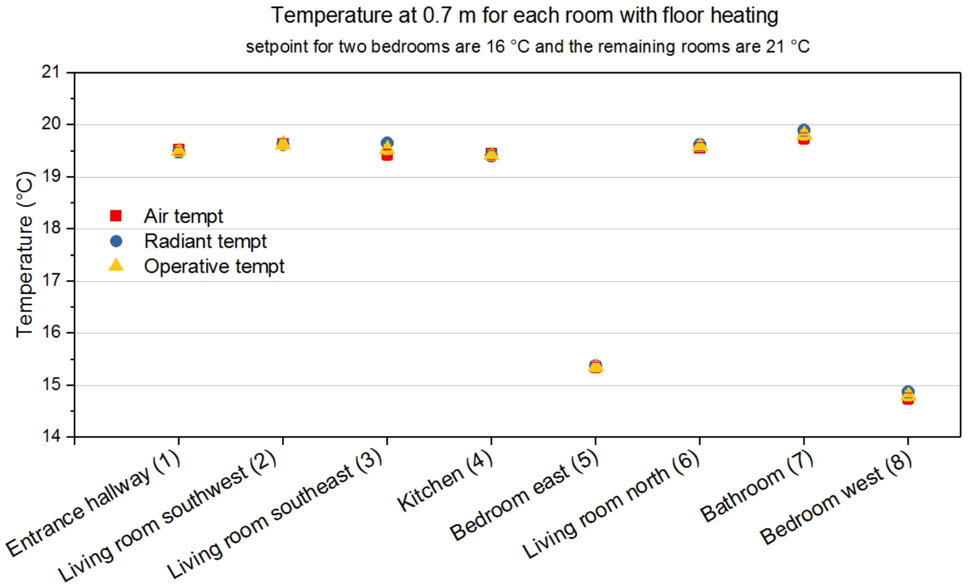


Figure 7.10 Temperature difference between rooms for non-uniform floor heating with internal door closed (case 2)

7.3.3 Radiator with set-point at 21 °C, no night setback, internal doors closed (case 3) and open (case 4)

The time profiles of the air temperature for each room with internal door closed and open are shown in Figures 7.11 and 7.12, respectively.

As for the floor heating cases, the building was heated uniformly as initial condition. The radiator heating with closed internal doors was then imposed suddenly. Compared to case 2, the outdoor temperature was milder during this experiment with the electric radiator. A bedroom temperature of about ~16°C was also reached but after a longer period of time than in the floor heating case (with colder outdoor temperatures). It took about four days to make this transition between 20°C and 16°C in bedrooms. It is clearly incompatible with the expectations of many users reported in Chapter 2. Some of them want daily time variations of the indoor temperature, with the possibility to quickly change the indoor temperature when they would like to. In the present building, if the bedroom had been heated up during daytime, it would have been impossible to have the bedroom cooled down to 16°C in the course of one night. In fact, the situation could be even more critical. The occupancy periods in bedrooms where dummies were activated is shown in red-shaded areas in Figure 7.11. During these periods, it is worth noticing that the indoor temperature increased 1 to 2°C due to these internal gains.

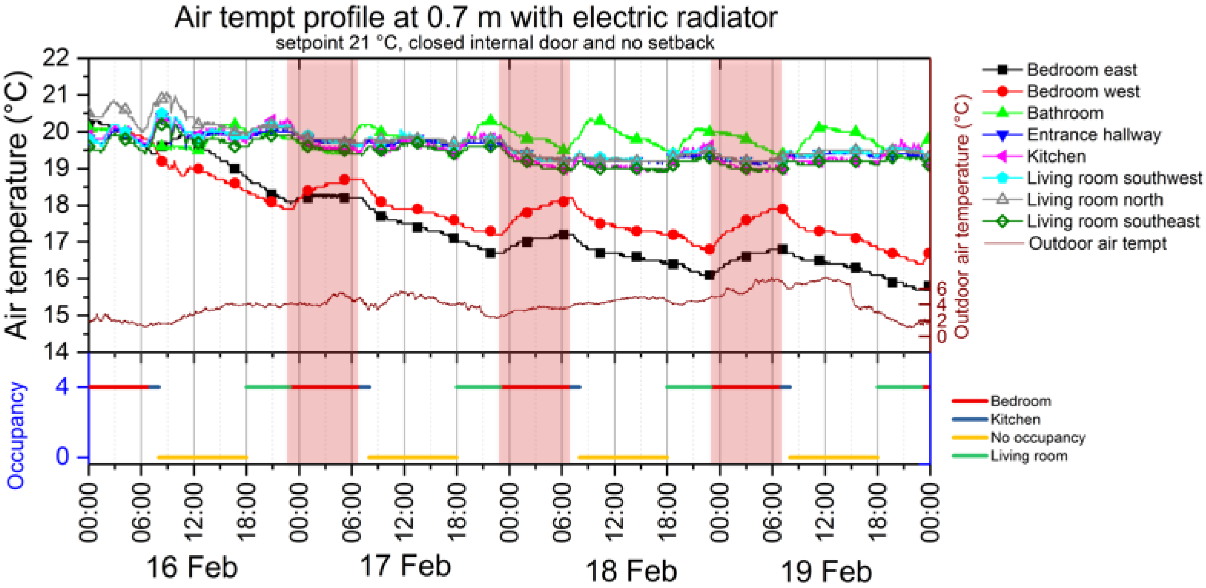


Figure 7.11 Starting from a uniform temperature distribution, indoor air temperature evolution for radiator with no night setback and internal doors closed (case 3).

Case 4 was directly applied after case 3, meaning that internal doors were suddenly open after a long period with thermal zoning with closed internal doors. Figures 7.12 illustrates the time evolution of the indoor air temperatures after opening the internal doors at 8 AM on the 20th of February. The air temperature in the two bedrooms rapidly increased to the temperatures of the north living room. Two conclusions can be given. Firstly, the increase of bedroom temperatures by opening the door was significantly quicker than the decrease of the bedroom temperatures by closing the doors. In case 4, a couple of hours were enough to heat up bedrooms. This is due to large bi-directional airflow in the open doorway that generates a significant heat transfer between rooms. In addition, the sliding doors of the Living Lab bedrooms are relatively large (more than 2 m), significantly larger than standard internal doors (about 1 m wide). For a given temperature difference between two rooms connected by a doorway, the heat transfer is proportional to the doorway width. Secondly, the resulting temperature difference between the north living room (also called studio) and bedrooms were less than 1°C. With a single heat source, it is possible to get a quasi-uniform temperature distribution inside the ZEB Living Lab. Again, natural convection inside the building (including through doorways) is a major process that creates this temperature homogeneity. Quite surprisingly, the temperature level reached was at about 19°C (not the expected set-point of 21°C). This can be explained by the placement of the radiator during experiments where the proximity of both heat emitters may have influenced their measure of the temperature and the resulting control of the thermostat. In other words, our assumption is that this placement of radiators created a local increase of the air temperature that disturbed the control. Alternatively, the total power of 1600 W may not have been enough to reach the set-point temperature of 21°C. This hypothesis looks less credible as the outdoor temperature was between 0 and -4°C during case 4. This is way above the design outdoor temperature (DOT) of -20°C where the building has a nominal space-heating power of 3 kW. Nevertheless, focusing on temperature differences between rooms rather than on their absolute values, these experiments remain meaningful.

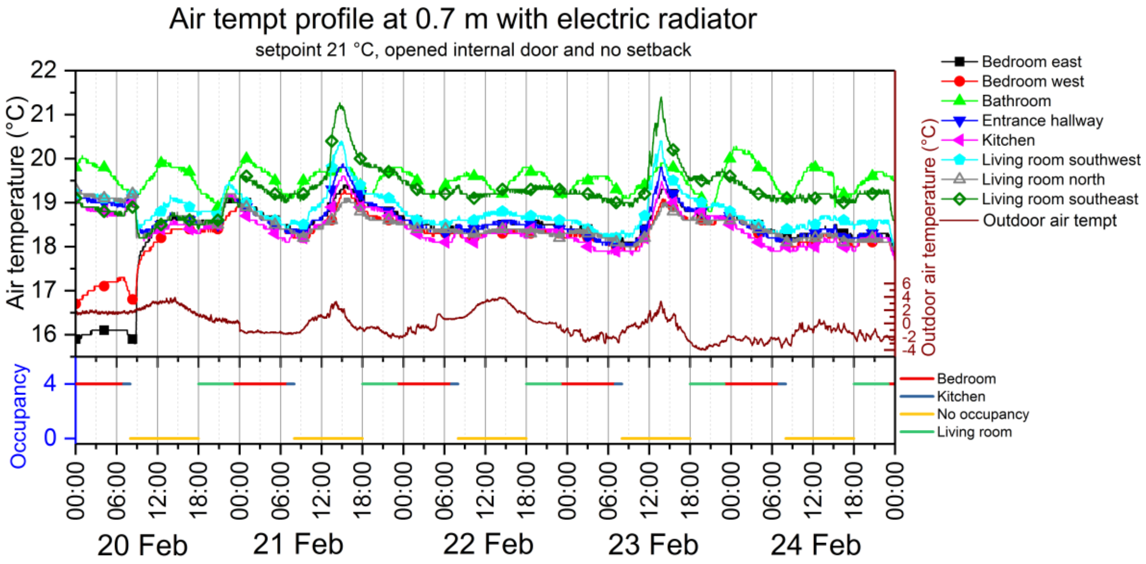


Figure 7.12 Air temperature evolution with open internal doors and no night setback (case 4).

The vertical temperature stratification for closed (case 3) and open (case 4) internal doors can be found in Figures 7.13 and 7.14, respectively, for the kitchen, north and south living rooms.

For case 3, the temperature profile has a similar shape as for the floor heating test. In general, the vertical temperature difference for radiator heating with door closed (case 3) had an average value of 1.4°C between the ankle (0.1 m) and heat level (1.7 m), which is slightly larger than using floor heating (cases 1 and 2). But this temperature difference is still acceptable for local thermal comfort.

For case 4, the maximum temperature difference between ankle and head level was 2.1°C in the kitchen. The corresponding percentage of dissatisfaction for the case 4 is 1.9 % according to ISO 7730 [52]. Unlike case 3, case 4 exhibits an unexpected temperature decrease 3.5 m above the floor in the south and north living rooms, as shown in Figure 7.14. The reason for this phenomenon is unclear. For case 4, the average temperature difference between 0.1 m and 1.7 m in these three rooms was 1.6 °C. Again, the vertical temperature difference is acceptable regarding the local thermal comfort.

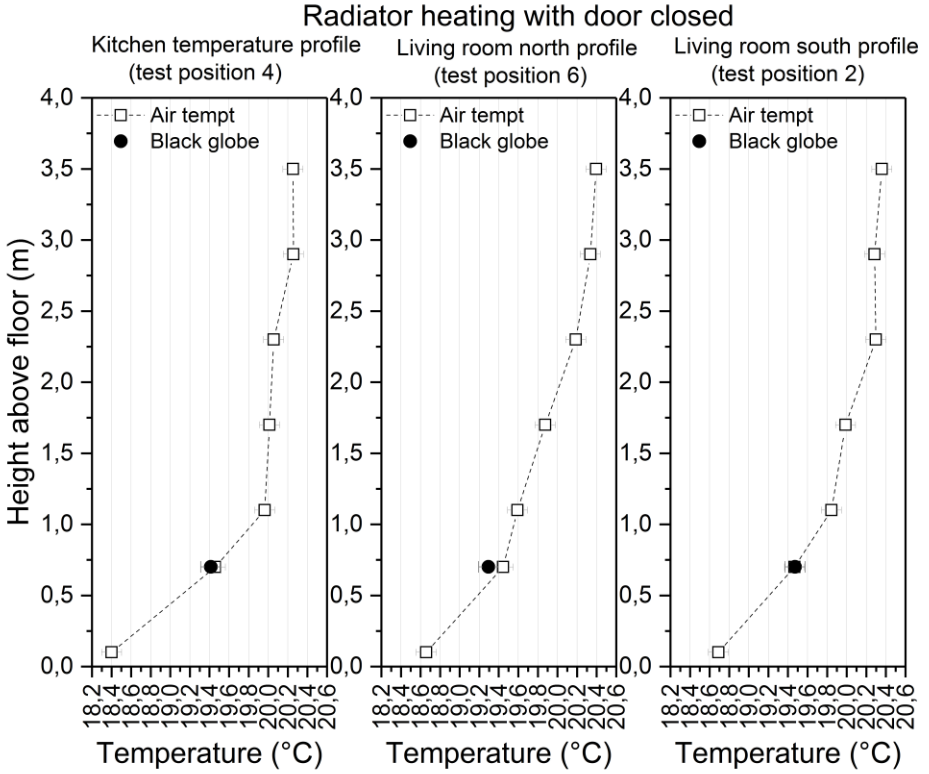


Figure 7.13 Vertical temperature stratification for radiator heating with door closed (case 3)

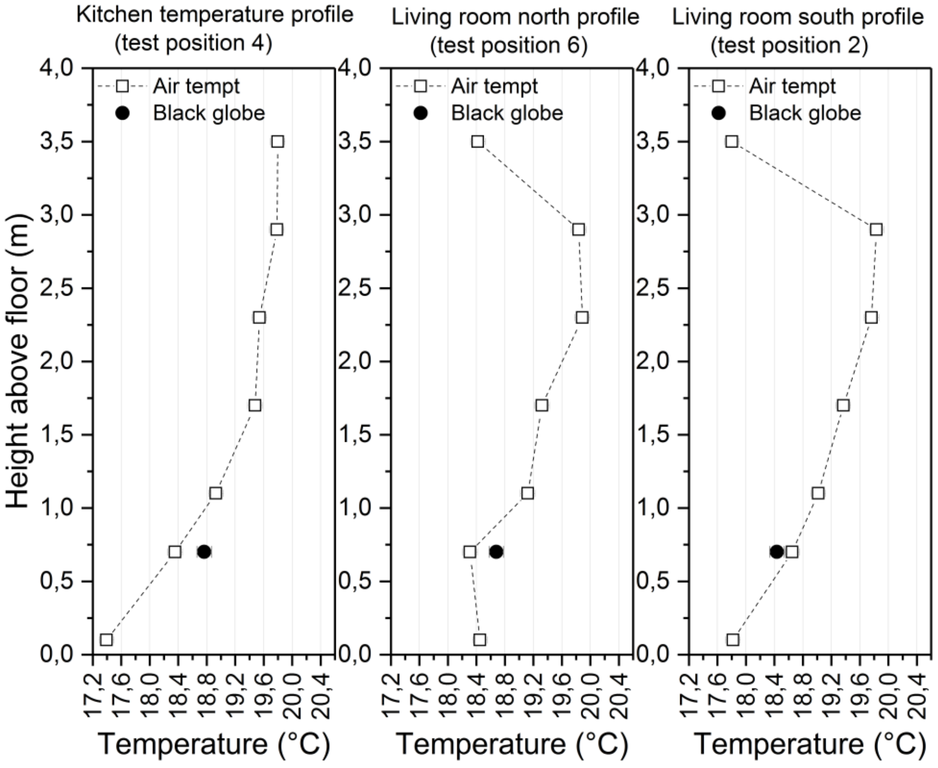


Figure 7.14 Vertical temperature stratification for radiator heating with open doors (case 4)

7.3.4 Radiator heating with night setback, open (case 5) and closed doors (case 6)

To further investigate the influence of the radiator control on thermal comfort, the radiator was switched off during nighttime (23:00-07:00). The set-point of the radiator (Tset,SH) was still at 21 °C during daytime. This intermittent temperature control is termed “night setback” in this study. This strategy enabled to check whether it is possible to generate colder bedrooms during nighttime in super-insulated Living Lab without having to open bedroom windows (which would lead to a significant increase of the space-heating needs).

Figure 7.15 shows the time evolution of the indoor air temperature for the case 5. The night setback period is marked as the grey-shaded regions. At 14:30 on the 20th of March, the bedroom doors were closed (i.e. start of case 6) and one can observe the resulting temperature decrease in bedroom from that time. Generally, the air temperature in case 5 was very similar in all rooms, but presents a sinusoidal evolution. This experiment has been performed later during the space-heating season, when solar gains started to be important and the outdoor temperature to be milder. It can be seen in Figure 7.15 that south facing rooms had higher temperature than north facing ones during daytime, especially in the early afternoon. This additional contribution of solar gain makes the direct comparison with constant heating difficult (case 4). Let’s also mention that the installed heating power was limited to 1600 W which is a modest value to perform intermittent heating (i.e. to reload the thermal mass quickly). It took several hours (despite the contribution of solar gains) to reheat the building to ~19°C (which was the indoor temperature obtained with the corresponding test case with constant heating, case 4). It is well-known that the power needed to perform intermittent space-heating is relatively more important in super-insulated building envelopes. These measurement results were thus expected.

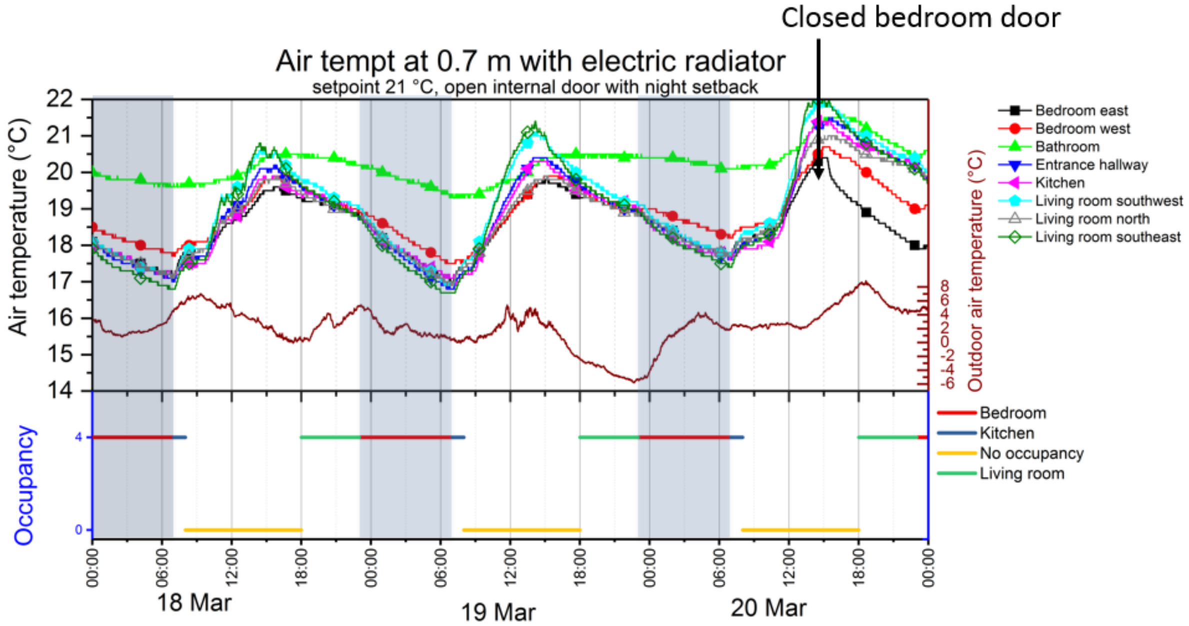


Figure 7.15 Indoor air temperature evolution for the radiator using night setback and open bedroom doors (case 5)

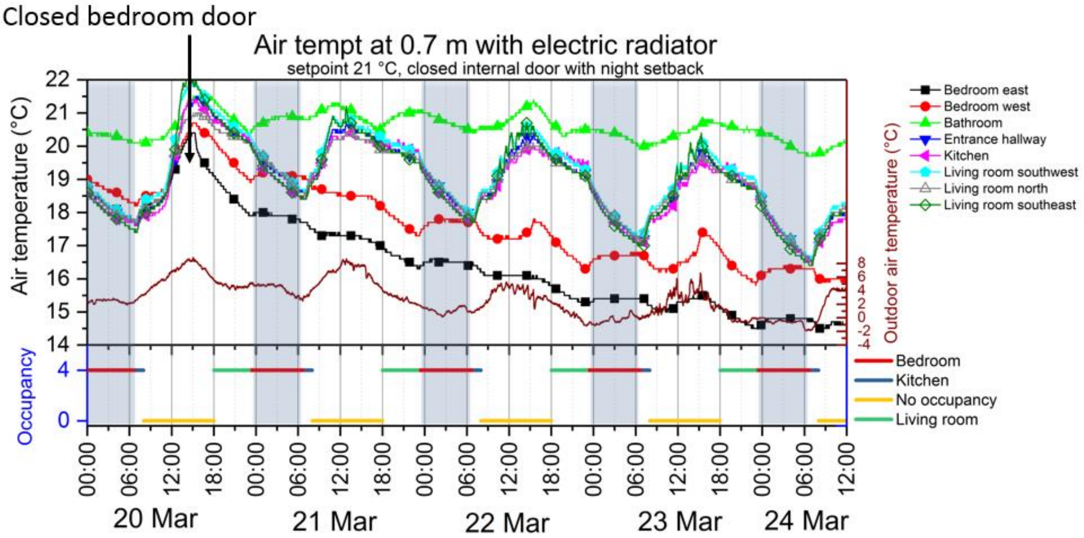


Figure 7.16 Indoor air temperature evolution for the radiator with night setback and closed bedroom doors (case 6)

Case 6 investigated if an intermittent heating applied in living areas may further improve the thermal zoning generated by closed doors, compared to the baseline strategy of constant heating (case 3). Results suggest that bedroom temperatures did not decrease quicker with intermittent heating (Figure 7.16) in living areas than using constant heating (shown in Figure 7.11). Both cases have been investigated with an outdoor temperature fluctuating between 0 and 4°C. Starting from a uniform temperature distribution (case 5), it took several days (about 3-4 days) after the door closing for the bedroom temperature to reach ~16°C. Again, this temperature decrease is still not fast enough to generate cold bedrooms in the range of 16°C without window opening and within one day. This is in line with conclusions from Chapter 4 and 5 using detailed dynamic simulations: reducing the set-point temperature of the living areas during nighttime does not improve the thermal zoning significantly.

7.4 Conclusions

Six experiments have been performed in the ZEB Living Lab using floor heating or a punctual heat source (here two electric radiators). All cases have been run using synthetic internal gains, leaving user behavior outside the scope. Some main conclusions resulting from these experiments can be given:

1. With internal doors open, the temperature inside the Living Lab was (quasi-)uniform, even using a single heat source (i.e. the radiator). The mean radiant temperature was also very similar to the air temperature in each room. This temperature uniformity between rooms has been amplified in the ZEB Living Lab by the size of the sliding doors between the bedrooms and the studio. They are indeed very wide (more than 2 m wide). From these experiments, it is not proved that the temperature mixing would be as effective in a building with traditional door sizes (about 1 m wide).
2. Closing internal doors, it was possible to create a temperature zoning between the living areas of the ZEB Living Lab and its bedrooms. A temperature difference of 4-5°C has been measured which is significantly larger than field measurements in apartments and row houses of Chapter 3, or values frequently reported in the literature (about 1-2°C degrees). The reason for this difference has not been investigated in detail. It could be explained by the building typology of a one-level detached house, where bedrooms are relatively more exposed to external walls than a more compact geometry of row house, or apartment building. Doors are open or closed constantly which also significantly differs from real operation with occupants. In the ZEB Living Lab, it is thus in theory possible to have living areas at 21°C with bedrooms at 16°C without window opening.

3. Nevertheless, the main merit of these experiments was to clearly show the slower thermal dynamics of super-insulated buildings. With closed internal doors, it took several days (2 to 4 days) to decrease the bedroom temperature from 21 to 16°C. This is not compatible with the requirements of some users (see Chapter **Error! Reference source not found.**) that would like to quickly change the indoor temperature in the course of one day. For instance, if a bedroom had been heated at 21°C during daytime, its temperature would never decrease “naturally” to 16°C in the course of one night (without opening the bedroom windows). On the contrary, internal gains from occupants may even increase the bedroom temperature during nighttime. This conclusion has nothing to do with the space-heating simplification concept. It is rather defined by the physics of super-insulated building envelopes with one-zone mechanical ventilation with heat recovery. This slower dynamics has indeed been found for both floor heating and the simplified distribution using one radiator.
4. Applying an intermittent heating in living areas (meaning switch-off of the heating system in the living room during nighttime) did not improve thermal zoning. It did not significantly accelerate the temperature decrease in bedrooms. This result is confirmed by detailed dynamic simulations in Chapters 4 and 5.
5. The temperature stratification has been measured in living areas. This stratification was limited. It was an expected result for floor heating but it had to be proved for the radiator case. No local discomfort due to stratification was reported according to the limits of ISO 7730 [52].

8. Overall conclusions

This chapter combines results from the different works reported from Chapter 2 to 7 in order to answer the research questions introduced in Chapter 1 (section 1.2) in a pragmatic way that aims to give guidelines to practitioners. Conclusions are distinguished between results that are inherent to the simplification of the space-heating distribution (and that would not be found using standard heat distribution systems, such as floor heating), and results that are specific to super-insulated building envelopes (and that would be found for any space-heating distribution). In the present work, the case of a simplified space-heating distribution using one radiator per floor with (pre-)heating of the ventilation air and floor heating in the bathroom is considered. The case with less than one heat emitter per floor is not covered in this study (for instance, one wood stove for the entire building). In all investigated cases, the building is equipped with balanced mechanical ventilation using one centralized heat recovery and one set-point temperature for the ventilation supply air.

8.1 What are the resulting temperature differences between heated and non-heated rooms found during real operation?

The temperature in non-heated rooms, typically bedrooms, cannot be easily predicted due to the complex heat balance in the building and the influence of the user behaviour. Results should distinguish between closed and open internal doors, closed and open bedroom windows.

In Chapter 3, short-term measurements of two weeks in Miljøbyen Granåsen during a relatively mild period showed:

- With closed internal doors and closed bedroom windows, we have not reported cases with a bedroom temperature colder than ~2°C than the heated living areas.
- With open internal doors and bedroom windows closed, we have reported typical temperature differences of ~1°C between heated living areas and non-heated bedrooms. This value can change momentarily with the presence of important solar gains.
- With internal doors mostly closed and bedroom windows opened over an extended period, the typically measured temperature difference was of ~5°C. Opening the bedroom windows enables temperature zoning as long as the doors are closed.

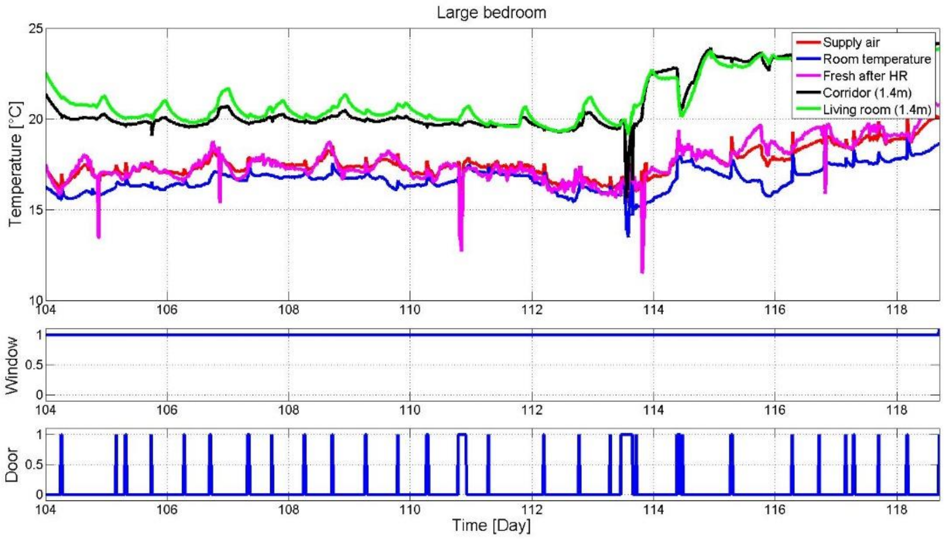


Figure 3.12 Measured temperatures in bedroom 1 (room air and supply ventilation air) and adjacent rooms in Apartment 2.

In Chapters 4 and 5, calibrated detailed dynamic simulations (here multi-zone simulations using IDA-ICE) enabled to investigate the temperature differences between rooms over the entire space-heating season. In fact, the temperature differences between the heated living areas and non-heated bedrooms increase with decreasing outdoor temperatures. Temperature differences between rooms should not be considered as constant values. Simulations showed (see for example Figure 4.6):

- With a supplied air temperature of ~20°C, with closed internal doors and closed bedroom windows, the bedroom temperature never reaches the temperature range of 16°C (or lower), even during the coldest day of the winter (see baseline curve in Figure 4.6).
- With internal doors mostly closed and bedroom windows opened during several hours every day, it is indeed possible to reach the range of 16°C (and lower), even during the milder period of the winter (see Control 4 curve in Figure 4.6). Again, opening the window is an effective way to create temperature zoning (but not energy efficient as it has been explained).
- With internal doors open during daytime to heat up the bedroom and closed during night-time along with open windows to decrease bedroom temperatures, it takes several hours for the bedroom temperature to reach a new "regime". For example, in the case of the apartment, the window opening during one night is not long enough to bring the bedroom temperature back from ~20°C to ~16°C (see Control 4b curve in Figure 4.6).

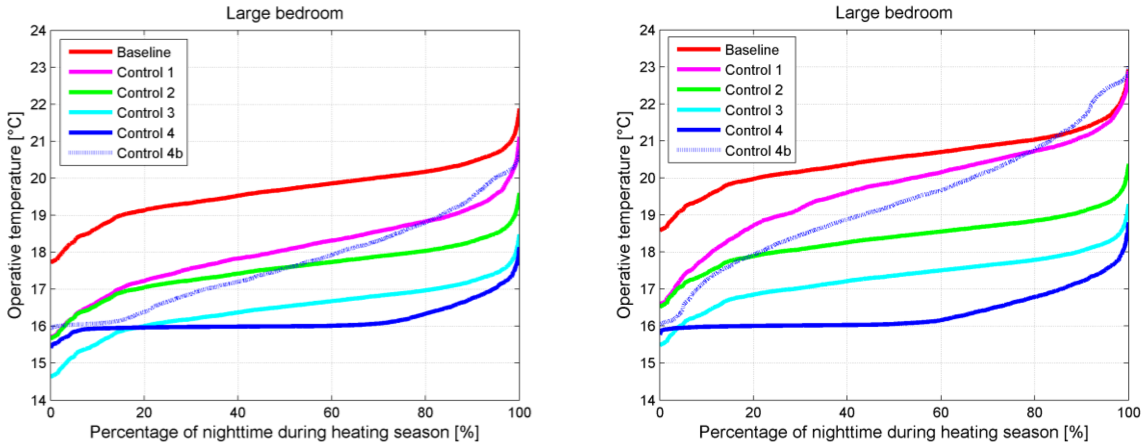


Figure 4.6 Simulated duration curve for the bedroom operative temperature (during nighttime and the heating season) for a flat in Miljøbyen Granåsen: case with a corridor constant set-point temperature Tset,SH of 21°C (left) and 24°C (right).

8.2 How to get warm bedrooms?

If occupants would like warm bedrooms (such as 21°C), closing internal doors does not create large temperature differences between bedrooms and heated areas. Their opening turned out to be an efficient way to reduce these temperature differences. In addition, the user may slightly increase the supply air temperature as a way to increase bedroom temperatures (as the supply ventilation air will be directly supplied in bedrooms). Interviews in Chapters 2 and 3 have not reported complaints about bedrooms that are experienced as too cold, mostly the contrary. Also, we have not measured in bedrooms a temperature lower than the expected temperature from users. It is confirmed by the work of Berge et al. [18, 19]. In addition, it is also not astonishing to read that these authors reported a very limited number of occupants that would have liked a local heat emitter in bedrooms.

In conclusion, it is very difficult to give a definitive answer, but results showed that the risk of cold bedrooms with simplified distribution, or complains to get a local heat emitter in bedrooms, are in practice very limited. Nevertheless, from a theoretical point of view, there is a loss of flexibility when removing heat emitters in each bedroom. Firstly, a local heater is most probably needed to reheat the bedrooms quickly after a period with low indoor temperatures. Secondly, if users increase the supply ventilation air temperature to get some bedrooms warm, it will make even more complicated to get cold temperatures in the other bedrooms (e.g. some bedrooms used as an office, recreation room, or living area, and some other bedrooms used as sleeping rooms).

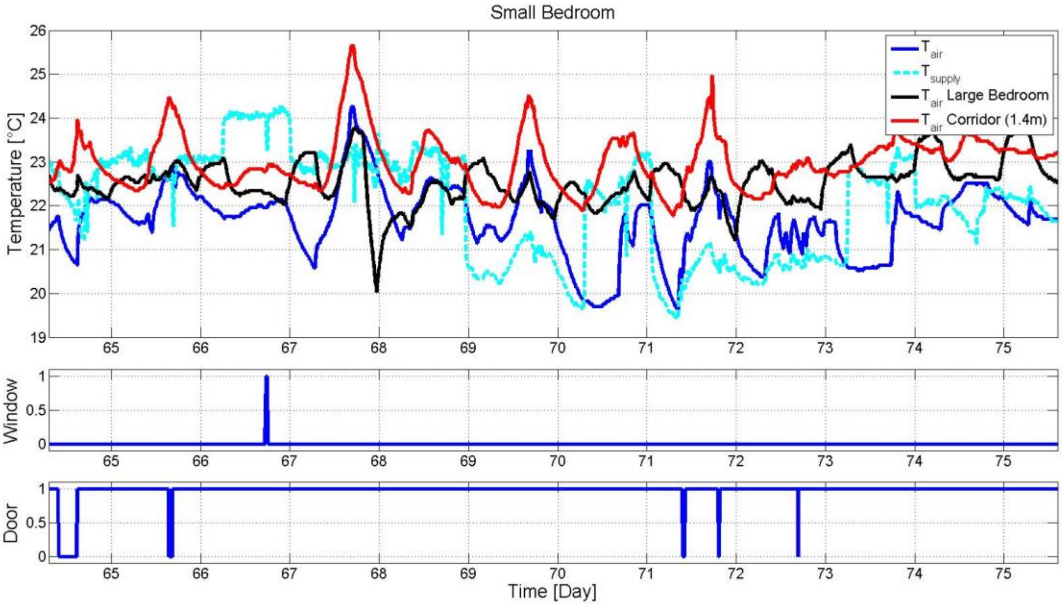


Figure 3.18 Measured air temperatures, door and windows status of the small bedroom 1 in House 1: with open door, the air temperature difference between the non-heated north-facing bedroom (blue) and the heated corridor (red) is limited to 1-2°C.

8.3 How to get cold bedrooms?

Berge *et al*. [18, 19] already pointed out that many occupants would like cold bedrooms with indoor temperatures of ~16°C or even lower. This is not proven for all countries in Europe but at least in Norway. This expectation for a cold bedroom is confirmed in the present project in interviews and measurements. Measurements and simulations have shown that it is difficult to create large temperature differences between the heated living areas and the bedrooms by only closing internal doors and keeping bedroom windows closed. This temperature difference is even more limited with mild outdoor temperatures than during the coldest periods of the winter. This question is in fact not inherent to the space-heating simplification and can be found for any heat emission system. For instance, it was here shown in the ZEB Living Lab (Chapter 7) where many occupants have turned off the floor heating in bedrooms and still experienced them as too warm.

From a physical point of view, it is therefore not surprising that occupants regulate the bedroom temperature using window opening. Berge *et al*. have indeed shown that many occupants open in average the bedroom window several hours every day during winter time. The main motivation reported for window opening is temperature control rather than the indoor air quality (IAQ). This way to regulate bedroom temperature is confirmed in the present measurements combined with interviews in Miljøbyen Granåsen (where all window openings have been recorded).

In the case of apartments in Miljøbyen Granåsen, the radiator has been placed in a central position in the floor plan (i.e. the corridor), probably to ensure a good distribution of heat in the entire building. In fact, as getting warm bedrooms is not the challenge but rather to get cold bedrooms, this radiator could have been placed directly in the living room, the further away from bedrooms.

8.3.1 Can we get cold bedrooms without window opening by a proper control?

It is confirmed with measurements that building users do not always coherently operate the building to reach the desired indoor temperature. Typically, they keep the set-point temperature for the supply ventilation air high even if they would like cold bedrooms. The legitimate question is to check if a proper control of the heating and ventilation system could lead to low bedrooms temperatures (~16°C) without intensive window openings. This improvement can be made by reducing the set-point temperature for the supply ventilation air at the cost of a reduction of the energy recovered, or by applying a night temperature setback in the living room (i.e. intermittent heating):

- The *night temperature setback* is not an effective way to decrease the bedroom temperature. It indeed helps but does not change the level in bedroom temperatures sufficiently. This has been investigated using detailed dynamic simulation in Chapters 4 and 5 as well as in measurements of the ZEB Living Lab in Chapter 7.
- Simulations in Chapters 4 and 5 showed that *decreasing the set-point temperature for the supply ventilation air* is much more efficient to lower bedroom temperatures. Limiting this temperature to 16°C gives cold bedrooms in the coldest period of winter. Reducing this temperature to 14°C would give cold bedroom temperature during almost all the space-heating season. Current air handling unit (AHU) may not allow setting such a low set-point temperature. Following standards for thermal comfort, a supply temperature of ~14°C is likely to generate a thermal discomfort due to cold draft [52]. Nevertheless, in practice, it should not be worse than opening windows, and many occupants do not consider this as a problem. Nevertheless, it is not proven that decreasing the set-point temperature for the supply ventilation air to ~14°C will not impact the thermal comfort in the heated living areas. Consequently, with such a lower temperature for supply ventilation air, there is a risk of local discomfort in the heating living room that should be investigated. Detailed dynamic simulations cannot capture such phenomena. This method should then be validated using computational fluid dynamics (CFD) or measurements.

8.3.2 What is the increase of the space-needs induced by window opening or a reduction of the set-point temperature of the supply ventilation air?

This aspect is investigated in Chapters 4 and 5 using detailed dynamic simulation (assuming the user behaviour known). Using a set-point temperature for supply ventilation air of ~20°C and closed windows, the space-heating needs are close to the values expected for passive houses (in the range of 15 kWh/m².year). Opening windows every night to keep the bedroom temperature at 16°C would lead to a significant increase in the space-heating needs (roughly 60-80%). These results suggest that opening windows to regulate bedroom temperature is not acceptable as it impacts space-heating needs and then the concept of passive house too strongly. A solution has to be found.

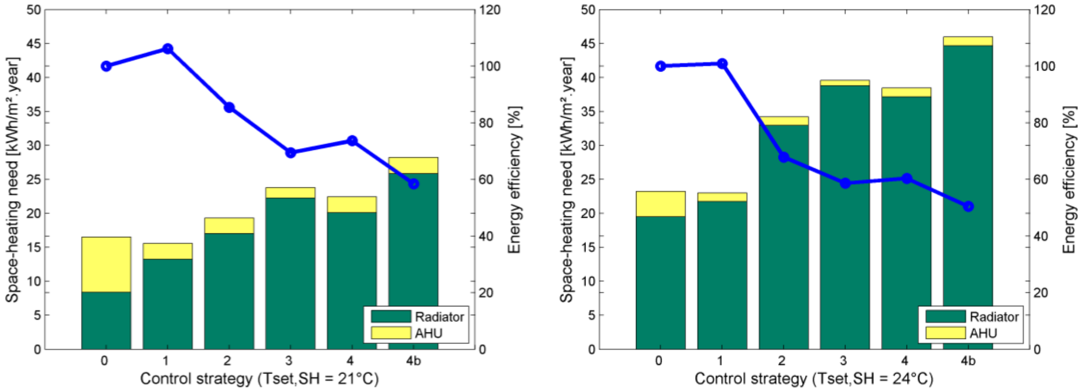


Figure 4.5 Simulated yearly net space-heating needs for five control strategies and a living room set-point temperature (Tset,SH) of 21°C and 24°C in the Miljøbyen Granåsen flat: baseline case is case "0", opening windows are cases "4" and "4b", reducing the heat recovery efficiency correspond to cases "2" and "3".

Measurements of energy use for space heating and window opening in many similar buildings during an entire space-heating season would be a better and more definitive demonstration than the present simulations.

Reducing the set-point for the supply ventilation air to 14°C is an alternative, but simulations show that the resulting space-heating needs would also increase significantly. In the present investigations, these energy needs are comparable to the strategy using window opening. It cannot be seen as an improvement. Therefore, more research is required to find a conclusion for this question.

8.3.3 Is there energy efficient ways to control the building to create temperature zoning, or more drastic technical measures should be taken?

From our investigations using simulations, improved control strategies seem not satisfactory to reach cold bedrooms (with 16°C or lower). This work suggests that the solution is not just a question of control of the building. To get low temperature in bedrooms, it rather requires for a change of the building concept in itself. In other words, the idea of super-insulated building with high-performance centralized balanced mechanical ventilation with a heat recovery unit and a single air supply temperature does not provide enough flexibility to users to create different temperature zones inside the building envelope.

For instance, Berge *et al.* [28] investigated a change of ventilation strategy by applying a ventilation system with different supply temperatures in living areas and bedrooms. Other ventilation strategies could be investigated, or some part of the current ventilation concept reconsidered, such as the concept of *cascade ventilation*. Measures could be taken on the building envelope as well, typically by increasing the insulation of partition walls. In fact, the buildings investigated are lightweight, and their partition walls are already insulated with thermal insulation material but, mostly, for acoustic reasons (using typically 5 to 10 cm of mineral wool). Preliminary results using simulations suggest that adding more insulation would not improve the situation a lot, most of the effect is already performed by the first centimetres of insulation in the partition walls. A buffer zone with an intermediate temperature level could also be created in the building. Nevertheless, it remains to be proved that users would accept such a temperature level and, if not, that users are ready to sacrifice a part of the living area in their building for this purpose (knowing that the real estate price per m² is particularly high in Norway). Therefore, adaptations of the ventilation concept look a more promising way to create temperature zoning and keep energy efficiency high.

An aspect that has not been investigated in detail is the user adaptation. With relatively warm bedrooms (>18°C), users may need to change their habits or expectations. In other words, instead of changing the building concept, it is rather the occupants that have to adapt to this new environment. This aspect was beyond the scope of our research and would require different research methods to be investigated properly. For instance, it would be important to check the optimal indoor temperature for sleeping from a medical point of view.

8.4 Is the thermal environment in heated living areas comfortable?

This question may look irrelevant at first sight. If the room is equipped with a radiator and, a fortiori, in a super-insulated building, is there any reason to experience discomfort? Is there any difference with a traditional space-heating distribution with heat emitter(s) in each room? The answer is “yes”, with a simplified space-heating distribution, only one single heat emitter is installed in one or several rooms.

In the case of Miljøbyen Granåsen, one radiator is placed in the corridor in the case of apartments. For the terraced houses, one radiator is placed in the hallway close to bedrooms and one in the living room (or, alternatively, in the basement). In each case, the air temperature at two opposite horizontal locations inside the living room has been measured along with the vertical temperature stratification. In each case, the horizontal temperature distribution is rather uniform with limited temperature stratification. Some exceptions were found in apartments, but it was most probably due to an initial default in the building construction leading to significant infiltrations. In the case of the ZEB Living Lab, a single radiator provides for heat for two separated and large living areas. Measurements showed a uniform temperature distribution between the rooms with limited stratification.

To recap, we investigated several configurations (i.e. one radiator in corridor connected to living room and kitchen, one radiator in living room connected to corridor and kitchen, one radiator in the middle of two living rooms and even the case of one radiator in the basement connected to the living room by an open staircase) and measurements showed a comfortable thermal environment. These measurements are supported by interviews and confirm a comfortable thermal environment in living areas (again, except for one apartment in Miljøbyen Granåsen). The work of Berge *et al.* [18, 19] also showed a high degree of satisfaction with the thermal comfort and the heating system in the living areas. In conclusion, it is again very difficult to give a definitive answer, but results showed that the risk of thermal discomfort in the living areas is in practice very limited.

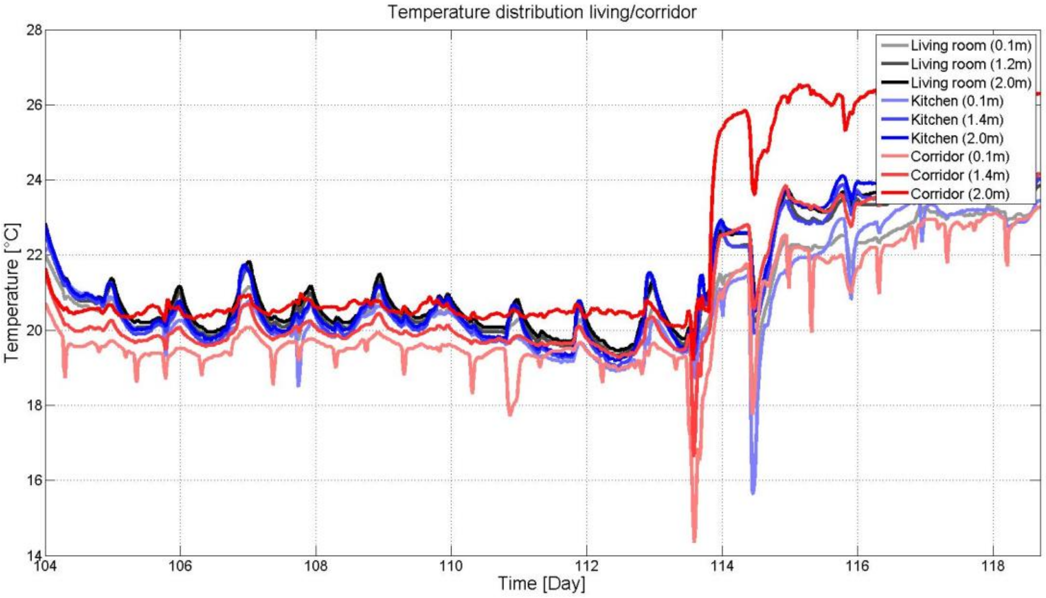


Figure 3.14 Measured stratification temperatures in living room, kitchen and corridor of Apartment 2.

The present work also confirmed that the expected and applied indoor temperature in living rooms is ~22-24°C. In addition, interviews in Chapter 2 showed that thermal comfort was considered as more important than energy savings by many occupants.

8.5 Is the building enough "*responsive*" in a change of set-point temperature?

Super-insulated buildings are per definition better energy storages than older less insulated buildings: it takes more time for the indoor temperature to decrease when the space-heating is stopped. It is translated in technical terms by a longer time constant for such super-insulated buildings [32].

If a night temperature setback is applied, additional space-heating power is needed to reheat the building in the morning from the lower night-time temperature to the higher daytime temperature within a reasonable period (typically a few hours). The building thermal mass mainly dictates the magnitude of this additional power. This quantity is not expected to change a lot with increasing insulation levels. Nevertheless, with increasing insulation levels, this additional power for intermittent space-heating becomes more and more important compared to the space-heating power needed to keep a constant indoor temperature. For super-insulated buildings, the magnitude of both powers is comparable leading to a risk of power oversizing which is technically not desirable. This explains why intermittent space-heating is most often not promoted in super-insulated buildings. In addition, energy savings resulting from intermittent space-heating are also more limited in such buildings.

Combining both effects, super-insulated buildings are physically less responsive than traditional less insulated buildings to a change of set-point temperature. It has nothing to do with the simplified space-heating distribution but inherent to the super-insulation concept:

- Interviews in Chapter 2 aimed to highlight how the previous experience from occupants influences their behaviour when they move in super-insulated buildings. Some occupants reported that they would like to change the indoor temperature in the course of a day or to be able to quickly increase the indoor temperature after a colder period if they would like to. It was not possible to do so in the ZEB Living Lab, and this was experienced as negative.
- Responsiveness has not been pointed out as a problem in the detailed measurements and interviews in Miljøbyen Granåsen. Measurements showed that users seldom changed the set-point temperatures for radiators or the supply ventilation air (most often no change in the course of the two weeks of measurements). This aspect has not been reported by Berge *et al.* [18, 19] either.
- In Chapter 7, detailed measurements in the ZEB Living Lab without occupants (but with artificial internal gains according to NS3700 [2]) enabled to analyse the building physics in more detail. Experiments showed that it takes between 2 to 5 days (depending on the outdoor temperature) for the bedroom temperature to move from ~20°C to ~16°C. The time constant is long even though the building is constructed of lightweight materials.

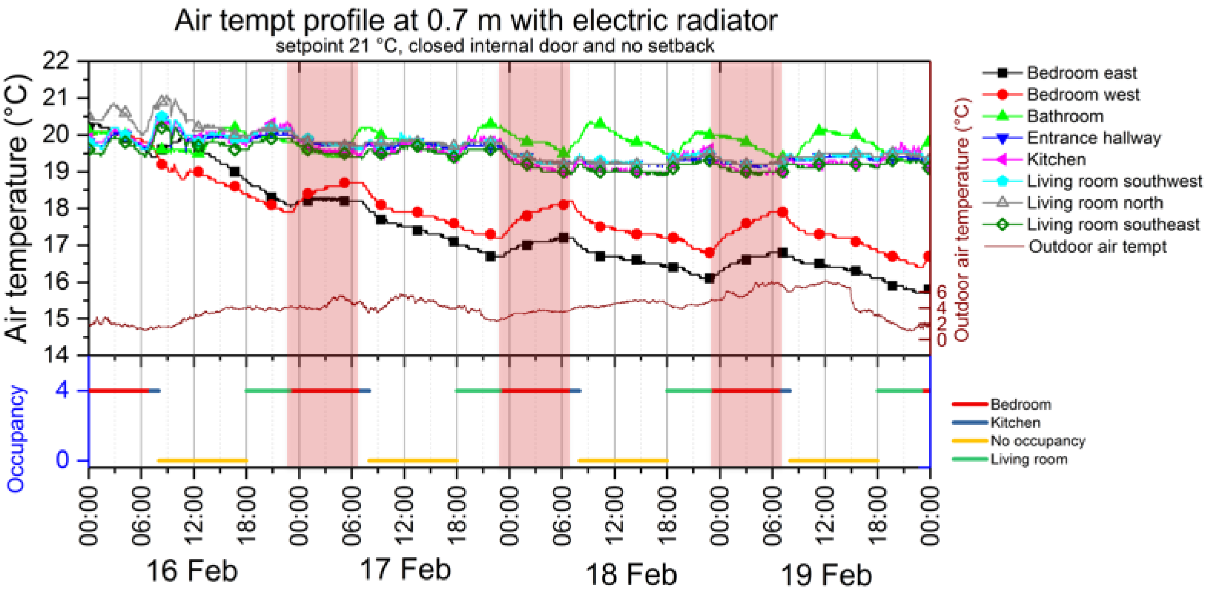


Figure 7.11 Starting from a uniform temperature distribution, measured indoor air temperature evolution in the ZEB Living Lab heated by one radiator after a sudden closing of internal doors.

In conclusion, further research is needed in this area. The responsiveness is not directly linked the simplification of the space-heating distribution. It rather questions the concept of super-insulated buildings. Without more evidence, this problem should a priori not be underestimated as interviews showed that occupants want to be in control of their thermal environment and consider it as important.

8.6 Does the simplification of the space-heating distribution increase the energy efficiency compared to a traditional distribution in each room?

The simplification of the space-heating distribution has been originally proposed in passive houses to reduce the investment costs for high-performance buildings. Could it be other technical reasons for reducing the number of heat emitters inside the building?

Using a standard distribution with at least one heat emitter in each room, the pipework is relatively longer than using a simplified distribution. When the building is super-insulated, thermal losses from these pipes are not small anymore compared to the heat emitted by radiators so that the energy efficiency of the space-heating distribution may be impacted. At the same time, super-insulated buildings are better heat storages than traditional less insulated buildings. So, if heat is emitted in an uncontrolled way by pipes inside the building envelope, the fraction that is usefully recovered for the space-heating is higher in these super-insulated buildings [32]. In other words, thermal losses from pipes are relatively more important in super-insulated buildings, but they are better recovered to cover the space-heating needs. Consequently, the resulting distribution efficiency is unknown and cannot be estimated easily (as it is again a complex physical problem where the thermal dynamics should be investigated in detail). As the simplified distribution has less pipework than the standard one, could this simplification be a way to limit these losses and ensure the energy efficiency of the distribution?

This aspect has been investigated in Chapter 6 using dynamic simulations with a detailed modelling of the heat distribution system. A row house of Miljøbyen Granåsen has been considered as a test case with exposed pipes (meaning pipes not embedded in walls).

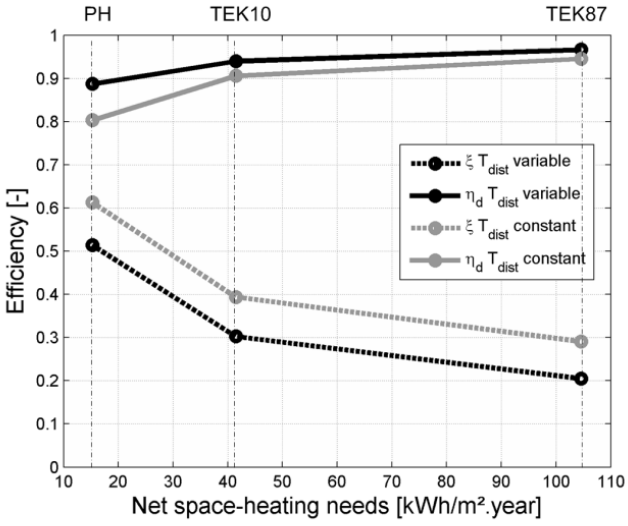


Figure 6.9 Simulated yearly performance of the 60°C/40°C standard distribution loop without pipe insulation for three building insulation levels, with (black line) and without (grey line) weather-compensated heating curve: ξ is the fraction of the heat emitted by pipes, η_d is the resulting distribution energy efficiency.

It gave the following result for standard loops (see Figure 6.9). If a standard distribution loop is installed in the passive house, the fraction of heat emitted by pipes compared the heat delivered to the distribution system is large (ξ in graph). For a loop with non-insulated pipes and dimensioned at 60°/40°C using a weather-compensation heating curve, up to 50% of the heat is delivered by the pipes and the other 50% by the radiators. Even though these losses are substantial, the resulting yearly distribution efficiency remains high, typically ~90% (η_d in graph). This number is not prohibitive. If pipes are insulated, or the temperature level decreased, this efficiency can be improved. On the contrary, one can see that the distribution efficiency is more affected in the passive house building than in less insulated buildings if a weather-compensated heating curve is not applied (see grey curve with constant water temperature). In conclusion, the influence of distribution thermal losses are also limited in the passive house if state-of-the-art technics are applied (i.e. weather compensation curve, low distribution temperature).

The case of the simplified distribution should be discussed more carefully. One should distinguish between a simplified distribution where most of the pipes cross heated zones and where most of the pipes cross non-heated zones (meaning bedrooms or the technical room). One should also distinguish between desired temperatures in bedrooms: cold (16°C or lower) or temperature taken equivalent to other heated living areas (~21°C).

- If cold bedrooms are desired, the temperature increase in these rooms resulting from pipe thermal losses does not provide for any additional comfort, quite the opposite. The simplified loop with pipes mostly crossing non-heated areas does not significantly perform better than the standard loop. On the contrary, the simplified loop with pipes only crossing heating areas reaches a better efficiency (99%), both with high and low water distribution temperatures (60°C/40°C and 40°C/30°C, respectively) and with and without pipe insulation. Depending on the scenario, up to ~1 kWh/m².year can be saved compared to the standard loop.
- If warm bedrooms are desired, the temperature in the neighbouring heated zone should be increased slightly above its set-point temperature to reach high enough temperatures in bedrooms. In that case, the simplified distribution can use up to ~1 kWh/m².year more than the standard distribution.

In conclusion, simulation results show that simplified distribution does not necessarily lead to higher energy efficiency than a standard distribution loop. If cold bedrooms are desired, the simplified distribution is more energy efficient especially if pipes are mostly located in heated zones equipped with a radiator. The magnitude of the energy use is about 1 kWh/m².year lower than using standard distribution. This value is not significant compared to the other sources of inefficiencies in super-insulated buildings. User behaviour can impact the energy use for space-heating for more than ~5kWh/m².year, for instance by window opening. The present work suggests that the question of the energy efficiency of the hydronic space-heating distribution in super-insulated buildings is a secondary problem. The main motivation for simplifying the space-heating remains to be the investment costs. Further research is needed, especially to validate these results against experiments.

8.7 Do the building users have a good understanding of the way they should operate the building?

Berge *et al*. [18, 19] already showed that users do not operate the building coherently to reach the desired indoor thermal environment. For example, 65% of the respondents in [19] who keep the bedroom window open all night (or all day) have pre-set the supply air temperature to a level which requires post-heating during a large portion of the winter season. This is confirmed in the present measurements that some users have high set-point temperatures for the supply ventilation air even though they would like cold bedrooms. Nevertheless, the reasons for this inconsistency remain unclear. For instance, according to interviews in Chapter 2 in Miljøbyen Granåsen, the majority of households stated that they had been given sufficient information to be able to regulate the heat. Interviews in Chapter 3 led to opposite results. Further work is needed in this area.

To improve past research works, these questions should be better structured for this problem. For instance, they should clearly distinguish between the technical information given to use control panels (e.g. how to change a set-point) and the understanding of the set value to apply in order to reach the desired thermal comfort or IAQ: some users know how to change a set-point value in the control panel interface (meaning which button to press), but do not know which set-point value to select to reach their objective (i.e. the consequence of their action). They should also distinguish between opinions of users that think to be in control of the heating system, whether the information initially given was correct, whether the understanding of users is accurate and the actions they take in reality.

8.8 Simplified space-heating distribution, keep it or leave it?

This study adds up to the existing knowledge about space-heating of passive houses. It is hard to give a definitive answer to this question, but this work gave some confirmations regarding the simplified space-heating distribution using radiators (with one radiator per floor):

- The thermal environment in heated living areas is confirmed to be comfortable, even if these rooms are large and only equipped with one heat emitter. The temperature distribution is uniform and the thermal stratification limited. Some cases of two rooms heated by a single radiator have also been analysed and turned out to be successful as well.
- Even if bedrooms are not equipped with a heat emitter, they are often experienced as too warm. In our investigations, bedrooms have never been experienced as too cold. In the work of Berge *et al.* [18, 19], only a very limited number of occupants would have liked a heat emitter in each bedroom. The fact that bedrooms are experienced as too warm is related to the concept of super-insulated building envelope with centralized balanced mechanical ventilation with efficient heat recovery unit and one set-point temperature for the supply ventilation air. This problem would be found for other space-heating emission systems as well, such as floor heating.

- The energy efficiency of the simplified space-heating distribution is not necessarily higher than a standard loop with a heat emitter in each room. It is indeed possible to reduce thermal losses from pipes but it increases the risk to have higher set-point temperatures applied in heated zones if occupants would like warm non-heated bedrooms (meaning heating bedrooms with open doors). If state-of-the-art technics are applied, this research suggested that the energy efficiency of standard distribution loops can be kept also high even if the building is super-insulated. Besides the question of investment costs, the standard loop should not be systematically excluded. Further research is needed, especially with validation using experimental data.
- In theory, the simplified distribution is less flexible because it is more difficult to get bedrooms with different temperature levels and to reheat the building quickly after a period at a lower temperature, users may also not want to have bedrooms doors open to get warm bedrooms. Nevertheless, unlike theory, complaints related to these aspects have not been found in practice. As a trade-off between investment cost, complexity and flexibility, it is also possible to consider a simplified space-heating distribution with one radiator per floor but adding one movable electric radiator for particular or occasional use (as long as the user is well informed that it is should not be used frequently).

9. References

1. Feist, W., et al., *Re-inventing air heating: convenient and comfortable within the frame of the Passive house concept.* Energy and Buildings, 2005. **37**: p. 1186-1203.
2. Standard Norge, *NS 3700:2010 Criteria for passive houses and low energy houses (residential buildings)*. 2010.
3. Houlihan Wiberg, A., et al., *A net zero emission concept analysis of a single-family house.* Energy and Buildings, 2014. **74**: p. 101-110.
4. Dokka, T.H., et al. *A Norwegian Zero Emission Building Definition*. in *Passihus Norden 2013*. 2013. Götheborg, Sweden
5. Georges, L., M. Berner, and H.M. Mathisen, *Air heating of passive houses in cold climate: investigation using detailed dynamic simulations.* Building and Environment, 2014. **74**: p. 1-12.
6. Georges, L., Ø. Skreiberg, and V. Novakovic, *On the proper integration of wood stoves in passive houses: investigation using detailed dynamic simulations.* Energy and Buildings, 2013. **59**: p. 203-213.
7. Georges, L., Ø. Skreiberg, and V. Novakovic, *On the proper integration of wood stoves in passive houses under cold climates.* Energy and Buildings, 2014. **72**: p. 87-95.
8. Blumrich, F., et al., *Protokollband nr. 36: heizung mit biobrennstoffen für passivhäuser*, P. Institut, Editor. 2007, Passivhaus Institut: Darmstadt.
9. Thalfeldt, M., J. Kurnitski, and A. Mikola, *Nearly zero energy office building without conventiona heating.* Estonian Journal of Engineering, 2013. **19**(4): p. 309-328.
10. Wigenstad, T., *Prosjektrapport 39: prosjektveileder forenklet anlegg for vannbåren oppvarming av boliger*. 2009, SINTEF Byggforsk.
11. Georges, L. and H.M. Mathisen, *Convective heat transfer between rooms in nordic passive houses.* Energy Procedia, 2015. **78**(6th International Building Physics Conference, IBPC 2015): p. 2941-2946.
12. EQUA, *IDA Indoor Climate and Energy*. 2016, EQUA Simulation AB: Stockholm.
13. Kvale, S., *InterViews: An Introduction to Qualitative Research Interviewing*. 1996: SAGE Publications.
14. Ellsworth-Krebs, K., L. Reid, and C.J. Hunter, *Home -ing in on domestic energy research: "House," "home," and the importance of ontology.* Energy Research & Social Science, 2015. **6**: p. 100-108.
15. Shove, E., *Converging Conventions of Comfort, Cleanliness and Convenience.* Journal of Consumer Policy, 2003. **26**(4): p. 395-418.
16. Andresen, I., *The ZEB Pilot Buildings*, in *Zero Emission Buildings*, A.G. Hestnes, Editor. 2017, Fagbokforlaget.
17. Goia, F., L. Finocchiaro, and A. Gustavsen, *The ZEB Living Laboratory at the Norwegian University of Science and Technology: a zerom emission house for engineering and social science experiments*, in *Passihus Norden, Sustainable Cities and Buildings*. 2015: Copenhagen.
18. Berge, M. and H.M. Mathisen, *Perceived and measured indoor climate conditions in high-performance residential buildings.* Energy and Buildings, 2016. **127**: p. 1057-1073.
19. Berge, M., J. Thomsen, and H.M. Mathisen, *The need for temperature zoning in high-performance residential buildings.* Journal of Housing and the Built Environment, 2016: p. 1-20.
20. Geertz, C., *The Interpretation of Cultures*. 1973.
21. CenBio, *CenBio Bioenergy Innovation Center: Final Report*. 2017, SINTEF Energy Research.
22. Heschong, L., *Thermal delight in architecture*. 1990, Cambridge, Mass.: MIT Press.
23. Wen, K., *Simplified space-heating distribution in highly-insulated apartment buildings*, in *Energy and Process Engineering Department*. 2017, Norwegian University of Science and Technology (NTNU).

24. Håheim, F., *Simplified space-heating distribution in highly-insulated residential buildings*, in *Department of Energy and Process Engineering*. 2016, Norwegian University of Science and Technology (NTNU): Trondheim.
25. Georges, L., et al., *Simplified space-heating distribution using radiators in super-insulated apartment buildings.* Energy Procedia, 2016. **96**: p. 455-466.
26. L. Georges, F. Håheim, and M.J. Alonso, *Simplified space-heating distribution using radiators in super insulated terraced houses.* Energy procedia, 2017.
27. Berge, M., J. Thomsen, and H.M. Mathisen, *The need for temperature zoning in high-performance residential buildings.* Journal of Housing and Built Environment, 2016.
28. Berge, M., L. Georges, and H.M. Mathisen, *On the oversupply of heat to bedrooms during winter in highly insulated dwellings with heat recovery ventilation.* Building and Environment, 2016. **106**: p. 389-401.
29. Allard, F., et al., *Air flow through Large Opening in Buildings*, in *Annex 20: Air flow patterns within Buildings*, J. van der Maas, Editor. 1992, International Energy Agency.
30. Scott, D., R. Anderson, and R. Figliola, *Blockage of Natural Convection Boundary Layer Flow in a Multizone Enclosure.* International Journal of Heat and Fluid Flow, 1988. **9**(2): p. 208-214.
31. Georges, L., G. Cao, and H.M. Mathisen. *Further Investigation of the Convective Heat Transfer between Rooms through Open Doorways*. in *12th REHVA World Congress*. 2016. Aalborg.
32. CEN, *EN ISO 13790-2008 : Energy performance of buildings, calculation of energy use for space-heating and cooling*. 2008, European Committee for Standardization.
33. Maivel, M. and J. Kurnitski, *Low temperature radiator heating distribution and emission efficiency in residential buildings.* Energy and Buildings, 2014. **69**: p. 224-236.
34. Standard Norge, *NS 3031 Beregning av bygningers energiytelse (calculation of energy performance of buildings)* 2014.
35. CEN, *Heating systems in buildings : method for calculation of system energy requirements and system efficiencies, part 2-3*, in *Space-heating distribution systems* 2007.
36. Olesen, B.W. and M. de Carli, *Calculation of the yearly energy performance of heating systems based on the European Building Energy Directive and related CEN standards.* Energy and Buildings, 2011. **43**: p. 1040-1050.
37. CEN, *Heating systems and water based cooling systems in buildings : method for calculation of system energy requirements and system efficiencies, part 3*, in *Space-heating distribution systems (DHW, heating and cooling)*. 2014.
38. Standard Norge, *SN/TS 3031:2016 Energy performance of buildings*, in *Calculation of energy needs and energy supply*. 2016, Standard Norge.
39. Georges, L., T. Ivanek, and M. Thalfeldt. *Energy efficiency of hydronic distribution systems in super-insulated residential buildings*. in *Building Simulation 2017*. 2017. San Francisco.
40. KRD, *Byggteknisk forskrift TEK 10* 2010, Kommunal-og-regionaldepartementet.
41. KRD, *Byggteknisk forskrift 1985*. 1984, Kommunal-og-arbeidsdepartementet.
42. Standard Norge, *NS-EN 12831 Heating systems in buildings: method for calculation of the design heat load* 2003.
43. ProgramByggerne, *SIMIEN, SIMulation of Indoor climate and ENergy use*. 2012: Skollenborg.
44. Claridge, D.E., *Building simulation for practical operational optimization*, in *Building Performance Simulation for Design and Operation*, J.L.M. Hensen, Lamberts, R., Editor. 2011, Spon Press: Oxon. p. 143-179.
45. ISO, *ISO 12241 : Thermal insulation for buildings equipment and industrial installations: calculation rules*. 2008, International Organization for Standardization (ISO).
46. Winterton, R.H.S., *Where did the Dittus and Boelter equation come from?* International Journal of Heat and Mass Transfer, 1998. **41**: p. 809-810.
47. Churchill, S., Chu, H., *Correlation equations for laminar and turbulent free convection from a horizontal cylinder.* International Journal of Heat and Mass Transfer, 1975. **18**: p. 1049-1053.

48. Incropera, F., et al., *Fundamental of heat and mass transfer*. 6th ed. 2007, New Jersey: John Wiley and Sons.
49. CEN, *NS 15603: Energy Performance of Buildings, overall energy use and definition of energy ratings*. 2008.
50. Dar, U.I., et al., *Influence of occupant's behavior on heating needs and energy system performance: a case of well-insulated detached house in cold climates.* Building Simulation, 2015. **8**: p. 499-513.
51. Klein et al., *TRNSYS 17 : Volume 4, Mathematical Reference*. 2010.
52. CEN, *EN ISO 7730 : Ergonomics of the thermal environment: analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local comfort criteria*. 2005, European Committee for Standardization.

APPENDIX

Interview guide for the ZEB Living Lab

Hvilken temperatur har du i Living Lab og hvilken temperatur hjemme?

- Har dere samme temperatur i alle rom? (hjemme og i Living Lab)
- Lukker dere dører mellom rom?
- Føler dere trekk ved vinduer?
- Er det gulv kaldt? For varmt?

Er det er godt inneklima i Living Lab og hjemme? Er dette det samme i alle rom? Variere det i løpet av en dag?

- Har dere justert varmen? (temperatur ute, mange på besøk)
- Luftet gjennom vinduer?
- Opplever dere at det lukter?
- Opplever dere at luften er god?
- Opplever dere at luften er fuktig eller tørr?
- Er dere tørr i øyene eller har rennende nese? Vondt i hodet? Trøtt? Er dere tørr i huden eller klør det i huden?
- Er der mer eller mindre støv i Living Lab enn hjemme?

Ble oppholdet i Living Lab påvirket at ventilasjonssystemet?

- Fulgte dere med på driften av den?
- Hører dere lyden fra den?
- Hører dere susing, eller dur fra noe annet i bygget?
- Er dette noe dere ønsker å ha i eget hjem?
- Har dere åpnet eller stengt vinduer for å støtte ventilasjonen?

Påvirker følgende aktivitetene inneklimaet i Living Lab og hjemme?

- Matlaging
- Røyking
- Klesvask
- klestørk
- Husvask
- Personlig hygiene / dusjing
- Oppvarming
- Kjøling/ Lufting
- Besøk av gjester
- Andre forhold?

Hvordan er det å sove i Living Lab og hjemme?

- Er det god luft om natta/om morgenen?
- Sover dere med åpen vindu? Er det OK å sove med åpne vinduer?
- Blir det varmt/kaldt?
- Hører dere lyden fra ventilasjonssystemet om natten?

Føler du at du «mestrer» bruken av Living Lab? Ville du/ dere hatt mer eller mindre kontroll over temperatur, luftskifte og teknisk styring i huset?

Endre dere på noe på vei inn eller ut av Living Lab/ hjemme? (lys, varme)

Hvordan er det å bo i et hus med så mange sensorer?

Følger dere med på strømforbruk hjemme/ Living Lab – daglig, ukentlig ellers?

Er Living Lab et komfortabelt hus? Hva er det som skaper komforten? Forskjellen mellom Living Lab og hjemme?

Fungerte alt etter forventninger (teknisk, funksjonalitet, komfort)?

Har dere vært syk under oppholdet i Living Lab?

Har dere eller har dere hatt allergier, høysnue, eksem?

The Research Centre on Zero emission Buildings (ZEB)

The main objective of ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition. The Centre will encompass both residential and commercial buildings, as well as public buildings.

NTNU – Trondheim
Norwegian University of
Science and Technology

SINTEF

ZEB The Research Centre on
Zero Emission Buildings

FORSKNINGS-
SENTER FOR
MILJØVENNLIG
ENERGI

Partners

NTNU
www.ntnu.no

SINTEF
www.sintef.no

Skanska
www.skanska.no

Weber
www.weber-norge.no

Isola
www.isola.no

Glava
www.glava.no

Protan
www.protan.no

Caverion Norge
www.caverion.no

ByBo
www.bybo.no

Multiconsult
www.multiconsult.no

Brødrene Dahl
www.dahl.no

Snøhetta
www.snoarc.no

Forsvarsbygg
www.forsvarsbygg.no

Statsbygg
www.statsbygg.no

Husbanken
www.husbanken.no

Byggenæringens Landsforening
www.bnl.no

Direktoratet for byggkvalitet
www.dibk.no

DuPont
www.dupont.com

NorDan AS
www.nordan.no

Enova
www.enova.no

SAPA Building system
www.sapagroup.com

Sør-Trøndelag fylkeskommune
www.stfk.no

Entra Eiendom AS
www.entra.no