Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 96 (2016) 455 – 466

Energy Procedia

SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki

Simplified space-heating distribution using radiators in super-insulated apartment buildings

Laurent Georges[a,*], Kang Wen[a,b], Maria Justo Alonso[c], Magnar Berge[a], Judith Thomsen[c] and Ruzhu Wang[b]

[a]*Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*
[b]*Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China*
[c]*SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway*

Abstract

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. In these envelopes, 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 each window. There is lack of fundamental knowledge to support this simplification of the SH distribution system. The present contribution especially focuses on apartment buildings heated using a reduced number of radiators. It aims at comparing the balance between energy efficiency, thermal comfort and user satisfaction using simplified SH distribution. For this purpose, two flats built according to the Norwegian PH standard have been investigated using building simulations (using IDA-ICE), field measurements and occupant interviews. With a simplified distribution, one may suspect that occupants experience the thermal environment of rooms without heat emitter as too cold, typically bedrooms. On the contrary, the super-insulation and the high-efficiency heat recovery prevent significant temperature zoning to takes place between rooms. Even though the SH distribution is simplified, occupants rather complain about the bedroom temperature which is too warm if they do not open windows. Unfortunately, this way to control indoor temperature has a strong adverse influence on the space-heating needs, which is here investigated for different control strategies. Another limitation is the time needed to heat a bedroom only using internal door opening. It takes several hours to adjust to a higher set-point temperature; an aspect that can be critical if the bedroom temperature should be changed between daytime and nighttime.

Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.

Keywords: Passive House; Space-Heating; Simplified Distribution; Radiator; Apartment Building

* Corresponding author. Tel.: +47 73592484 ; fax: +47 73593186.
E-mail address:laurent.georges@ntnu.no

Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.
doi:10.1016/j.egypro.2016.09.177

1. Introduction

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. While the construction of passive envelopes is more challenging, these envelopes also offer opportunities. Given their level of insulation and the use of high-performance 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 each window. A well-known simplified approach is the so-called centralized air heating [1, 2], but one could also consider a wood stove [3, 4], or a limited number of low-temperature radiators. In practice, there is lack of fundamental knowledge to support the simplification of the SH distribution system in super-insulated buildings. The simplification tends to reduce costs and thermal losses from pipes, while it may reduce the flexibility for users and increase control losses. Therefore, the present work aims at comparing the balance between energy efficiency, thermal comfort and user satisfaction for simplified SH distributions. The contribution especially focuses on low-temperature radiators in apartment buildings.

For this purpose, two flats built according to the Norwegian PH standard NS3700 [5] have been investigated. Both building are located in Trondheim (in Norway) and are equipped with a simplified hydronic system. The temperature distribution between rooms has been measured during two weeks in spring 2016. In addition, qualitative interviews have been performed with occupants. Based on these measurements, detailed dynamic simulations using IDA-ICE have been calibrated. These models enable to investigate the influence of alternative operating scenarios on the space-heating needs and thermal comfort.

Space-heating in highly-insulated buildings in Nordic countries was already investigated by previous works, but they essentially focused on other aspects. Wigenstad et al. [6] investigated simplified space-heating distribution in Norwegian passive houses but did not perform measurements or evaluated the temperature differences between rooms. Smedegård [7] and COWI [8] essentially focused on large buildings and costs. Thalfeldt et al. [9] performed detailed dynamic simulations on office building without conventional heating.

2. Case description

2.1. Passive house apartments

The two investigated flats are part of Miljøbyen Granåsen, the largest PH construction project in Norway. It will consist of 430 dwelling units located in Trondheim with a total heated area of 34000 m^2. Miljøbyen Granåsen is developed by Heimdal Bolig and is also part of the EBLE, Concerto and Eco-city research projects. Both flats have exactly the same layout and are located above each other in building block B4-H2, Figures 1 and 2. Each flat has a heated area of 80 m^2 and consists of two sleeping rooms for one and two persons, respectively. The living room facing south is coupled to the kitchen and the corridor where a radiator is placed. This radiator is the only heat emitter in the flat except in the bathroom which is equipped with floor heating, and the supply ventilation air that can be heated by a heating coil located after the heat recovery unit. Nevertheless, the door of the bathroom is almost always closed so that the floor heating influence over the entire flat is here limited.

The building is constructed in wood frame construction and insulated with mineral wool. External walls have a U-value of 0.17 W/m²K, the gable wall to the atrium 0.16 W/m²K. The U-value of the internal floors and walls between flats is estimated to be 0.25 W/m²K. As the building is lightweight, the internal partition walls between rooms are insulated, here with 7 cm mineral wool giving a U-value of 0.49 W/m²K. The normalized thermal bridges are 0.02 W/m²K. Infiltrations have not been measured for these specific flats but the designed value is 0.6 ach at 50 Pa. The balcony is glazed with sliding windows. The balanced mechanical ventilation generates a cascade flow where fresh air is supplied in bedrooms 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 depends on the number of occupants (26 m^3/h per person), meaning 52 and 26 m^3/h for the double and single sleeping rooms, respectively. The design air supply rate (Vn) is 1.5 m^3/h per m², 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).

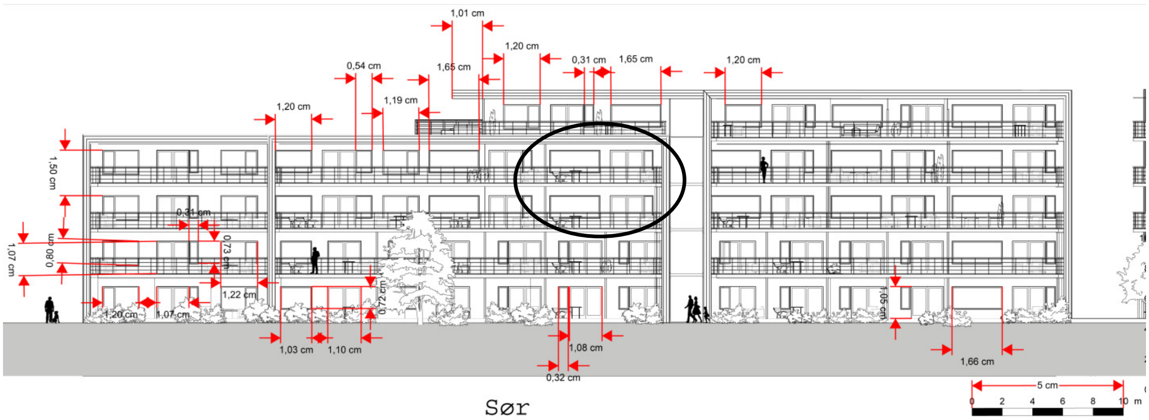

Fig. 1. South façade of the building block B4-H2.

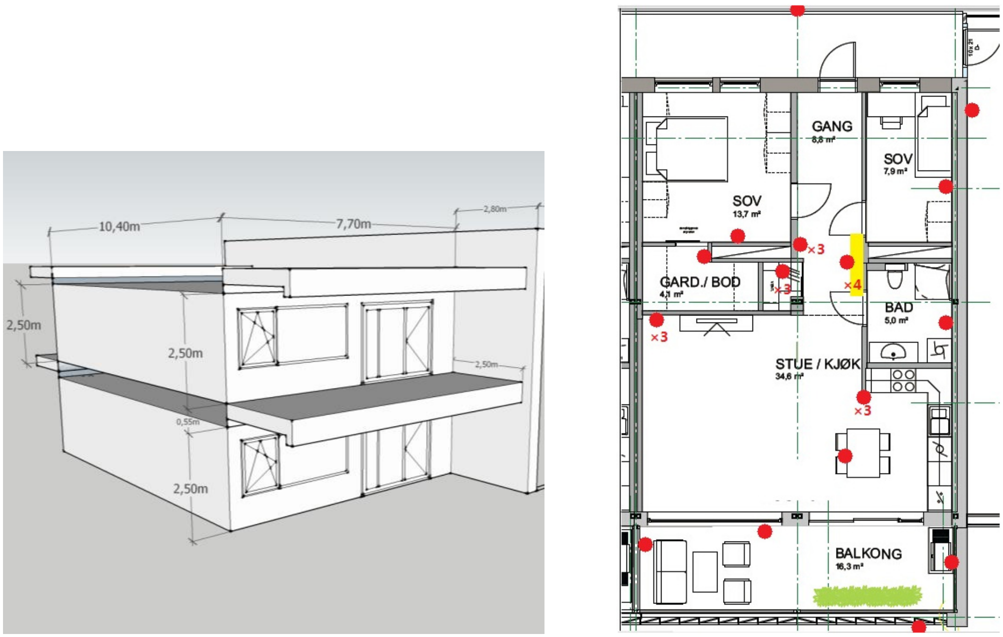

Fig. 2. (a) Three-dimensional view of the two flats with internal dimensions, (b) flat layout with temperature sensors in red and the main radiator location in yellow (North points upwards).

2.1. Measurements

A first measurement campaign has been performed during two weeks in November 2015 in order to develop the setup. After this preliminary investigation, it turned out that both the temperature and the opening of windows and internal doors should be monitored simultaneously in order well understand the thermal dynamics of the building.

For the final measurement campaign in March and April 2016, temperature sensors iButton DS1922L-F5 with an accuracy of ±0.5°C have been placed in each room in the building (at height of ~1m above the floor), and at three different heights in the living room, kitchen and corridor to monitor the vertical temperature stratification. Additional temperature sensors were positioned inside the air handling unit, at all air terminal devices (ATD) and to measure the outdoor temperature at the different façade orientations as well as in the atrium. Sensors were also placed on the bulb of the radiator thermostatic valve, on its water inlet and outlet pipes as well as its surface. Occupants were able to log in a diary the position of the radiator thermostatic valve (Tset,SH), the set-point temperature (Tset,AH) and airflow rate of the air handling unit. Both flats being occupied by a single person, they usually reduce the ventilation flow rate to level one (i.e. one half of the nominal value, Vn). The opening 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. Field-based results

3.1. Interviews

A qualitative interview was performed with the single occupant of both apartments. The occupant of the first flat initially felt that the living room temperature was too low (~22°C) while the desired temperature was about 24°C. The occupant reported a significant temperature difference between the corridor and the living room. In the meantime, a larger radiator has been placed and some corrections implemented on the sliding window to the balcony (i.e. improve the air tightness). The situation is reported to have improved even though it was not possible to identify whether the lack of space-heating power was a result of an undersized radiator or a default in the window air tightness. The final measurement campaign has been performed after these improvements have been applied. Nevertheless, this initial lack of space-heating power led the occupant to get into the habit to apply a rather high set-point temperature for the supply air (Tset,AH) of 20°C. At first sight, one may believe that a limited number of heat emitters would imply that rooms not equipped with radiators may be experienced as too cold by users, for instance bedrooms in the present case. On the contrary, the user experienced the bedroom temperature as too warm, 16-18°C being described as the ideal temperature. The window of the main bedroom is opened a few minutes before bedtime to cool down the room, but the window is closed during night due to outside noise. If the outdoor was quiet, the occupant said she would open the window during the night. The internal doors of bedrooms are kept closed to keep the spatial circulation easier for the occupant in the corridor, not for a question of privacy or thermal comfort.

The second occupant is in general satisfied with his indoor thermal environment. Nevertheless, he also experienced the living room as too cold during winter while the desired temperature is said to be 22°C. No corrections have been done to improve the situation. As for the first occupant, the second occupant would like to have a cold bedroom, 12-15°C being reported as his ideal bedroom temperature. He therefore keeps the main bedroom window open all the time, except during the coldest periods during winter. In addition, the doors of the bedroom are kept closed to create a temperature difference between the living room area and bedrooms.

These results are in good agreement with the work of Berge et al. [10]. They performed a questionnaire distributed to the residents of 62 houses from the Miljøbyen Granåsen. Detached and terraced houses were investigated but no apartments. Even though the building typologies are different from the present work, conclusions are valuable as the number of persons questioned is larger and thus results more representative. In addition, a same space-heating 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 motive for people to open the bedroom window is the temperature control (not IAQ).

3.2. Measurements

Final measurements where performed during two weeks at the end of the space-heating season (March-April) where the outdoor temperature varied between 0 and 5°C. Both flats have not been measured in parallel but sequentially. They cannot be compared directly due to different boundary conditions (typically the weather).

The temperature distribution within the living room and the corridor is displayed in Figures 3 and 4. The temperature distributes evenly in the living room and the kitchen. In addition the temperature stratification is limited to ~1.5°C. The analysis of the corridor is more critical. In the first apartment, a temperature difference of 1-2°C appears between the corridor and the living room. The stratification is higher due to the radiator but remains limited. During measurements, this radiator had to deliver heat continuously to the room.

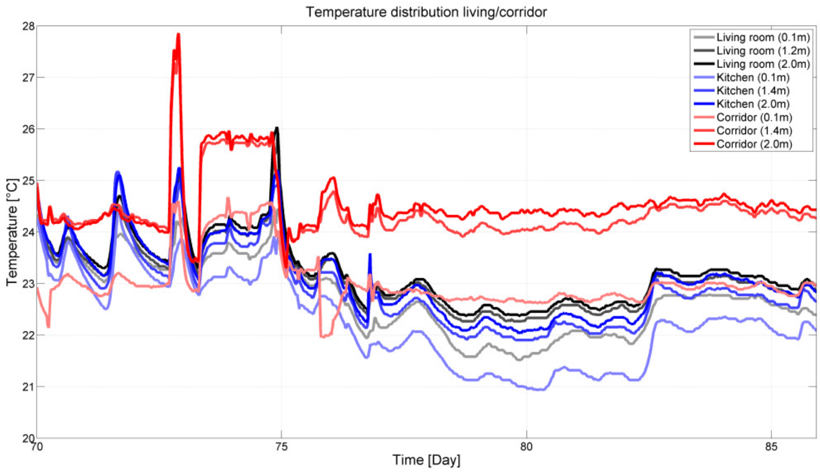

Fig. 3. Temperature distribution in the living room and corridor for apartment #1.

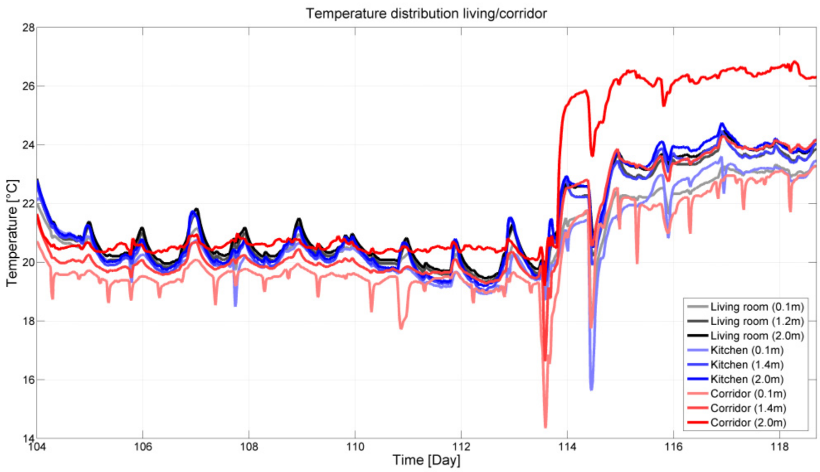

Fig. 4. Temperature distribution in the living room and corridor for apartment #2.

On the contrary, the radiator of the second flat is only active during the last three days of the measurement campaign. When the radiator is off, the temperature is very similar in the corridor and living room, both with limited stratification. When the radiator delivers heat to the room, the stratification increases significantly in the corridor but no general offset of temperature is found between the corridor and the living room. Due to the potential air leakage on the sliding window on the south façade, it is rather difficult to determine if this temperature difference found in the first flat is expected or not. Given the narrow shape of the corridor, the natural convection between the radiator and the living room is difficult to predict [11] so that it not trivial to estimate the expected temperature difference between both zones.

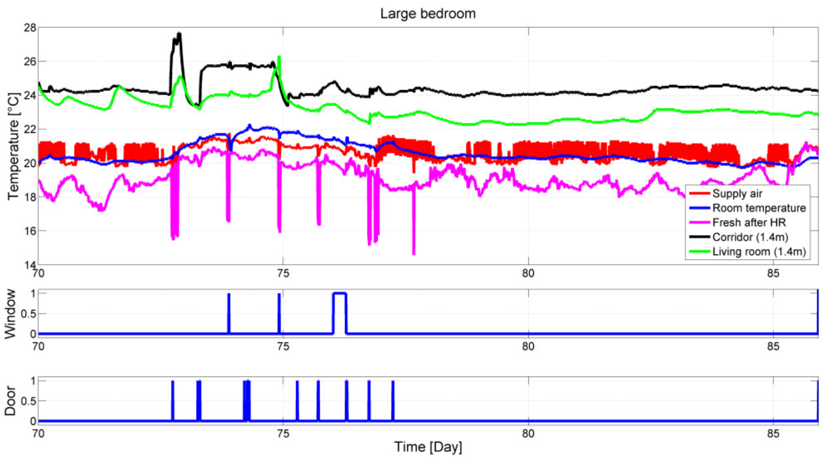

Fig. 5. Temperatures influencing the large bedroom for apartment #1.

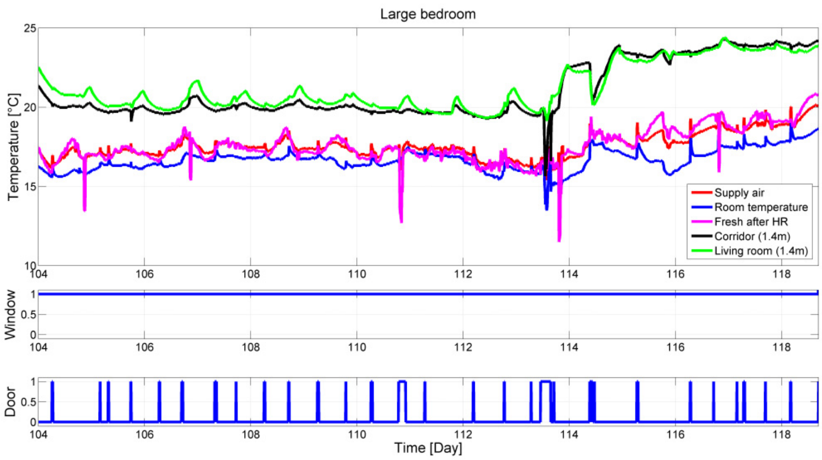

Fig. 6. Temperatures influencing the large bedroom for apartment #2.

Figure 5 reports on the different temperatures influencing the large bedroom in the first apartment. In addition, the opening of the bedroom door and window is also displayed. It confirms that they are most of the time closed as reported in the interview. The bedroom temperature oscillates between 20 and 22°C, a temperature higher compared to the desired temperature. With closed internal doors, a typical temperature difference of about 2°C is recorded with the corridor (which shares the largest wall with the bedroom). Although the bedroom temperature is felt too high, the user still applies a supply air set-point temperature of 20°C. This confirms the findings of Berge et al. [10]

showing that "*many occupants do not control the supply air temperature in a manner that provides thermal comfort in bedrooms*". If no pre-heating of the fresh air had been applied by the battery, the temperature of the supply air to the rooms would correspond to the outlet temperature of the heat recovery. The heating battery here always adds 1-2°C to the fresh air. In addition, the heat recovery efficiency is not reduced when its outlet temperature is above its set-point (Tset,HR). Reducing efficiency could in fact be done by decreasing the rotation speed of the heat recovery wheel. In other words, the first action actually taken by the occupant to regulate the bedroom temperature is to open the bedroom windows, while there is still room for decreasing the bedroom temperature by reducing the set-point of the supply air (Tset,AH) and the efficiency of the heat recovery (Tset,HR).

Figure 6 reports on the different temperatures influencing the large bedroom in the second apartment. The window sensor confirms that the user keeps this bedroom window open all the time (here continuously during two weeks). The bedroom door is most of the time closed. This strategy enables to reach the desired temperature in the bedroom, about 16°C. Coherently, no pre-heating of the supply air is applied after the heat recovery unit. Again, with closed bedroom door, the temperature difference with the corridor can be significant, here 4-5°C. Although providing the desired thermal comfort, controlling the bedroom temperature using window opening is not a favourable strategy as regards energy efficiency. Significant bidirectional airflow is created between indoor and outdoor increasing thermal losses locally in the bedroom. This could eventually lead to a large increase of the space-heating needs of the building.

Measurements showed that the radiator in the corridor operates correctly in both flats. The temperature measured at the level of the thermostatic valve is very close to the corridor temperature at the same height. The evolution of the corridor temperature follows correctly the set-point temperature of the thermostatic valve. These results are not reported here for the sake of the brevity.

4. Simulation results

One should be careful in the expected outcome of detailed building performance simulation (BPS) applied to this problem. Standard room models consider an isothermal zone (fully-mixed assumption), such as in IDA-ICE. Therefore, thermal stratification cannot be investigated. In addition, the bidirectional flow in large openings, such as between the corridor and the living room, is modeled assuming a bulk flow [12]. 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 true, especially in the context of a narrow zone like a corridor [11]. 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. Firstly, the influence of different control strategies over the bedroom temperature and the space-heating needs can be compared. Secondly, the energy balance of the different rooms can be better understood.

4.1. 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 is applied in the simulation weather file as well as the horizontal total shortwave radiation measured 3km away from the building. The set-point for the radiator (Tset,SH) and the ventilation levels reported in the diary are imposed. 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 made as representative as possible based on the information collected during interviews. Real nominal ventilation flow rates are assumed equal to design values (Vn). Results of the calibration are reported on Figures 7 and 8. It is clear that BPS manage to reproduce the temperature difference between rooms in a satisfactory manner. It is not perfect but it is in the range of the accuracy expected by a building simulation. For instance, one can notice that the temperature in the large bedroom is well reproduced which means that BPS can be used to investigate different control strategies and their impact on the net space-heating needs. In addition, it means that the convective heat flow generated by the open window is well reproduced by the simulation (here with 20% window opening).

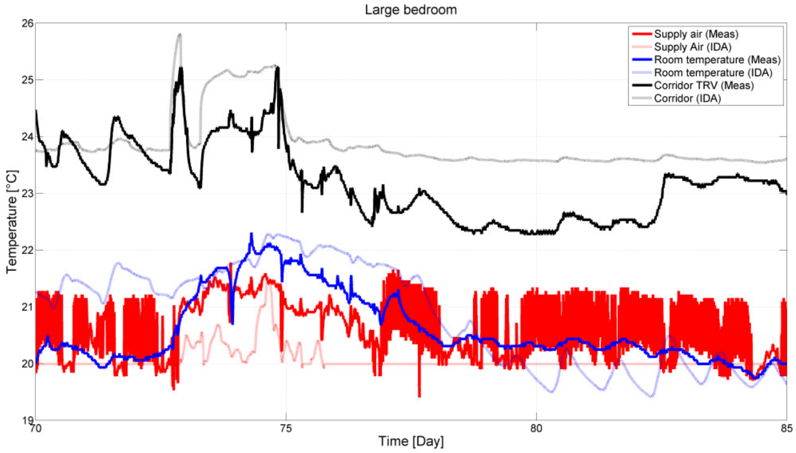

Fig. 7. Calibration of the IDA-ICE model for apartment #1.

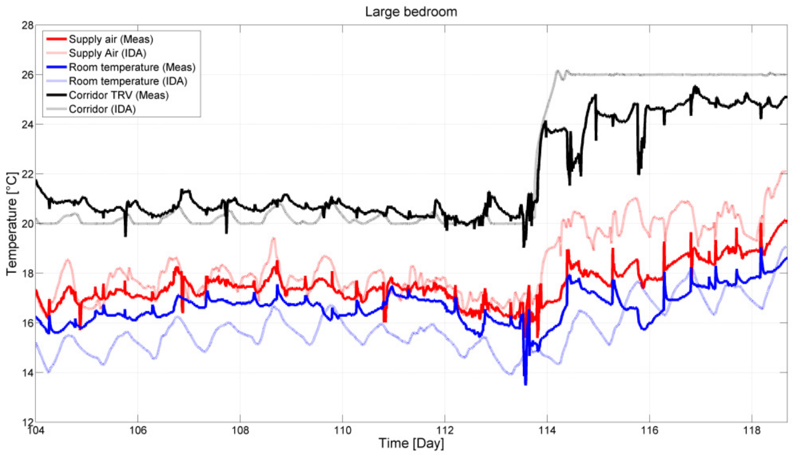

Fig. 8. Calibration of the IDA-ICE model for apartment #2.

4.1. Alternative scenarios: Thermal comfort

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 1. Apartment 1 is here taken as test case.

- Control 0 (baseline): The baseline control corresponds to real measurements.
- 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 (Tset,HR) is lowered to 16°C.

- Control 2b: A same control than 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: A same control than 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.
- 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 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.

Table 1. Summary of the investigated control strategies

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

From Figure 9, 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 to not exceed 16°C (Control 2), the bedroom temperature is reduced of two degrees, ranging from 18-20°C. It is worth noticing that a night setback did not improve the situation (Control 2b), only a constant reduction of the corridor temperature gives a significant decrease of the bedroom temperature (Control 2c). Further limiting the recovered heat to a temperature of 14°C, an additional reduction of 1°C is gained 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 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 Norwegians. Alternative strategies exist to further decrease the bedroom temperature in passive houses but they require a major modification of building technical equipments. For instance, a ventilation system with two temperature levels could be installed [10, 13], or internal walls could be further insulated. These cases are not investigated here.

As expected, the opening of the window enables to decrease the bedroom temperature. Ideally, this opening do 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 is 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 flow through the open doorway. The corresponding heating power is therefore limited so that several hours are needed for the temperature to come back from lower nighttimes temperatures to higher daytime temperatures (above 20°C). A same situation appears with the open window during night time. The temperature decreases progressively, never reaching a steady-state. In practice, the window could be more widely opened than 20%, so that the heat stored in the bedroom could be flushed more quickly. This case 4b illustrates a limitation of the simplified space-heating distribution when a room not equipped with a local heat emitter has to adjust to a set-point temperature changing for a short period of time (like a day).

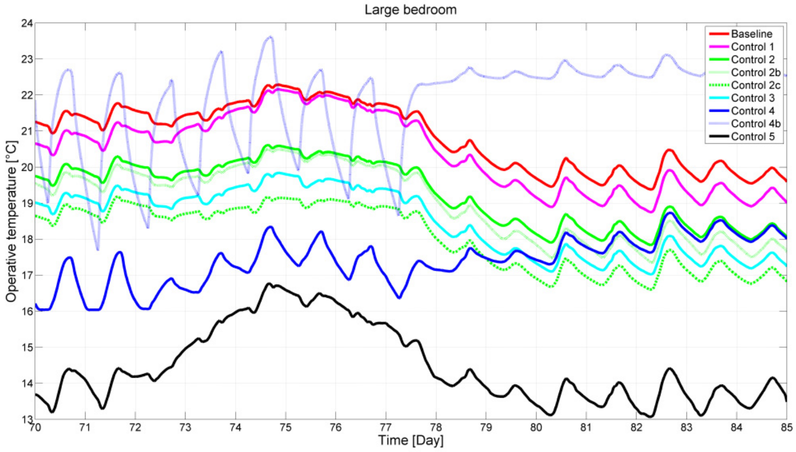

Fig. 9. Influence of control strategies over the thermal comfort in the large bedroom in apartment #1.

4.1. Alternative scenarios: Energy efficiency

Except for the baseline and Control 1, all the investigated strategies have a cost in terms of energy efficiency, 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. create a local heat sink). The performance of Control 0 to 4 is thus compared. The Control 2c is not considered as it has a different temperature level in the corridor and the living room than 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 during the coldest periods during the winter.

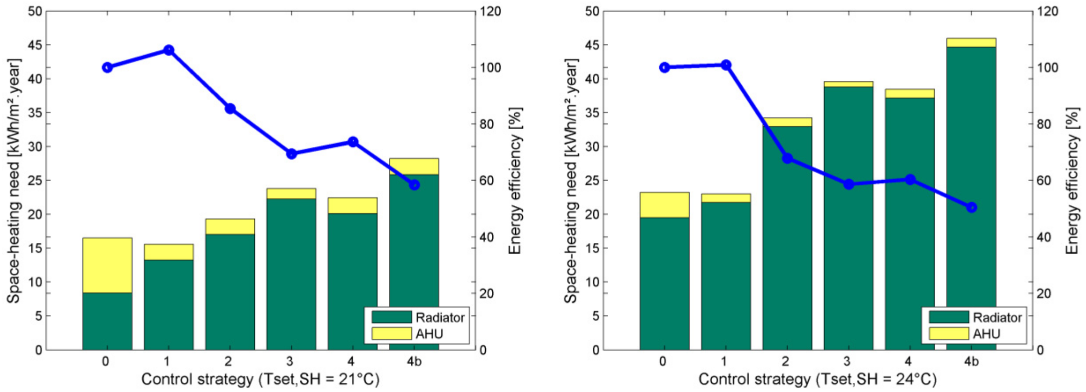

Fig. 10. Yearly net space-heating needs for five control strategies and a set-point temperature (Tset,SH) of 21°C and 24°C: the efficiency in "blue" is evaluated by taking the baseline control 0 as a reference.

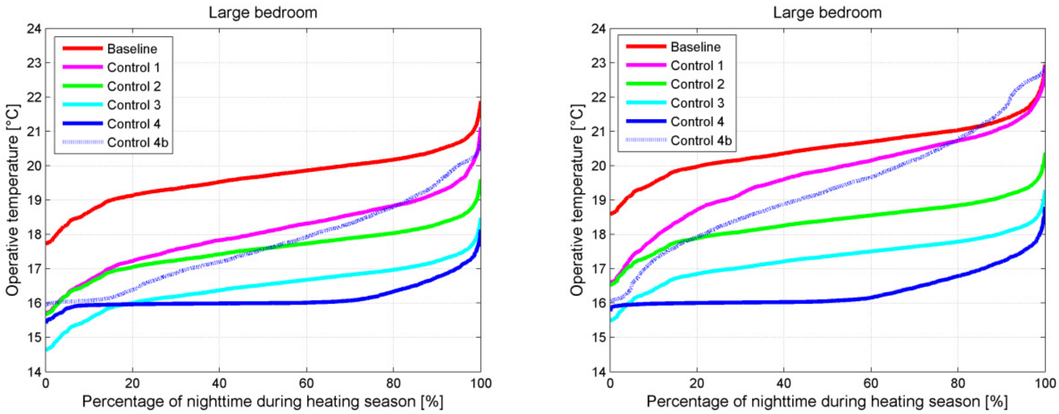

Fig. 11. Duration curve for the operative temperature in the large bedroom (during nighttime and the heating season): case with a corridor constant set-point temperature Tset,SH of 21°C (left) and 24°C (right).

It has been here decided to evaluate the space-heating needs using standardized conditions reported in NS 3700, in terms of internal gains, schedules and ventilation airflow rates. Two different constant set-point temperatures for space-heating (Tset,SH) has been taken for the radiator and the bathroom: 21°C as in NS3700 and 24°C.

From Figure 10, one clearly notices that the baseline control is a mix of radiator and air heating, especially with a Tset,SH of 21°C. When lowering the heating battery set-point (Control 1), the space-heating becomes dominated by the radiator. In both cases, the space-heating needs with Tset,SH of 21°C are representative for standard reference values of passive houses, i.e. about 15 kWh/(m²year). 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 11. By progressively reducing the set-point for the AHU with Control 2 and 3, the temperature in the bedroom further decreases 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 drop of energy efficiency induced by window opening or reduced heat recovery is more important when the space-heating set-point (Tset,SH) is higher.

An important aspect 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 open more widely than 20%). Finally, energy needs reported in Figure 10 also 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/(m²year), three times higher than the value computed using normative conditions, ~15 kWh/(m²year). Conclusions about space-heating needs will be further consolidated when the measured energy consumption of both flats will be available.

5. Conclusions and discussions

Two passive apartments have been measured during two weeks and combined with occupant interviews and detailed dynamic simulation (here using IDA-ICE). Both apartments are similar and equipped with a simplified hydronic system, where one radiator located in the corridor is the main space-heating emitter. From measurements, the temperature distribution in the living room appeared uniform with limited temperature stratification. Nevertheless, occupants reported too low living room temperatures during winter time. This lack of the space-heating power could be explained by infiltrations around one of the living room windows. A temperature difference between the corridor and the living room has been recorded for one apartment. Further investigations are needed to verify whether this temperature difference is an expected result of the spatial configuration of the apartment, or due to increased infiltration losses in the living room.

The thermal comfort in bedroom is more critical. Occupants, as many Norwegians, would like cold bedrooms while the super-insulated envelope tends to homogenize temperature in the entire apartment, and this, even if no heat emitter is placed in bedrooms. Consequently, occupants tend to adjust the bedroom temperature using window opening which has an adverse effect on space-heating needs and potentially on the indoor environment (e.g. noise). Different control strategies have been compared by calibrated dynamic simulations in terms of bedroom temperature and increased space-heating needs. The performance of each control strategy is a function of the outdoor temperature that changes throughout the heating season and the set-point temperature 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 window opening during several hours, resulting to a large drop in energy efficiency. The situation is more critical if a Tset,SH of 24°C is applied to the radiator. There is no easy way to 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 an increase of about 65%. The most critical case is when the bedroom is cyclically heated up and cooled down every day. In this case, heating the bedroom with the open doorway as the only heat source results to a limited power, so that several hours are needed to reach higher daytime temperatures (above ~20°C).

Finally, it could be recommended to move the radiator as far as possible from bedrooms. For the present plan layout, installing the radiator in the living room could have improved thermal comfort in this room and simultaneously reduce the temperature of the corridor which is the main thermal zone in contact with bedrooms. The temperature of the corridor could be further reduced by installing an internal door between this zone and the heated living room (i.e. creating a buffer zone).

Acknowledgements

The authors want to thank Husbanken for their support, as well as the industry partner, Heimdal Bolig. In addition, the authors would like to acknowledge the Research Council of Norway as this work was partially done within the Norwegian Research Center on Zero Emission Building (ZEB) and the EBLE project.

References

[1] Feist, W., J. Schnieders, V. Dorer, and A. Haas, *Re-inventing air heating: convenient and comfortable within the frame of the Passive house concept.* Energy and Buildings, 2005. **37**: p. 1186-1203.
[2] 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.
[3] Blumrich, F., W. Feist, W. Hasper, H. Krause, J. Nitsch, R. Pfluger, and R. Strauss, *Protokollband nr. 36: heizung mit biobrennstoffen für passivhäuser*, P. Institut, Editor. 2007, Passivhaus Institut: Darmstadt.
[4] 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.
[5] Standard Norge, *NS 3700:2010 Criteria for passive houses and low energy houses (residential buildings)*. 2010.
[6] Wigenstad, T., *Prosjektrapport 39: prosjektveileder forenklet anlegg for vannbåren oppvarming av boliger*. 2009, SINTEF Byggforsk.
[7] Smedegård, O., *Analyse av forenkla vassborne varmedistribusjonssystem for større bygningar*, in *Institutt for energi- og prosessteknikk*. 2012, Norges teknisk-naturvitskaplege universitet.
[8] COWI, *Faktastudie: kostnader for elektrisk og vassboren oppvarming*, Enova, Editor. 2012.
[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] 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.
[11] 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.
[12] Allard, F., D. Bienfait, F. Haghighat, G. Liébecq, K.v.d. Maas, R. Pelletret, L. Vandaele, 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.
[13] 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.