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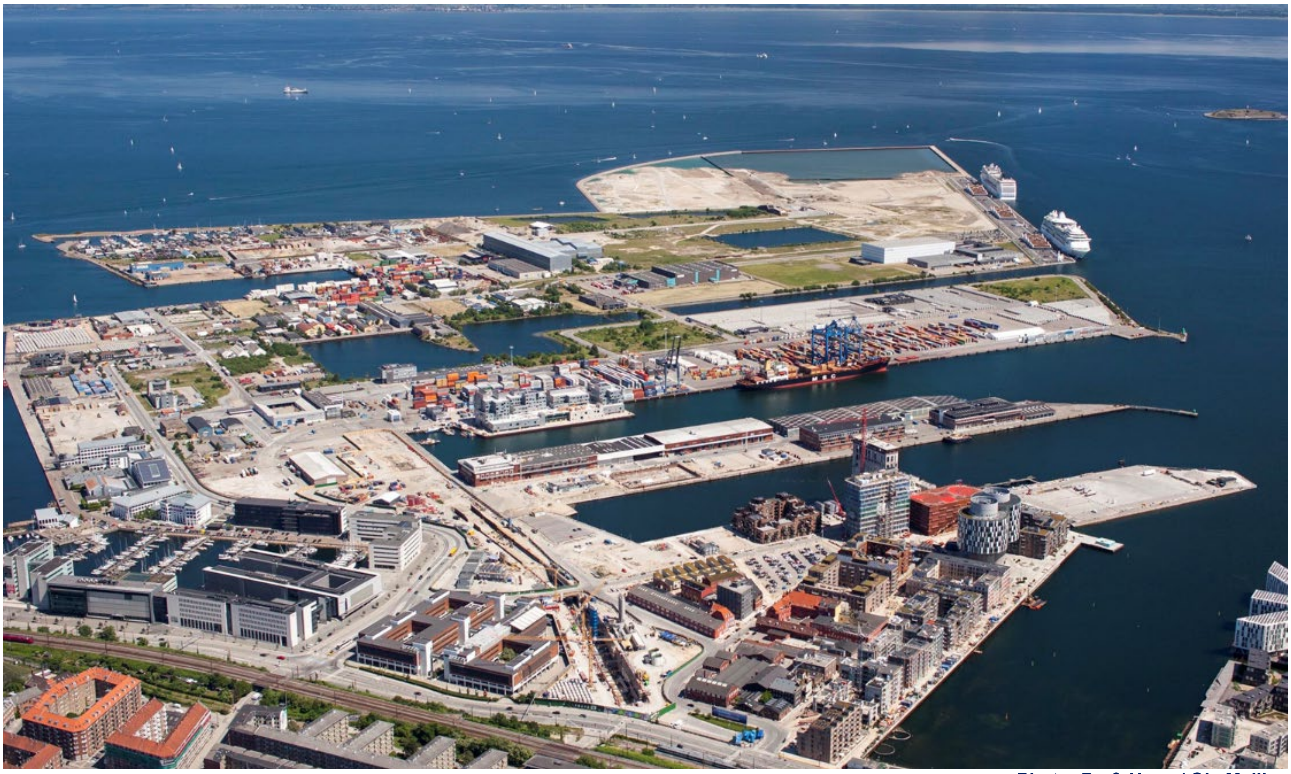

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Preface

EnergyLab Nordhavn – New Urban Energy Infrastructures is a project that has been using Copenhagen's Nordhavn district as a full-scale smart city energy lab, with the main purpose to do research, development and demonstration of possible energy solutions for the future with maximum use of renewable energy. The goal is to identify the most cost-effective smart energy system, which can contribute to solving the major climate challenges the world is facing.

Budget: The project has a total budget of DKK 143 m (€ 19 m), of this DKK84 m (€ 11 m) funded in two rounds by the Danish Energy Technology Development and Demonstration Programme (EUDP).

Forord

EnergyLab Nordhavn – New Urban Energy Infrastructures er et projekt, der foregår i den Københavnske bydel, Nordhavn, der fungerer som et fuldskala storbylaboratorium, hvor der skal undersøges, udvikles og demonstreres mulige løsninger til fremtidens energisystem med et maksimalt brug af energi fra vedvarende kilder. Målet er at finde fremtidens mest omkostningseffektive energisystem, der samtidigt kan bidrage til en løsning på de store klimaudfordringer, verden står overfor nu og i fremtiden.

Budget: Projektets totale budget er DKK 143 mio. (EUR 19 mio.), hvoraf DKK 84 mio. (EUR 11 mio.) er blevet finansieret af Energiteknologisk Udviklings- og Demonstrationsprogram, EUDP.

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Executive Summary

Low-energy buildings, such as those in the new district of Nordhavn, use high levels of thermal insulation to retain heat. This, combined with floor heating, should allow for hot water supply temperatures of 35°C or less when used for space heating. Unfortunately, due to lack of resources to monitor and maintain installations, many buildings develop undetected faults and errors that require higher temperatures to meet demand. Since heating systems often rely on central control of supply temperatures, as in the case of Havnekanten, undetected errors in several apartments can dictate the minimum operation temperatures for the whole building, which can lead to excessive heat demand. This indicates the importance of monitoring heating systems to diagnose local faults and minimize operation temperatures.

The authors used data from Danfoss Link™ central controllers to assess the performance of the floor heating systems in the case building and inferred interesting system behavior from the data. In one of the analyzed apartments, the authors inferred from the data that several thermostats had been switched between rooms, which caused excessive heat consumption and overheating. Furthermore, the data analysis showed that it was important that occupants closed the doors between rooms when applying different temperature setpoints. Through simulations, the authors demonstrated that the heating in high-setpoint rooms (e.g. bathrooms) was highly active while the heating in all other rooms was inactive. The elevated air temperatures in low-setpoint rooms resulted in greater heat loss, which increased total heat consumption. The continuous hot water flows in the high-setpoint rooms also contributed to higher total return temperatures.

The data analysis also showed that many occupants used a scheduled setpoint mode, which changed the temperature setpoints according to a scheduled occupancy. The schedule is intended as an energy saving measure, which should allow the air temperature to decrease (and thereby reduce heat loss) when the apartment is unoccupied. However, when used with concrete floor heating, the indoor temperatures remain high long after the controller reduces setpoints and stops the hot water flow. In one of the case apartments, each day's entire heating consumption was supplied during a 3-hour 'home' period. This demonstrated the extent to which 40 °C supply temperatures were excessive. Furthermore, when this 'home' period coincides with peak demand in a district heating network, it exacerbates the peak. According to project participants from the district heating company HOFOR, the peak period is from 6:00-9:00 and from 17:00-20:00. Through data analysis and simulations, the investigation showed that a constant temperature setpoint would improve performance and reduce demand during these peak periods. Using heat consumption data for the entire building, the authors evaluated the

difference between the hourly space heating demand and the 24-hour running average. When comparing the averages for each hour of the day, the peak difference coincided with the default activation of the 'home' temperature setpoint in the controller from 6:00 to 7:00. During this hour, the space heating demand exceeded its 24-hour running average by an average of more than 30 kW in three of the five coldest months and up to 35 kW in the coldest months. The latter represents a 42% increase above the average. Therefore, one could achieve a substantial reduction in peak space heating demand by simply implementing a constant temperature setpoint in all devices as a starting point.

The report also demonstrated the potential of floor heating to shift heating loads away from peak periods. When using a constant indoor temperature setpoint, the analysis found that reducing the setpoint during the peak period (6:00-9:00 & 17:00-20:00) could shift the entire space heating load to non-peak periods. Simulations further demonstrated that even on the coldest days, there would be a negligible impact on indoor temperatures. The daily-average space-heating demand of the case building exceeded 40 kW from November '18 to March '19. During these months, with a constant indoor temperature setpoint, the space heating demand would likely remain at or above 40 kW for most hours due to the high thermal inertia of concrete-embedded floor heating. Therefore, after implementing a constant indoor temperature setpoint, the additional load shift potential from reducing setpoints during peak periods (6:00-9:00 & 17:00-20:00) would be upwards of 40 kW from November to March. To avoid rebounds in demand after the peak periods, the hot water supply temperature should be minimized. The temperature should be sufficient to meet the demand with only 18 hours of non-peak-period operation but low enough to avoid excessive rebound.

The sum of these measures (i.e. a constant indoor temperature setpoint during non-peak periods and a decreased indoor temperature setpoint during peak periods) could offset the entire typical peak load for space heating in the case building without negatively impacting thermal comfort. In 2018 and 2019, the average space heating demand was 111 kW, 99 kW and 88 kW, in the first, second and third hours of the morning peak respectively in the months from November to March. The equivalent demand in the afternoon peak was 85 kW, 88 kW, and 88 kW for the three hours respectively. Thus, upwards of 85 kW of peak demand could be shifted by implementation of smart thermostatic control during the five coldest months. Integrating the peak demand, an average of 558 kWh of peak demand could be shifted daily in the case building from November to March when implementing the recommended smart thermostatic control in the case building.

Version Control

Version	Date	Author	Description of Changes
1.0	2020-07-28	Nan Hu, Kevin Michael Smith	First version
1.1	2020-08-03	Jan Eric Thorsen	Comments
1.2	2020-08-03	Kevin Smith	Updated based on comments
2.0	2020-09-24	Kevin Smith	Updated based on feedback from milestone review
3.0	2020-09-25	Jan Eric Thorsen	Final comments/Verified

Quality Assurance

Authors	Reviewer	Approver
Nan Hu and Kevin Smith	Morten Herget Christensen	WPL group

Status of deliverable		
Action	**By**	**Date/Initials**
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Reviewed	Morten Herget Christensen	
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1. Introduction

Deliverables 10.2a and 10.2b documented the technology and concept behind the Smart Cloud Control of floor heating systems from Danfoss A/S. In the three years since, Danfoss established the capacity to communicate control setpoints to Danfoss Link™ Central Controllers (CC) and record values for temperature setpoints, measured temperatures, control actions (i.e. duty cycles) and operating states (e.g. HOME/AWAY, manual/scheduled). This presented new opportunities to understand the behaviour of floor heating systems. Thus, energy flexibility became just one of several investigated aspects. The recorded data enabled a behavioural analysis of floor heating systems in terms of heat distribution between rooms, the return water temperatures to the district heating network, detection and diagnosis of potential faults and the impact of setpoint scheduling by the occupant. All of these factors have the potential to impact district heating operation, as outlined in this report, and the Smart Cloud Control by Danfoss enabled this investigation.

Before detailing the methods and results, it is necessary to provide a state of the art in district heating design and operation to clarify the aims of this work. Lund et al. proposed the concept of 4th generation of district heating (4GDH) in 2014 to identify the future challenges of reaching a non-fossil heat supply [1]. This included low temperature district heating in buildings, integration with renewable heat sources, low distribution heat losses and integration with smart energy grids. In this optimization revolution, lower heating demand can enable low supply and return temperatures in the water used for space heating, which will be referred to as “operation temperatures” in this report. These lower operation temperatures will facilitate improved district heating efficiency both now and in the future. Low return temperatures will increase the heat output from new condensing biomass boilers in the near term, and low supply temperatures will improve the efficiency of heat pumps in the smart energy systems of the future, which will have a high share of renewable electricity production. Minimized operation temperatures provide the added benefit of reducing parasitic heat losses, such as heat loss from pipes and excessive heat demand from faulty installations. It is therefore important that society establishes low temperature operation ahead of these new investments to maximize cost effectiveness.

Radiant floor heating is widely applied in both existing buildings and new constructions. The installation of radiant floor heating accounts for almost 100% in Korean residential buildings [2] and 85% in northern Chinese rural houses [3]. And 30-50% of new residential constructions in Denmark are equipped with radiant floor heating systems [4]. The popularity of radiant floor heating is due to its advantages over conventional radiator systems. In terms of thermal comfort, radiant floor heating provides an even indoor temperature distribution due to a large heat emission area. It also offers low draught risk and local discomfort in the feet region because of small temperature fluctuations and vertical temperature gradients [5]. Floor heating consumes less energy than radiator systems since it can achieve same level of thermal comfort at lower air temperatures. And the supply temperature for radiator-based systems can be up to 85°C while radiant floor heating requires up to 35°C. As mentioned, these low operation temperatures result in high plant efficiency and low primary energy consumption [6] while permitting the utilization of low temperature heat sources.

Low-energy buildings, such as those in the new district of Nordhavn, use high levels of thermal insulation to retain heat. This, combined with floor heating, should allow for operation temperatures of 35°C or less. Unfortunately, due to lack of resources to monitor and maintain installations, many buildings develop undetected faults and errors that require higher operation temperatures to meet demand. Since many heating systems rely on central control of supply temperatures, as in the case of Havnekanten, undetected errors in several apartments can dictate the minimum operation temperatures for the whole building. In turn, these higher operation temperatures lead to excessive heat demand. This indicates the importance of monitoring heating systems and having the potential to quickly and easily diagnose local faults to minimize operation temperatures.

Earlier studies conducted in Sweden demonstrated these points and found that return temperatures were higher than theoretically estimated. They concluded that the high return temperatures mainly depended on individual factors in customer installations like components not being properly designed, components not working properly, deviations from standard designs, high temperature levels of heating systems, faulty connections and incorrect control [7]. The optimization method for lowering system operation temperatures is complicated due to a multitude of different faults that may occur in many different parts of the customer installation [8]. One earlier investigation carried out at Södertörn District Heating in Sweden concluded that most of the detected errors caused high return temperatures but only one-third of the faults were related to comfort problems [9]. This increases the difficulty of fault detection, which highlights the importance of using data from smart heating systems to optimize their performance. This report describes the use of smart thermostat data from the Danfoss Link™ central controller to detect and diagnose faults in the heating system in the hope that this can be applied broadly in future systems.

In addition to low operation temperatures, the fourth generation district heating focuses on the smart energy system where electricity, gas, heating, cooling and transport systems in cities are combined and coordinated to utilize synergies between them and achieve an optimal solution [10]. Heat storage and intelligent control are introduced to shift peak loads and adjust system operation based on market information. The heavy concrete element of a floor heating system provides a substantial buffer (i.e. first-order filter) for the release of heat to rooms. The dynamics are often so slow that hot water flow can be stopped for several hours without a perceptible change to indoor air temperatures in low-energy buildings. This report demonstrates the potential of floor heating to shift heating loads during peak periods. In light of this observation, it does not make sense to change hourly setpoints based on occupancy schedules during each day, since the temperature does not decrease during the unoccupied period. Since many programmable thermostats include this feature, it is helpful to analyse the negative effect of scheduling “home” and “away” setpoints in each day, as the “home” period often coincides with peak heating demand in the district heating network. If all heat demand coincides with the peak period, it makes sense to first address this issue before implementing a proper load shift. This report uses simulations and real data to analyse the impact of scheduled setpoint modes on the timing and magnitude of heating consumption. It follows this with an assessment of the load shift potential in the case building.

2. Data analysis

The investigation started with data analysis from the smart heating systems in the case building. This included the gathering of information from available technical documents, analysing massive historical data from the Danfoss Link™ Central Controllers (CC) and visiting two apartments. The general data analysis on every apartment was carried out first. Based on the assessment of the thermal environment and energy consumption, two general issues were inferred: open internal doors and a scheduled setpoint mode. Two representative apartments were selected and used for the specific analysis. When it came to the specific analysis, the setpoint, indoor temperature and energy consumption for every room were analyzed. Some local faults were found in one apartment, including mismatched room thermostats and a valve that had never opened. These local faults did not need the further investigation but would increase the difficulty of the data analysis.

2.1 Introduction to the case building

Havnekanten is a six-story resident building with 85 apartments, which also functions as a living lab for research on smart control of water-based floor heating within the EnergyLab Nordhavn project. Based on technical documents, the construction standard for this building is based on building class 2020 in the Danish Building Regulations, BR18 [11]. Thus, Havnekanten is a low energy building that has low heat demand. In the basement, the supply water temperature is centrally controlled by an electronic mixing shunt (i.e Danfoss ECL 310), which offers the possibility to implement a weather compensation curve to adjust supply temperatures. The design supply temperature is 35°C under the assumption of extreme outdoor temperatures and no internal heat gain. However, the extreme design condition rarely occurs in normal system operation. Based on the daily average outdoor temperatures in Denmark, the daily heat demand could be under part-load operation of 60% or lower for the majority of heating season [12]. Thus, there is a potential for even lower supply temperatures if there is no operation error in the heating system. The actual temperature of supply water in Havnekanten is around 40°C. In 2019, the supply temperature was adjusted to 35°C in an attempt to lower operation temperatures. But there were many complaints from residents about insufficient heating, which implied that there could be local faults in the system. It became the first task to discover the errors influencing the operation temperatures.

2.2 General analysis

Under this subsection, the data for December 2019 was analyzed from three aspects: setpoint, room air temperature and duty cycle, to conclude some common features. For reference, the duty cycle is a signal representing the opening time of the valve in a given period to achieve the desired setpoint temperature in a room. Its value is determined by the Danfoss Link™ CC using a proportional-integral (PI) control strategy and the room air temperatures measured by wireless room thermostats. Its maximum value is 255, which represents a fully open valve for the whole period. The general data analysis used visualizations of the air temperature and duty cycle for each apartment.

Unfortunately, not all apartments in Havnekanten successfully connected to the server. The data of some apartments was invalid because the recorded period was not within the typical heating season or the data was outdated. After a preliminary screening, 11 apartments remained. The next step was to check the integrity of the data. It was found that three apartments did not have duty cycle data, which roughly correlates to the hot water flow volume, and not all rooms in another apartment were connected. Thus, the general data analysis included seven apartments. Two apartments were selected for further analysis because they exhibited interesting behavior, which we have labelled apartment A and apartment B in this report.

2.2.1 Setpoints

In the Danfoss floor heating system, there are two ways to regulate the setpoint: manual or scheduled. Under the manual regulation mode, the setpoint will remain constant unless the users adjust the setpoint. As for the scheduled setpoint mode, the users set a HOME setpoint and AWAY setpoint as well as their daily occupancy schedule. The default weekday schedule has a HOME period from 6:00 to 8:00 and from 16:00 to 22:30, while the default weekend schedule has a HOME period from 6:00 to 22:30. In the scheduled mode, the setpoint is switched automatically according to the corresponding schedule.

Some residents selected the manual control mode and used constant setpoints over the whole month of December while other residents used schedule setpoints.

According to the setpoint data from the sample of apartments, it is common to have different setpoints for different rooms within each apartment. In most apartments, the setpoint in the bathrooms was higher than that of other rooms. For each room type, the setpoints differed between apartments, which demonstrates the different preferences of residents for thermal comfort.

2.2.2 *Air temperatures*

It was found that the individual room temperature control did not result in the desired temperatures in every room. The setpoints differed between rooms, but the common result was uniform temperature distribution within the whole apartment.

In every apartment there were some rooms with similar temperature patterns even though the room types and room setpoints were different. Normally, these rooms consisted of the living room and the rooms close to it. The temperature of each room of apartment A is shown in Figure 1. The living room, office and bathroom entrance had similar temperature profiles and used slightly different setpoints. Their HOME/AWAY setpoints were 23.5/21, 23.5/20 and 23/21 °C, respectively. This shows the dominant effect of the HOME setpoint when using a relatively high supply temperature of 40 °C, as the room temperatures did not cool to the AWAY setpoints, even after many hours. If the building were to use a much cooler hot water supply temperature, the AWAY setpoint may dominate instead.

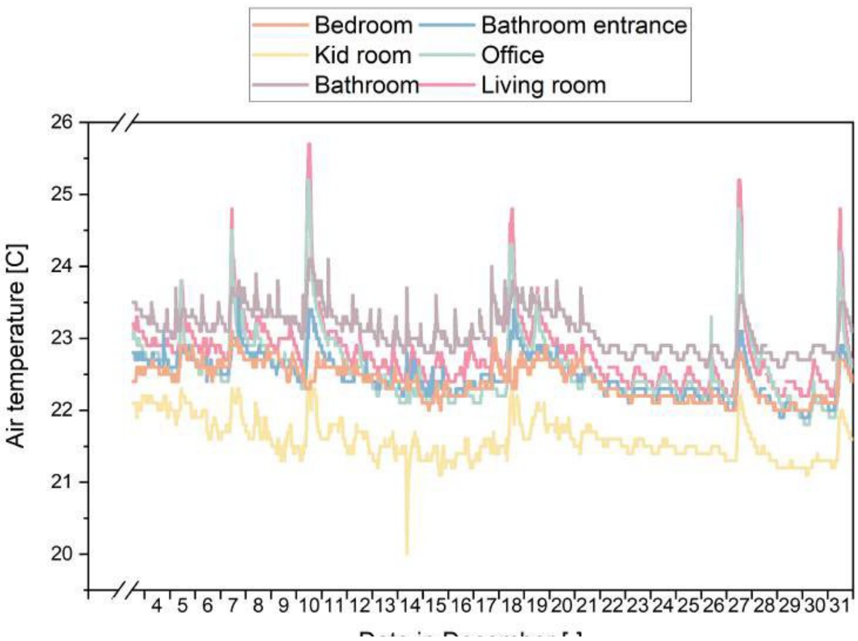


Figure 1. The room temperature of a sample apartment in December 2019

2.2.3 *Duty cycle*

A '0 duty cycle' room represents a room where the heating is never active, and it appears to be a very common phenomenon. All of the seven apartments had at least one '0 duty cycle' room. Normally the room had a low setpoint, which was significantly lower than its temperature. The 'rooms with duty cycles close to 100%' had high setpoints, like living rooms and bathrooms, and the desired air temperatures could only be achieved with the floor heating at close to full capacity. There were not as many rooms of this type as the '0 duty cycle' rooms. But if an apartment had both types of rooms, it likely had very uneven hot water flow to these rooms. Four out of the seven apartments had this phenomenon. For example, the duty cycle of each room in apartment A is shown in Figure 2.

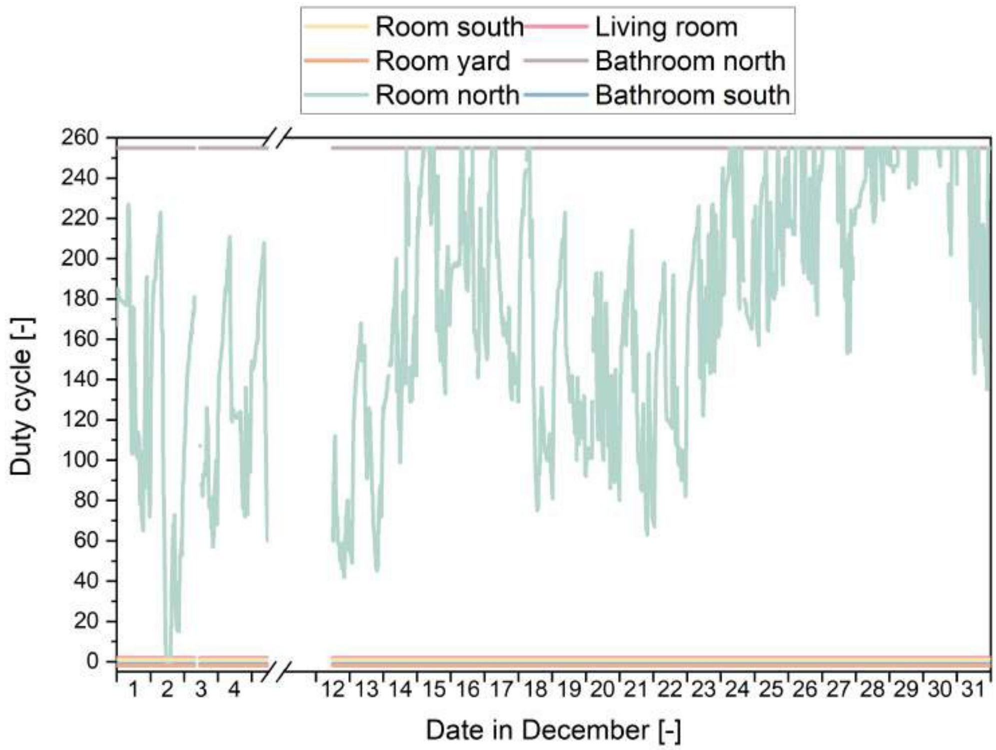


Figure 2. The duty cycle of different rooms in a sample apartment in December 2019

During the analysis of the duty cycle patterns, it was found that three of the seven apartments had a scheduled setpoint that changed regularly. The large duty cycle only appeared during a fixed portion of each day, which coincided with the HOME state. At all other times, the duty cycle remained at 0. As an example, the duty cycle of different rooms in apartment B is shown in Figure 3. Again, the high duty cycles corresponded to the HOME periods of the scheduled setpoints.

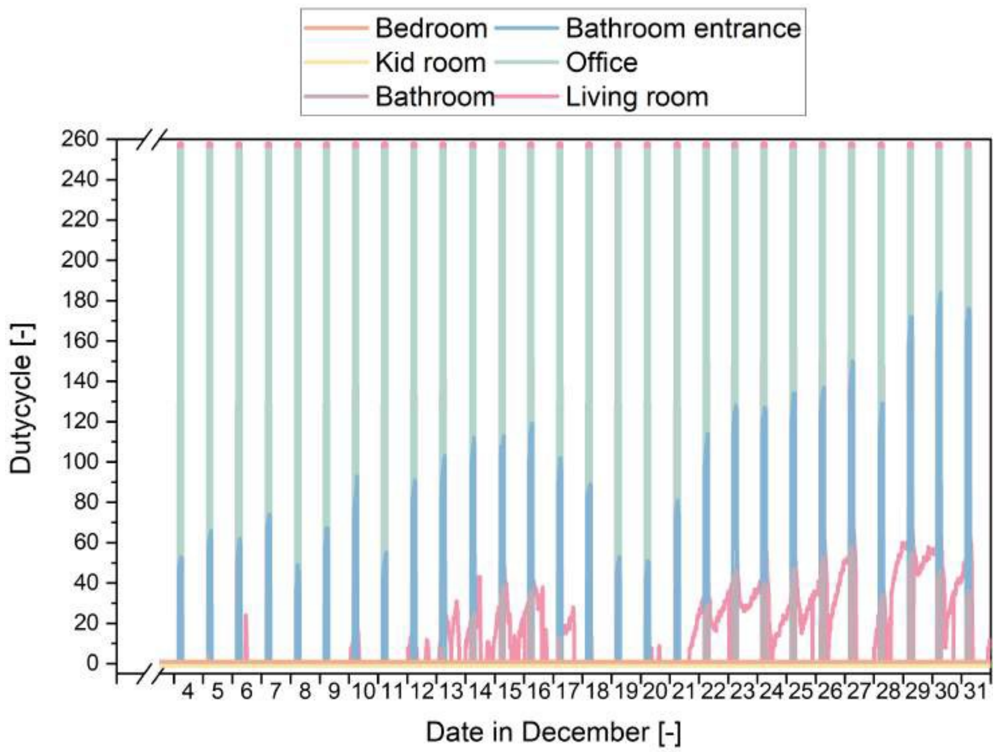


Figure 3. The duty cycle of different rooms in a sample apartment in December 2019

There are four findings concluded from the above general data analysis. There are often:

- Uniform temperature distributions within an apartment
- Similar temperature patterns between rooms
- Uneven distributions of volume flow to rooms, inferred from the duty cycles
- Concentrated periods with high heat demand due to scheduled setpoints

Open internal doors may be blamed for the first three phenomena. If all internal doors are open, it enhances the inter-zonal transfer of air, which connects the individual rooms as a whole space. This mixing will directly result in uniform air temperatures within an apartment and similar temperature patterns between rooms. As for the influence on energy consumption, the room with a low setpoint will steal heat from the room with a high setpoint, rather than relying on its own floor heating loop. For the room with a high setpoint, the increase in heat demand will result in substantially higher duty cycles (i.e. average hot water flow rates) and higher return temperatures. Thus, open internal doors will make the floor heating of a high-setpoint room operate at full capacity and will put the floor heating of the low-setpoint room in a sleep state. This causes the thermal environment and energy consumption to deviate from ideal situations. Therefore, open internal doors remove the potential for individual room temperature control and results in higher energy consumption due to the increased air temperatures (and thereby heat loss) in low-setpoint rooms.

The scheduled setpoint setting is likely the cause for the last phenomenon, which is high heat demand during short periods. Normally, the HOME setpoint is higher than the AWAY setpoint. When the scheduled state is switched to HOME, there is a sudden increase in setpoint which requires immediate heating. When the AWAY period restarts, the setpoint is low, so the heat demand is also low. The duty cycle it is often at 0 during these periods. The original intention of this schedule setpoint mode is to save energy by lowering the room temperature when there are no occupants in the apartment. But providing the entire heat consumption of a whole day within a short period is not efficient, especially since the HOME period often coincides with peak demand in the district heating network (i.e. morning and evening).

Therefore, open internal doors and the schedule setpoint mode were seen to cause poor operation of floor heating from the general data analysis.

2.3 Anomaly detection in apartment A

In apartment A, the rooms had similar temperatures even though their setpoints were different, and the duty cycles were rather uneven. Therefore, the apartment was selected to represent the influence of open internal doors. The apartment consisted of six rooms, three bedrooms, two bathrooms and a large living room. The floorplan of the apartment is shown in Figure 4.

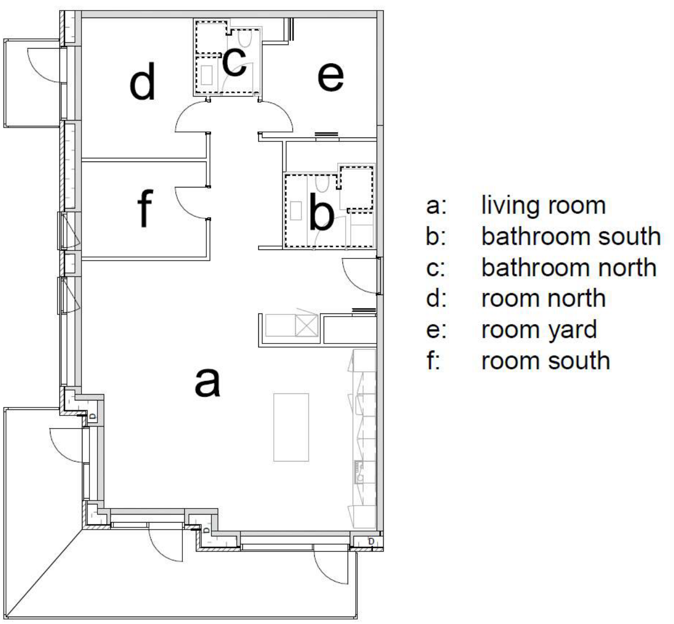
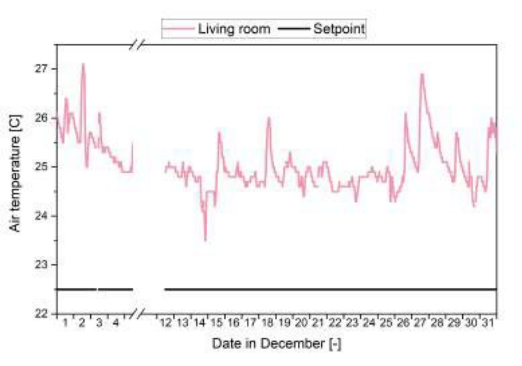
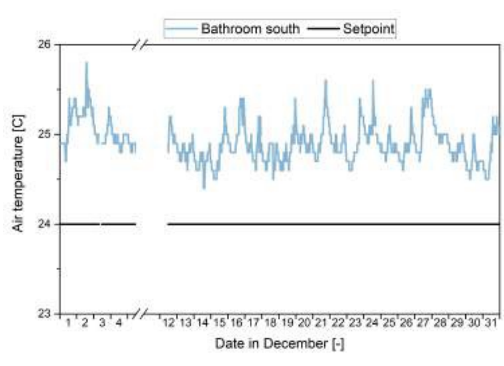


Figure 4. The floorplan of apartment A

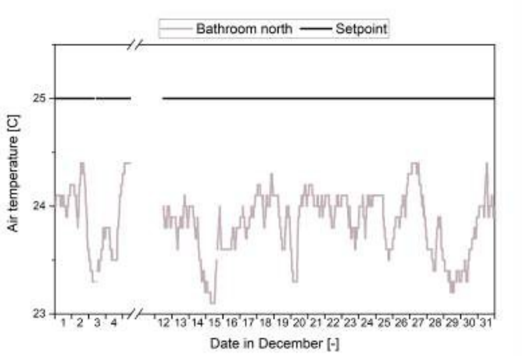
The indoor temperatures and setpoint for each room over the whole of December are shown in Figure 5.



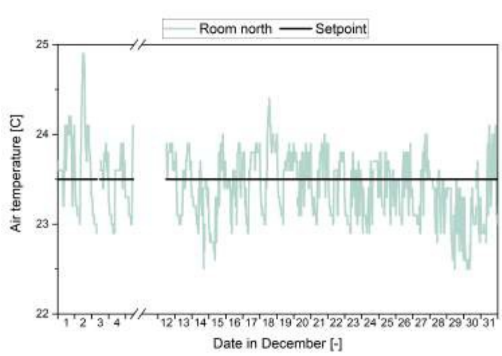
(a) Living room



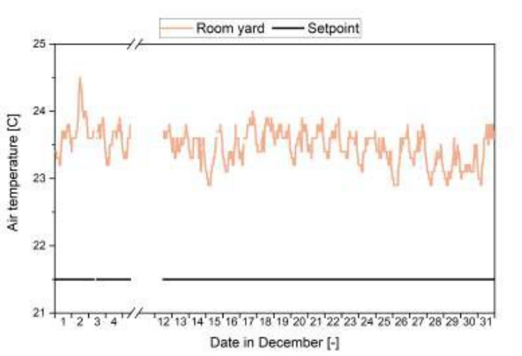
(b) Bathroom south



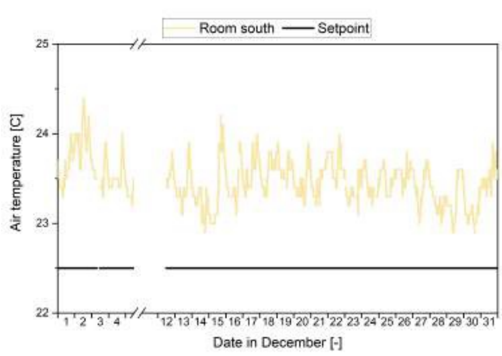
(c) Bathroom north



(d) Room north



(e) Room yard



(f) Room south

Figure 5. The comparison between indoor air temperature and setpoint for each room in apartment A

It was found that only the temperature of the 'room north' oscillated around its setpoint. For the other five rooms, four of them (living room, bathroom south, room yard and room south) had overheating relative to their setpoints and the other (bathroom north) could not meet the thermal requirement. Initially, one might suspect open internal doors as the cause, but 'bathroom north' and 'room north' had consistently lower temperatures than 'living room' and 'bathroom south', so the former could not be heating the latter above their setpoints. Something else had to cause the issue.

Regarding the duty cycle, the value was constantly 0 for the living room, room yard, room south and bathroom south during the whole month of December. This implied that the overheating problem was not caused by an unreasonable floor heating regulation because the valve should not have been opened in these rooms.

For 'room north', the relation between indoor air temperature, setpoint and duty cycle within a typical day is shown in Figure 6. The duty cycle profile was almost symmetrical with the indoor temperature. The duty cycle increased when the room temperature decreased, and vice versa. Thus, the controller's response to indoor temperatures was reasonable. Conversely, the thermal response of the room temperature seems abnormal, since the temperature deviated from the setpoint substantially. This indicate a separate potential issue.

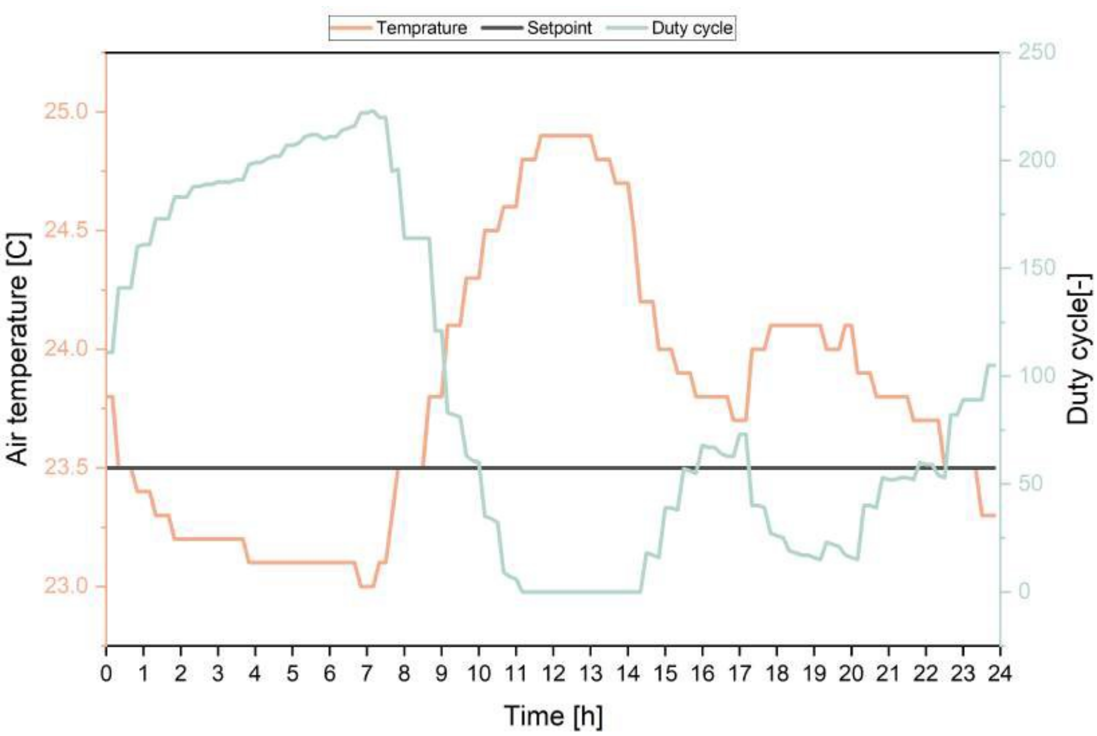


Figure 6. The relation between indoor air temperature, setpoint and duty cycle in a typical day for Room north

Looking further at the data, the temperature in 'bathroom north' never reached the setpoint in December, so the valve was kept open all the time. Dimensioning of the floor heating is based on the design heat demand, which is calculated under extreme outdoor temperatures and no internal heat gains. In most cases the floor heating is under part-load operation. However, the heating in 'bathroom north' was at maximum capacity for the whole month and still could not reach the setpoint. There are two possible explanations for this situation:

- Insufficient flow: This could be caused by hydraulic imbalance or small pipe size. Based on the limited information, it was difficult to conduct detailed analysis of whether the system had hydraulic imbalance. By checking the technical documents, it was found that the water pump power for each vertical riser was rather large and should have been enough to supply sufficient flow for every branch. In addition, the sample apartment was on a lower floor and only two rooms required heating. The possibility of insufficient flow caused by hydraulic imbalance was rather low. An under-dimensioned floor heating pipe is one possible cause, especially since bathrooms often come as pre-fabricated units, but it was difficult to check this from the data. It may have been possible with energy meter data, which often includes volume flow rates, but that data was not available for this particular apartment.

- Flow is transmitted to the incorrect rooms: This could be caused by mismatched room thermostats. As mentioned above, the Danfoss Link™ uses a wireless connection. It is likely that the room thermostat did not match the corresponding actuator. The temperature in Bathroom north was consistently below the setpoint even though the controller sent a constant signal of '100% duty cycle'. Furthermore, the temperatures in 'living room' and 'bathroom south' exceeded their own setpoints as well as the temperatures of all other rooms despite having 0% duty cycle. Thus, it seems likely that the heating intended for 'bathroom north' and perhaps 'room north' was instead supplied to the 'living room' and/or 'bathroom south' due to mismatched thermostats.

The authors followed-up the above analysis with a visit to the apartment. As seen in the data, the residents mentioned that the temperature in all bedrooms could not be decreased below 24 °C. The manifold was checked and there was no pre-set resistance applied to the valves, but this was not enough to diagnose poor hydraulic balance, so this was not investigated further. To verify our suspicion of mismatched thermostats, a thermographic camera was used to capture the temperature of the actuator and the pipe connected to it. The setpoint of one room was adjusted to be far above the current room temperature. The system sent a signal to the corresponding actuator to open. In the images obtained from the thermographic camera, the opened actuator and connected pipe had a bright color as shown in Figure 7a. In Figure 7b, it can be seen that every actuator was marked with a room name. If the room name on the illuminated actuator was different from that of the room with the adjusted setpoint, it meant that the actuator and thermostat were mismatched. As speculated from the data analysis, it was found that the thermostats of the two bathrooms were mismatched. The same problem occurred with the two other rooms (living room and room north), which explained the heating issues in the apartment. The mismatched thermostats were switched to their correct location. In the follow-up communication, the residents said the floor heating performed better after the thermostats were switched. This demonstrates the potential of use smart thermostat data to detect local faults in heating systems.

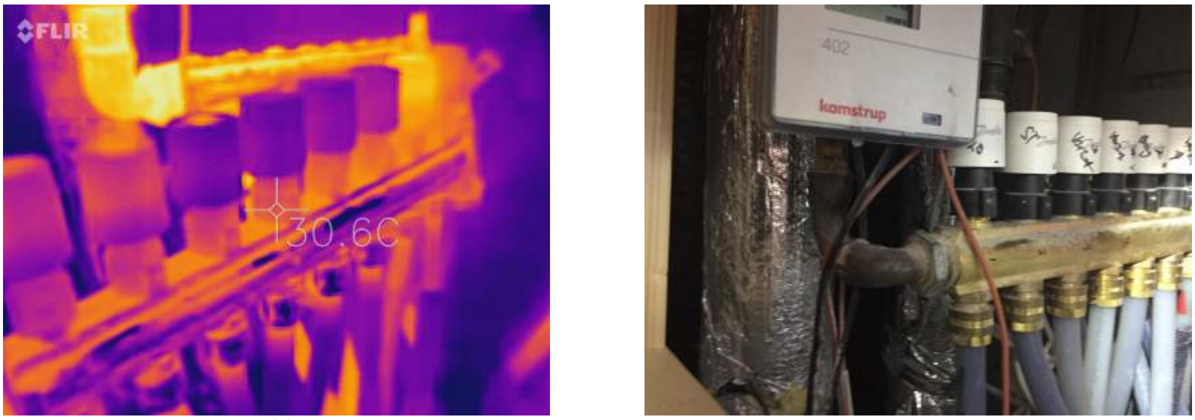
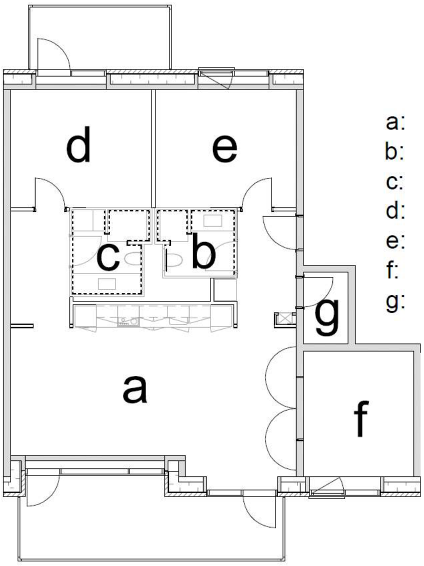


Figure 7. (a) The picture of flat substation taken by thermographic camera when the setpoint in one room was increased, and (b) The marks on actuator telling the name of the controlled room

The residents were also asked about the status of the internal doors. They said they only kept the bedroom door closed at night and the rest were left open. Even though it was the personal behavior of one family, it showed the possibility of open internal doors in apartments with different setpoints. It also confirmed the authors' speculation from the data analysis for this particular case.

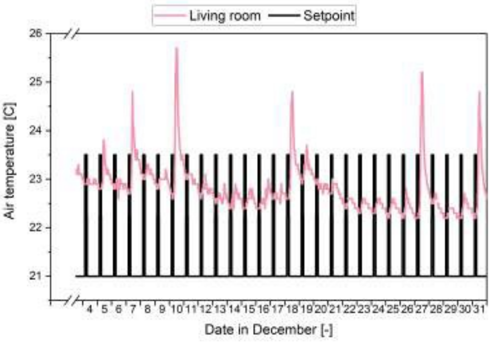
2.4 Anomaly detection in apartment B

In apartment B, the scheduled setpoint was used throughout December and the controller's duty cycles were concentrated in a short HOME period of each day. The measurement data was analyzed in detail to understand how the floor heating operated as a result of this schedule. The apartment faced South, and its floorplan is shown in Figure 8. The indoor temperature and setpoints for each room are shown by Figure 9.

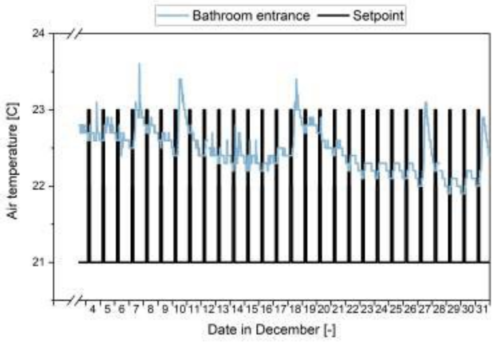


a: living room
b: bathroom entrance
c: bathroom
d: bedroom
e: kid room
f: office
g: depot

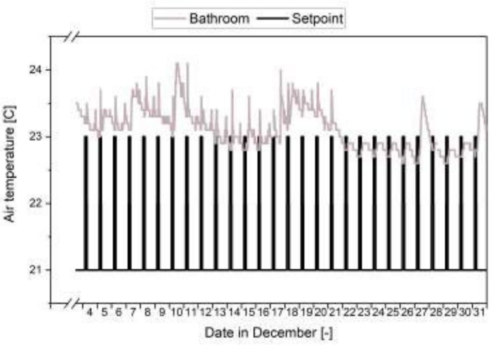
Figure 8. The floorplan in apartment B



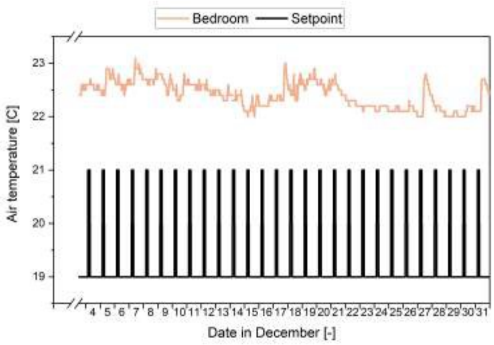
(a) Living room



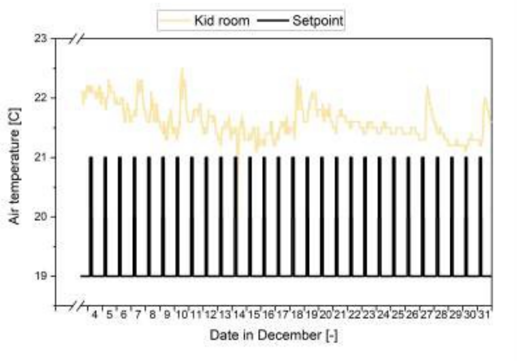
(b) Bathroom near entrance



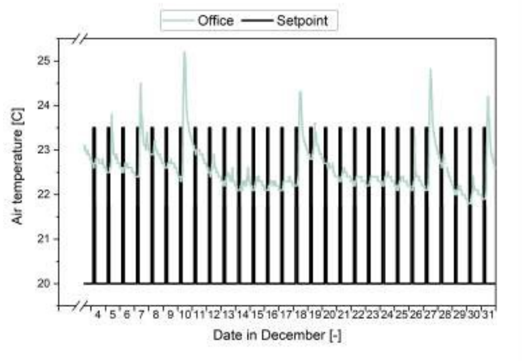
(c) Bathroom



(d) Bedroom



(e) Kid yard



(f) Office

Figure 9. The comparison between indoor air temperature and setpoint for each room in apartment B

The apartment used the scheduled setpoints with large differences between the HOME and AWAY setpoints. The 'bedroom' and 'kid room' were overheated, as the room temperatures were consistently higher than both the HOME and AWAY setpoints. The resulting duty cycle (and likely heat supply) was 0 for the whole month in both of these rooms. For the other four rooms (living room, bathroom entrance, bathroom and office), the rooms could not achieve their setpoints during the HOME periods and consistently exceeded their setpoints during the AWAY periods. Taking the living room as an example, the room temperature was maintained between the HOME and AWAY setpoints during the whole month, if we neglect a few brief temperature increases. When the setpoint switched to HOME, the duty cycle became non-zero. The four rooms with active floor heating had similar profiles for room temperatures and duty cycles. Therefore, the data of the bathroom near the entrance was selected for detailed analysis. Figure 10 shows the variation of temperature, setpoint and duty cycle within a typical day. The HOME setpoint was applied daily from 4.00 to 7.00 and the heat input only occurred within this period.

According to the data analysis, there is no problem with the thermal environment or floor heating operation in this apartment. However, it is clear that the room temperatures did not decrease with the lower setpoints and the high thermal requirement during the HOME period could not be met. Furthermore, all non-zero duties cycles occurred during a 3-hour period in each day, which implied that heat was delivered only during these periods. Had the HOME period coincided with peak demand in the district heating network, it would have exacerbated the peak instead of offsetting it.

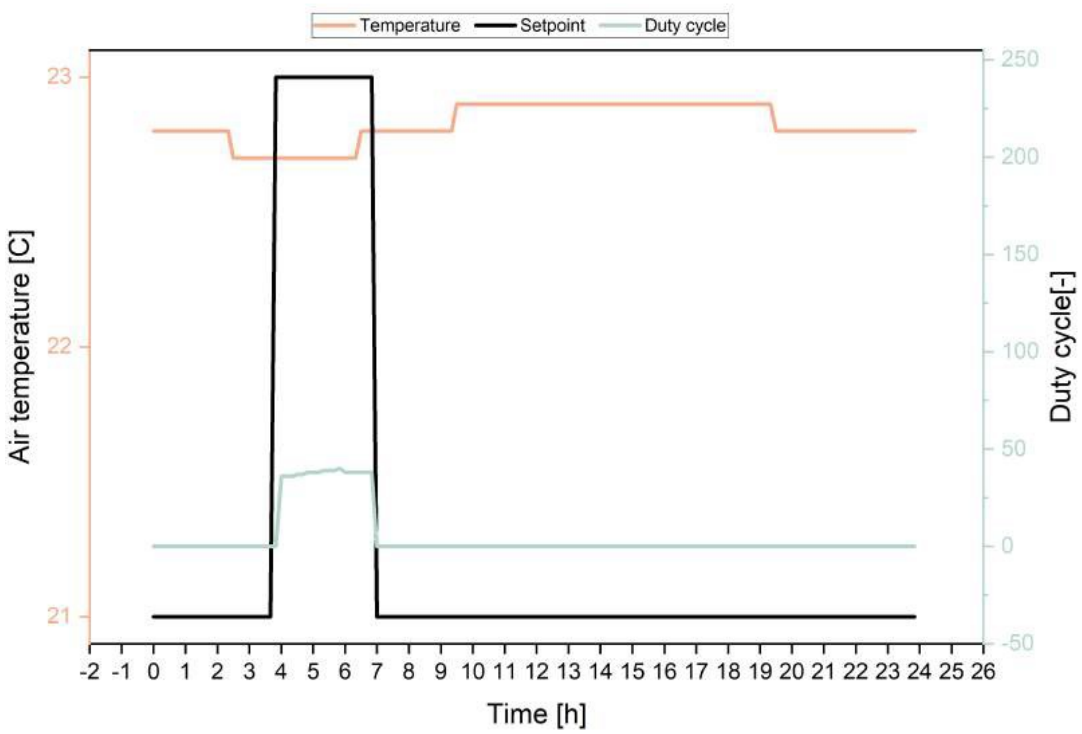


Figure 10. The relation between indoor air temperature, setpoint and duty cycle within one typical day for bathroom

An onsite investigation at the apartment was made around 16.00 on Mar. 4, 2020. The floor heating system was not active as the visit took place during the AWAY period in the scheduled setpoint mode. As a result, the temperature of the manifold was around 18.8 °C as shown in Figure 11.

Figure 11. The picture of floor heating manifold taken by thermographic camera during the AWAY state with low temperature setpoints

Residents mentioned that they did not use the floor heating systems very much, nor did they change the settings of floor heating. It indicates that the schedule setpoint mode may have been the default setting in Danfoss Link™ devices. But the application of the scheduled setpoint mode did not achieve an energy-saving effect. The drawbacks of the scheduled setpoint mode were explained to the resident who decided to remove the HOME schedule and keep the whole schedule in the AWAY state.

3. Simulations

Numerical simulations were introduced to analyze the influence of open internal doors and the schedule setpoint mode, based on problems inferred from the data analysis in the previous section. The applied simulation software is called IDA Indoor Climate and Energy (IDA ICE) provided by EQUA Simulation AB. In the case of internal door opening behaviour, the thermal environment and energy consumption for closed and open doors were compared. For the scheduled setpoint scenario, the impact of various AWAY setpoints was investigated first. Subsequently, simulations compared the scheduled and constant setpoint operation.

3.1 IDA-ICE Model

The simulated apartments were apartment A and apartment B from the previous section. The final physical models in IDA ICE are shown by Figure 12. The thermal environment in these adjacent rooms is assumed to be an ideal state. The typical room setpoints are based on the room type and their thermal environment requirements are achieved by ideal room units. The IDA ICE model includes the apartment itself as well as the rooms adjacent to the apartment, which are marked by red box.

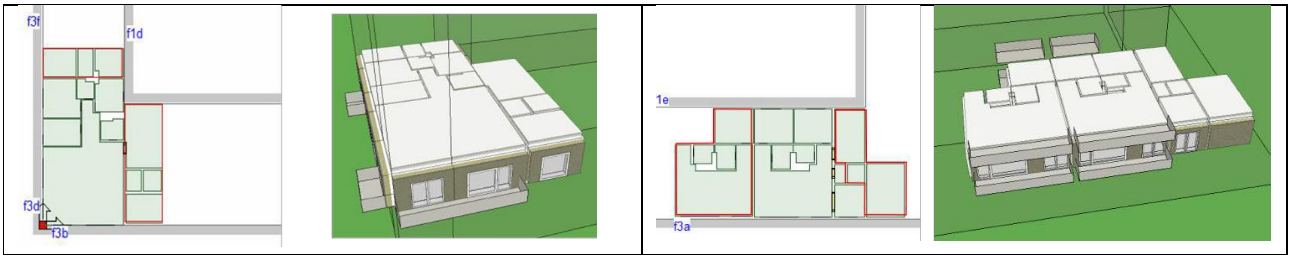


Figure 12. Floor plan and 3D model of apartment A and apartment B from the test site

According to the detailed drawings for building construction, the materials and their dimensions were estimated. The U-value for different construction elements are listed in Table 7 in the Appendix.

To show the influence of the two general issues in a common situation, the actual setpoints in the two apartments were not used in the IDA ICE models. Typical setpoints were assumed based on the room types. The setpoints for the living room, bedrooms and bathrooms were 22, 20 and 24 °C for both models. The base model applied a constant internal heat gain of 5 W/m^2.

With reference to the calculation examples in DS/CEN/TR 16798-2:2019 [13], the exhaust air from the bathroom was assumed to be 15 L/s with the rest coming from the living room, which is integrated with kitchen. The supply air was allocated to the living room and bedrooms by area. The temperature of the supply air in the building was assumed to be 19 °C. The detailed supply and return air flow rates for different rooms in the two models are listed in Table 8 in the Appendix. The design heat loads are given in Table 9 in the Appendix.

3.2 Internal door opening behaviour

It was inferred from the data analysis in Section 2 that open internal doors caused similar air temperatures and uneven energy consumption in all rooms. This section aims to verify this inference by comparing indoor the air temperature and heat consumption in two different scenarios – all internal doors open or all doors closed.

3.2.1 Scenario with closed internal doors

The model of the apartment A was simulated with closed internal doors. The simulation period was the month of December, 2019.

- Bedrooms

Figure 13 shows the simulated room temperatures of three bedrooms as well as the outdoor temperature. It is clear that the changes to indoor temperature in the three bedrooms followed the overall trend of the outdoor temperature. When the outdoor temperature reached its lowest point between Dec. 19 and Dec. 21, the three bedrooms' temperatures were also at their lowest value. There was no heat consumption during the entire month of December in the three bedrooms. The internal heat gains were enough to make up for the transmission and ventilation heat loss, so the floor heating was inactive. Thus, it is possible for a bedroom to achieve thermal balance or even be overheated without active floor heating if the heat loss is small (e.g. low setpoint and good insulation level), even with closed bedroom doors.

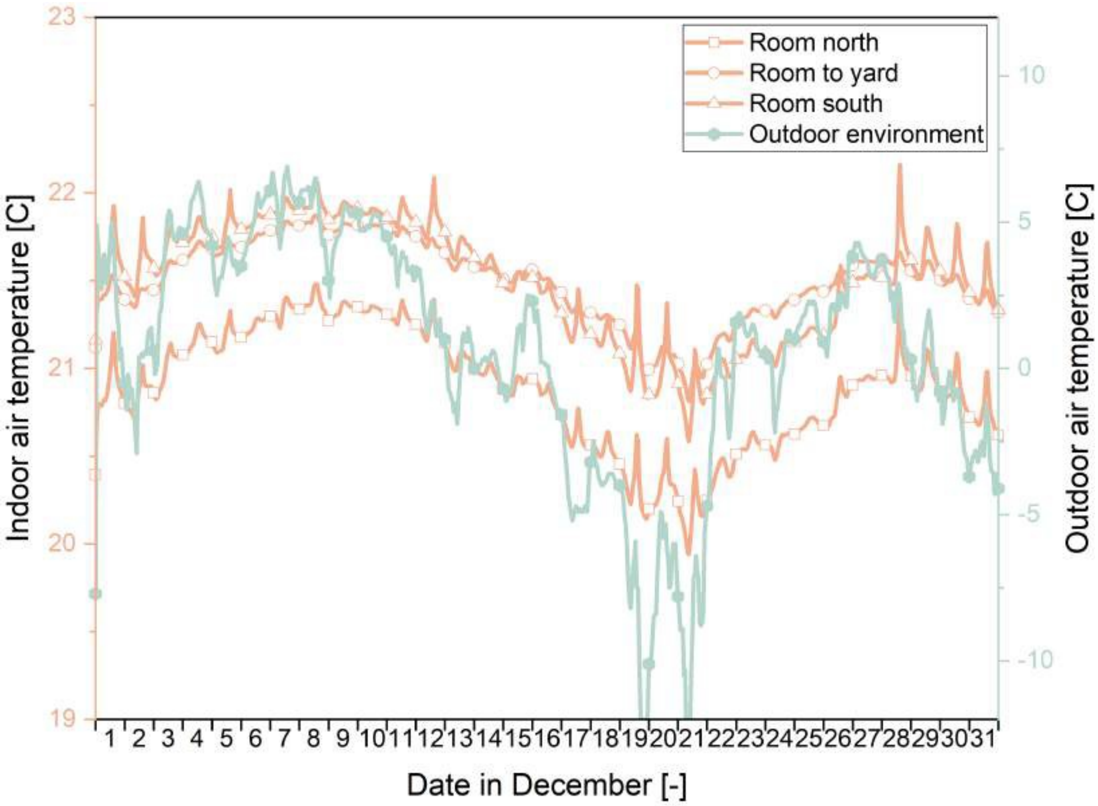


Figure 13. The relation between indoor temperature of the bedrooms and outdoor temperature

- Living room

Figure 14 shows the simulated indoor air temperature and heat consumption of the living room as well as the solar radiation. The temperature pattern of the living room did not follow the outdoor temperature. Instead, it followed the changes to solar radiation. When the solar gain was large, the average temperature was high and there was a peak around noon. When the solar radiation was weak, the temperature curve was flat throughout the day and the temperature level was only slightly higher than the setpoint. The heat consumption curve was opposite to that of the solar radiation profile. When solar radiation was strong, no heating was required. In the night when there was no solar radiation, the floor heating was necessary to maintain the 22 °C desired indoor temperature. In some cases, the floor heating power varied with the outdoor temperature. This was especially true on particularly cold days.

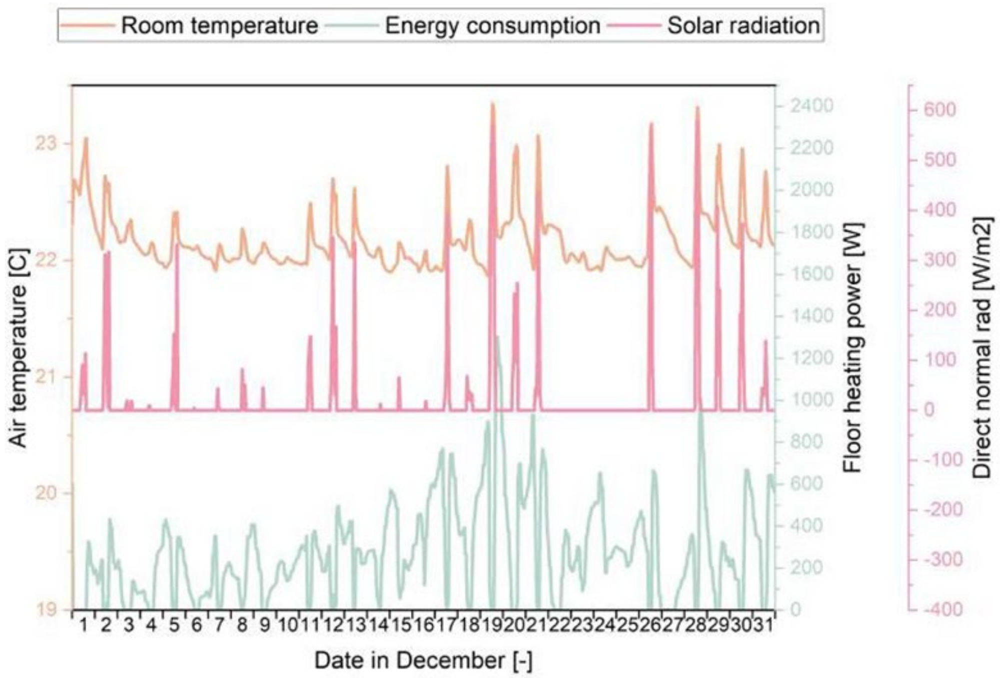


Figure 14. The relation between indoor temperature, heat consumption of living room and outdoor solar radiation

- Bathrooms

Figure 15 shows the simulated temperature and heat consumption in the two bathrooms as well as the simulated temperature in the living room. The temperature curve of the bathroom was mostly flat, and only when there was an obvious temperature increase in the living room did the temperature in the bathroom rise slightly. The bathroom did not have any exterior walls or windows, so it was primarily influenced by the temperature of the air that entered from the living room. Exhaust air was constantly extracted from the bathroom at a rate of 15 L/s, and the replacement air came from the living room. This influenced the bathroom's heat balance and increased its air temperature. The floor heating power curve was also stable, as it was not influenced by the outdoor temperature or solar radiation.

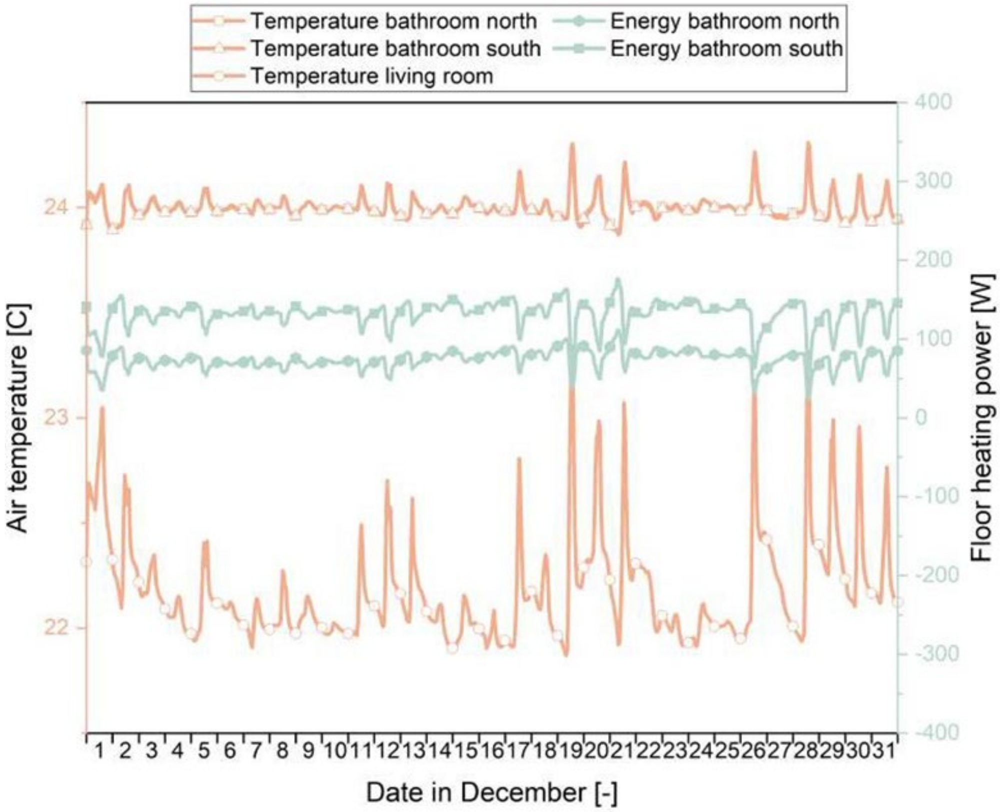


Figure 15. The relation of indoor temperature, heat consumption of bathroom and living room temperature

The average energy consumption and return temperatures for different rooms in December under the closed internal doors are listed in Table 1. The living room had the highest energy consumption due to its large area, while two bathrooms had the highest energy consumption per unit area as well as the highest return temperature. The energy consumption per area and return temperature are related to the room setpoint, since the room requires a higher floor temperature. The simulated total energy consumption of this apartment in December was 364 KWh with closed internal doors.

Table 1. The energy consumption and return temperatures for different rooms in December

	Energy consumption [KWh]	Energy consumption per unit area [KWh/m^2]	Average return temperature [°C]
Living room	205.2	2.4	23.4
Room south	1.4	0.1	21.6
Room north	2.4	0.12	21.0
Bathroom north	55.0	12.2	26.1
Boom yard	1.4	0.1	21.5
Bathroom south	98.6	16.1	27.0

In summary, under the scenario with closed internal doors, each room type had a different indoor air temperature and heat consumption pattern. The rooms with low setpoints achieved or exceeded their thermal requirement without active floor heating due to the relative similarity between their heat loss and heat gains. The rooms with high setpoints consumed a high amount of energy per unit area and yielded a high hot water return temperature.

3.2.2 Scenario with open internal doors

In this subsection, the model of apartment A was simulated with open internal doors. Except for the state of doors, the simulations were the same. The simulated air temperature and heat consumption of each room are shown in Figure 17 where the simulation results of the closed door scenario are also shown for comparison.

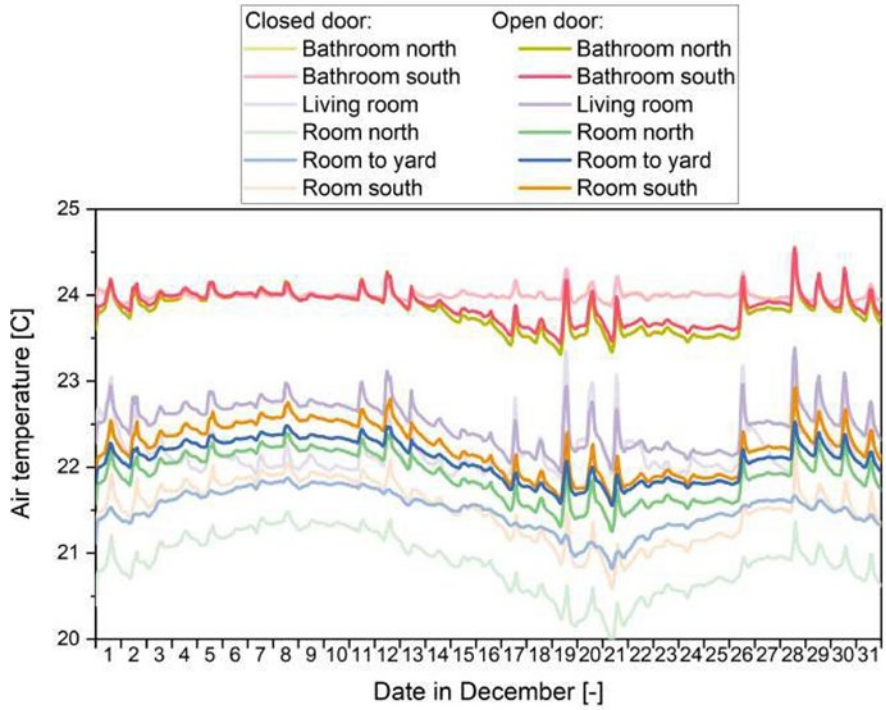
Figure 17a yielded three main findings:

- The temperatures of the living room and three bedrooms increased.
- The temperature patterns of the living and three bedrooms became similar.
- The thermal requirement of two bathrooms was not met from Dec. 13 to Dec. 25.

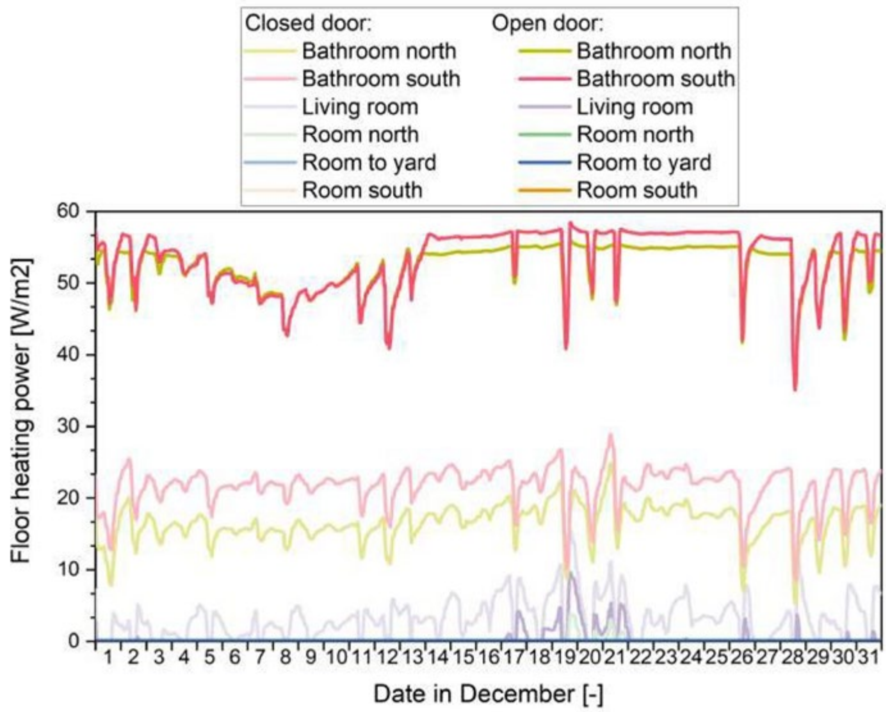
Figure 17b yielded two main findings:

- The heat consumption in the living room decreased to 0.
- The floor heating of the two bathrooms increased substantially and operated at maximum capacity from Dec. 13 to Dec. 25.

Under the open doors scenario, the air in all rooms mixed rather well, resulting in similar temperature profiles. The rooms with a low setpoint received heat from the rooms with a high setpoint. The increased air temperature in the rooms with a low setpoint resulted in higher overall energy consumption. In this scenario, the individual control failed and it became a centralized control system based on the highest setpoint. The floor heating of the room with a high setpoint operated at close to full capacity while the floor heating in the other rooms were inactive.



(a) Air temperature in different rooms under close and open internal doors



(a) Floor heating power in different rooms under close and open internal doors

Figure 16. The comparison between two simulations under different door opening conditions

The average energy consumption and return temperature for different rooms with open internal doors are listed in Table 2.

Table 2. The average energy consumption and return temperatures for different rooms under open internal doors

	Energy consumption [KWh]	Energy consumption per unit area [KWh/m^2]	Average return temperature [°C]
Living room	25.9	0.3	22.6
Room south	1.3	0.1	22.3
Room north	1.3	0.1	21.9
Bathroom north	174.8	38.9	29.5
Room yard	1.3	0.1	22.1
Bathroom south	242.5	39.7	29.9

The energy consumption of the bathrooms almost tripled compared to the closed doors scenario. To cover the high heat demand in two bathrooms, a higher total water volume was required, which increased the return temperature of the two bathrooms by 3 °C compared to the closed doors scenario. The total energy consumption with open doors was 447.1 KWh, which was 83.1 KWh higher than that of the closed door scenario. This represented a 22.8% increase in heating consumption.

In summary, open internal doors led to thermal discomfort, excessive energy consumption and high return temperatures. This information should be conveyed to customers. Hopefully this would encourage them to keep the internal doors closed when applying different setpoints to rooms. If the residents prefer to have open doors, the residents should apply the same setpoint to rooms. This finding likely applies to radiator-based heating systems as well.

3.3 Schedule setpoint mode

Based on the findings from Section 2, the implementation of a scheduled setpoint can cause all heat to be consumed within the HOME period, which is often very short. A scheduled setpoint is often advertised as an energy saving measure, which should allow a decrease in air temperature (and thereby heat loss) when the occupants are not at home. It must be clear that this does not apply to all installations. More specifically, in building with heavy floor heating and/or low heat demand, the temperature may not cool down during the setback period. This section describes a simulation-based investigation into the impact of a scheduled setpoint mode for concrete-embedded floor heating operation in the two reference apartments (apartment A, apartment B). The investigation is divided into two phases:

- Investigation into how the settings of the two setpoints, HOME and AWAY, influence the apartment's thermal environment and energy consumption
- Comparison of the heat demand between the scheduled setpoint scenario and constant setpoint scenario

3.3.1 Setpoint scheduling

Replicating the actual Danfoss Link™ controller in IDA ICE was non-trivial. The standard PI controller in IDA ICE includes a time constant and a tracking time. The latter provides anti-wind-up when the setpoint cannot be realized due to physical constraints (e.g. insufficient heating capacity or overheating outside of the heating season). However, wind-up is handled differently in the Danfoss Link™ controller, and there was not a straightforward way to replicate the behavior of the Danfoss controller in IDA ICE. It was therefore decided to use a proportional controller, even though it would produce a steady state error. This was taken into account in the analysis of the results.

The user guide of the Danfoss Link™ cautions the user about the scheduled setpoint setting: the customer should not lower the temperature by more than 1-2 °C because lowering the temperature too much would prevent the system from reaching the low temperature and it will cause a heavy burden on the heating source when it switches to the HOME mode. However, when the authors checked the recorded data from customers, the maximum temperature difference between the HOME and AWAY modes was 7 °C (i.e. from 16 °C to 23 °C in one of the bathrooms).

Therefore, the impact of different scheduled setpoints should be understood before further investigation. Four cases with temperature differences of 1 °C, 2 °C, 4 °C and 6 °C were simulated and analyzed.

The simulations applied typical setpoints to the HOME mode (i.e. living rooms, bedrooms and bathrooms used 22, 20 and 24 °C respectively) and applied the temperature differences above to determine the AWAY setpoint. Taking the living room as an example, the HOME setpoint was 22 °C, and the AWAY setpoint was 21, 20, 18 and 16 °C respectively. The HOME setpoint was applied from 4 am to 7 am with the consideration of preheating the apartment after night set-back.

For the thermal environment analysis, Dec. 18 was selected for further investigation because of its extreme outdoor temperature and lack of solar radiation, which corresponded to critical floor heating operation.

Firstly, it was found that the room air temperature curve was very flat regardless of the applied temperature difference between the HOME and AWAY states. The difference between the maximum and minimum temperature on Dec. 18 for every room under the four cases is listed in Table 3. The bathrooms experienced the greatest variation in temperature, which became larger with increased setpoint changes. However, even in the bathroom, the difference between the maximum and minimum temperature never exceeded 0.7 °C. In all cases, the room temperature variation was rather small compared to the change in setpoint.

Table 3. The difference between maximum and minimum temperature on Dec. 18 for every room under cases with different setpoint change

	Case 1	**Case 2**	**Case 3**	**Case 4**
$\Delta T_{HOME,AWAY}$	1°C	2°C	4°C	6°C
Living room	0.3	0.3	0.3	0.3
Bathroom left	0.4	0.6	0.6	0.6
Bathroom right	0.4	0.7	0.7	0.7
Room left	0.1	0.2	0.2	0.2
Room right	0.1	0.1	0.1	0.1
Depot	0.1	0.1	0.1	0.1
Office	0.3	0.3	0.3	0.3

Secondly, the indoor temperature level had a strong correlation to the HOME setpoint and very little correlation to the AWAY setpoint. Table 4 shows the average indoor air temperature under different cases. It is clear that the average temperature is close to the HOME setpoint despite the HOME state being active for only 3 hours per day. The average temperature did not change significantly between the four cases, except for the case of the bathroom. Even in this case, the difference was only 0.7 °C.

Table 4. The average temperature on Dec. 18 for every room under different cases

	HOME setpoint	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Living room	22	21.9	21.8	21.8	21.8
Bathroom left	24	23.6	23.1	23.0	23.0
Bathroom right	24	23.6	23.0	22.9	22.9
Room left	20	20.2	20.2	20.2	20.2
Room right	20	20.3	20.2	20.2	20.2
Depot	20	21.4	21.4	21.4	21.4
Office	20	21.1	21.1	21.1	21.1

The average bathroom temperatures were always closer to the HOME setpoint than the AWAY setpoint, but they did not fully achieve their HOME setpoint, especially in Cases 2-4. This was likely due to the very short HOME period of only 3 hours. Figure 20 shows the indoor temperatures for case 2 on Dec. 18. The temperature is on an upward trajectory when the heating stops ahead of the AWAY period.

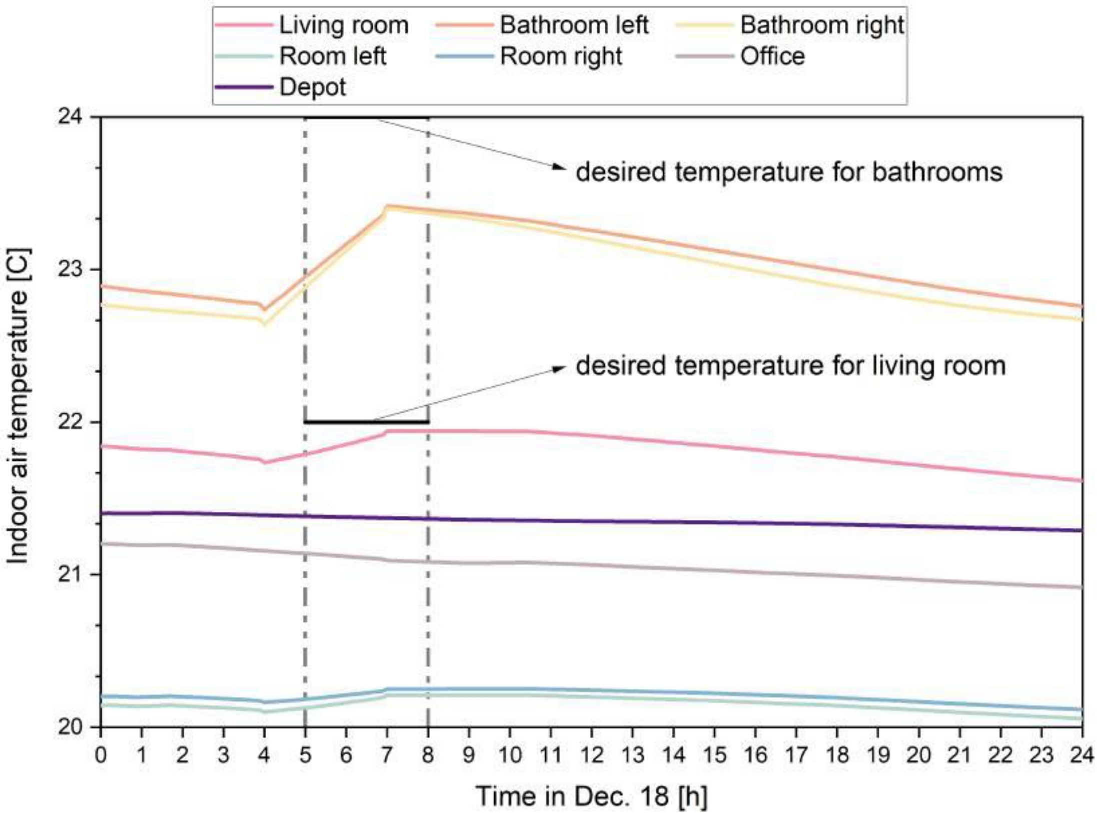


Figure 17. The indoor temperature curves for different rooms under case 2

In terms of total energy consumption, the results show very little difference between the four cases. Case 1 has a slightly higher temperature and energy consumption because the indoor temperature falls within the proportional band during the AWAY period. The peak demand and total energy consumption for all cases are shown in Table 5. Figure 22 shows the heating power in the living room for Cases 1, 2 and 3. Case 4 was omitted since it had the same results as Case 3.

Table 5. The peak demand and total energy consumption over one day for different cases

	Case 1	**Case 2**	**Cases 3 & 4**
Peak demand [W]	1546	1727	1836
Total consumption [KWh]	5.3	4.8	4.8

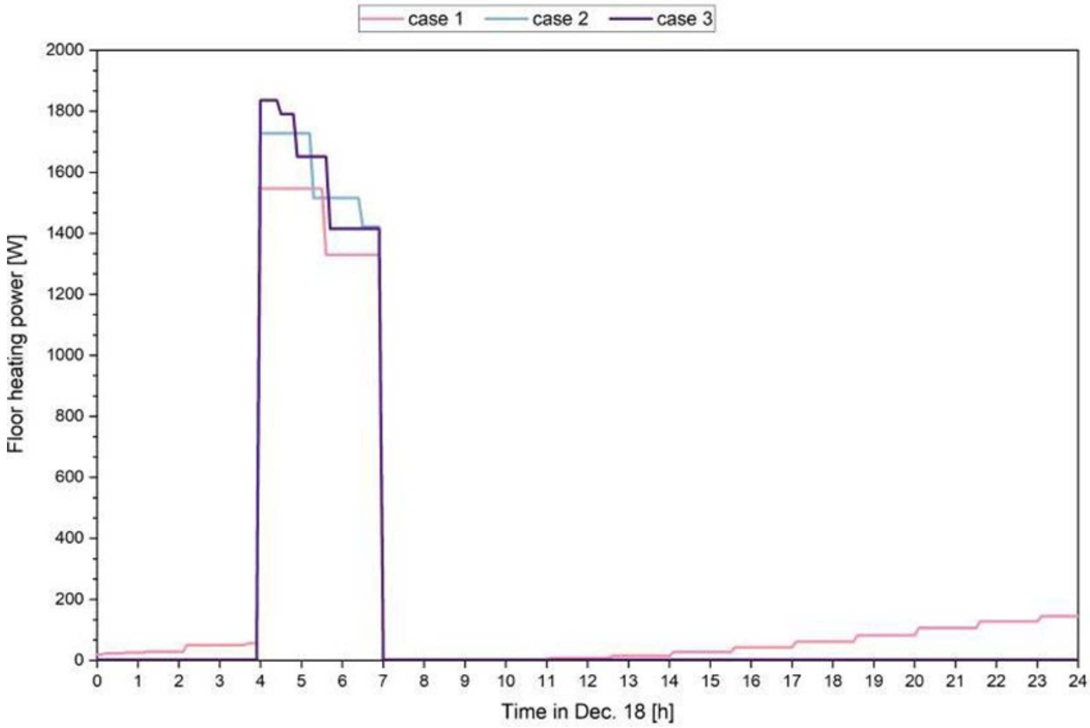


Figure 18. The heat consumption of the living room under three cases

In summary, the magnitude of the setpoint change between the HOME and AWAY modes had very little influence on thermal comfort and energy consumption since the HOME setpoint generally determined the temperatures throughout the day. This was true for HOME periods as brief as 3 hours. It should be noted that this is likely due to the high hot water supply temperature, as it yields a high heating capacity. With lower hot water supply temperatures, the resulting indoor temperature would likely settle closer to the AWAY setpoint for all cases.

3.3.2 Constant versus scheduled setpoint

This section describes a comparison between the scheduled and constant setpoint modes regarding energy consumption. For the scheduled setpoint mode, the investigation focused on Case 2 from the previous subsection, which had a 2 °C temperature difference between HOME and AWAY. Figure 23 shows the heat consumption curves of both modes under three typical winter climates, represented by three dates with different outdoor temperatures and very little solar radiation. The scheduled setpoint mode had a typical night set-back pattern with a morning re-heating from 4:00 to 7:00. All heat demand occurred during this period, as there was no heat demand during the AWAY period. For the constant setpoint mode, the heat consumption was rather flat, representing stable heat demand.

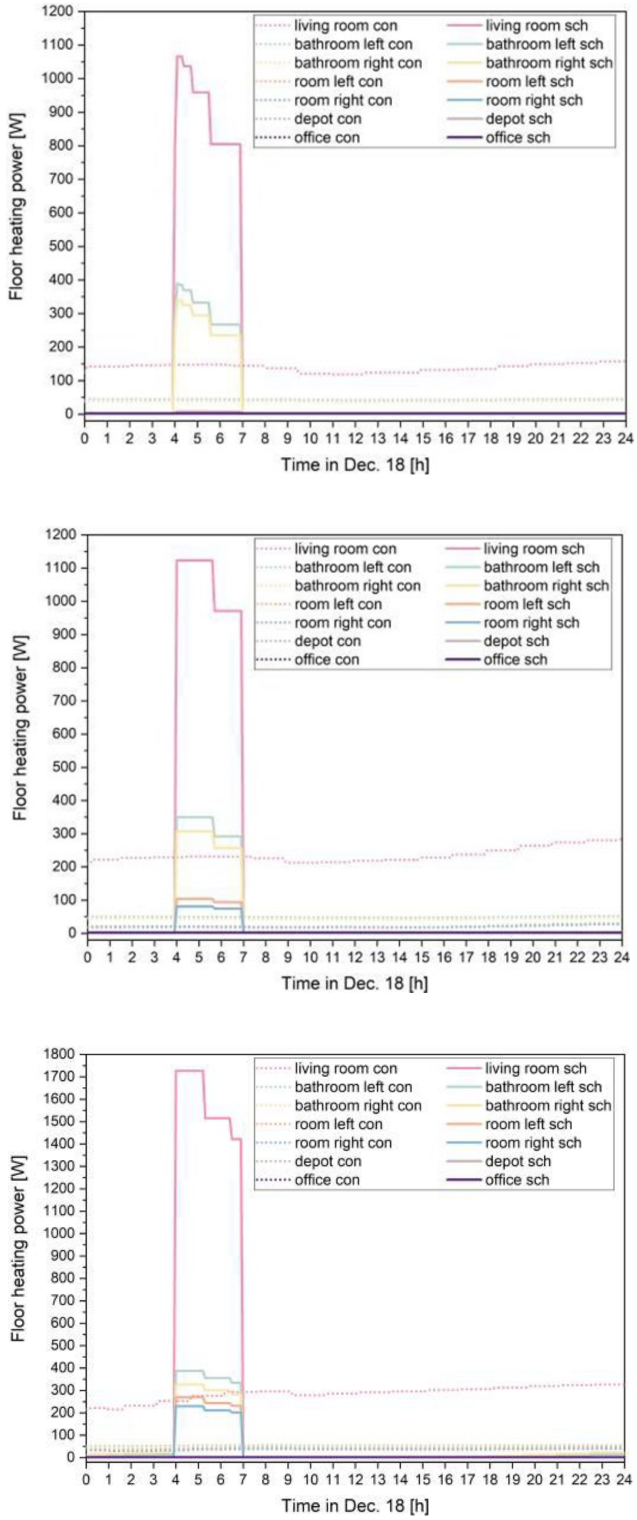


Figure 19. The comparison of heat consumption between schedule setpoint (sch) mode and constant (con) setpoint mode under three typical winter climates: Dec. 10 (top), Dec. 14 (middle) and Dec. 18 (bottom)

The results yielded several relevant insights. Firstly, the HOME setpoint, when applied only during the peak period, exacerbates peak demand in the district heating network.

Secondly, the required heating for a whole day may be provided in a 3-hour period without a noticeable impact on thermal comfort when using a supply temperature of 40 °C. This represents a part-load of roughly 12.5% (i.e. 3h/24h). With smart thermostatic control, this could yield a potential energy flexibility, where shifting thermal loads eases the strain of peak demand on the district heating network. However, with excessive heating power, the floor may be excessively charged. The resulting increase in energy consumption and return temperatures could be caused by overshoot due to the thermal lag or by faulty control, such as mismatched thermostats or inadvertently opened windows. Energy flexibility should not result in excessive energy consumption and/or operation temperatures, so operation temperatures should be lowered before applying a load shift.

4. Load shift potential

In the previous sections, the main drawback of a schedule setpoint mode was revealed. In the simulations, most energy was consumed during the short HOME period and this resulted in a high hot water return temperature. The constant setpoint mode was a straight-forward solution since it yielded a relatively flat demand curve and lower hot water return temperatures. But even under the constant setpoint mode, energy was consumed during the peak periods (from 6:00 to 9:00 and from 17:00 to 20:00). The constant setpoint mode does not reflect the load shift potential of the concrete floor's high thermal inertia. The indoor temperature can be kept fairly constant even if the floor heating is turned off for a short period. The ideal situation of load shifting is as follows: the floor heating is turned off during the peak periods but the temperature reduction during these periods is negligible. The heat consumption is slightly higher in the off-peak periods to compensate for the reduced consumption in the peak periods. Overall, there is minimal change to the total daily energy consumption because the indoor temperatures remain approximately the same. This strategy aims to relieve stress on the thermal grid and improve system reliability. It also aims to create economic benefits for the customers if the heating bill is based on Time-of-Use pricing. From the perspective of the district heating utilities, the expensive peak heating load boiler may be avoided if the load shift is broadly implemented. To investigate the effect of load shifting on the case building, a load shifting measure was implemented in several apartments on Mar 31 and Apr. 2 to 4 of 2020. The average outdoor temperature was 4.4 °C for all four dates, which was less than the monthly averages from December to March. On these dates, the setpoint was reduced by 2 °C from 6:00 to 9:00 and from 17:00 to 20:00.

Thus, the influence of load shifting on the thermal environment and energy consumption will be studied in this section based on the experimental data analysis. The dynamic simulation will also be conducted as a supplementary explanation.

4.1 Data analysis

For this subsection, the air temperature, setpoint and duty cycle data for all connected apartments was collected, filtered and analyzed.

After a screening, only six apartments had rooms that could be used for load shift analysis. This included four living rooms, four bedrooms and eight bathrooms.

The general findings from the data analysis are listed below:

- The influence on the thermal environment in the peak period was negligible.

  Checking the daily temperature profiles for the different rooms, it was found that most bathrooms and bedrooms had very stable indoor temperatures. There was little or no temperature decrease during the morning and evening peaks for these rooms. For the living rooms, the temperature rose in the morning peak due to the influence of solar radiation. During the evening peak, the temperature fell but the decrease was negligible, as the temperature in most of rooms decreased by less than 0.5 °C. There were also some exceptions. In one case, the maximum temperature drop was 1.7 °C, but the sharp decline was likely caused by an open window since the temperature decrease was uncharacteristic of the data as a whole.

- The 0 duty cycle during peak periods implied that heat demand was removed with the implementation of the load shift measure.

  The signal for the duty cycle was kept at 0 during the peak periods in most rooms because the room temperature was much higher than the setpoint. Since this load shifting experiment was implemented late in the heating season, the result was likely influenced by direct solar radiation. The duty cycle for most rooms was between 20 and 80 (out of 255) and there were many apartments with duty cycles of 0 in all rooms. It was straightforward to reduce the duty cycle to 0 during this period by simply reducing the setpoint. This method was implemented in January, but due to an unexpected software update at the turn of the new year, the load shift was not realized. This, as well as connectivity issues, delayed the implementation to later in the heating season. It would be relevant and interesting to repeat the experiment with similarly low outdoor temperatures without the risk of direct solar radiation.

- A schedule offset of -2 °C is not a panacea.

The reason for a -2 °C schedule offset was that this would cover the maximum integral term in the Danfoss Link™ floor heating controller. If the indoor temperature is well regulated by the floor heating, the temperature will be close to the room setpoint. When the setpoint is abruptly decreased by 2 °C, the room temperature will remain the same due to the thermal inertia of the concrete floor. Under these circumstances, the duty cycle is 0 and the valve remains closed. But when the room setpoint is high and the temperature does not reach the setpoint due to insufficient heating capacity, the indoor temperature may be within 2 °C of the shifted setpoint. This occurred in one of the bathrooms in the analyzed period. The original setpoint for the morning and evening peak was 26 °C, which was decreased to 24 °C during the load shift experiment. During the off-peak period, the heating system could not maintain 26 °C in the bathroom, perhaps due to open internal doors. Instead, the temperature was between 24 and 25 °C. Therefore, the indoor temperature was only slightly above the setpoint of 24 °C during the peak period, so the duty cycle was non-zero for a brief period after the change. Thus, the load shift measure with a -2 °C setpoint offset decreases the duty cycles to 0 during the peak periods in a well-functioning system (e.g. attainable temperature setpoints and closed internal doors), but it may be necessary to use a schedule offset of -3 °C in rooms with unattainably high setpoints to immediately minimize the duty cycle.

Therefore, according to the data recorded by the Danfoss Link™ devices, it was found that a scheduled setpoint offset of -2 °C between 6:00 and 9:00 and between 17:00 and 20:00 reduced duty cycles to zero during the peak periods with negligible impact on indoor temperatures. However, it only showed the effect of load shifting in the transition season from winter to spring. While the average outdoors temperatures on the test dates were less than the monthly averages from December to March, there was a risk that solar radiation influenced the results. The load shift potential in the rest of the heating season was not yet known, so simulations were performed in IDA ICE to assess this potential.

4.2 Simulation results

Dynamic simulations were conducted to investigate the influence of load shifting during the typical heating season (from November to February). A comparison between the scenarios with and without the load shift were carried out. The model of apartment A was used to show the difference between the constant setpoint mode and the scheduled setpoint mode with peak-shifted loads. Since the situation in different rooms was similar, the living room was selected for illustrative purposes. Figure 24 shows the floor heating power under the original setpoint and the modified setpoint during the coldest week. It is clear that there was no energy consumption in the morning and evening peak periods under the modified setpoint. The energy consumption during the off-peak periods increased slightly, and there appeared to be a rebound effect immediately after the peak periods. This was likely due to the high heating power supplied by 40 °C water. When the load shift was applied, it stopped the energy consumption during peak periods but the heating consumption became more concentrated in the off-peak periods, which slightly increased the return temperatures. The consequence of higher return temperatures should be evaluated against the benefit of shifted peak loads. However, a solution to both these issues would be a reduction in hot water supply temperature, as 40 °C far exceeded what was necessary to meet demand. A reduced supply temperature would decrease the heating capacity and thereby limit the rebound effect while also decreasing return temperatures.

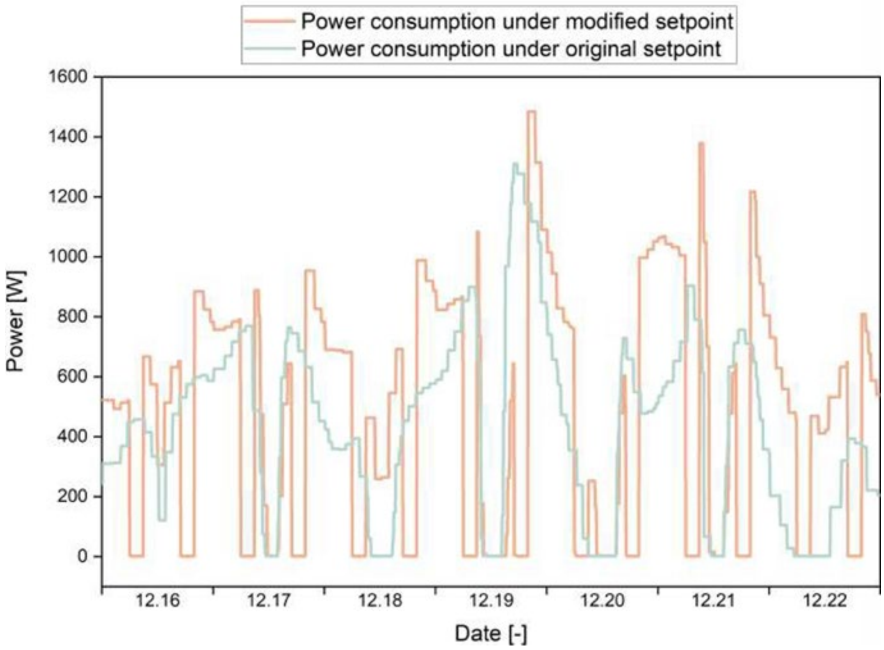


Figure 20. The floor heating power in the living room of apartment A during the coldest week with and without the load shift measure

Figure 25 shows the temperature variations over the coldest week for the original setpoint and the load-shifted setpoint in apartment A. As expected, the air temperature difference between the two scenarios was slightly larger during the peak periods, but the temperatures were very similar overall.

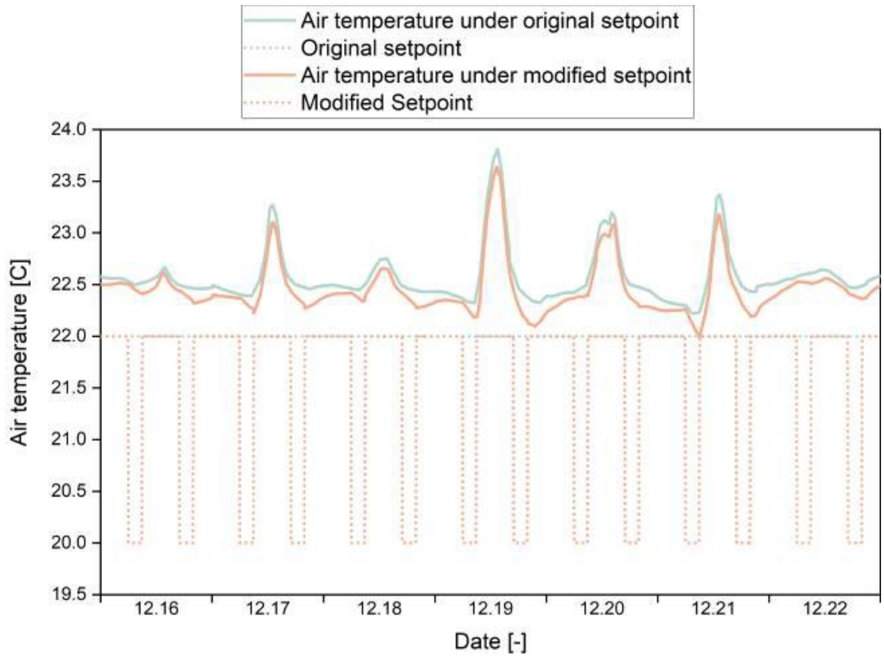


Figure 21. The indoor temperatures in the living room of apartment A during the coldest week with and without the load shift measure

Based on the analysis of the thermal environment, it was found that a setpoint reduction could shift the load from the peak period to the off-peak period on the coldest days with minimal effect on the indoor temperature.

4.3 Estimated total potential

To estimate the total load shift potential for the building, the authors used consumption data from the central district heating meter for all of 2018 and 2019. The data included consumption of domestic hot water (DHW), so the authors estimated the hourly DHW consumption profile by averaging the hour-by-hour consumption in July and August. The authors then subtracted this profile from each day in the dataset to estimate the space heating demand. Shows the resulting data in hour-by-hour box plots.

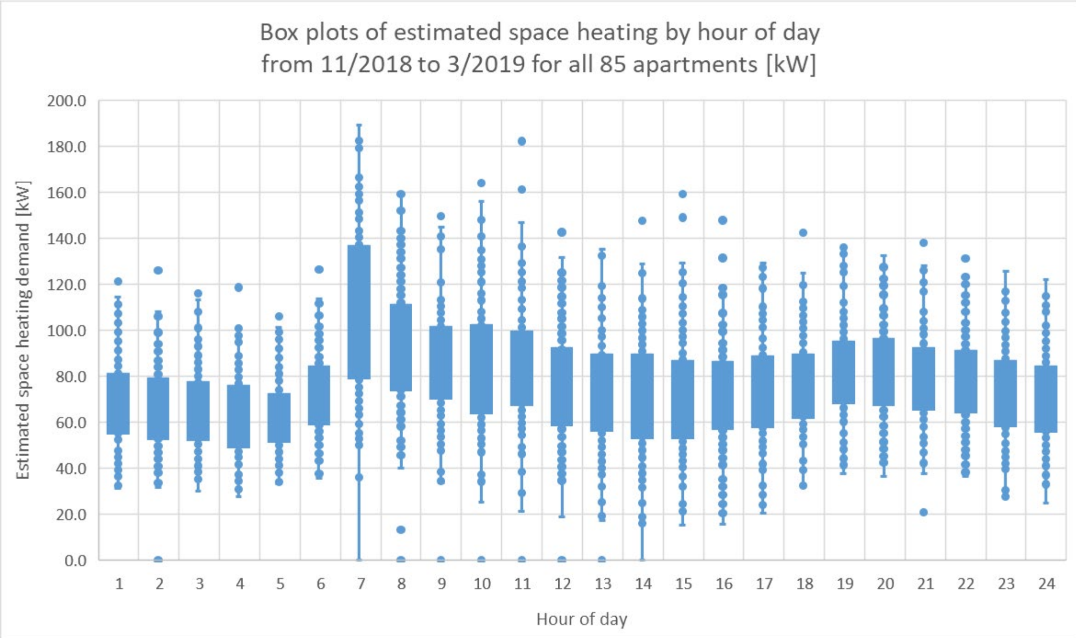


Figure 22. Box plots of the estimated hour-by-hour space heating demand based on the heat meter data for the building. The data clearly shows a peak in demand during the 7th hour from 6:00 to 7:00, which coincides with the start of the default HOME state in the floor heating controller as well as the start of the local peak district heating period.

Using the estimated space heat consumption data for the entire building, the authors evaluated the difference between the actual hourly space heating demand and the 24-hour running average. Figure 19 showed that the heat demand is likely to be fairly constant on cold days with minimal solar radiation when using a constant indoor temperature setpoint. Therefore, the 24-hour running average space heating demand may provide a reasonable estimation of the heat demand with a constant setpoint. When comparing the average space heating demands to the 24-hour running average, the peak difference coincided with the default activation of the 'home' temperature setpoint in the controller from 6:00 to 7:00, as shown by Figure 23. During this hour, the space heating demand exceeded the 24-hour running average by an average of more than 30 kW in three of the five coldest months and up to 35 kW in the coldest month. The latter represents a 42% increase above the 24-hour running average. According to project participants the local district heating company HOFOR, the peak period is from 6:00-9:00 and from 17:00-20:00. Therefore, the case building could achieve a substantial reduction in peak space heating demand by simply implementing a constant temperature setpoint in all thermostats as a starting point.

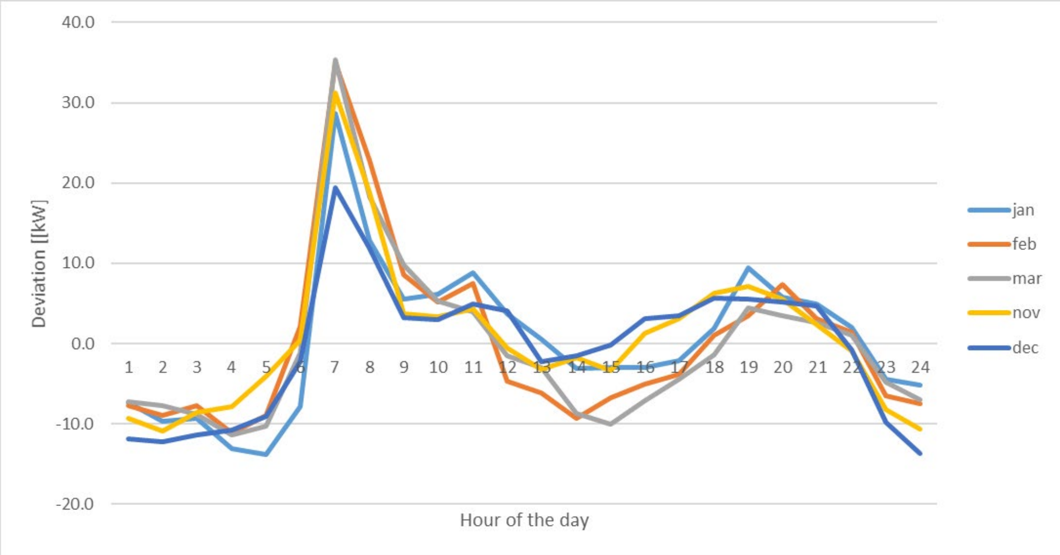


Figure 23. The average hour-by-hour deviation between the space heating demand and its 24-hour running average in all 85 apartments during the months from November to March in 2018 and 2019.

The prior subsections demonstrated the potential of floor heating to shift space heating loads away from peak periods with minimal effect on thermal comfort. When using a constant indoor temperature setpoint, the analysis found that reducing the setpoint during the peak period (6:00-9:00 & 17:00-20:00) could shift the entire space heating load to non-peak periods. Simulations further demonstrated that even on the coldest days, there would be a negligible impact on indoor temperatures. According to heat meter data from the case building, the daily-average space-heating demand exceeded 40 kW from November ‘18 to March ’19. During these months, with a constant indoor temperature setpoint, the space heating demand would likely remain above 40 kW for most hours due to the high thermal inertia of the floor heating. This assumes a relatively low amount of solar radiation in these months and that heat demand is fairly stable on non-sunny days when using floor heating, as inferred from simulations. Therefore, after implementing a constant indoor temperature setpoint, the additional load shift potential from reducing setpoints during peak periods (6:00-9:00 & 17:00-20:00) would be upwards of 40 kW from November to March. To avoid rebounds in demand after the peak periods, the hot water supply temperature should be minimized. The temperature should be sufficient to meet the demand with only 18 hours of operation but low enough to avoid excessive rebound.

The sum of these measures (i.e. a constant indoor temperature setpoint during non-peak periods and a decreased indoor temperature setpoint during peak periods) could offset the entire typical peak load for space heating in the case building without negatively impacting thermal comfort. In 2018 and 2019, the average space heating demand was 111 kW, 99 kW and 88 kW, in the first, second and third hours of the morning peak respectively in the months from November to March. The equivalent demand in the afternoon peak was 85 kW, 88 kW, and 88 kW for the three hours respectively. Thus, upwards of 85 kW of peak demand could be shifted through smart thermostatic control on average during the five coldest months. Integrating the demand, an average of 558 kWh of peak consumption could be shifted daily in the case building from November to March when implementing the recommended smart thermostatic control.

5. Conclusion

The authors used data from Danfoss Link™ central controllers to assess the performance of the floor heating systems in the case building and inferred interesting system behavior from the data. In one of the analyzed apartments, the authors inferred from the data that several thermostats had been switched between rooms, which led to high duty cycles (i.e. length of valve openings) and overheating. Furthermore, the data analysis showed that it was important that occupants closed the doors between rooms when applying different temperature setpoints. Through simulations, the authors demonstrated that heating in high-setpoint rooms (e.g. bathrooms) was highly active while the heating in all other rooms was inactive. The elevated air temperatures in low-setpoint rooms likely resulted in greater heat loss, which would have increased total heat consumption. The continuous hot water flows in the high-setpoint rooms likely also contributed to higher total return temperatures. The data analysis also showed that many occupants used a scheduled setpoint mode, which changed the temperature setpoints according to their scheduled occupancy. This was intended as an energy saving measure, which should allow the air temperature to decrease (and thereby reduce heat loss) when the apartment was unoccupied. However, the indoor temperatures remained high long after the controller changed setpoints and stopped the hot water flow. In one case, each day's entire heating consumption was supplied during a 3-hour 'home' period. This demonstrated the extent to which 40 °C supply temperatures were excessive. And had this 'home' period coincided with peak demand in the district heating network, it would have exacerbated the peak. Thus, through data analysis and simulations, the investigation showed that constant temperature setpoints provided better performance than scheduled setpoints with setback. The investigation also demonstrated the potential of smart thermostatic control to shift loads from peak periods. The analysis indicated that reducing the indoor temperature setpoints during the peak periods (6:00-9:00 & 17:00-20:00) had a negligible effect on thermal comfort due to the high thermal inertia of the floor heating and the high heat retention of the building envelope.

As a starting point, the report recommends using the same temperature setpoint in rooms that often share an open interior door and closing the doors between rooms with different setpoints. In modern buildings with hydronic floor heating, the report recommends using a constant indoor temperature setpoint to avoid the peaks caused by night setback. In the case building, this measure alone could reduce peak demand by up to 35 kW in the coldest months. As an added measure, reducing the setpoint during the peak period could shift the remaining load, even on the coldest days, with a negligible effect on indoor temperatures. In total, upwards of 85 kW of peak demand could be shifted through smart thermostatic control on average during the five coldest months. Integrating the demand over time, an average of 558 kWh of peak consumption could be shifted daily in the case building from November to March when implementing the recommended smart thermostatic control.

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7. Appendix

Table 6. U-value of different constructions elements

Construction Element	U-value [W/m^2]
External Wall A	0.1253
External Wall B	0.1256
Internal Floor	0.2634
Bathroom Floor	0.9163
Non-bearing Wall	1.131
Bearing Wall	3.434
Bathroom Wall	1.422
Triple glazed window	0.53
22% window frame	1.8

Table 7. The assumed ventilaiton rates of different rooms in the models

First sample apartment	Supply air [L/s]	Return air [L/s]
Living room	36.6	27
Room yard	6	0
Room south	6	0
Room north	8.4	0
Bathroom south	0	15
Bathroom north	0	15
Second sample apartment	Supply air [L/s]	Return air [L/s]
Living room	27.8	23
Bedroom	9	0
Office	8.9	0

Kid room	6	0
Bathroom entrance	0	15
Bathroom	0	15
Depot	1.3	0

Table 8. The assumed design heat loads of the two modelled apartments

First sample apartment	Design heat load [W/m^2]
Living room	15.7
Room yard	4.7
Room south	7.5
Room north	9.5
Bathroom south	30.6
Bathroom north	28.4
Second sample apartment	Design heat load [W/m^2
Living room	14.3
Bedroom	10.5
Office	9.9
Kid room	8.9
Bathroom entrance	20.3
Bathroom	23.7
Depot	1.6