Laboratory test of commercial smart radiator thermostats when used for load shifting

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Abstract. The recent development of smart radiator thermostats has made it possible to integrate them in demand response programs. Advanced control strategies for demand response such as Model Predictive control (MPC) can be combined with radiator thermostats in a hierarchical way for the regulation of space heating systems: the MPC controller calculates the optimal set-point temperature to be tracked by the PID controller of the thermostat. Coupling MPC and thermostat-based control gives the possibility to regulate independently each radiator flow and therefore has the advantage of an efficient room temperature control. Currently, several smart thermostats available on the market are programmable, can be controlled remotely and allow to implement advanced control algorithms. In addition, the thermostats used for load shifting should be reliable, fast responding to changes in settings and precise in tracking a room temperature set-point. The purpose of this study was to compare the performance of different commercial smart radiator thermostats by performing laboratory experiments and to evaluate whether they are appropriate for load shifting purposes. The thermostats tested were Danfoss Eco 2, Eurotronic Spirit Z-Wave Plus and MClimate Vicki. The experiments were carried out in a room where the temperatures in strategic locations were measured. The experiments were designed to evaluate how the thermostats reacted to a changed set-point and if they were able to maintain the desired room temperature. Additionally, the experiments assessed how an increasing temperature set-point affected the flow, the radiator cooling and the thermal comfort in proximity to the radiator. The results obtained so far show that the three tested thermostats had different behaviours in terms of temperature control reliability and accuracy. The three products had different advantages and drawbacks and they all require adjustments for successful integration in an MPC system.

Keywords. Smart thermostats, thermostat performance, load shifting, Model Predictive Control.
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1. Introduction

Demand response has a crucial role for reaching the increasingly ambitious targets of energy efficiency and penetration of renewable energy sources. Many studies have demonstrated that exploiting the building thermal mass can have a substantial demand response potential for heating supply systems such as district heating (1–4). Advanced control strategies of space heating of rooms in residential buildings such as Model Predictive Control (MPC) are frequently proposed in current literature as a mean to realise this potential, see e.g. (5). This type of MPC typically modulate the thermal power of room heaters throughout the day constrained by considerations on thermal comfort to obtain demand response purposes and therefore use this thermal power as control input for room heaters. This is easy to implement if space heating is based on direct electrical heaters, but it is not directly implementable for hydronic radiator systems where the thermal power is a function of temperature and flow of the fluid in the heater as well as the room air temperature. The thermal output from radiators is often determined by a manually set position of a thermostatic radiator valve (TRV) controlling the water flow through the radiator with e.g. a wax motor. In recent years, TRVs that use electronic sensing of temperatures and PID controllers to mechanically adjust the valve position to maintain a desired temperature set point have become commercially available. Some of these TRVs can also be remotely controlled which in principle makes them applicable for MPC as these thermostats are able to receive and track a continuously updated variable set-point schedule modulating the flow in order to achieve the desired demand response. Very few studies have been reported using TRVs for this purpose (6). Overall, there is a lack of knowledge on how commercially available electronic TRVs for hydronic systems reacts when prompted the fluctuating temperature set-point schedules of an MPC.

The study reported in this paper investigated the ability of three different commercial smart thermostats to realise the heating set-point schedule of typical demand response control strategies. The following sections provide a description of the equipment and test room used and of the design of the experiments, followed by an overview and a discussion of the results obtained, and ending with concluding remarks.

2. Research methods

2.1 Experimental setup

The objective of the study was to evaluate and compare how three commercial smart thermostats – Danfoss Eco 2, Eurotronic Spirit Z-Wave, and MClimate Vicki – behave when subject to changes in set-point temperature.

A series of experiments (see section 2.2 for details) were performed in a 15 m^2 test room with a room height of 2.8 m and one insulated wall with a window facing outdoors to the south (Figure 1). The window glass was covered with non-transparent tape on the outside to avoid solar heat gains disturbing the experiment. All other wall surfaces were insulated and faced other heated rooms, and the highly insulated floor faced an unheated basement. The entrance door was on the internal wall opposite the window. The room had one radiator supplied by district heating located at one of the internal walls. The only piece of furniture present was a table placed at the internal wall opposite to the radiator and a chair in front of the radiator.

The specifications of the used sensors, data loggers, and the measured variables are summarized in Table 1. The air temperature sensor of the brand *Lansen Lan-Wmbus–G* was placed on the table in a distance of two meters from the radiator and the height is one meter above floor. The data from the sensor was assumed to be a measure of the general air temperature in the room. In addition, an air temperature data logger of the brand *TinyTag Ultra 2* was placed 0.6 m from the centre of the radiator at a height of 0.5 m to enable evaluation of air temperature near the radiator. An ultrasound flow meter of the brand *Katronic Katflow 230* measured the flow and water temperature of the inlet and outlet radiator pipes. All three thermostats had an internal temperature sensor measuring a temperature used as control variable; this data was also logged. Figure 1 shows the location of all equipment, and Figure 2 is a picture of the setup at the radiator.

The experiments were performed by controlling the thermostats remotely. The Danfoss and Vicki thermostats were controlled through a Bluetooth and LoRawan gateway, respectively. The Eurotronic thermostat was included in a Z-wave network and was controlled through a Raspberry Pi. Unlike the Danfoss thermostat, the thermostats by Eurotronic and Vicki allowed the customization of many settings. The Eurotronic thermostat allowed adapting the set-point temperature offset as well as direct control of the valve opening, and the Vicki thermostat allowed modification of the PI controller parameters. In this study, the three thermostats were compared using their default settings.

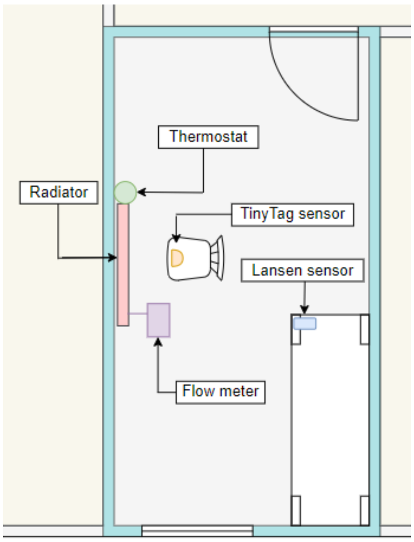

Fig. 1 – Layout of the test room and position of equipment.

Fig. 2 – Radiator, TinyTag data loggers and flow meter

Tab. 1 – Measured entities by different pieces of equipment, temporal resolution and accuracy

Product name	Measured entity	Data logging frequency	Reading resolution
TinyTag Ultra 2	Air temperature in front of the radiator at a distance of 60 cm and height 50 cm	1 minute	0.01 °C
Katronic Katflow 230	• Flow through the radiator • Inlet and outlet water temperature in the radiator	1 minute	• Volume flow: 0.001 l/h • Temperature: 0.01 °C
Lansen Lan-Wmbus-G	Air temperature at a distance of 2 meters from the radiator, at a height of 1 meter	5 minutes	< 0.01 °C
Danfoss Eco 2	Room air temperature	15 minutes	0.5 °C
Eurotronic Spirit Z-Wave Plus	Room air temperature	1 minute	0.1 °C
Vicki MClimate	Room air temperature	5 minutes	0.1 °C

2.2 Experiments

Three experiments were designed to explore the behaviour of the thermostats during step changes in temperature set-point – which is often prompted by an MPC to provide demand response – as well as their behaviour during set-point tracking. The behaviour was evaluated in terms how fast the internal temperature sensor in the thermostats reached a new set-point, the flow control strategy to realize the set-point, how the internal thermostat sensor compares to the other sensors, and the consequential cooling (difference between supply and return temperature) and the air temperatures measured by the two room sensors.

Experiment 1 had the purpose of evaluating how the thermostat reacts to a sharp increase in set-point. The experiment was conducted by changing the temperature set-point to the maximum value (28°C) and keeping it for five hours before returning to the initial set-point.

Experiment 2 was designed to evaluate how the thermostats tracks a set-point after an increased set-point was reached. The experiment was performed by increasing the set-point by 3 °C above a current (initial) temperature measured by the thermostat. The increased set-point was kept for ten hours before changing it back to the initial value.

In Experiment 3, the temperature set-point was increased gradually by setting the set-point 1 °C higher than the temperature measured by the thermostat every 15 minute. This step increase was stopped and the set-point changed back to the initial value after the temperature measured by the thermostat had reached 26°C, or when the temperature increase became too small (lower than 0.5°C increase in 8 hours).

Each of the three experiments were performed using a starting set-point of 18°C prior to the experiment (i.e. starting the experiment with radiators turned off) and with a starting set-point of 22.5°C (starting the experiment with radiators already on, or having been on a short time before), respectively. The reason for the relatively high starting set-point temperature in the latter experiment was to ensure that the radiators were on as the temperature in the test room never dropped below 20-21°C without heating.

3. Results

The data measured during the experiments are shown in Figure 3-8. The plots in the top show the set-point temperature and the temperatures measured by the thermostat as well as two meters and 0.6 m from the radiator, respectively. The plots in the middle report the inlet and outlet radiator pipe temperature and the plots in the bottom show the water flow to the radiator.

The results of Experiment 1 with a starting temperature of 18°C and 22.5°C are shown in Figure 3 and 4, respectively. Once the temperature set-point was changed to 28°C, the flow controlled by the Danfoss ECO increased to a maximum level andstayed there until the set-point was reduced again. This behaviour was as expected, as the internal temperature sensor (the control variable of their PI controller) never reached the setpoint. The temperature 0.6 m from the radiator was significantly higher than the temperature measured by the internal sensor. The sensor placed two meters from the radiator displayed a temperature somewhat lower than the internal sensor.The Eurotronic Spirit showed a similar behaviour in terms of flow compared to Danfoss ECO, but in the experiment displayed in Figure 4 the heating was continued even after the set-point was decreased, as a result of the integral action of the PI control. The temperature 0.6 m from the radiator was significantly higher than the temperature measured by the internal sensor, as observed with the Danfoss

ECO. The sensor placed two meters from the radiator, however, displayed a temperature slightly higher than the internal sensor. The flow control strategy of the M-Climate Vicki was different compared to the two others as it fluctuated around approx. 50% of the maximum flow but it also had a district supply temperature which was 10 °C higher than in the experiments featuring the other two thermostats. Furthermore, the internal sensor in the M-Climate Vicki reached the set-point before the set-point was reduced again, the temperature 0.6 m from the radiator was on par with the internal temperature sensor throughout the experiment, while the temperature two meters from the radiator was a couple of degrees lower than measured with the internal sensor. The cooling was minimal for Danfoss ECO and Eurotronic Spirit due to the large flow and somewhat higher for the M-Climate Vicki due to a higher supply temperature.

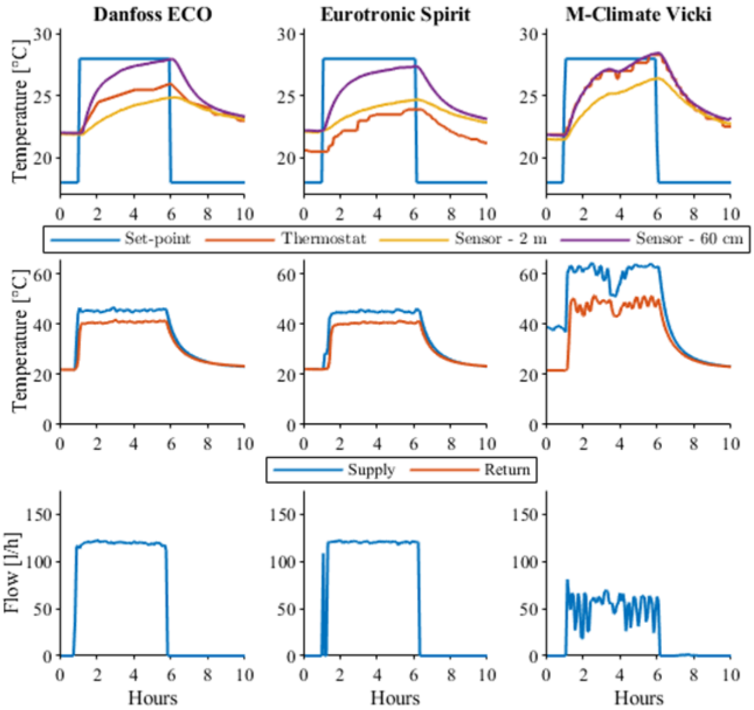

Fig. 3 – Results from Experiment 1 – starting temperature at 18°C

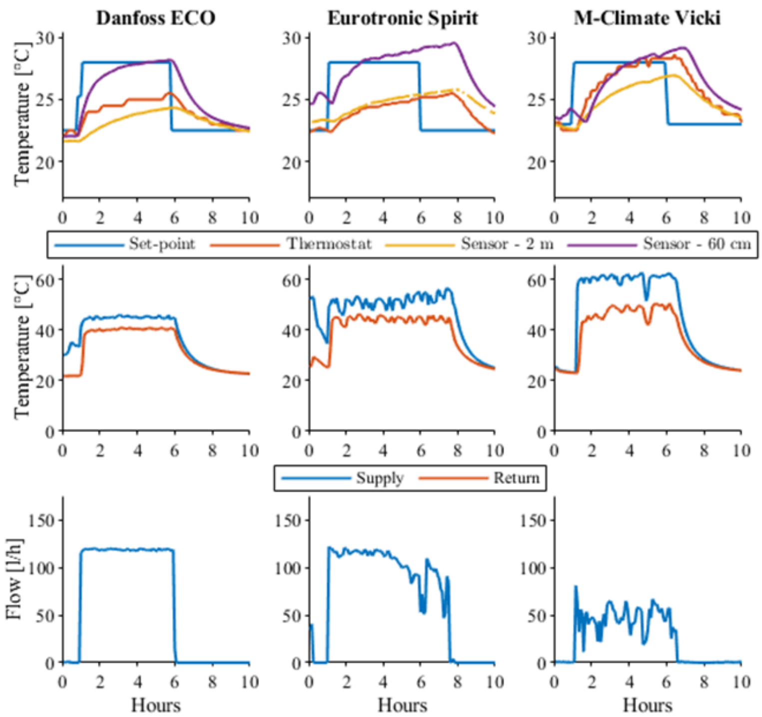

Fig. 4 - Results from the first experiment – starting temperature at 22.5°C

Figure 5 and 6 show a clear difference in behaviour among the thermostats during Experiment 2. The internal temperature sensor of the Danfoss ECO reached the set-point after a period of utilising the maximum flow available resulting in a low cooling, and then tracked the set-point rather precise by minor adjustments of a lower constant flow – and consequently a higher cooling. However, after few hours the flow went to zero for unknown reasons, and the temperatures consequently dropped more than 1°C below the set-point. This behaviour was also observed when the experiment was repeated several times. The temperature 0.6 m from the radiator was in general higher than the temperature of the internal sensor while the sensor placed two meters from the radiator displayed a temperature somewhat lower than the internal sensor – which was also observed in Experiment 1. The Eurotronic Spirit displayed the same initial behaviour as Danfoss ECO but once the temperature of the internal sensor had reached the set point, the temperature oscillated somewhat around the set-point using an on/off control of the flow. The temperature measured by the room sensors were shifted the same way as in Experiment 1. The M-Climate Vicki did not start out with utilising the maximum flow available to reach the set point as the two other thermostats. Instead, a relatively low flow was used to overshoot the set-point temperature before entering a set-point tracking with significant oscillations employing an on/off flow control. The temperature 0.6 m from the radiator was on par with the temperature of the internal sensor, while the sensor placed two meters from the radiator displayed a temperature significantly lower than the internal sensor – which was also observed in Experiment 1. As in Experiment 1, the cooling was somewhat higher due to a higher supply temperature.

The results obtained from Experiments 3 are shown in Figure 7 and 8. The length of the time axis differ among the three thermostats because of the different speeds at which the thermostat temperature increased. Using the Danfoss ECO, the flow did not initially go to the maximum available flow as in Experiment 2 but increased gradually as the set-point rose. This was also the case for Eurotronic Spirit but the flow oscillated much at the beginning of the experiment until it stabilized at a constant value instead of using an on/off control as in Experiment 2. It is noted that the temperature measured by the internal sensor in Danfoss ECO and Eurotronic Spirit never reached the set-point as in Experiment 2 an therefore the flow was almost always at the maximum value. The M-Climate Vicki required a shorter amount of time to reach the set-point temperature as its internal temperature measurement increased faster than in the other thermostats. The room temperatures and cooling displayed the same behaviour as in Experiment 1 and 2 for all three thermostats.

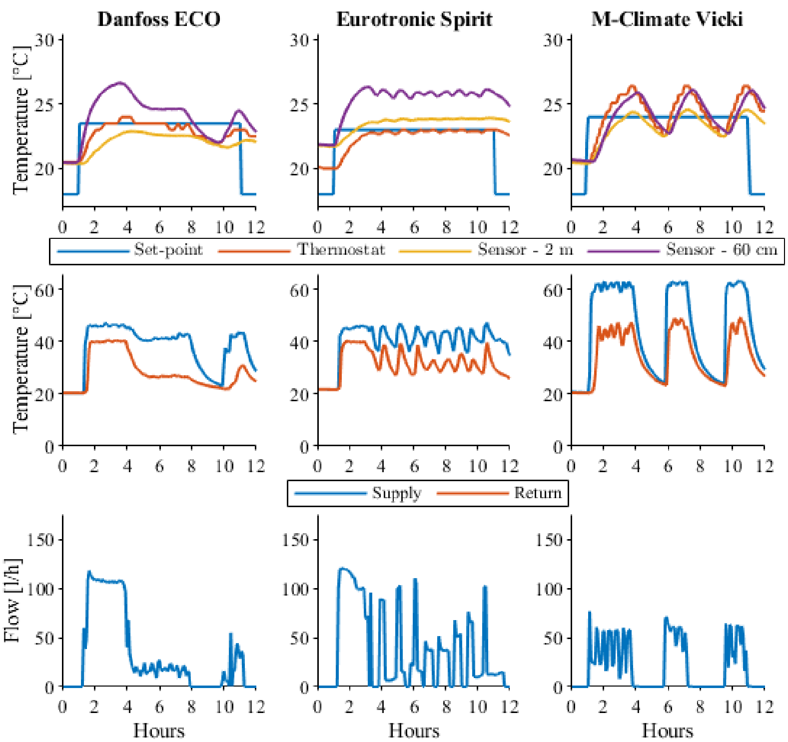

Fig. 5 - Results from the second experiment – starting temperature at 18°C

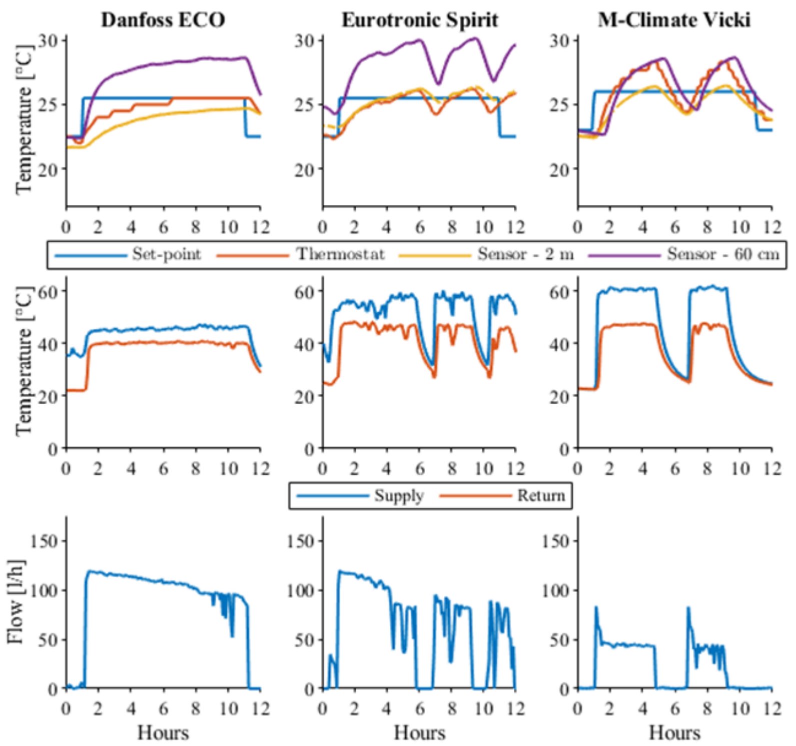

Fig. 6 - Results from the second experiment – starting temperature at 22.5°C

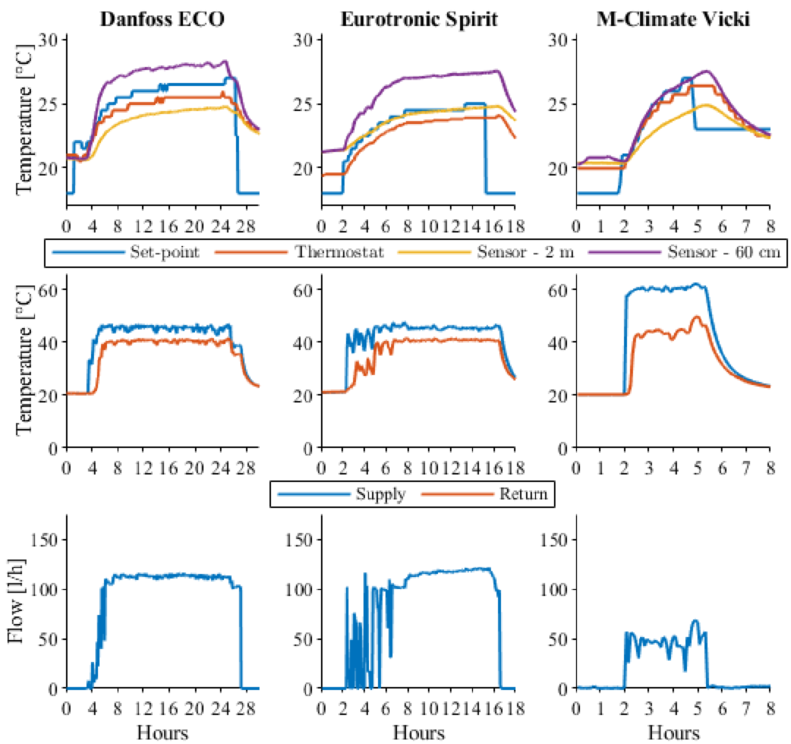

Fig. 7 - Results from the third experiment – starting temperature at 18°C

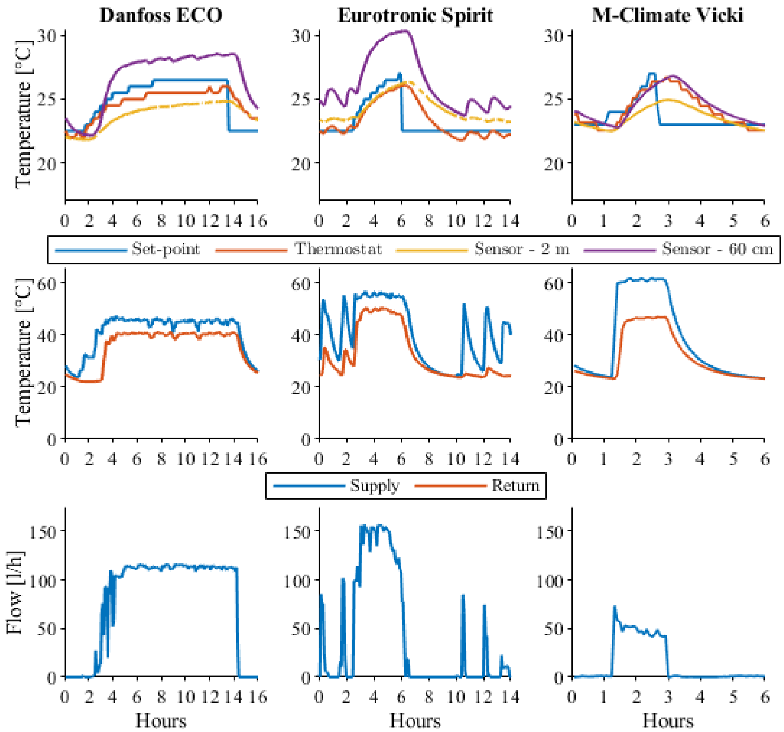

Fig. 8 - Results from the third experiment – starting temperature at 22.5°C

4. Discussion

The experiments gave many different insights about how different thermostats react to a changing set-point as well as their strategy to track a set-point. Below is a list of general observations deemed important to be aware of then using the thermostat for MPC:

- Common for all thermostats was that it was possible to make them follow a variable set-point schedule and that the thermostats reacted to changing set-points within few minutes.
- There were significant differences in the way the thermostats control the flow to track the set-point temperature.
- The two different ways of changing the set-point in Experiment 1 (one instant step change) and Experiment 3 (gradual change) resulted in significantly different flow patterns at the start of the experiment. However, when the set-point in Experiment 3 reached a certain level, the behaviour was similar to Experiment 1.
- The internal temperature sensor in the thermostats used as control variable seems to aim at representing different room temperatures. Danfoss ECO and Eurotronic Spirit is most similar to a room temperature far away from the radiator (absolute difference not higher than 1°C), whereas M-Climate Vicki is quite similar to the temperature close to the radiator.
- The data obtained about cooling of the radiator water are not always directly comparable across the experiments because of supply temperatures. What can be observed is that the radiator cooling tended to decrease between 5°C and 15°C depending on the case when increasing the set-point, and that the cooling followed the oscillations in flow (as expected). A higher cooling was obtained when the set-point during the gradual change of set-point (up to 24°C) of Experiment 3 but ended at the same level as the other experiments.
- The experiments had to start over several times because the thermostats lost their wireless connection and were therefore not able to receive set-points.

A general challenge for all three thermostats was to ensure a stable wireless connection. This is critical if they are employed for MPC where new set points are sent to the thermostat regularly to obtain demand response. Making the connection more reliable and ensuring that the thermostat keeps tracking a desired set-point if the connection is lost is important future work.

The different thermostats have different behaviour with pros and cons, and it is therefore difficult to pinpoint whether one thermostat is better for MPC than the others. One important issue to consider across the different thermostats is how their control strategy impact the room temperature near as well as far from the radiator – locations where people are present and where temperature is a proxy for their thermal comfort. The internal sensor in the thermostats used as control variable was not an expression of the temperature in the room for any of the thermostats (except for the M-Climate Vicki that closely expressed the temperature close to the radiator) and it might therefore be relevant to use one of the room temperature sensors as control variable to ensure thermal comfort.

It is noted that the thermostats were tested using their default settings and future studies could therefore investigate if customisable settings of the thermostats can be tuned for optimal performance in an MPC scheme. For example, it is possible to regulate the temperature offset or to control directly the valve opening of the Eurotronic Spirit, and to tune the PI control parameters of the M-Climate Vicki. It is not possible to customise the Danfoss ECO.

Limitations of this study could also be explored in future research. For example, the experimental results are all things being equal affected by the physical circumstances of the test room; repeating the thermostats in rooms with a different geometry and heat loss to surroundings is likely to lead to different results.

5. Conclusions

The paper reports on a study on how three wireless remotely controlled thermostats for a hydronic radiator behave following a variable set-point schedule typical to MPC schemes. The study shows that there are different issues that needs to be dealt with before the thermostats are expedient for MPC. As such, the study points at different focus areas for future product development of wireless remotely controlled thermostats useful for realisation of demand response through MPC of hydronic radiator systems in buildings.

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The datasets analyzed during the current study are not publicly available because of practical reasons but are available on request from the corresponding author Virginia Amato (viam@cae.au.dk).

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