Are bedroom air temperatures affected by temperature boosts in adjacent rooms?

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Abstract. Recent research has indicated that economic model predictive control (E-MPC) of residential space heating can be a significant demand response (DR) asset in district heating systems. Typical E-MPC formulation for this purpose relies on acceptance of occasionally increased indoor temperatures and the DR potential is thus limited by thermal comfort constraints. This paper reports on a field experiment on whether bedroom air temperatures are affected by temperature boosts in adjacent rooms in three case buildings. The measured bedroom air temperature was increased slightly but interviews with the residents indicate that they did not notice the increase. E-MPC in rooms adjacent to the bedroom in these or similar houses can therefore be utilised for providing DR to district heating systems.

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1. Introduction

Energy flexibility of various temporal resolution is increasingly considered to be an important asset in the management of thermal energy systems with a high penetration of intermittent renewable energy sources. The thermal mass of residential buildings can for instance be utilised as short-term heat storage [1-2] for demand response using model predictive control (MPC) of heating systems triggered by price-based demand response programs resulting in so-called economic MPC (E-MPC), see e.g. [3-5] to mention a few, or in combination with signals on CO_2 emissions [6]. The demand response potential of the individual building in absolute terms is relatively small [7] but current simulation-based studies have demonstrated that the aggregated demand response potential of MPC of residential space heating systems can be an asset to operational challenges in urban district heating systems [8-11].

A typical formulation of E-MPC is to minimize heating costs constrained by thermal comfort criteria. A thermal comfort criterion often used is that occupants are assumed comfortable if temperatures are within a predefined comfort band, e.g. defined by a preferred temperature and an acceptable deviation from it. In addition, limitation on the steepness of ramping the temperature up or down are also applied [3]. The common behaviour of this MPC formulation for residential space heating is that the MPC boost the indoor temperature to a user-defined upper comfort limit during low-price periods - thus storing heat energy in the thermal mass of the building - so that the indoor temperature can drift in free float back to a lower comfort limit during the subsequent high-price period. The MPC is therefore tracking either the upper or the lower boundary of the comfort band, meaning that the air temperature is rarely the preferred temperature of occupants (i.e. somewhere between the upper and lower comfort limit). Alternative strategies taking offset in tracking a preferred temperature during normal operation and then provide demand response by either boosting up to the upper limit or drifting down to a lower limit have therefore been proposed [12,13]. However, neither the typical formulation of thermal comfort criteria nor the mentioned alternative is applicable for all functions of a residential building. Especially ramping up from a preferred indoor temperature – denounced *temperature boost* henceforth – to an upper comfort limit may be problematic for some function, e.g. the bedroom; here, the preferred temperature might be the upper comfort limit.

There seems to be a tendency that residents in Northern European countries with temperate climate prefer a bedroom temperature either on par or lower than the preferred temperature in the remaining rooms of the home – also during the heating season. This is e.g. evident in the results from a questionnaire study involving residents in 28 Norwegian low-energy buildings where no one felt 'hot', ~10% felt warm, ~40% felt slightly warm, ~45% found the temperature appropriate, and ~5% felt slightly cool [14], and in another Norwegian study interviewing 38 residents in low-energy homes where the residents in general prefer a bedroom temperature that is lower than what they are experiencing [15]. Madsen and Gram-Hanssen [16] derive from 17 interviews with residents of 14

Danish single-family houses built between 1969-2013 that *"the interviews reflected a cool bedroom as comfortable in contrast to the warmth of the living room*". A similar conclusion can be drawn from the study by Larsen and Johra [17] investigating user engagement with smart home technology for enabling building energy flexibility in 12 apartments and four terrased houses in the greater Copenhagen area built between 2004-2017. However, a study by Mlecnik et al. [18] on 88 responses from a questionnaire on end-user experiences in nearly-zero energy houses in the Nederlands did not indicate the same level of dissatisfaction as the previously mentioned study; here, only 1% and 8% were very dissatisfied or dissatisfied, respectively, with the indoor climate in the bedroom during winter time. Strøm-Tejsen et al. [19] found in a study involving 20 residents of identical dorm rooms that the sleep quality of residents was affected negatively when the bedroom air temperature was increased by 2 K above their preferred bedroom air temperature (mean: 22 ˚C, SD: 1.3 ˚C). Additional data from the experiment indicate that sleep quality was not affected if the bedroom air temperature decreased approx. 1.4 ˚C below their preference [20]. The study also indicated that it is probably not a low room temperature that residents desire but the notion of fresh indoor air that comes with cool air.

The above-referenced studies indicate that it is difficult to pinpoint the preferred temperature in bedrooms, but a common denominator seems to be that the temperature in the bedroom should not be increased above the preferred temperature – in many cases it should in fact be lowered. This comfort criterion means that radiators in bedrooms should not be controlled by E-MPC schedules that allows temperature boosts – let alone be affected by temperature boosts in adjacent zones. The latter issue is a concern raised in simulation-based studies by Clauβ et al. [21] and Johnsen et al. [22]. Here it was found that bedroom temperatures were not strongly dependent on the heating control strategies applied in the other rooms. However, to the knowledge of the authors of this paper, there has been no reports on field measurement of the phenomenom. This paper therefore present data from field measurements of bedroom air temperatures in three different Danish single-family houses during an investigation on the effect of night-time temperature boosts in the kitchen, living room, and hallway.

2. Method

The data presented in this paper origins from a field experiment first reported in Christensen et al. [23] where focus was on evaluating how residents experience leaving the bedroom and enter zones of the house with air temperatures elevated 1 or 2 ˚C above their normal temperature. The elevated temperature was the result of a temperature boost schedule designed to mimic the behaviour of an E-MPC attempting to store heat energy in the thermal mass of the building to avoid using heat for space heating during the morning peak energy use of the local district heating system. There was no attempt to analyse the effect of the temperature boosts on the bedroom air temperature in [23]; this effect is presented in this paper.

The following sections recap the case buildings and their installed experimental equipment as well as the experimental design.

2.1 Case buildings

Three houses with the layout shown in Fig. 1 was featured in the experiment. The houses are in Aalborg, Denmark, which has a temperate climate. The three houses, henceforth named House 1, 2 and 3, are low-energy houses built in 2018 on the foundations of old houses from the 1960s. Inner walls are of light weight concrete with an R-value of 0.12 m^2K/W, which is a common construction in Denmark for buildings from this period. House 1 and 3 are single-family houses, and House 2 is part of a two-family house. House 1 was occupied by an elderly retired couple (male and female), the residents of House 2 were a young couple (male and female) attending their higher studies, and House 3 was occupied by a male adult and a female child.

The houses were equipped with sensors from Lansen measuring air temperature (±0.2 °C), relative humidity (±2 %), and CO_2 concentration (±50 ppm) every five minutes. Window and door opening state was also monitored with sensors. Radiators were equipped with Danfoss ECO thermostats that enables wireless remote control of temperature setpoints. The thermostat has an imbedded PID controller using an internal temperature sensor as control variable. Location of sensors and thermostats are shown in Fig. 1.

2.2 Experimental design

Three temperature schedules designed to mimic the behaviour of a boosting E-MPC as described in the introduction was created, see the last three graphs in Fig. 2. The schedules varied in temperature boost as well as duration. The weekly experimental schedule shown in Table 1 was executed three times

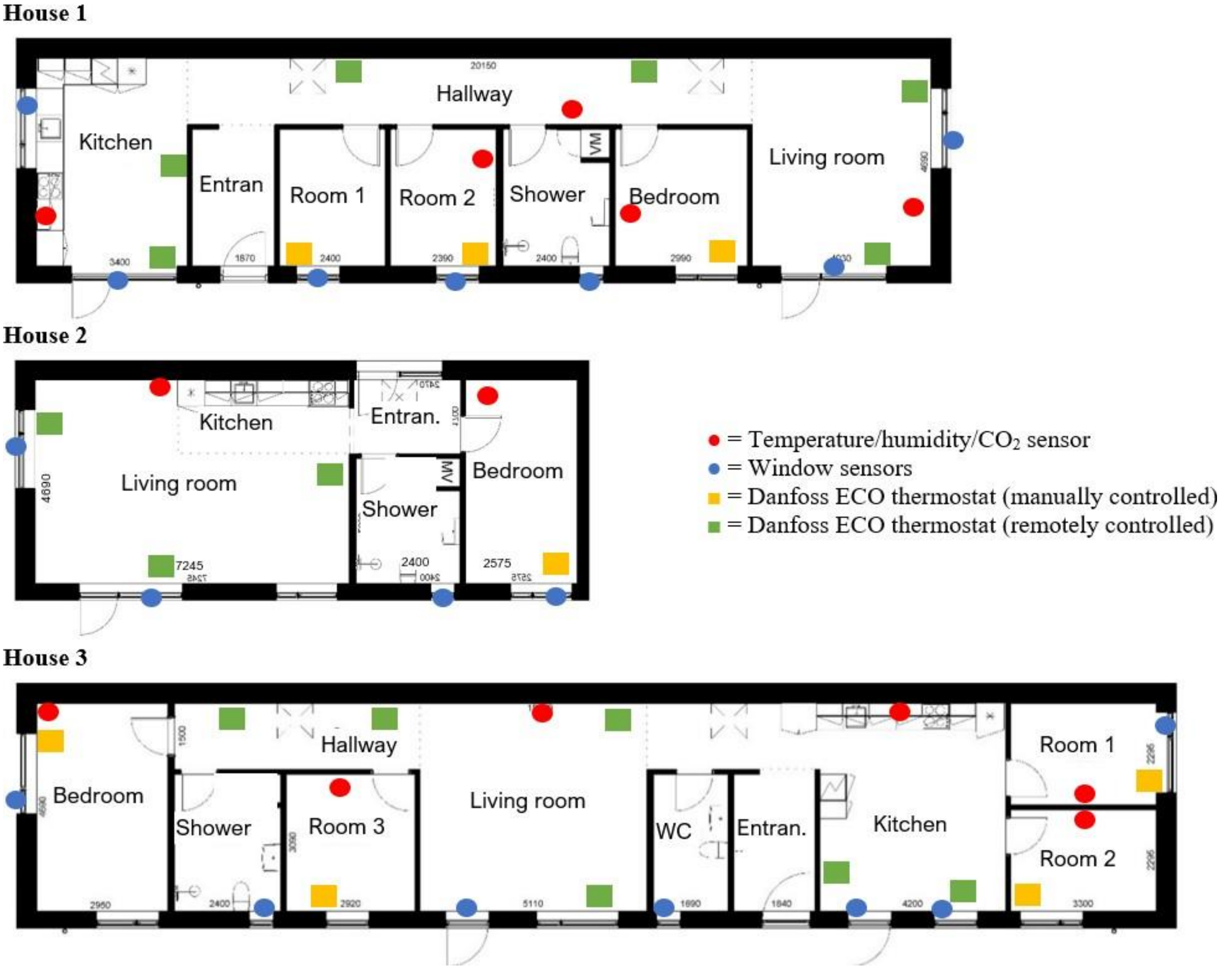

Fig. 1 – Floor plan layout and location of experimental equipment (from paper [23]).

during what is usually considered the coldest month of the heating season in Denmark (Feb 8th to Feb 28th 2021). The boosts were always ended at 7:00 am.

The occupants provided feedback on thermal comfort using "right-here-right-now" questionnaires during the experiment and they were interviewed at the end of the experiment; see paper [23] for further details about the design of the questionnaires and interviews.

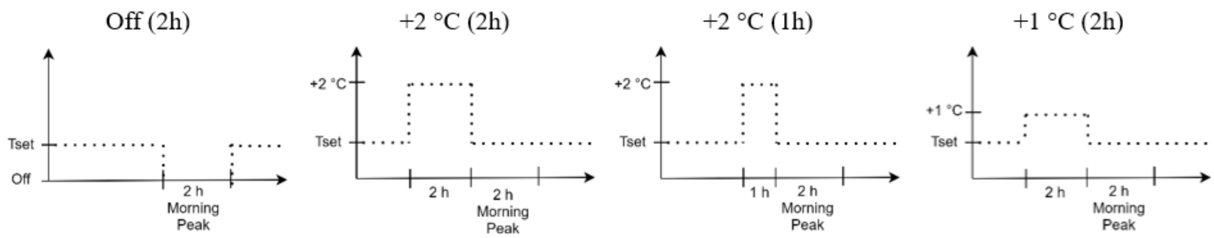

Fig. 2 – Temperature boost schedules (from paper [23])

Tab. 1 – Weekly schedule for the experiment (from paper [23]).

Week	Mon	Tue	Wed	Thu	Fri-Sun
1	-	-	-	-	-
2	Off (2h)	+2 °C (2h)	+1 °C (2h)	+2 °C (1h)	-
3	+2 °C (2h)	+1 °C (2h)	+2 °C (1h)	Off (2h)	-
4	+2 °C (1h)	Off (2h)	+2 °C (2h)	+1 °C (2h)	-

3. Results

Fig. 3 illustrates the trajectory of the air temperature in the bedrooms (first column of graphs) alongside the trajectory of the air temperature in the adjacent room (second column of graphs) in the three houses during the temperature boost schedule *+2 ˚C (2h)*. The residents in House 3 were only present in week 2 of the experiment which is why there is only a graph for week 2 for this house. The schedule *+2 ˚C (2h)* was potentially 'worst case' in terms of effect on the bedroom air temperatures. Data from these experiments exemplifies the trajectory of the temperature in the different rooms across the entire experiment but the magnitude of effect on the bedroom air temperature were somewhat different.

The bedroom of House 1 was in close connection to the living room and the hallway where the temperature boosts were executed (see Fig. 1). It is unknown whether the bedroom door was open during the temperature boosts. The air temperature in the bedroom was increased by 1, 0.9 and 0.6 ˚C during the *+2 ˚C (2h)* schedule, 0.7, 0.7, and 0.6 ˚C during the *+2 ˚C (1h)* schedule, and 0.8, 0.4, and 0.5 ˚C during the *+1 ˚C (2h)* schedule in week 2, 3 and 4, respectively. It is noted that the setpoint of the thermostat in the bedroom was 6 ˚C (i.e., the radiator was not heating the room).

In House 2, there is a small hallway without a radiator between the bedroom and the living room where the temperature boosts were executed (see Fig. 1), and the bedroom door was partly open during the temperature boosts. The air temperature in the bedroom was increased 0.3, 0.2 and 0.2 ˚C during the *+2 ˚C (2h)* schedule, 0.1, 0.2 and 0.1 ˚C during the *+2 ˚C (1h)* schedule, and 0.2, 0.1 and 0.1 ˚C during the *+1 ˚C (2h)* schedule in week 2, 3 and 4, respectively. It is noted that the setpoint of the thermostat in the bedroom was between 21-23.5 ˚C during the three weeks.

The bedroom in House 3 was adjacent to a small hallway in open connection to the living room (see Fig. 1), and the bedroom door was closed during the temperature boosts. Temperature boosts were executed in both the hallway and the living room. The air temperature in the bedroom was increased 0.67 during the *+2 ˚C (2h)* schedule, 0.31 ˚C during the *+2 ˚C (1h)* schedule, and 0.35 ˚C during the *+1 ˚C (2h)* schedule in week 2. It is noted that the setpoint of the thermostat in the bedroom was 6 ˚C (i.e. the radiator was not heating the room).

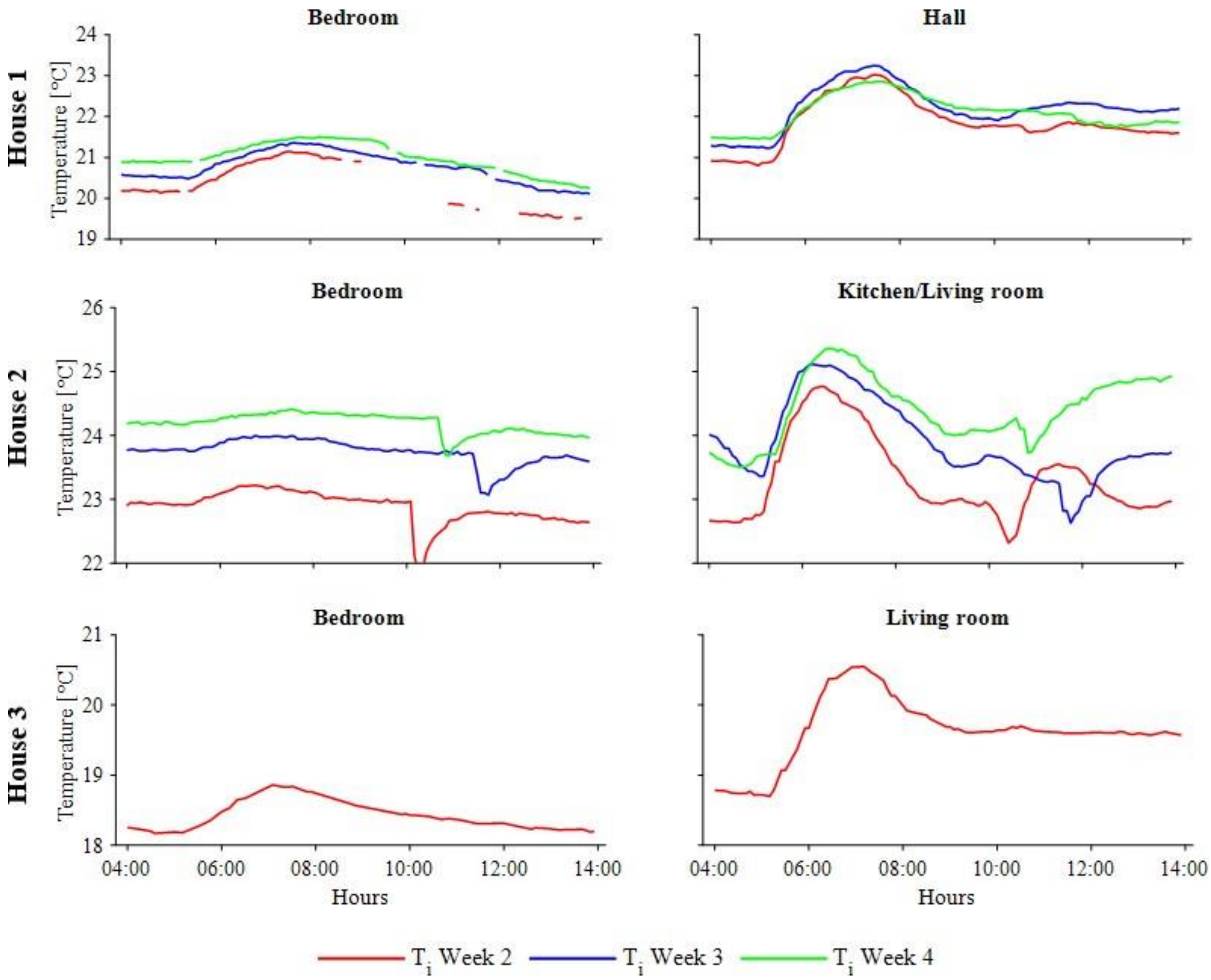

Fig. 3 – Air temperature (T_i) in the bedrooms and adjacent rooms with temperature boosts during the schedule *+2℃ (2h)*.

There was no solar radiation during the temperature boosts as the sun had not yet risen, and the ambient temperature was -1.66 °C ± 6.3 °C. It was therefore not expected that the ambient conditions caused any variation in the bedroom temperatures.

Data from the interviews with the residents after week 4 of the experiment indicate that they did not notice the increased bedroom air temperatures.

4. Discussion

The data from the experiments indicate that the bedroom air was slightly affected by the temperature boosts in other rooms of the house. Data suggest that the magnitude of the increase depends on how close the bedroom is to the rooms where temperature boosts were executed, and whether the residents want the bedroom air temperature to be lower or on par with the room temperature of the remaining house. There is no indication in data on whether open or closed bedroom door affected the bedroom temperature. Results for the individual houses are further discussed in the following.

The bedroom air temperature of House 1 had the highest increase of bedroom air temperature; 0.6-1 °C during the *+2 °C (2h)* schedule. This was probably due to a combination of the bedroom being in close connection to the rooms with temperature boost while the radiator in the bedroom was also turned off – most likely due to a desire for a lower temperature than in the rest of the house.

Data from House 3 also indicates a desire for a lower temperature in the bedroom compared to the rest of the house but the effect of the temperature boosts on bedroom air temperature were less pronounced than in House 1 probably because of less connection between the bedroom and the rooms with temperature boosts.

The bedroom air temperature in House 2 was not affected significantly by the temperature boosts. The situation in House 2 is somewhat different for House 1 and 3 as the residents seemed to desire a bedroom air temperature close to the temperature of the remaining house. Furthermore, there was a passively heated hallway between the bedroom and the room with temperature boost that probably worked as a thermal buffer between the two rooms.

5. Conclusion

This paper reported on field measurements on the effect of air temperature boosts in rooms adjacent to the bedroom in the three different case buildings. The measured bedroom air temperature was increased slightly but interviews with the residents indicate that they did not notice the increase. A slightly increased bedroom air temperature in these houses is therefore not a hindrance for utilising the remaining house for employing MPC formulation for residential space heating that boost the indoor temperature to store heat energy in the thermal mass of the building for demand response purposes.

It is noted that no general conclusions can be made based on these three case studies. The case studies represent a rather common building type in Denmark, but the identified tendencies might be different in other layouts or type of buildings with better or worse energy-efficiency of building enclosures and systems.

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