Case study of personal heaters in a Plus energy building – Simulations of potential energy savings and results from a field test

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Case study of personal heaters in a Plus energy building – Simulations of potential energy savings and results from a field test

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Abstract. Personal Comfort Systems (PCS) for heating, such as foot warmers, heated chairs and infrared heaters, can compensate for a lowering of up to 10°C in ambient temperatures in a heating situation. They are found to lead to a significant increase in occupant satisfaction with the thermal environment, as they enable for a personalized thermal environment. In this way, the use of PCS systems can ensure occupant satisfaction while widening the temperature dead-band, or difference between heating and cooling set-points in buildings. Several field studies from North America have indicated that the average dead-band between heating and cooling set-points is between 1 and 2 °C, leading to considerable amounts of energy used for over-heating and over-cooling. This kind of systems may therefore be an important contributor towards Plus energy buildings, but they are seldom used. The objectives of this study were (1) to test PCS heaters in a modern Norwegian office environment and see how they are appreciated by office workers and (2) to investigate how large energy savings such systems can contribute to in a Plus energy building. Powerhouse Kjørbo was selected as a case building for the study. Potential energy savings were calculated using energy simulations. The results in this case study were not able to confirm an increase in occupant thermal acceptability rate due to the use of a PCS heater. Interviews of occupants however suggest that PCS heaters are a good solution for improving the satisfaction of the limited number of occupants who have special needs, preferences or are located in a place with lower temperature. In buildings with an effective heating source, such as ground source heat pumps, PCS solutions are not likely to contribute to notable energy savings. In an indirect way, they may however still contribute toward realizing Plus energy buildings as PCS systems can help relax the demands set to other climate installations in the building. This again can allow the use of more environmentally friendly solutions such as utilization of thermal mass, temperature stratification and natural ventilation. They can also reduce installation costs by eliminating the need for more complicated and costly HVAC systems.

1. Introduction

Most office buildings in Europe and North America are controlled to a tight temperature dead-band between heating and cooling set-points, where the mean dead-band is found to be 1-2°C in North America [1,2] and 2°C in Norwegian buildings [3]. Tight temperature dead-bands come at a high cost in terms of both energy use, construction costs and system complexity. Therefore, solutions which make it possible to loosen the temperature dead-bands may be a significant contribution toward Plus energy buildings.

At the same time, the percentage of buildings in the ASHRAE Global Thermal Comfort Database II meeting the threshold of 80% satisfied occupants was found to be only 8%, if one includes votes from 0 to +3 ('neutral' to 'very satisfied'). In total 43% of the occupants are thermally dissatisfied, 19% neutral and 38% satisfied [4]. The reasons for this gap between the predicted and actual satisfaction is found to lie in personal differences between occupants, both clothing and metabolic rate

[5], as well as expectations and personality [6]. These studies conclude that the prediction accuracy of the PMV-PPD model is too low, and suggest that wider temperature dead-bands along with personal control would result in higher occupant satisfaction rates.

Personal Comfort Systems (PCS) is a collective term for systems that cool or heat individual occupants [7]. Several researchers see these systems as in important part of the solution for improving occupant satisfaction, while at the same time widening temperature dead-bands and saving energy. A review of scientific studies on PCS systems [7] has found that they can provide a corrective power (CP) of -1 - -6°C for cooling and 2 – 10 °C for heating. Corrective power is defined as the difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. The same study also gathered information on occupant satisfaction from 13 of the studies, showing an impressive increase in occupant satisfaction for the PCS systems, also for ambient temperatures well outside of normal set-points. See illustration in Figure 1.

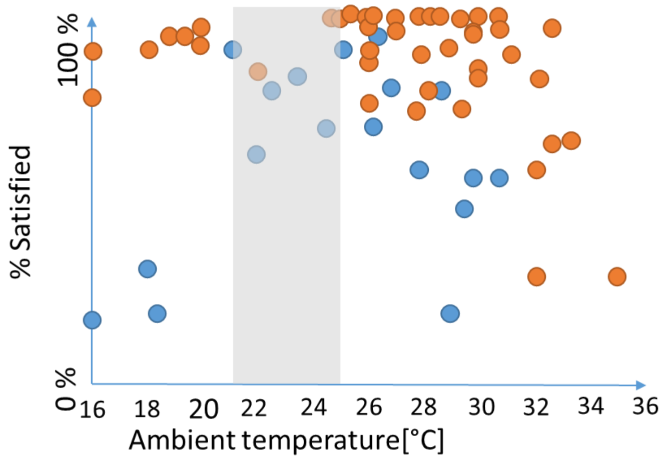

Figure 1. *Percent satisfied with thermal conditions in studies with PCS (red dots) and without PCS (blue dots). After Zhang, Arens & Zhai (2015)*

Aside from the benefits mentioned above, PCS can offer a wealth of data that can describe how individuals interact with heating/cooling devices in their own environment. This allows individuals' comfort and behaviour to be learned, and can inform centralized systems to provide “just the right” amount of conditioning to meet occupant needs [8].

Research on positive effects of widened temperature dead-bands have shown large potential effects. A North American parametric simulation study of seven climates and six model types found that reducing the heating set-point from 21.1 °C to 20°C saves an average of 34% of terminal heating energy. [9]. This result is however dependent on climate type, building envelope, heating system and heat source.

All the reviewed research suggests that PCS systems can have a strong positive effect on occupant thermal satisfaction. However, even though the idea of PCS systems has been a focus area of researchers since the nineties, there are still very few practical examples of organized use of PCS systems in commercial buildings. The objectives of this study are therefore (1) to test PCS heaters in a modern Norwegian office environment and see how they are appreciated by office workers and (2) to investigate how large energy savings can be anticipated in a ZEB building. Powerhouse Kjørbo has been selected as a case building for the study. Potential energy savings were calculated using energy simulations. A field test was conducted, where the occupants of 26 workplaces received web-based questionnaires with and without PCS heaters during a period of close to 4 months in the heating season.

2. Methods

2.1 Case Building

Both the field study and simulations are conducted with the plus energy building Powerhouse Kjørbo as a case example. Powerhouse Kjørbo is a complex of 5 cube-shaped office buildings which are connected by hallways. They are located at Kjørbotangen in Sandvika, west of Oslo, Norway. Only Unit 5 was used for energy simulations, while the field test was conducted in an open office landscape in the 1st floor of Unit 5. The building has an envelope heat loss coefficient of 0.25 W/m²K, is extremely air tight and has a high thermal mass. The ventilation system utilizes displacement ventilation and central air pre- heating and cooling with an efficient rotary heat exchanger. The heating system consists of centrally placed radiators and a ground source heat pump. The heated floor area of Unit 5 is approximately 1870 m².

2.2 Field study

The field study was conducted in the fall of 2018 in a part of the 1st floor. 26 workplaces were included in the test. It was known that several of the occupants in the room had previously complained about cold temperatures. The field study was part of a larger study where a complete system for continuous subjective occupant feedback was tested.

The test lasted for close to four months (Nov. 05 2018 to Feb 02, 2019), and web-based questionnaires were distributed to the occupants at 3 different instances. The first survey was done as a reference, before any equipment was installed. In Phase 2, a QR-code with an explaining text was attached to each desk. If scanned with a smartphone, the user would be taken to a webpage displaying four buttons for complaints regarding the indoor climate. No changes to the indoor climate were made when the buttons were pressed. The second survey was done when users had used this system for 11 days. In Phase 3, an infrared heater was installed under each desk. The heaters would warm the thighs and legs of each occupant when turned on. If a user scanned the QR code and pressed “Too cold”, the heater would turn on for 30 minutes. An email was sent to the users notifying them that heaters had been installed. After 36 days, three randomly selected users were interviewed in an . After feedback from the users, the QR codes were removed and the users were offered a manual control possibility for controlling the heaters. The third survey was done when users had used this system for 12 days.

Table 1. Field study sequence and progress

	Date	**Comment**
Study start	05.11.2019	14 temperature sensors of type Disruptive technologies were installed in the space
First survey distributed	16.11.2019	Last response made 19.11.2019
QR codes installed	19.11.2019	
Second survey distributed	30.11.2019	Last response made 03.12.2019
Under desk heaters installed	04.12.2019	
QR code removed and changed to manual control of heaters		
Interview of 3 occupants	10.01.2019	
Third survey distributed	23.01.2019	Last response made 24.01.2019
End of study	02.02.2019	

2.2.1 Digital complaint and PCS system

The goal of the system was to be non-intrusive, affordable, and provide real-time data. For these reasons, a solution using a web page tailored for smartphones was used in combination with unique QR codes printed and attached to each work desk was chosen. No installation was needed, users could scan the

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QR code with their smartphone and reach a webpage with buttons to complain about “Too cold”, ”Too hot”, “Bad air” or “Draught”. Entries into the complaint webpages were tracked and logged in a database. In Phase 3, database entries for “Too cold” were set to activate “smart plugs”. The smart plugs were programmed to switch off after 30 minutes. The under desk heaters were connected to the smart plug at each desk, and glued to the underside of the desk with an adhesive backside. The heaters are 30x60 cm large and have a power range of 40-150W, but were pre-set to approximately 50W power producing surface temperatures of 40-50 C. All products were commercially available at low cost.

Figure 2. *QR code and webpage.*

Figure 3*. Under desk heater.*

Figure 4*. IR image of infrared heater.*

2.2.2 Temperature measurements

Temperature measurements were done with 14 button sensors from Disruptive Technologies. The sensors have an absolute accuracy of 0.4 °C. The sensors were distributed throughout the space, as shown in Figure 5. There was approximately one sensor per 14 m² of floor space. Four of the sensors were placed by the floor, marked in blue in Figure 5. The others were either under desks or at approximately 1.2 m height.

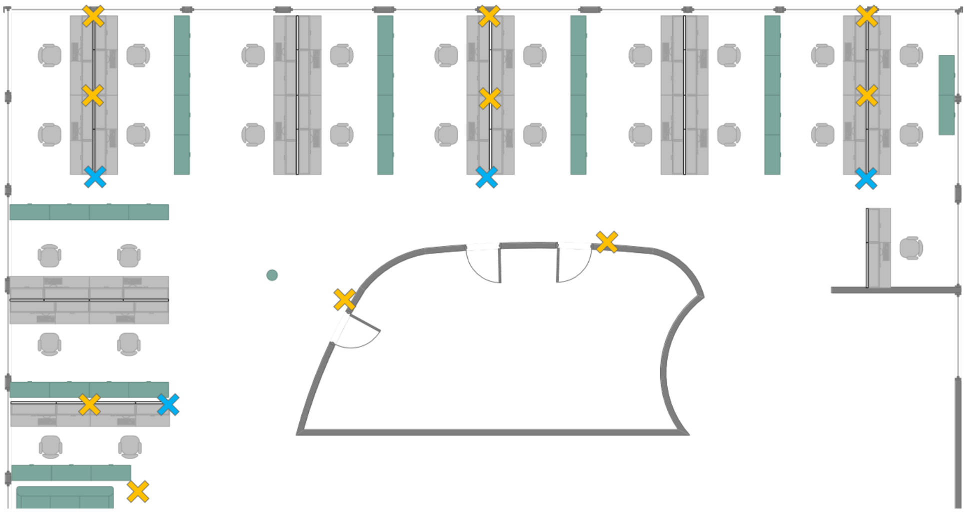

Figure 5. *Placement of temperature sensors. Four at floor level (Blue) and ten at 1.2 m height (orange).*

2.2.3 Survey

An electronic survey was distributed to the test subjects via an email link. The survey included multiple questions, but only four of the questions were relevant for this study. The respondents were asked to take the last week into consideration when answering all the questions. The relevant questions (translated from Norwegian) and answer scales are shown in Table 2.

Table 2. Survey questions

	Question	Answer scales
Whole-body thermal sensation vote (according to NS-EN 15251)	*"Where on this scale would you place your experience of the temperature?"*	*"Cold" [-3]* *"Cool" [-2]* *"Slightly cool" [-1]* *"Neutral" [0]* *"Slightly warm" [1]* *"Warm" [2]* *"Hot" [3]*
General temperature acceptability (according to NS-EN 15251)	*"How did you experience the temperature during the period?"*	*"Entirely acceptable" [1]* *"Barely acceptable" [1]* *"Not acceptable" [0]* *"Entirely unacceptable" [0]*
Perceived control	*"How much control do you think you have over your indoor climate?"*	*"No control" [0]* *"Some control" [1],* *"Much control" [2],* *"Very much control" [3]*
Portion who used QR code / heater	*"Have you used the (QR code / heater) during the period?"*	*"Yes" [1] / "No" [0]*

2.2.4 Interview

Three randomly selected respondents took part in a focus group interview. The interview questions relevant for this study were:

1. Have you used the QR codes / personal heater? If not, why?
2. What do you think of the solution with QR code / personal heater?
3. What could be done better?

2.3 Energy simulations

Potential energy savings were calculated using the software SIMIEN ver.6.0.10 and the original design phase energy model. The under desk heaters were assumed to have a corrective power of 2.8 °C, according to a study of under desk heaters with similar surface temperatures [10].

For the reference case, the year-round heating set-point was set to 22 °C. For the PCS case, the set-point was lowered to 19.2 °C. The supply air set point was also lowered from 20 °C to 19.2 °C. No other changes were made to the energy model.

3. Results

3.1 Field study

3.1.1 *Temperature measurements*

Results of the temperature measurements are given in Figure 6. White boxes show the median and 25th and 75th percentiles of the mean room temperature in each phase. The phase is set to the week preceding each of the surveys, as respondents were asked to answer for the preceding week. Blue boxes show the equivalent means for the lowest room temperature readings, and red boxes for maximum room temperature reading. The highest room temperatures were typically in the central areas of the building, (near the radiators), while the lowest room temperatures occurred near the floor and toward the corners of the building. Only daytime temperature readings between 07:00 and 18:00 were included.

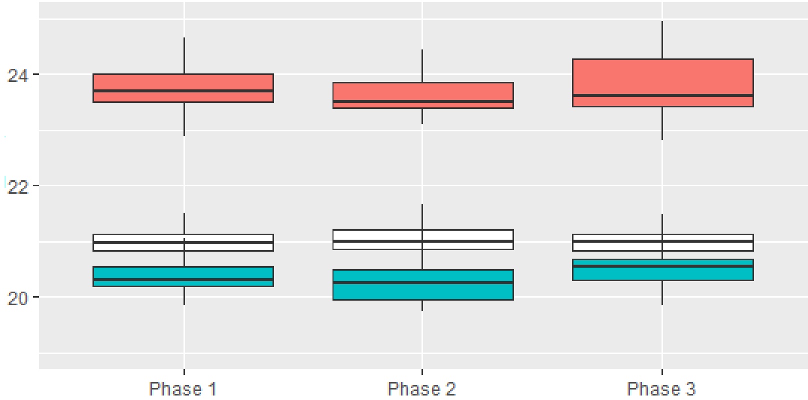

Figure 6. *Temperature measurements in the three weeks of survey. Mean room temperatures (white), max room temperatures (red), min room temperatures (blue).*

3.1.2 Survey results
Results from the survey questions are given in **Table 3**.

Table 3. Survey results

	1st survey	2nd survey	3rd survey
Number of respondents	16	10	11
Mean thermal sensation vote	-1.0	-1.2	-1.0
General temperature acceptability (% acceptable)	75 %	80 %	82 %
p-value 1st – 3rd survey			*p=0.68*
p-value 2nd – 3rd survey			*p=0.92*
Perceived control [0-3]	0.64	0.60	1.18
p-value 1st – 3rd survey			S1: p=0.07
p-value 2nd – 3rd survey			S2: p=0.10
Portion who used QR code / heater (% Yes)	-	20%	45 %
p-value 2nd – 3rd survey			*p=0.23*

3.1.3 *Interview results*
The focus group interviews produced the following main findings:

- Two of three have used the heater «all the time». They say several others around them do the same. They say many of them think it's generally too cold in the building.
- The third person's heater did not work, but he is content with the temperature as it is and does not want one.
- Two of them want to keep the heater. One of them claims "I love it".
- "Half an hour is way too short. That's why I have disconnected the heater from the smart plug and use the manual control. I have helped several others do the same."

3.2 Simulation results
Results of the energy simulations are provided in **Table 4**.

Table 4 Results of energy simulation

	Heating energy [kWh/m²]	Total energy [kWh/m²]	
	Net heating energy demand	Net energy demand	Gross energy use
22 °C heating set-point (Reference)	18.1	44.5	26.6

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19.2 °C heating set-point	13.7	40.2	25.4

Net heating energy demand was reduced by 4.4 kWh/m², or 24%. Net total energy use was reduced by 4.3 kWh/m², or 9%. Gross energy use was reduced by 1.2 kWh/m², or 5%. Additional energy use for PCS heaters was not included.

4. Discussion

Results show that the temperature conditions across the three survey periods were similar. The survey answers for "Mean thermal sensation" confirm this as the respondents perceived all three phases as "slightly cool". Temperature acceptability is slightly higher in the 3rd survey with the PCS heater present, but this finding is not statistically significant due to the small number of respondents and relatively high temperature acceptability in the reference case. A clearer difference in acceptability may have been obtained if the test was conducted with lower ambient temperatures. Perceived control was however substantially increased with the PCS heater present, although still not significant. 45% of the respondents reported to have used the heater, compared to 20% who used the QR code while it only had the "complaint" function.

As opposed to the other studies studying satisfaction with PCS systems, this survey only asked for general thermal acceptability over the previous week. Other studies have used "right now" surveys asking for acceptability and thermal sensation "right now" while the PCS device was in use. This may be a large contributor to the fact that no significant improvement on occupant satisfaction was found in this study.

The interview results revealed that some select users were very satisfied with the PCS heater, and used it "all the time". These users also reported to be very cold under normal conditions, before the heater was introduced. It also revealed that the system using a QR code and smartphone to activate the heater for 30 minutes was not suitable, and the users preferred manual control over the device.

The energy savings by lowering the heating set-point from 22 °C to 19.2 °C was 24% net heating energy or 9% total savings. Total gross energy savings were however only 5%, due to the high efficiency of the ground source heat pump. The additional energy required for use of the PCS heater was not calculated. Assuming there are 170 occupants in the building, and 45% of these are thermally uncomfortable and use the heater, each of these occupants may use the heater for 72 whole workdays before the gross energy savings are zeroed out by heater use. If the heater is used on average 2 hours each day by each of the thermally uncomfortable occupants (77 occupants, 45% of 170) for the length of the heating season (approximately 120 workdays), this would result in an increased annual energy use of 0,5 kWh/m².

5. Conclusions

The results in this case study were not able to confirm an increase in occupant thermal acceptability due to the use of a PCS heater. Interview results however suggest that PCS heaters are a good solution for improving the satisfaction of the limited number of occupants who have special needs, preferences or are located in a place with lower temperature. The potential energy savings are dependent on heating need of the building and efficiency of the heating source. According to the calculated energy savings for Powerhouse Kjørbo of 1,2 kWh/m² and the assumed energy use for PCS heaters of 0,5 kWh/m², it is likely to assume that the heaters would provide some energy savings, even in this efficient building.

Based on the findings in the study, as well as the reviewed literature, it is likely but not proven that PCS systems can directly contribute toward realizing Plus energy buildings. However, they have been found to have the potential to provide personal control and increased thermal satisfaction to the occupants. This is especially true for those few occupants who have special needs or are placed in problematic areas of the building. In an indirect way, this may still contribute toward realizing Plus energy buildings as PCS systems can help relax the demands set to other climate installations in the building. This again can allow the use of more environmentally friendly solutions such as utilization of thermal mass, temperature stratification and natural ventilation. They may also reduce installation cost by eliminating the need for more complicated and costly measures for accommodating indoor climate demands, as well as provide valuable usage data for system learning.

The potentials of using PCS systems as a strategic contribution toward the climatization of Plus energy buildings should be investigated further. Especially in regard to its potential for dealing with problematic areas, old or existing buildings, natural climatization solutions and usage data collection.

6. Acknowledgements

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