Investigation of PECS on the basis of a virtual building controller

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Abstract. Thermal comfort is one of the key parameters for occupant satisfaction and, accordingly, for the energy performance of buildings. In recent years, decentralized heating and cooling systems, so called personal environmental comfort systems (PECS) are gaining more interest for research and the market. PECS include, for example, office chairs with heating and cooling functions, thermoelectric heating and cooling walls, or even desk fans. Studies have shown that these systems can reduce the heating and cooling demand of the central HVAC systems by improving comfort.

This paper presents a newly developed adaptive building controller that uses a holistic approach in the consideration of central HVAC systems and a heated and cooled office chair, within the framework of the building simulation software Esp-r. The presented building controller can adapt the setpoint temperatures of the central heating and cooling system and also regulate the usage of the office chair's climate function based on the thermal sensation and comfort values of a virtual thermal manikin with the help of PhySCo a transient "Physiology, Sensation and Comfort Model". This approach can be used for an analysis of the potential of PECS.

In this context, the virtual adaptive building controller with a wide deadband and adaptive setpoints between 18 to 26 °C is compared to a basic controller with a fixed and narrow setpoint range between 21 to 24 °C. The simulations were performed for temperate climate (Mannheim, Germany) that is classified as Cfb climate according to the Köppen-Geiger classification.

The results showed that the newly developed adaptive controller with the PECS kept the comfort values at the same level as the basic controller. An office chair with heating/cooling function had been added to the controller and helped to keep comfort while reducing the heating demand (13 % in winter, 4 % in spring) and the cooling demand (10.3 % in spring, 2.6 % in summer).

Keywords. decentralized heating and cooling systems, PECS, office chair with heating and cooling function, virtual building controller, thermal comfort.
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1. Introduction

The building sector has a high influence on greenhouse gas emission. Buildings together with the buildings construction sector are responsible for over one-third of the global end energy consumption and almost 40 % of the direct and indirect CO2 emissions [1]. New solutions are required to reduce the global warming compared to the pre-industrial era and to achieve near climate neutrality [2]. The European EPBD (Energy Performance of building directive) supports buildings which will be offer new control devices for monitoring and controlling the indoor air quality (IAQ) [3]. As the energy balance of buildings is highly driven by the thermal comfort satisfaction of building occupants and by occupant behaviour (e.g., window opening, heating and cooling periods/time and heating/cooling setpoints) [4][5] further solutions are required.

Office buildings are often maintained with a tight, so called deadband, with setpoints around 21 °C to 24 °C, in order to sustain a thermally comfortable state. In reality building occupants prefer a more adaptive deadband and room temperatures which are not predefined in a strict range [6]. In addition, maintaining a tight deadband consumes a higher amount of energy to satisfy the temperature range[7].

To reduce the energy demand of office buildings, the usage of decentralized heating and cooling systems, or so called "Personal Environmental Comfort Systems" (PECS) seems a promising approach. During a few years an increasing interest of these systems can be seen in research and the market. They influence the direct environment of building occupants by heating or cooling local body parts or supply fresh air. From a thermal comfort aspect individual body parts should get more consideration, as the discomfort of individual body parts can drive overall discomfort [8].

Thermal comfort is affected by personal factors of the activity level (metabolic rate), the clothing insulation (e.g., winter/summer clothing) but also from environmental conditions as air temperature, radiant temperature, air velocity relative humidity and direct solar influence. Aside from the above mentioned the cultural background has an impact on thermal comfort [9] and the thermal history of people, as considered in the "Adaptive Comfort Model", implemented in the ASHRAE Standard 55. Moreover, particular body parts indicate different sensitivities to heat or cool effects. While the head is susceptible to heat and might lead to a general feeling of discomfort, the feet are more sensitive to cold stimuli. The total overall comfort is determined by a few strong body parts with a high influence on overall comfort like chest, back, pelvis [8].

Liu et al. found that building occupants alter their working environment in reaction to discomfort [10, 11], and that the ability to control the direct environmental conditions around a person can improve their satisfaction [11], which support the usage of PECS. Various studies have demonstrated the energy-saving effects of PECS by increasing the comfortable deadband [12]. Office chairs with heating and cooling functions could reduce the setpoint temperatures of the central HVAC system to 18 °C or even 16 °C [13]. Few studies are available for even lower room temperatures, as mentioned in the review paper from Rawal et al. [14].

For this reason, the application of decentralized heating and cooling systems in office buildings seems promising, as they have the ability to directly change the occupant's immediate environment and consider individual body parts. Also, the individual needs can get considered. Decentralized heating and cooling systems or PECS like office chairs [13, 15, 16], fans [18, 19], and thermo-electric cooling walls [28–30] have been researched for their cooling properties. Foot warmers [20], office chairs [16, 17, 21] and further solutions, such as localized floor heating mentioned by Rawal et al. [14] can be used for heating purpose. Fig.1 shows a few of the used systems in the "Living lab smart office" space in Kaiserslautern.

Some of these systems are already available on the market but proper planning tools for architects, facility manager, etc. are missing for an estimation, whether it is worthwhile for the operation and acquisition of these systems.

Fig. 1 – Decentralized heating and cooling systems in the Living lab smart office space: an office chair with heating and cooling function, a foot warmer and a desk-fan.

The aim of this paper is to present the developed virtual building controller which consider the office chair with heating and cooling function. All the previous mentioned environmental influences must be included in the planning phase of the building and plant systems in order to account for the energy demand of buildings. For the planning stage building simulation software can get used. For the controlling of PECS, the calculation of detailed local sensation and comfort values is fundamental. For this the coupled "Physiology, Sensation and Comfort" model PhySCo was used [21–25]. PhySCo is based on the work of the 65-Node model of Tanabe [26], Huizenga [27], Hoffmann [28]. The "Sensation and Comfort Model" is based on the equations of Zhang et al. [8, 29, 30] and Zhao [31]. PhySCo can be used as a standalone version or coupled with the building simulation software Esp-r [22].

To calculate detailed sensation and comfort values, it is mandatory to gather detailed MRT-values for the Physiology model. This happens with the approach of "(Wo)Man in Cube" [24]. This solution gathers detailed view-factors for long time building simulations. The view-factors are used for the comprehensive MRT calculations for different body parts. The approach is based on a precalculated view-factor set for different manikin positions like sitting/standing. The manikin can be moved in the building zone and allows the consideration of asymmetric and transient conditions.

This presented work will contribute to an approach that allows an analysis of the potential of decentralized heating and cooling systems in terms of occupant comfort and possible energy savings using a building simulation tool. The study shows how to regulate decentralized heating and cooling systems as well as the central heating and cooling system using a virtual adaptive building controller that takes specific thermal comfort values of a manikin into account.

2. The virtual building controller

2.1 General information

PhySCo is coupled with the building simulation software ESP-r [21, 32]. The Physiology model calculates 16 skin and core temperatures based on the environmental conditions like dry bulb temperature, relative humidity, mean radiant temperature, air velocity and solar influence. Furthermore, personal parameters like the clothing insulation and the metabolic rate are considered. For the) calculation the physiology model takes thermoregulation processes as sweating, shivering, vasodilatation and vasoconstriction of the blood vessels into account. With the 16 skin and core temperatures the local sensation S_l is calculated.

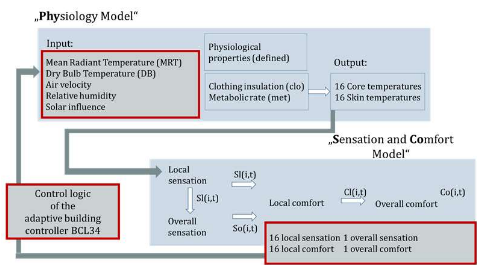

Fig. 2 – Coupling of PhySCo within the virtual adaptive building controller BCL34 to maintain thermally comfortable conditions.

Based on the (S_l), overall sensation (S_o) is calculated and in combination with the latter local comfort (C_l) can get determined. Overall comfort (C_o) is based on the local comfort (C_l) values.

2.2 The adaptive building controller

The virtual adaptive building controller is based on an ideal basic controller (BCL00) in ESP-r. BCL00 considers the area-weighted mean radiation fraction. In addition, the indoor air temperature Q_a is included as a convective component. The percentage ratio (C) between air temperature and the mean radiant temperatures Q_r can be set separately for the sensor and the actuator. The mixed sensed temperature Q_s is calculated as following:

$$Q_s = \frac{Q_a * C}{100} + \frac{Q_r * (100 - C)}{100} \quad (1)$$

If the sensed temperature Q_s exceeds the upper setpoint TU, heat energy is dissipated in the next time step (equation 2). $\dot{Q}$ represents the heating and cooling demand of the next timestep. If the temperature falls below the lower setpoint TL, heat energy is supplied in the next timestep (equation 3).

$$Q_s > \mathrm{TU} \quad \dot{Q}^* = -Q \quad (2)$$

$$Q_s < TL \ \ \dot{Q}^* = +Q \quad (3)$$

Changes have been made for the setpoints (TU, TL) of the controller, which are controlled based on sensation and comfort values of a virtual manikin instead of fixed setpoint-temperatures. The sensation and comfort values can be shown with an extended ASHRAE-7-point scale based on Zhang's et al. publication [29]. For sensation a 9-point scale is used, which ranges from very cold (-4) over neutral (0) to very hot (+4). For thermal comfort a 6-point scale, without a neutral point, is used. A person feels either comfortable or uncomfortable. The range is from very uncomfortable (-3) to very comfortable (+3). Fig. 3 shows a one-day simulation in summer with the adaptive building controller.

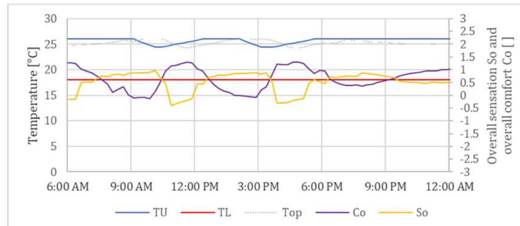

Fig. 3 – One day simulation in summer with the adaptive building controller based on thermal sensation and comfort.

In Fig. 3 the cooling setpoint TU was relevant and have been adapted according to a negative comfort value Co (< 0). If Co is negative, the overall sensation (So) level of the manikin decides about raising or reducing the setpoint. In the above shown case, So was in a warm direction (> 0). Accordingly, the controller lowers the cooling setpoint (TU) unless a positive comfort level is reached. If Co is between 0.5 to 1.0 the setpoints of the HVAC system are slowly set back to the initial setpoints (TU = 26°).

2.3 The adaptive building controller in combination with the office chair with heating and cooling function

To increase the comfort of the adaptive building controller further and subsequently reduce the energy demand of the central HVAC system, a decentralized heating and cooling system was added to the building controller. The office chair with heating and cooling function (Fig. 4) already on the market, was modelled and used in the controller.

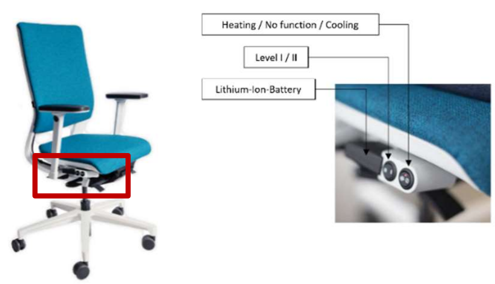

Fig. 4 – Office chair with heating and cooling function and control panel (climate functions, power level).

Modelling the usage of climate functions

The climate changes for the chair directly affect the exposed body parts as back, pelvis and thighs, in the physiology model. For this purpose, equation 4 (proposed by Madsen et al. [33]) of the equivalent temperature $t_{eq,i}$ is relevant. This equation is calculated for each of the 16 body parts (i). It considers the influence of the zone air temperature t_a, the mean radiant temperature of the single body parts $\bar{t}_{r,i}$, the air velocity at the single body parts $v_{a,i}$ and the clothing insulation $I_{cl,i}$ of the specific body parts.

$$t_{eq,i} = \left(0.55t_a + 0.45\bar{t}_{r,i} + \frac{0.24-0.75\sqrt{v_{a,i}}}{1+I_{cl,i}}(36.5 - t_a)\right) \tag{4}$$

Based on the control logic of the adaptive controller (Fig. 5), the chair temperature is changed for no use, cooling (-4 K) or heating (+4 K). The temperature difference is assumed based on a subjective experiment in the “living lab smart office space” in Kaiserslautern.

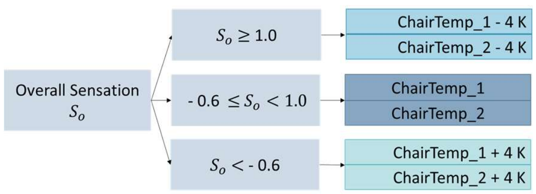

Fig. 5 – Decision of the control logic of the adaptive building controller for the office chair with heating and cooling function, based on overall sensation S_o. ChairTemp_1 represents the backrest, ChairTemp_2 represents the seat.

In the case of a negative S_o value, the control logic decides for the use of the chairs heating function (ChairTemp + 4 K) on the basis of the equation 5. Accordingly, the cooling function will be used for a positive S_o value higher than 1.0 on the sensation scale (equation 6).

Heating function:

$$t_{eq} = \left(0.55t_a + 0.45\bar{t}_r + \frac{0.24-0.75\sqrt{v_a}}{1+I_{cl}}(36.5 - t_a)\right) + 4\,K \tag{5}$$

Cooling function:

$$t_{eq} = \left(0.55t_a + 0.45\bar{t}_r + \frac{0.24-0.75\sqrt{v_a}}{1+I_{cl}}(36.5 - t_a)\right) - 4\,K \tag{6}$$

2.4 Use of the adaptive building controller in combination with the office chair with heating and cooling function

The following figures show the use of the adaptive building controller with the chair for a one-day simulation in summer and the local sensation and comfort values for the back. The left y-axis shows the chair temperature; ChairTemp_1 for the backrest and ChairTemp_2 for the seat, DB represents the dry bulb temperature for the comparison and for the case no climate function is used. The secondary y-axis represents the overall sensation (So), which is responsible for the controlling of the chair temperature.

The following graph shows the usage of the cooling and the heating function. First the cooling function is used (visible due to the 4 K decrease compared to DB). Around noon the heating function is used, as S_o dropped below the sensation setpoint for cooling of -0.6 on the sensation scale. The black lines show the S_o setpoints (SP) at -0.6 and +1.0. If S_o is within the SP, the temperature function of the chair is not used. The upper SP of 1.0 is exceeded at 9:00 AM, at 9:30 AM as well as at 13:30 AM, so the cooling function is used. Once S_o falls below the lower SP value of -0.6, the heating function is used.

Fig. 6b shows a clear effect of the office chair with heating and cooling function in local thermal sensation (S_l), which results in a change in local thermal comfort (C_l). After using the cooling function of the office chair there is an increase for the back (C_{l_back}). After using the heating function of the office chair, there is an increase in the S_l with an initial increase in C_l until it decreases later on. After using the cooling function at 1:30 pm (**Fig. 6**), there is once again an increase in C_l.

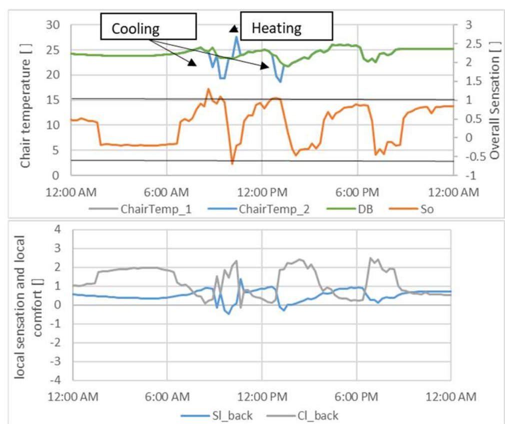

Fig. 6 - One day simulation in August with the adaptive controller with chair. a) use of the cooling and heating function, based on overall sensation, b) local sensation S_l and local comfort C_l for the back

3. Simulation study

3.1 Simulation model and parameter

To show the influences on thermal comfort and on a possible reduction of the energy demand, the newly developed adaptive controller (BCL34) with variable setpoints is compared with a basic controller (BCL00) with fixed setpoints. A simulation study has been conducted with a shoebox model, consisting of one zone, with the dimensions of 5m length x 3m width x 2.7m height.

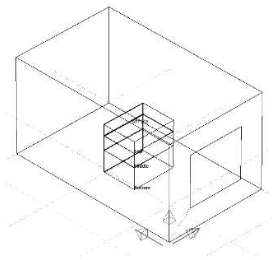

Fig. 7 – One zone shoebox-model with “(Wo)Man in Cube”, window-to-wall ratio 30 %

Tab. **1** shows the heating and cooling capacity of the basic controller BCL00 with a tight deadband and fixed setpoints and the adaptive controller BCL34 with a wide deadband and variable setpoints.

Tab. 1 - Heating and cooling capacity, heating (TL) and cooling setpoint (TU) of the basic controller BCL00 and the adaptive controller BCL34.

	BCL00	BCL34
Max. heating capacity [W]	2000	2000
Max. cooling capacity [W]	2000	2000
Heating setpoint TL [°C]	21	18
Cooling setpoint TU [°C]	24	26

Table 2 shows the different simulation periods regarding of the used clothing insulation values. The activity level (met) is always constant with 1.0 met. Simulation timesteps (TS) are chosen with 4 TS per hour; the number of TS are shown for each period.

Tab.2 - Simulation periods based on clothing insulation.

Simulation periods	Clothing [clo]	Activity [met]	timesteps [n]
15th October to 15th March	1.0	1.0	14496
15th March to 15th May	0.7	1.0	5856
15th May to 15th October	0.5	1.0	14688

3.2 Simulation results

Figure 9a shows the frequency of comfort values for BCL00, BCL34 and BCL34_Chair during the winter period (15th October to 15th March). It can be seen, that BCL00 reaches the highest frequency in the area from 0.4 to 0.8 on the comfort scale, whereas in the area of 1 to 2 the three controllers perform similar. The adaptive variants with BCL34/BCL34_Chair show a higher frequency in the area from -0.2 to 0.2 on the comfort scale. However, when comparing the heating and cooling demand for the building zone (Tab. **3**) for the winter period it is clear that the variant with chair has a 13.5% lower heat demand compared to the basic controller (BCL00). The proportion of the cooling demand is small during the winter period and can be neglected.

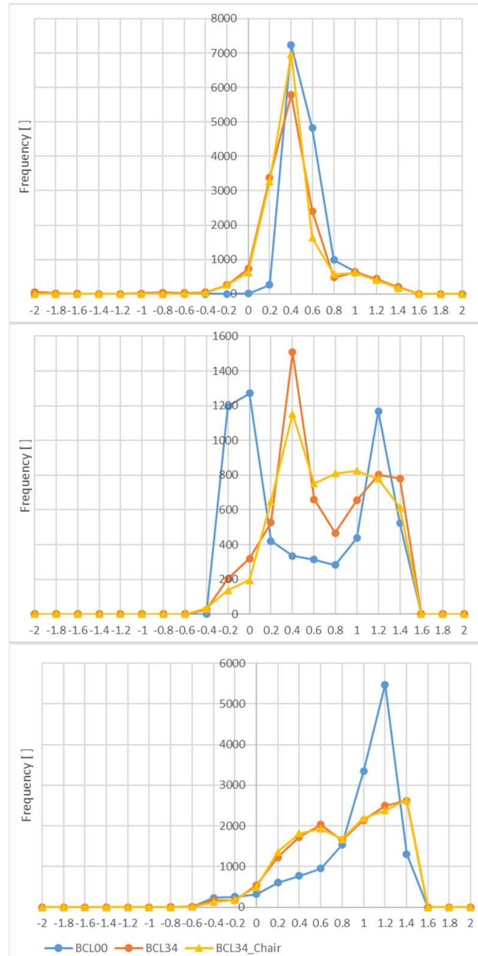

Fig. 8 - Frequency of the comfort values for the period from a) 15th October to 15th March, b) 15th March to 15th May, c) 15th May to 15th October for the different controllers: Basic controller BCL00, adaptive controller BCL34, adaptive controller with office chair with heating and cooling function BCL34_Chair

Tab. 3 - Heating demand (HD) and Cooling demand (CD) of the three periods (winter, spring, summer) and an annual comparison between BCL00 and BCL34_Chair

Comparison BCL00 und BCL34_Chair								
Time period	Winter		Spring		Summer		Annual	
Controller	**BCL00**	**BCL34_ Chair**	**BCL00**	**BCL34_ Chair**	**BCL00**	**BCL34_ Chair**	**BCL00**	**BCL34_ Chair**
Heating demand HD [kWh/m²]	54	47	5	5	0	0	60	52
Cooling demand CD [kWh/m²]	1	0	7	6	43	42	51	48
Reduction HD [kWh/m²]	13.50% (7.3)		3.60% (0.2)		--		12.70% (7.6)	
Reduction CD [kWh/m²]	--		10.30% (0.7)		2.60% (1.1)		5.40% (2.8)	
Chair power [kWhel]	--	39	--	9	--	4	--	52
Chair power [kWhel/m²]	--	2.6	--	0.6	--	0.3	--	3.4

The results for spring show an interesting distribution of the comfort values. BCL00 presents two frequency peaks in the area of -0.4 to 0 and in the area of 1 to 1.2, whereas the adaptive variants show a distribution in the area of 0.4 to 1. BCL34_Chair has less frequency in the area of 0.2 to 0.6 but a higher frequency in the area of 0.6 to 1 compared to BCL34.

Higher frequency can get reached with the adaptive variants for comfort values of 1.6. During the spring period, both the heating demand and the cooling demand can get reduced with BCL34_Chair. The variant saves 3.6% of heating demand and 10.3% of cooling demand compared to the BCL00.

For the summer months, the adaptive variants indicate a peak in the area of 0 to 0.6 and again for a comfort value of 1.4 compared to BCL00. BCL00 present a high frequency of comfort values in the area of 1 to 1.2. During the summer period, the controller with chair shows a 2.6 % lower cooling demand compared to the basic controller BCL00.

Compared to BCL00 for the adaptive controller with chair a reduction of the annual heating and cooling demand is evident. The heating demand was 12.7% lower compared to BCL00. The cooling demand was reduced by 5.4 % compared to BCL00.

4. Discussion

The simulations clarify that the comfort level can be mostly maintained in a positive range or even increased with the help of the chair with heating and cooling function simultaneously reducing the heating and cooling demand.
The usage of the office chair with heating and cooling function can be recommended for all season with regard to the thermal comfort level as well as the reduction of the energy demand.
Nevertheless, the reduction for the cooling demand of the central HVAC system is not as high as expected. For higher room temperatures above 28°C, the additional usage of a desk fan is recommended, as the heat sensitive head has a high influence on overall comfort. The supporting effect of an office chair with heating and cooling function regarding thermal comfort, which have been studied in various field and laboratory experiments, have been showed in the simulation study.

5. Outlook

The presented adaptive controller with chair can get used for a potential analysis for other decentralized systems like a thermoelectric cooling wall, fans or combinations of the systems. In the future, further systems should get implemented and the systems will be modelled as separate heating and cooling systems within the plant technology to allow a more detailed analysis.
The PhySCo model predicts detailed comfort values through annual simulations, which will support the planning process of the decentralized and the central HVAC system. The shown approach offers a promising solution for a base to analyses the potential of decentralized heating and cooling devices as they are coming more and more to the market.

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