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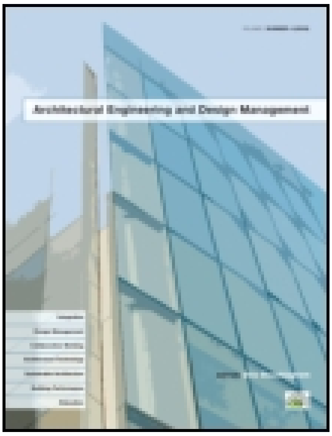

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Optimizing comfort for occupants and its related energy use is becoming more important. Presently, however, heating ventilation air-conditioning (HVAC) system installations often do not work in practice effectively and efficiently as the behaviour of the occupants is not included. The results are comfort complaints as well as unnecessary high-energy consumption. As the end-user influence becomes even more important within the energy process of sustainable buildings, it is necessary to integrate the occupants in the buildings' performance control loop. Laboratory experiments were performed to look for a correlation between infrared (IR) sensor temperature registrations and individual perceived thermal comfort in an individually conditioned workplace. It proved that it is in principle possible to use the third finger skin temperature as a control parameter for perceived thermal comfort. In another experiment in a real in-use office building, a wireless sensor network was applied to describe user behaviour on room and floor level. The results showed that it is possible to capture individual user behaviour and to use this to further optimize comfort in relation to energy consumption. Based on our experiments, we could determine the influence of occupants' behaviour on energy use and determine possible energy reduction by implementing the human-in-the-loop process control strategy.

Keywords: user influence; energy consumption; perceived comfort; process control strategy

Introduction

Buildings, especially sustainable designed buildings, do not in practice meet the intended levels of energy performance (Tetlow, Beaman, Elmualim, & Couling, 2012). The subject of energy has become increasingly contentious with current energy prices and the strict emissions targets for the future (CISBSE, 2012). In fact, energy consumption is frequently twice the design expectations; this discrepancy has been termed the 'performance gap' (Bordass, Cohen, & Field, 2004). This situation is the result of the applied energy modelling calculations conforming with building regulations and rarely considering the real in-use performance and, in particular, the actual behaviour of the building occupants (Tetlow et al., 2012). Designers look at regulated loads whereas facilities managers look at the whole energy bill including unregulated loads, representing the real occupants' behaviour (CISBSE, 2012). Traditionally, during the design process the construction industry has considered the building occupants only superficially. Efforts to reduce the energy consumption caused by the building occupants have largely revolved around the *information deficit model* which assumes that people will both interpret information as intended and act rationally to modify their behaviour accordingly. This somewhat simplistic

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approach to the behaviour of the building users has been shown to be largely ineffectual (Owens & Driffill, 2008) and there is now a growing realization that delivering sustainable, healthy buildings will require a greater appreciation of how the occupants interact with their environment (Tetlow et al., 2012). Clearly, the building occupants behave in a more complex way than current standard design models allow for. Human behaviour can influence the energy consumption by more than 100% (Brohus, Heiselberg, Simonsen, & Sørensen, 2010; Parys, Saelens, & Hens, 2010), so therefore it is necessary to incorporate human needs better in the control strategies. Sensing, monitoring and actuating systems in relation to user perception and preferences play a key role in reducing overall energy consumption in buildings. Optimized process control is a necessity for the improvement of energy performance of buildings (Yu, Zhou, & Deter, 2007). Overall the role of the occupant in relation to energy consumption has been found to be important (De Groot, Spiekman, & Opstelten, 2008; Haas, Auer, & Biermayr, 1998). Reduction of or optimizing energy use is often done without really taking into account the goal of energy consumption, human comfort. However, energy reduction can only be achieved if user comfort is individually addressed (De Groot et al., 2008). Trying to optimize energy efficiency without addressing occupant comfort is not going to work (Nicol, 2007). With smart energy-efficient buildings, the relationship between human behaviour and energy consumption has become significant, and should be looked into by applying building energy management systems (Pauw, Roossien, Aries, & Guerra Santin, 2009).

With today's smart technology it is, in principle, possible to take all individual settings for each occupant into account and find better solutions that can reach an optimal combination of efficient supply optimized comfort. However, currently energy management within buildings is far from optimal and improved control could save up to €600 billion worldwide (Webb, 2008). Recent research has shown a technical-saving potential of 170 Peta Joule primary energy and an emission reduction of 11 Mega ton CO_2 even in a small country such as the Netherlands (Opstelten, Bakker, Kester, Borsboom, & van Elkhuizen, 2007).

The potential savings of energy due to better use of information and communication technology (ICT) are well documented by Røpke, Christensen, and Jensen (2010); however, most of the research focusing on improved ICT often overlooks the role of the user in reducing energy conservation.

The 'human-in-the-loop'

One of the primary objectives of a HVAC system is to provide a thermally comfortable environment. A comfortable indoor environment for all the occupants in a building is difficult to reach because of individual differences between those occupants. Based on the literature, it is concluded that individual differences, including: age (van Oeffelen, 2007), gender (Choi, Aziz, & Loftness, 2010; Karjalainen, 2007), percentage body fat (Zhang, Huizenga, Arens, & Yu, 2001), metabolism (Havenith, Holmér, & Parson, 2002) and clothing resistance (De Carli, Olesen, Zarrella, & Zecchin, 2007), are of importance for the individual experienced thermal comfort. However, nowadays the Fanger comfort model (Fanger, 1970) is still mainly used to determine the (thermal) comfort inside office buildings. Individual preferences are not taken into account in this model. A lot of effort has been taken to design energy-efficient HVAC systems. However, in practice the intended comfort level of these HVAC systems is not achieved, resulting in more sickness absence and lower productivity of the building occupants (Fisk, 2000; Fisk, Seppanen, Faulkner, & Huang, 2003; Seppänen, Fisk, & Mendell, 1999; Wargocki, 2011; Wyon & Wargocki, 2006a, 2006b). This is mainly due to the fact that the control paradigm for HVAC systems has remained relatively unchanged, namely regulating indoor environmental variables such as air temperature without including the thermal state of the individual occupant in the control loop. The traditional thermal comfort models (see, e.g. Fanger, 1970) assume that people in buildings are passive recipients who are comfortable or not comfortable depending on the momentary thermal environment (temperature, airspeed, etc.), while others (e.g. Nicol & Humphreys, 1973; Paciuk, 1990) argue that also occupant behaviour and feedback loops for personal control are essential for modelling indoor climate-related occupant–environment relations (Claessen, Creemers, Boerstra, Loomans, & Hensen, 2012). For example, Boerstra and Beuker (2011) concluded – after an analysis of 20 field studies – that office buildings in which occupants perceive they have adequate control over their indoor climate are more comfortable and have less building-related symptoms. Reanalysing the Health Optimization Protocol for Energy-efficient buildings database (60 office buildings with over 6000 respondents), Boerstra, Beuker, Loomans, and Hensen (2012) found correlations between buildings with more perceived personal control on temperature and increased thermal comfort during winter and with more overall comfort during winter and summer. Furthermore, combinations of control options were found to be more effective at reducing building-related symptoms than single control options (except for control on noise). Their findings suggest that more perceived control over their indoor environment will improve comfort and health of the buildings occupants (Boerstra et al., 2012).

Human comfort and comfort control

The most recent research on human comfort looks at local sensations of individual body parts (Zhang, Arens, Huizinga, & Han, 2010) and thermoregulation with skin temperature predictions (Munir, Takada, & Matsushita, 2009). The interaction between indoor environment and skin temperature for normal office conditions is largely determined by mean radiant temperature, and therefore there is a large effect of mean radiant temperature on the energy consumption in a comfort-controlled office (Kang et al., 2010). By optimizing the responses to the individual human comfort differences, energy conservation of up to 25% is possible (van Oeffelen, Van Zundert, & Jacobs, 2010). The energy supply to a building must be related to actual dynamic changing comfort needs, behaviour of the occupants of the building and the behaviour of the building itself due the weather conditions. Therefore, more actual information is needed. The application of low-cost wireless sensors offers new practical applicable possibilities (Gameiro Da Silva et al., 2010; Neudecker, 2010). If so, then energy demand and energy supply could become more balanced and less energy wasted.

Measuring the radiating temperatures by a low-cost IR camera should make it possible by image post-processing to estimate energy fluxes and temperature distributions with comfort prediction. Correct temperature distribution measurements could be calculated by remote camera control and thermo graphic parameter correction (Revel & Sabatini, 2010). Thermal comfort for all can only be achieved when occupants have effective control over their own thermal environment (van Hoof, 2008). This led to the development of individually controlled systems with different local heating/cooling options (Filippini, 2009; Watanabe, Melikov, & Knudsen, 2010). We designed and built an experimental workplace with an individually controlled heating/cooling panel in front of the workplace and tested our specific approach to comfort and energy management. The implementation of such detailed dynamic approach to individual comfort control is new. However, it is necessary to look more closely at the individuals on a working space and personal level. So we did not look only at room temperatures and thermostat settings of heating or cooling devices. Instead we really looked into the dynamic parameters related to the individual thermal comfort, the actual occupancy, the use of appliances by the occupants and the actual parameters of the building services installations.

Human behaviour

Until now, in practice user behaviour has not been part of building comfort system control strategies in offices; the energy consequences of the user behaviour are not accounted for. However, occupant presence and behaviour have a large impact on space heating, cooling and ventilation demand, energy consumption of lighting and room appliances (Page, Robinson, Morel, & Scartezzini, 2007) and thus on the energy performance of a building (Hoes, Hensen, Loomans, de Vries, & Bourgeois, 2009). User behaviour may be defined not only by the presence of people in the building, but also by the actions users take to influence the indoor environment; for example, the opening or closing of windows or blinds. Human behaviour can be explained as a result of physical needs and psychological needs (Tabak & de Vries, 2010). Physical needs depend highly on the individual and concern space, light, climate conditions and sound (Zimmermann, 2006). The psychological needs are the result of interaction, privacy and personalization, so obviously are highly individual too. Human behaviour related to the physical conditions can be described in terms of user control of the installation systems and building facilities like windows. In this context, user behaviour may be defined as the presence of people in a workplace location in a building and the action users take (or do not take) to influence their indoor environment (Hoes et al., 2009). Recently models have been developed to describe human behaviour and are included in building performance analyses (Bourgeois, Reinhart, & MacDonald, 2006; Degelman, 1999; Hoes et al., 2009; Mahdavi, Kabir, Lambeva, & Proglhof, 2006; Nicol, 2001; Page et al., 2007; Reinhart, 2004; Rijal et al., 2007; Tabak & de Vries, 2010). However, only a few studies successfully demonstrated energy reduction from occupancy behavioural patterns that had been determined because there was no formal connection to the building energy management systems of these buildings (Dong & Andrews, 2009). The main research fields of user behaviour in office buildings were occupancy models and occupant control on shading devices, windows, artificial lighting, appliances and thermal environments. Several occupancy models have been made, but they are hard or even insufficient to apply, because they were targeted at specific buildings.

When the occupancy of the building can be predicted, major profits can be gained with regard to energy usage. In addition, users are shown to consistently over-turn actions in response to uncomfortable conditions, causing oscillations that can waste energy and create an uncomfortable environment. Especially for lighting and shading control, incorporating user behaviour in advanced control algorithms shows high potential to significantly reduce building energy loads. However, until now user behaviour was not part of the building comfort system control strategy in offices. As there is not much specific research on the effect of user behaviour in office buildings, first a user-actions analysis was performed in cooperation with Royal Haskoning, one of the major Dutch HVAC engineering consulting companies (Maaijen, 2012).

Analysis of human behaviourial impact on energy consumption

The third floor of one of their offices was chosen as it was a characteristic and representative example of a standard Dutch state-of-the-art office. Figure 1 shows the floor of the building and Figure 2 illustrates the parameters which might have an influence on the personal actions.

For the calculation of the effects of user behaviour on the energy consumption of the building, the latest version of the VABI (Vereniging voor Automatisering Bouw en Installaties, Society for automatization in Building Industry and Building Services) Elements heat/cooling load calculation tool was used. VABI is the most important Dutch software developer of software calculation tools for building systems, with emphasis on HVAC systems, thermal aspects, electricity and solar energy. The third floor of the case study office was modelled in the VABI elements

Figure 1. Test case third floor of an existing office building.

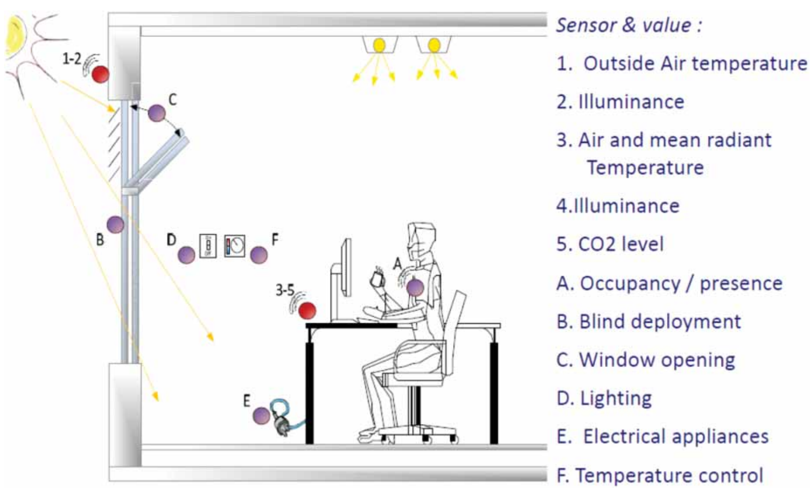
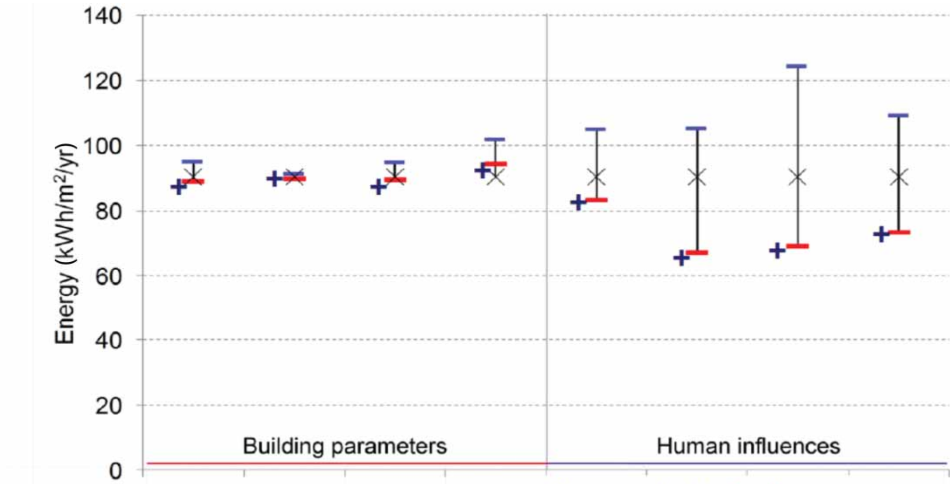


Figure 2. Personal actions and parameters in an example office.

model, this made it possible to calculate the effects caused by actions of the occupants. The input parameters were based on observations of the occupants' behavioural actions during a week. To test the sensitivity of the process outcome, in relation to specific user actions, input parameters were changed within an acceptable and realistic bandwidth based on the observations. The output results from the VABI model for the rooms 3.20–3.22 of the third floor are shown in



Bandwidth	U-value (W/m^2/K)	g-value (-)	RC-wall (m^{2}K/W)	RC-floor (m^{2}K/W)	Occup. (W/m^2)	Light (W/m^2)	Appliances (W/m^2)	F. Tin (°C)
Lower	3.2	0.25	3	0.4	6	5	6	20
Upper	1.1	0.4	6	1.5	20	15	20	23
Reference ×	1.6	0.3	4.5	1	10	10	10	22

Figure 3. Bandwith of results from VABI elements for the total energy demand of rooms 3.20–3.22 as caused by changing the specific input parameter and compared with the common Dutch reference value. *U*-value: thermal resistance of windows; *g*-value: solar factor glazing; RC-wall: thermal insulation value wall; RC-floor: thermal insulation value floor; Occup: internal cooling load based on the number of occupants per m^2; Light: cooling load from lighting per m^2; Appliances: internal cooling load caused by the use of electrical appliances and T_{in}: temperature setting within the office room.

Figure 3 and represent the total sum of the heating and cooling demand for a year. A high bandwidth means that the parameter is a critical performance indicator in relation to the occupants' behaviour, as it has a major impact on building performance.

Based on the above figures, it was concluded that some of the parameters (occupancy, lighting, electrical appliances and temperature setting) related to user behaviour have a clear and high influence (up to plus or minus 30%) on building performance. This underlines the importance for focusing on the inclusion of human behaviour for improving building process control performances.

First detailed analysis of human influence on energy consumption: perceived human comfort process control

Recently, individual-controlled (HVAC) comfort systems were proposed, which can cope with the individual differences (e.g. clothing behaviour and percentage body fat) between office workers. In addition, these systems focus on the body parts (hands, feet and head) which mainly dictate thermal discomfort in mild cool/warm office environments. In 'cooler' environment, the hands, feet and to a lesser extent the back are identified as the most sensitive parts. Under 'warmer' conditions, the head is the most sensitive part (Arens, Zhang, & Huizenga 2006; Zhang, 2003). A direct conditioning of these parts would be the most effective way to achieve thermal comfort. A set-up of such a concept is shown in Figure 4.

Literature shows that the hands are the most sensitive body parts for the human thermoregulatory system (Zhang, 2003). In addition, upper-extremity skin temperature is a sensitive indicator

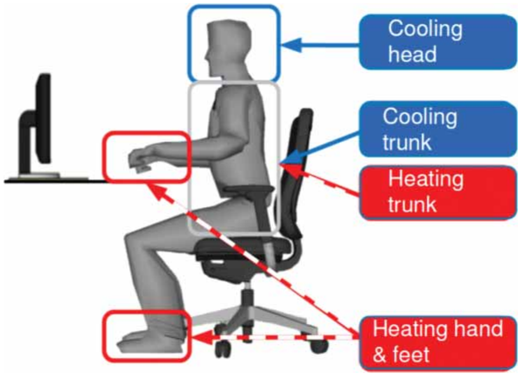


Figure 4. Set-up to provide most effective individual thermal conditioning.

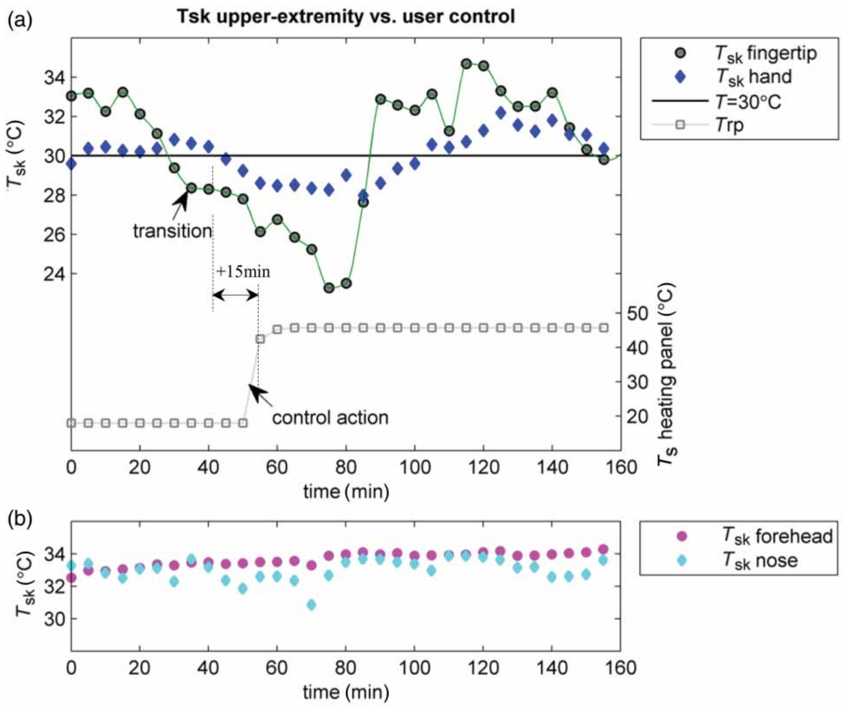
of the body thermal state in the cooling region (Wang, Zhang, Arens, & Huizenga, 2007). Studies in the automotive field have shown that facial skin temperature is a measure for overall thermal sensation (De Oliveira & Moreau, 2009). Both the hands and face are directly exposed to the environment and show potential to be remotely sensed.

The human body can regulate heat flow to the environment by increasing or decreasing the skin blood flow. During mild cool exposure, vasoconstriction is the most important thermoregulatory effecter, which can be clearly observed in the upper-extremity region. In addition, the variations in facial skin temperature may also indicate if a person is getting warmer or cooler. The challenge for automatic control of radiant heating is to detect the turning point from a neutral thermal state to a cooler thermal state before the user perceives any cool thermal sensation. The fact that the skin temperature can fluctuate within a range of temperatures without producing any temperature sensation (i.e. the neutral zone) is highly useful in this.

Experiments I: user-control proof-or-principle

A number of user-controlled experiments were performed, in mild cool conditions (T_{in} = 19–20°C), in order to determine if a decreasing trend in skin temperature of the hands or face was observed, before the user performed any heating control action. The only intervention in the individual thermal climate was the use of individually controlled IR-heating panels. The panels were placed vertically in front of the office desk and therefore not optimized to heating the hands. Two human subjects participated in this research. The results 'proof-of-principle' demonstrated that the finger skin temperature was a critical performance indicator of the body thermal state in the cooling region. To test whether the finger temperature was actually useful as a control signal, the experiments were reversed: from user control to automatic control. In the user-controlled experiments, the radiant-heating system was activated and the subject had the ability to control the panel surface temperature by the individual control unit. The room temperature was controlled to 20°C, which is below the thermo-neutral zone of the subject. In Figure 5 the results are shown for one of the six user-controlled sessions. The results of the other sessions can be found in Vissers (2012). The heating control action is presented by the surface temperature of the radiant panels, and is shown on the secondary vertical axis. When the skin temperature dropped below the 30°C line, it is called a 'transition'. The goal of these user-controlled experiments was to detect a feed forward transition out of the comfort zone, before the user took any control action.

Figure 5 shows a transition in fingertip skin temperature (t = 35 min), before the subject performed a control action (t = 50 min), resulting in a time delay of +15 min. This positive time delay



	T_a (°C)	T_r (°C)	V_a (ms^{-1})	RH (0-1)	PMV (-)
Mean±SD	20.0±0.2	20.3±0.3	0.07±0.02	0.40±0.05	-0.65±0.1

Figure 5. Upper-extremity- and facial skin temperature (from IR data) during the user-controlled test. (a) Fingertip and hand skin temperatures versus heating panel temperature and (b) forehead and nose skin temperature. Session#5 dd. 16-11-2012: male subject.

indicates that the fingertip skin temperature might be a useful parameter for automatic comfort control purposes.

In almost all sessions in this first series of experiments, the radiant-heating system was, despite the maximum panel temperature (set by the user), not able to compensate for the cool whole-body sensations. Skin temperatures of the finger and hand did not return to the comfortable zone.

Experiments II: automatic comfort control

An improved heating system was applied which radiates the heat more concentrated to the hands. This heating system consisted of two incandescent reflector heating lamps (Philips R125 IR250) focusing each on one hand, see Figure 6.

The finger temperature, measured by an IR thermograph, was tested as feedback control signal for automatic regulation of a radiant hand-heating system by applying different set-points: small, medium and large bandwidth. The bandwidth is defined as a range of skin temperatures in which the finger temperature was controlled.

By controlling the finger temperature in a small bandwidth (T_{sk} = 29–31.5°C), it was possible to automatically respond to user thermal preferences. Small changes in the skin temperature (≤2.5 K) were not perceived as cool by the subject. By controlling the finger temperature in such a small bandwidth, it was possible to react to the expected change in perceived thermal

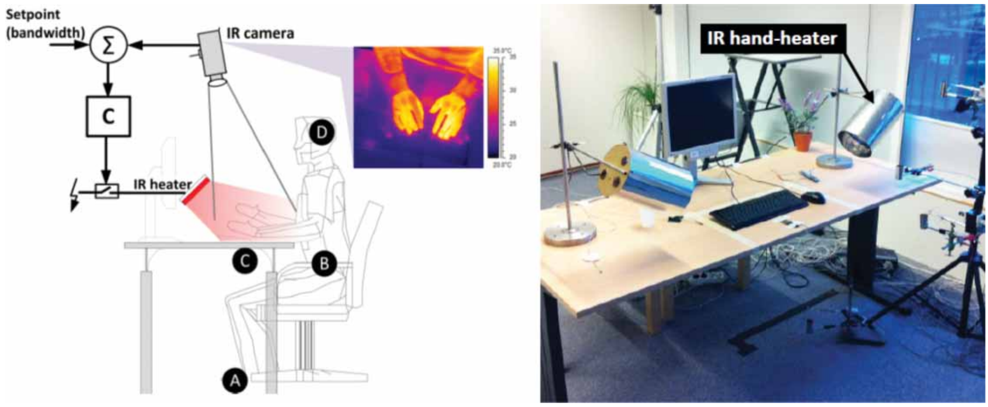


Figure 6. Local heating controlled by subjects' upper-extremity skin temperature. An experimental setting to measure the effect of individual-controlled additional radiative heating.

comfort by the occupant before his action responds to adjust his or her user thermal preferences (i.e. before cool discomfort occurred), while the basic room air temperature T_a was lowered from 22°C to 19.5°C (Figure 7). So before the occupant was conscious about feeling cold, the system could adjust the setting of the local heating control so that the effect of conscious perceived cold conditions will not occur.

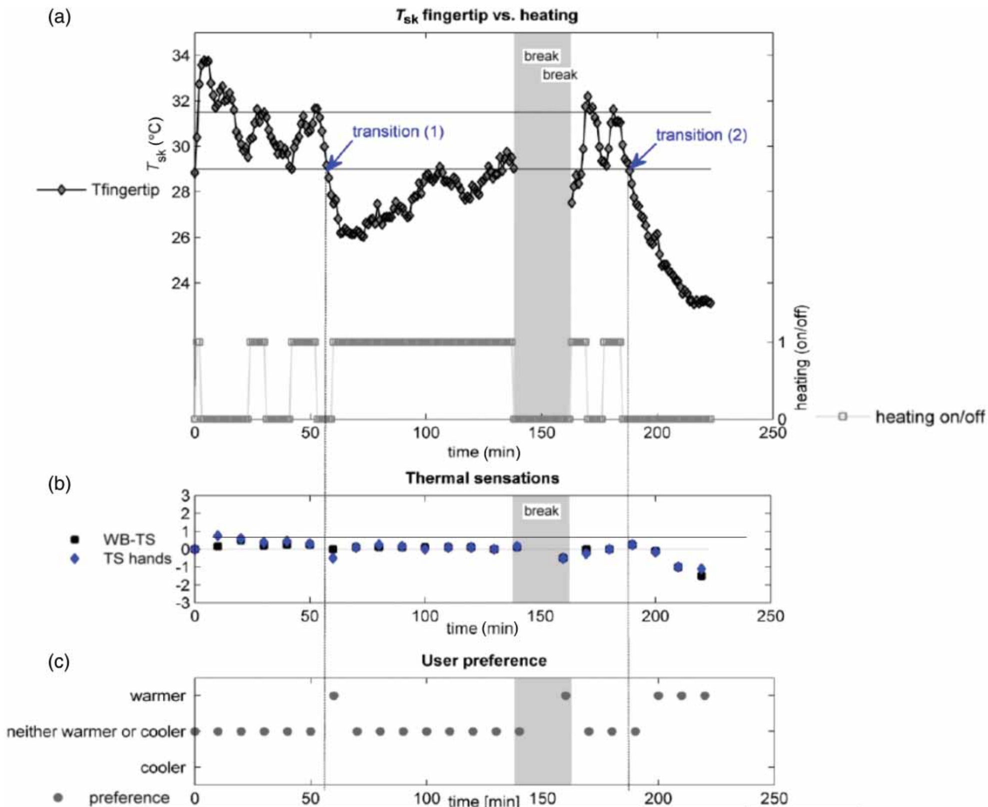
In total, seven different experimental sessions were held with two subjects (one male and one female), which generated around 150 measurement results on the finger temperature and overall sensation. A correlation between the finger temperature and overall sensation was found ($r^2 = 0.45$, $P < 0.05$). By modelling the preference that arises from the interactions with the user, this small bandwidth might be applicable to other individuals. When the actual need for comfort of the individual building user is addressed, this will lead to reduction of the energy consumption by the building systems.

Second detailed analysis of human influence on energy consumption: human movements within the building

The literature shows that occupants spend on an average only around 60% of their time on their workplace. Which could mean that for 40% of the time less strict thermal indoor conditions could be maintained in their workplaces. This could be done in its most simple form with a sensor; however, a more advanced control strategy would look at the movements of the occupants within the building. Therefore, it is necessary to use the individual building occupants' movements as input for the control system.

Arens, Federspiel, Wang, and Huizenga (2005) proposed a distributed sensor network for office rooms. At room scale, the control and actuation could take place within the room itself by a kind of remote controller. The persons' thermal state (comfort state) could be predicted from measured skin temperatures sensed through contact or remotely by IR sensors. In their concept user behaviour was taken into account by an occupancy sensor. Energy savings of up to 24% over the standard HVAC control system were achieved during experiments at MIT University (Arens et al., 2005).

Distributed information about the human movements could be obtained by low-cost wireless sensor networks (Tse & Chan, 2008), low-cost IR sensors (Buydens, Kassovsky, & Diels, 2006;



	T_a (°C)	T_r (°C)	V_a (ms^{-1})	RH (0-1)	PMV (-)	$T_{sk,mean}$ (°C)
Mean±SD	19.6±0.2	19.7±0.3	0.07±0.02	0.47±0.03	-0.71±0.05	31.8±0.3

Figure 7. Upper-extremity skin temperature controlled in a small bandwidth with two transitions out of the bandwidth. (a) Fingertip skin temperatures (moving average) versus heating level, (b) whole-body and local thermal sensation and (c) heating preferences. Session 10-02-2012: female subject (Vissers, 2012).

Revel & Sabatini, 2010). This distributed information could provide insights in the ongoing processes at different levels (personal, local and room level) which can be used for user-adaptive comfort control. Feldmeier and Paradiso (2010) developed a personalized HVAC system consisting of four main components: portable nodes, room nodes, control nodes and a central network hub. At the heart of the system was the building occupant, where comfort information was stored. To best assess the occupants' comfort level, a portable node was developed which senses the local temperature, humidity, light level and initial activity level of the user. Low-budget wireless sensor networks with portable nodes show high potential for real-time localization and monitoring of building occupants (Feldmeier & Paradiso, 2010). As a result, wireless sensor networks have become more popular for application in climate control (Gameiro et al., 2010; Georgievski et al., 2011; Jiang et al., 2011; Kim, Jung, & Kim, 2010; Neudecker, 2010; Park, 2011; Rawi & Al-Anbuky, 2011; Yu et al., 2013).

Still there is a huge gap in practice and therefore it was necessary to develop a new application of wireless sensor network (WSN) to be able to have a closer look into possible additional functionality of WSN in regards to human movements within a building. Applying the bottom-up approach, with the human in the control loop of building services systems, could only be achieved if users could be located within the building. Static wireless sensor nodes were mounted on the

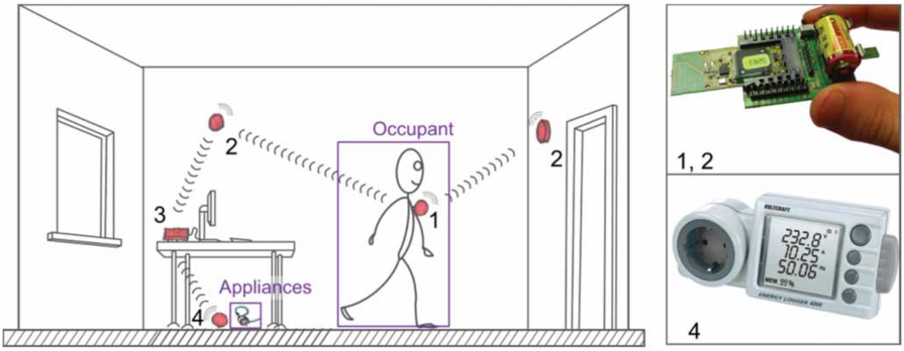


Figure 8. A wireless sensor network (2) tracks the mobile node (1) of the occupant and the energy use of appliances (4) and uses the real-time data for the building system control (3).

floor and communicated with mobile nodes (or in the future smart phones) carried by the occupant to determine the position of the occupant on workplace level. The measurement set-up is schematically shown in Figure 8.

The wireless static nodes for position tracking of the occupants were placed on points of interest, e.g. the workplaces, printer, coffee machine and toilet. Based on the signal strength, the nodes locate in which zone the occupant is. With the nodes a mesh was created consisting of 30 zones. Figure 9 shows that there was a more refined grid around the workplaces than, for example, in the

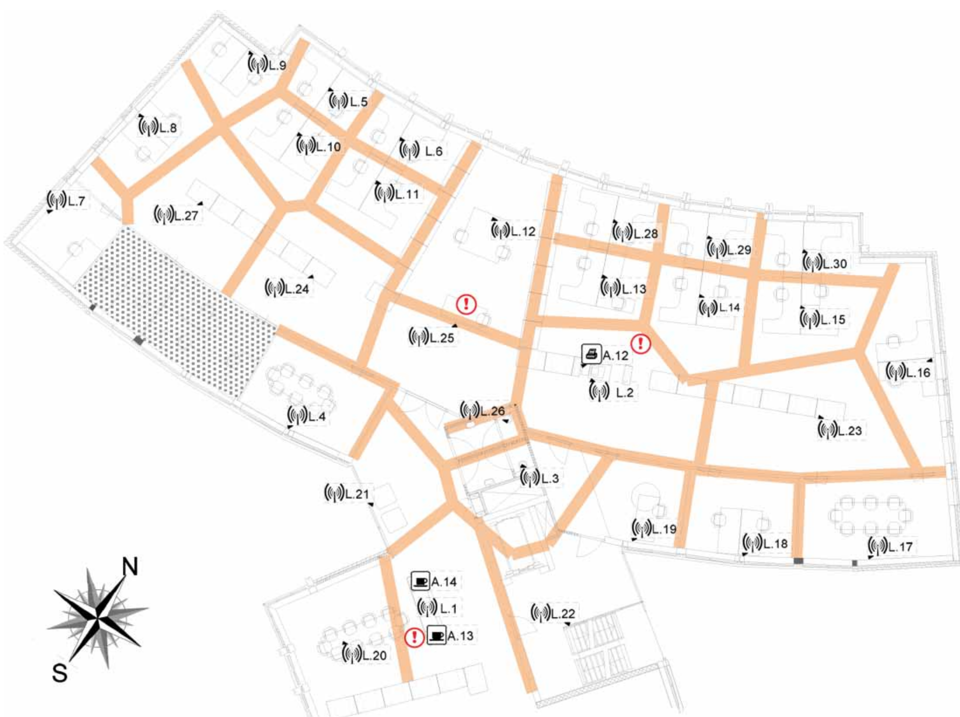


Figure 9. Positions of the static nodes creating a mesh of the zones for measuring the position of the building occupants on the floor. The transition region between the zones is marked by the broad light coloured line.

corridors. In every zone one power logger was installed, for measuring the energy use and to get an estimation of the heat production.

Results

Determination of user comfort and energy-saving potential

When the actual need for comfort of the individual building user is addressed, this will lead to reduction of the energy consumption by the building systems. A model was built to determine the primary heating and cooling energy demand for four different cases see Table 1:

(1) energy demand as designed,
(2) actual energy demand as measured,
(3) taking the 'human-in-the-loop' approach at room level,
(4) taking the 'human-in-the-loop' approach at workplace level.

The simulation was performed using a whole-building model programmed in the Simulink HAMBase environment. Contrary to earlier research by Zhang et al. (2009), this study took into account real occupancy profiles, appliances use, lighting profiles and the energy needed for personalized conditioning of the occupants. In the four cases the building parameters were the same, there was only a change in the user profiles. These user profiles input variables are explained in more detail.

Design input

In the design phase assumptions were made for the different user influences on building performance. The zones of the building model were equal to the rooms of the floor plan. The values are given in Table 1.

Actual energy demand

For the simulation of the actual energy demand, all measured profiles were applied. The occupancy contributed to both sensible and latent heat load in the room. The activity level of the occupants was assessed at 1.1 met (1 met = 58.2 W/m^2, A_d = 1.8 m^2), which is standard for office activities such as typing according to ASHRAE (2004). For heating, the measured temperature

Table 1. Overview of the input values for the building simulation on workdays.

Simulation input	(A) Design	(B) Actual	(C) Room	(D) Workplace
(A) Metabolism	10 W/m^2 8–18 hr	1.1 Met/prs Occ./room*	1.1 Met/prs Occ./room*	1.1 Met/prs Occ./zone*
(D) Lighting	10 W/m^2 8–18 hr	Power/room* 8–20 hr	Power/room* 8–20 hr	Power/zone* 8–20 hr
(E) Appliances	10 W/m^2 8–18 hr	Power/room* –	Power/room* –	Power/zone* –
(F) Temperature (heating) night	22 (8–18 hr) 19	Temp./room* Temp./room*	If occ. 23.5 else 25 18	19.5 with pers.heat. 18
(F) Temperature (cooling) night	24 (8–18 hr) 25	23.5 (8–18 hr) 25	If occ. 23.5 else 25 25	If occ. 23.5 else 25 25

profiles were used as the temperature set-point. In the winter, a temperature set-point of 23.5 °C during working time was assumed.

Occupancy control on room level

Here only the temperature set-point was changed compared with the actual energy demand. When the room was not occupied, a bigger bandwidth for the room temperature was allowed in both the winter and summer situation.

In Figure 10, the measured profiles for occupancy and appliances are shown for a typical reference day in the open plan office. The occupancy is presented as a fraction of the full occupancy. During the day, the maximum occupancy equalled 80%. For the appliances, the total heat load is presented in Figure 10. Remarkably even when the occupancy strongly decreases (e.g. during the lunch break at 12.00 h), the heat load of appliances did not significantly change. This showed that even in an environmental-friendly offices, the occupants do not take the effort to turn their PC's, lights, etc., off

'Human-in-the-loop' – workplace level

In this case, the model was divided into the 30 zones, which were the same as the conducted measurements on the case study floor. The internal heat gains of metabolism, lighting and appliance use were now applied on the zone level. From recent research (Vissers, 2012), it was concluded that by controlling the finger temperature in a small bandwidth the overall thermal sensation was maintained at neutral or slightly higher value, while an indoor air temperature of 19.5°C was applied. Therefore, hand heaters with a total power of 98 W were applied. Since no obvious results could be found for personal cooling, a comfortable temperature set-point of 23.5°C was assumed when a zone was occupied. The change of set-point was only applied on the workplaces, e.g. no hand heaters were applied in the toilet or near the location of the printer or coffee machine.

Simulation model to determine the effect of different scenarios on energy consumption

A simplified sketch of the simulation model in Simulink is shown in Figure 10 for case D, control on workplace level with 30 zones. In simulation A, B and C, the zones of the model corresponded to the physical rooms in the building. Climate data of the measured six-week winter period were coupled to the whole-building model. The indoor air temperature of the zones was the output of

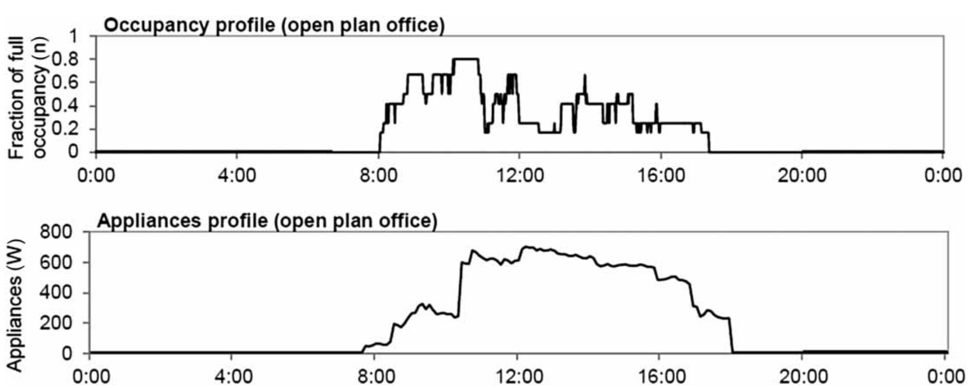


Figure 10. Measured profiles for occupancy and appliances for a typical winter day.

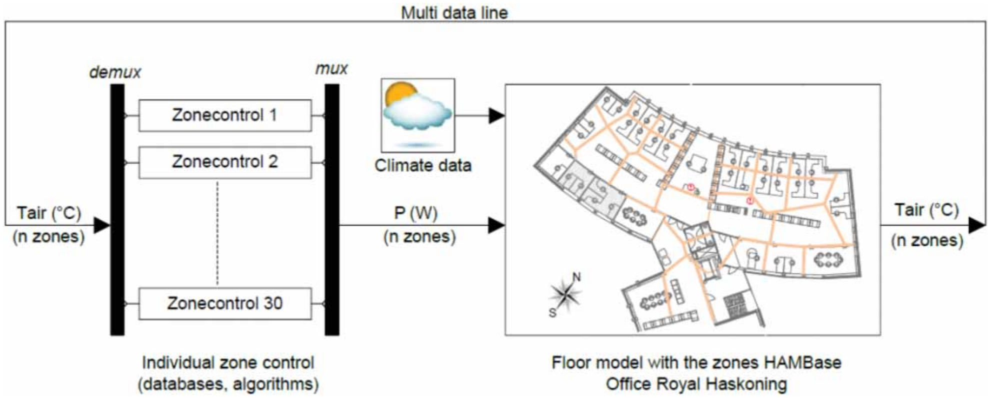


Figure 11. Simplified sketch of the simulation model in Matlab/Simulink. The air temperature was used as feedback control signal for the individual zone models.

the whole-building model. This information was used as the feedback signal for the control algorithms of the individual zones. A demultiplexer (demux) was used for selecting the data-output from this feedback signal. A multiplexer (mux) was used for combining several data lines into one single signal line. For further information on simulation model, see Figure 11:

- Each zone had its own control loop for regulating the indoor air temperature.
- For the basic room heating (P_{basic}) a proportional control algorithm was applied.
- In cases C and D, only control of the temperature was changed, meaning that ventilation rates were not changed according to the occupancy. It is highly likely that the energy demand will drop significantly when this is applied.

Energy

The (primary) energy-saving potential was calculated according to Equation (1). The energy needed for the case was divided by the energy needed for the reference situation which was the design situation. The results are presented in Figure 11.

$$\text{energy saving} = 1 - \frac{(Q_{\text{basic}} + \sum Q_{\text{local}})}{(Q_{\text{design}})_{@22^{\circ}\text{C}}}. \tag{1}$$

As a reference, the energy consumption was calculated by the simulation based on the presumed parameters from the design brief. This forms the zero level from which the differences in energy reductions were determined. The (primary) energy-saving potential for heating was calculated according to Equation (1) for different set-points of the indoor air temperature. The results are presented in Figure 12.

From the measured real energy loads in the office, it followed that an increase occurred in energy demand for both the heating (− 13% reduction, so actual 13% increase) and cooling (− 20% reduction) compared with the results of the simulation based on the design specification. When applying people-oriented control on room level, energy savings of around 3% for heating and 8% for cooling compared with the design reference situation were calculated. A much higher energy reduction was calculated when the temperature was controlled on workplace level applying the ‘human-in-the-loop’ control strategy with personal heating and cooling: 14% for heating and 18% for cooling. Compared with the energy demand based on the measured energy loads in

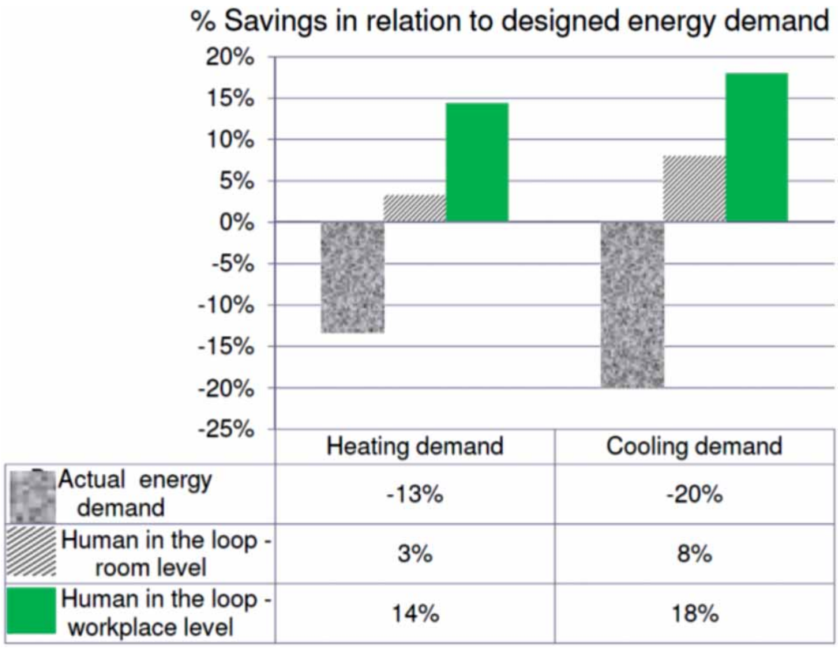


Figure 12. Energy-saving potential for heating and cooling calculated for a six-week period, compared with the designed energy use. The energy-saving potential of the people-oriented energy control on workplace level compared with the actual energy demand is indicated with the red arrows.

practice, this leads for the ‘human-in-the-loop’ strategy, to an potential energy saving close to 30% (from −13% to +17%) for heating and up to 38% (from −20% to 18%) for cooling, see Figure 12. The application of local heating shows high potential, especially when combining it with the possibilities of indoor localization of the occupant.

Comfort

Vissers (2012) showed that it was possible to respond to user thermal preferences (i.e. before cool discomfort was consciously felt by the occupant) when the basic room air temperature was 19.5°C. By conditioning the hands of the occupants with a radiation panel the local- and overall thermal sensation, it would be possible to maintain their neutral comfort state or adjust it to a slightly higher level. This will theoretically lead to an optimal predicted mean vote value of close to zero.

Discussion

Measurements

The measurements on the case study floor only took place for a period of six weeks in winter period. First this means that the obtained results may only be relevant to this measurement period and second they are only valid for this case study floor. Mahdavi and Pröglhöf (2009) already described that results from one building cannot be transposed without extensive calibration measures, considering differences in buildings use.

During the measurements not all building users wore a node. Since almost 80% of the floor users wore a node, the error might be kept at a minimum.

Simulation energy reduction results compared with the literature

The energy-saving potential of the most optimal scenario, the 'human-in-the- loop' process control strategy on workplace, for heating was 17%, when lowering the set-point of the indoor air temperature from 22°C to 19.5°C and taking into account personalized heating of 98 W per occupant (Vissers, 2012), see Figure 13.

It was important to compare our simulation results with those of others. Our results could be compared with those of Zhang et al. (2010), who also reported the potential energy savings by adjusting the temperature setting by which the room temperature was controlled (Zhang et al., 2010). The annual energy savings, obtained by their numerical study, for different climate zones in the USA are shown in Figure 14. The climate of the Netherlands is comparable with that of Minneapolis. Wang et al. (2007) achieved energy reduction by controlling the temperature at room level: 16% for heating and up to 28% for cooling compared with the actual situation.

In addition van Oeffelen et al. (2010) simulated the energy potential for a typical winter situation in the Netherlands. Oeffelen et al. (2010) calculated an energy-saving potential of about 25% for heating by decreasing the room temperature set-point from 22°C to 20°C, which is about 10% higher as found in our research. However, our research considered real occupancy profiles and real energy use for individual local heating, which made our results more realistic.

Klein et al. (2012) controlled the room temperature on room level by implementing a multi-agent comfort and energy system and achieved a reduction of 12–17%. The energy saving is 4–11% lower than found in this research. However, in the research of Klein the case study floor consisted of 33 rooms, he was able to divide the floor into only 17 thermal zones. When the floor could be divided into thermal zones corresponding with the number of rooms then it would reasonable that he would also have found higher energy savings.

Often the potential benefits of new technologies are reduced by so-called human rebound effects. Behaviour of the occupants is influenced by rebound, which is the way improved efficiencies are compensated by increased spending (Hens, Parys, & Deurinck, 2010). Therefore, we prefer predictive user-adaptive process control. To further optimize the performance of these

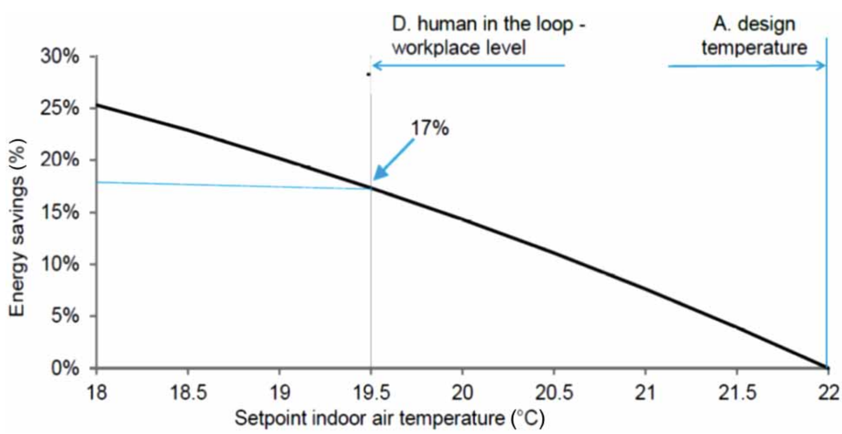


Figure 13. Energy-saving potential for heating energy calculated for a six-week winter period, by decreasing the indoor air temperature set-points and applying local heating per occupant. In the reference case, the indoor temperature is controlled at 22°C without local heating.

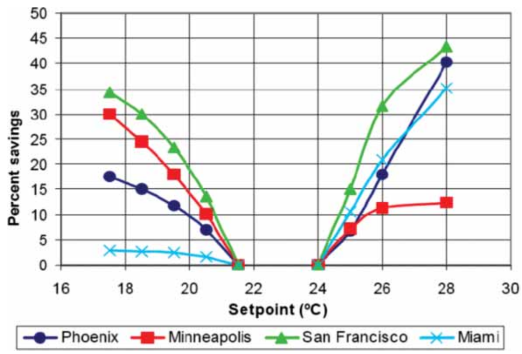


Figure 14. Per cent energy savings for widened air temperature set-points relative to conventional set-point range for different climate zones in the USA. The energy for local heating/cooling is not included (Zhang et al., 2009).

systems, further research is needed into the possibilities and the use of systems for individual comfort control on workplace level.

With new and more intelligent control strategies one must take into account the possible effects and find ways to compensate them. As a result there is a strong need to develop control strategies that can eliminate or at least mitigate such effects. Therefore, it is necessary to find intelligent control strategies that optimize energy efficiency and conservation as the outcome of multiple interactions between technological systems and human users (Midden, McCalley, Ham, & Zaalberg, 2008).

One of the limitations of current research is the focus on individual workplace, where as in practice there are often shared workplaces. The problem of shared spaces is inherently more difficult to solve, because all individual preferences and differences cannot be matched. One strategy in these settings could be to try to minimize the level of comfort conflicts within the group of shared working places.

Feedback to the user is very important and must be incorporated within the comfort energy management system (Tetlow et al., 2012). It is essentially sending the user information about what effect their action has had, salient, close in time, and specific to the conducted action (Byrne, 2008). Displaying real-time energy use to occupants through smart metres has been demonstrated to reduce consumption in the region of 5–15% (Darby, 2008). However, such savings can reduce significantly overtime (van Dam, Bakker, & van Hal, 2010). This has not been part of our research. Traditional methods to engage with the occupants are not always successful and this asks for a more holistic approach. Achieving energy efficiency in buildings is not solely a technological issue and the construction industry therefore needs to adopt a more user-centred approach (Tetlow et al., 2012).

The use of electrical appliances is the most influencing variable on building performance. In a previous research, Parys concluded that the operation of office equipment is obviously not driven by indoor environmental quality motives. Therefore, it is more logical to link the ratio of internal heat gains over the nominal power of office equipment to the occupancy rate (Parys, Saelens, & Hens, 2011)

When the averaged profiles for occupancy and use of electrical appliances are looked into, there is a strong correlation between them with a determination coefficient of 0.94. Looking at workplace level there is no clear correlation. This is proven in Figure 15 with the occupancy and appliance use for two reference days. Connections were visible, but the appliance use did not correlate with the occupancy.

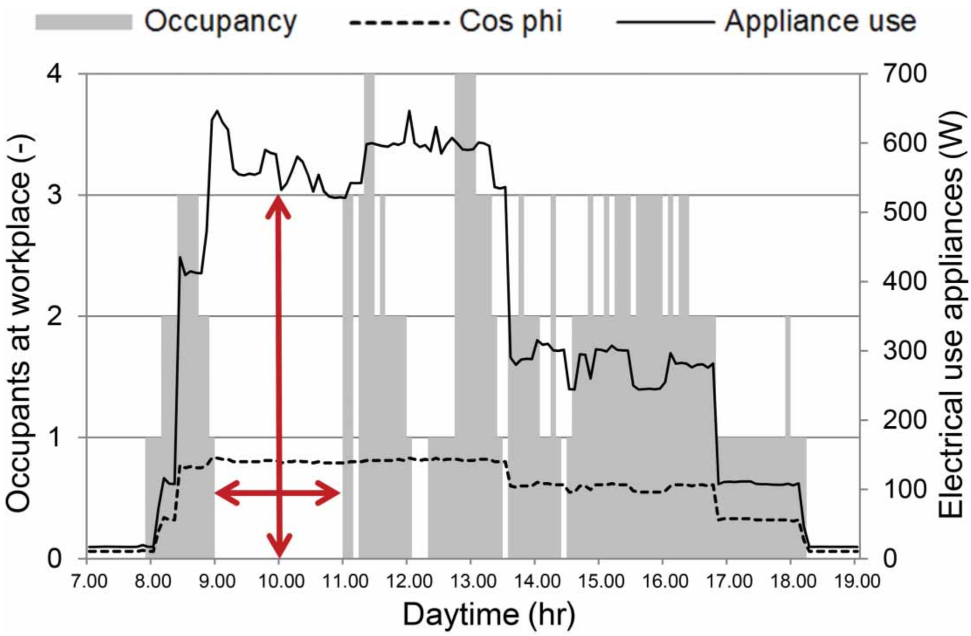


Figure 15. Occupancy for four workplaces and total energy demand for those places for a reference day, time step = 5 min. The arrows indicated a period that energy demand could be reduced as the occupants were not at their workplace.

Perceived comfort

The challenge is that the workplace should be correctly conditioned before the neutral thermal state of the occupant turns into a cooler or warmer thermal state. When the skin is adapted to a certain temperature, the skin temperature can fluctuate between the borders of the neutral thermal zone without causing any thermal sensation. Wang et al. (2007) exposed persons to a slightly cool environment of 19°C and very warm environment of 28.2°C. In the situation of the slightly cool environment, the test subjects voted their thermal sensation was cold after between 10 and 20 min. In the warm environment, the subjects voted warm after circa 10 min. This meant that it took around 10 min before the building user consciously perceives the too warm or too cold indoor environment. The building service systems must be capable of adjusting the conditioning of the workplace within those 10 min and correct the settings before the occupant consciously perceived discomfort.

The goal of our user-controlled experiments series 1 and 2 with individual climatization was to detect transition out of the comfort zone, before the user took any control action. Results showed that this transition is quite difficult to detect. Standard fluctuations of 2°C in finger skin temperature made it difficult to recognize an early and clear trend out of the neutral zone. Only after the transition had taken place it was easy to detect, as the occurred drop in the finger skin temperature was up to 8°C. Additionally, in some of the user-controlled experiments a decreasing trend in finger temperature showed before the user had taken any control action. While in other sessions the decreasing trend was recognized too late, which means that the subject already had taken a control action to compensate for his cool sensations. More research is necessary to look into the specific characteristics of the individual finger temperature transition points. The minimal observed cooling time of the finger temperature in the small bandwidth took about 5 min. This time was available for detection and reaction by the heating control system.

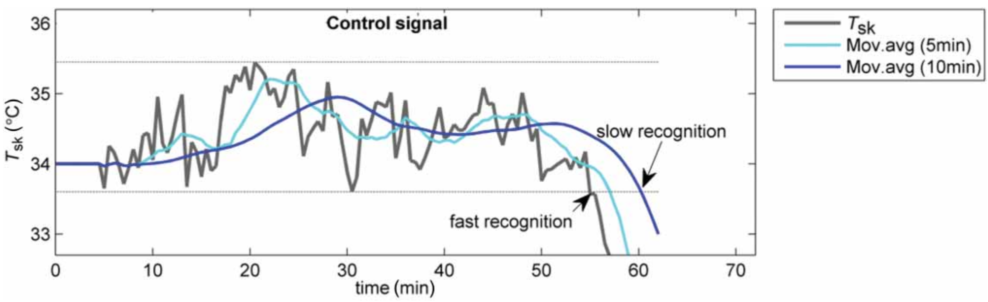


Figure 16. The measured finger temperature by IR thermography (T_{sk}), the moving average signals based on 5 and 10 min data, and the overall filtered area.

During the experiments, the moving average (over 120 s) finger temperature was used as control signal. The moving average is less sensitive for quick changes; however it increases the overall response time. Using a signal filter to eliminate the oscillating effect can overcome this problem, see Figure 16.

Occupancy and human movements within the building

The wireless sensor occupancy positioning method is able to locate the user position, so energy can be applied to the spots where there is a demand of the building user with his individual comfort. This does not mean that control devices, operable windows, and other adaptive-user actions on room or workplace level are superfluous. As the studies by Huizenga, Abbaszadeh, Zagreus, and Arens (2006) and Hoes et al. (2009) showed, the ability for a person to control his environment has a significant impact on occupant satisfaction. This asked for a system which combines (i) localizing the building occupant and automatic conditioning of his workplace, and (ii) the possibilities for adjustments of the users' environment. To apply the individual preferences on the workplace, the human should be included in the loop through controlling his individual comfort level to prevent discomfort and energy consuming behaviour of the occupant to restore his comfort level.

Conclusions

User behaviour can be defined as the presence of people in a workplace location and the action users take (or do not take) to influence their indoor environment. However, interactions with the buildings' environmental systems are difficult to predict at the level of an individual person. In general, building occupants interact with a building to enhance their personal comfort (e.g. by heating or cooling their local environment to improve their thermal comfort or adjust lighting system or blinds to optimize their visual comfort, etc.).

With increasing demands for improved energy reduction control strategies, the influence of the occupant becomes significant and should be looked into. In this case study, the human influence is 3–5 times higher than variations in building parameters. With the 'human-in-the-loop' approach, energy is only sent to those spots where it is required by localizing the building occupant and anticipating its influences. From measurements of 20 employees during six weeks on an office floor, it is clear that strong correlation can be distinguished between the occupancy and use of electrical appliances.

This article presents a new control strategy for automatic control of personalized radiant heating in mild cool office environments, by including the human body as sensor in the control loop. The personalized radiant heaters could be a kind of IR lamp, which could be integrated in a kind of desk lamp. The upper-extremity skin temperature, remotely sensed by IR thermography, was proposed as feedback control signals. The objective of this control strategy is to save energy, while maintaining thermal comfort of the individual building occupant. Improvement of the energy consumption was made possible by enhancing the individual comfort of occupants (individual comfort control strategy) and incorporation of their behaviour (wireless sensor position determination). By starting from the human perspective and using available and new technology, the outcome will be more focused on the ability to understand the critical aspects of the comfort of the end users. With the 'human-in-the-loop' approach on workplace (comfort control) and building level (occupant's positioning detection) more than 20% energy savings can be achieved on heating demand and up to 40% energy savings on cooling demand compared with the 'pre intervention' energy demand of the investigated standard office.

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