WIRELESS SENSOR TECHNOLOGY TO OPTIMIZE THE OCCUPANT'S DYNAMIC DEMAND PATTERN WITHIN THE BUILDING

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ABSTRACT

Energy needs to be used as effectively as possible by anticipating on the human behaviour with the purpose of providing optimal comfort. The purpose of this research is to assess the energy saving potential by sending the energy to those spots (hotspots) where needed and to determine how the user can be taken into account in the design to improve the performances of office buildings. Possibilities for human position tracking measurements by means of a WSN were investigated to determine the user behavior of aoocpants of a building. An experimental set-up was developed which was implemented on the 3th floor of one of the offices of Royal Haskoning consulting engineers. This showed the positive effect of using wireless technology to optimize the occupants comfort while minimizing the energy consumption,

INTRODUCTION

As until now in practice user behaviour has not been part of the building comfort system control strategy in offices, the energy consequences of the user behaviour are not accounted for. However, occupant presence and behaviour has a large impact on space heating, cooling and ventilation demand, energy consumption of lighting and room appliances (Page et al. 2007) and thus on the energy performance of a building (Hoes et al. 2009). User behaviour may be defined as the presence of people in the building, but also as the actions users take to influence the indoor environment, the opening or closing of windows or blinds. Human behaviour can be explained to result from physical needs and psychological needs (Tabak and de Vries 2010). Physical needs are highly individual and concern space, light, climate conditions and sound (Zimmerman 2006). The psychological needs are the result of interaction, privacy and personalization, so obviously 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 the building and the action users take (or does not take) to influence their indoor environment (Hoes et al. 2009). Recently models have been developed to describe human behaviour and include it in building performance analyses (Degelman 1999, Nicol 2001, Reinhart 2004, Bourgeois et al. 2006, Mahdavi 2006, Rijal et al. 2007, Page et al. 2007, Hoes et al 2009, Tabak and 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 and Andrews 2009). The main research fields of user behaviour in office buildings were occupancy models and occupant control on shading device, window, artificial lighting, appliances and thermal environment. 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 the building energy loads. However, as until now user behaviour were not part of the building comfort system control strategy in offices. As there is not many 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.

FIRST ANALYSIS OF HUMAN BEHAVIOUR ON ENERGY CONSUMPTION

The 3th floor of one of their office was chosen as it is a characteristic and representative example of their office working situation. Fig. 1 shows the floor of the building and Fig. 2 illustrates the parameters which might have an influence on the personal actions.

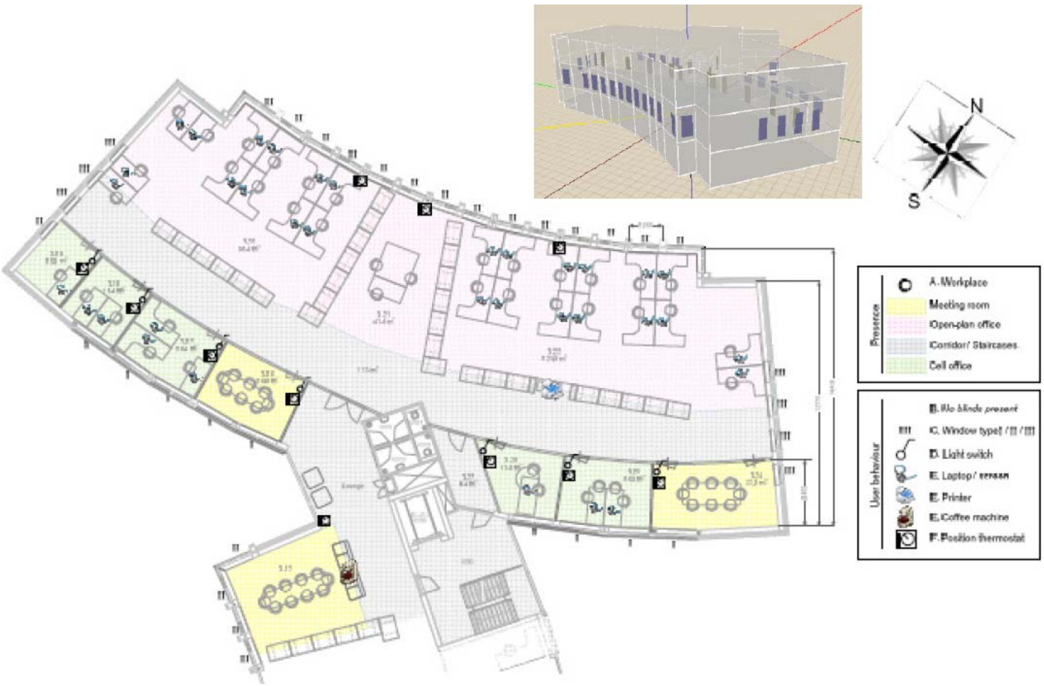
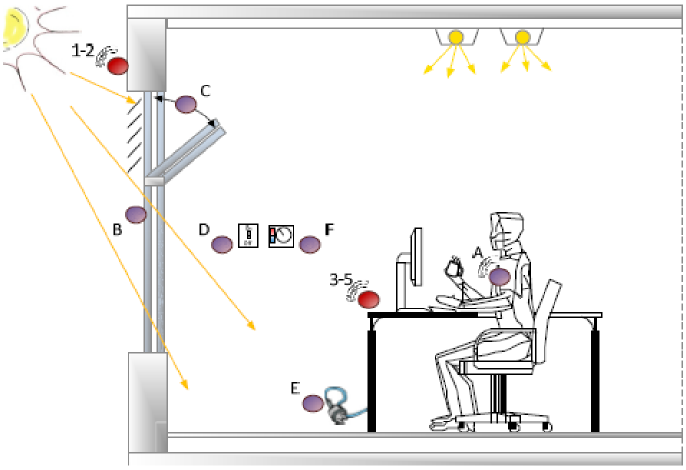


Figure 1 Test case 3th floor of an existing office building



Sensor Nr.	*Measured value*
	External
1.	Temperature
2.	Illuminance
	Internal
3.	Temperature
4.	Illuminance
5.	CO_2 level
A.	Occupancy / presence

Figure 2 Personal actions and parameters in an example office

For the calculation of the effects of the 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 Heating Ventilation and Air Conditionings systems, thermal aspects, electricity and solar energy. The 3th floor of the case study office was modeled in the VABI elements 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 office space 3.20 – 3.22 are shown in Fig. 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.

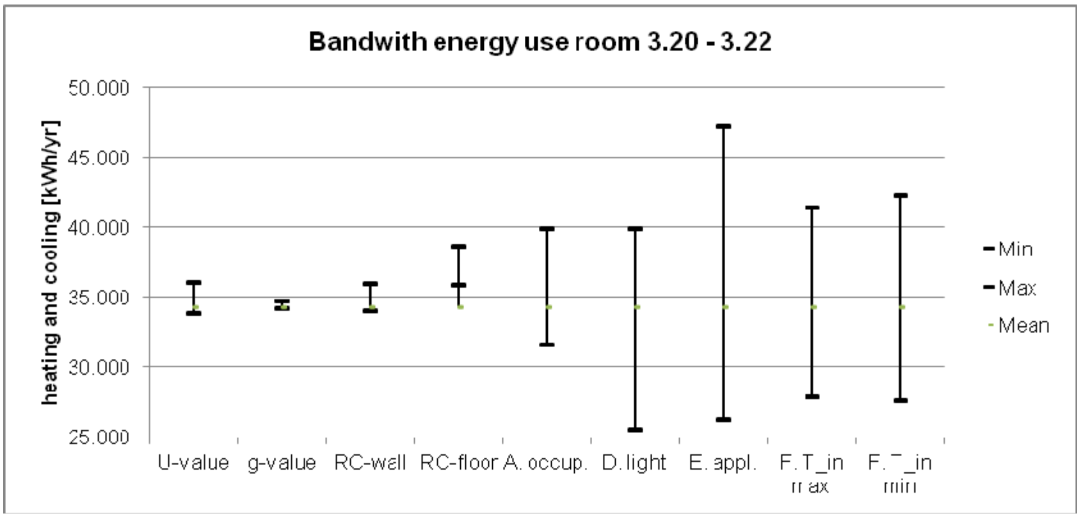


Figure 3 Bandwith of results from VABI elements for the total energy demand of room 3.20 – 3.22 as caused by changing the specific input parameter

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.

ANALYSIS OF OCCUPANTs' MOVEMENTS WITHIN THE BUILDING

The idea is that 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. Thereby, the control objective is to look how the individual building occupants' movements, their staying on different locations within their building.

Distributed information can be obtained by low-cost wireless sensor networks (Arens et al. 2005, Tse and Chan 2008), low-cost infrared sensors (Buydens 2006) (Revel and Sabattini 2010), and smart badges/portable nodes (Feldmeier and Paradiso 2010). This distributed information could provide insights in the ongoing processes on different levels (personal-, local-, and room level) which can be used for user-adaptive comfort control. Wireless sensor networks become more popular for application in climate control (Neudecker 2010, Gameiro et al. 2010, Kim et al 2010, Yu et al. 2011, Rawi and Al-Anbuky 2011, Jiang et al 2011, Georgievski et al. 2011, Park 2011). Still there is a huge gap to practice as there is at the moment only one company which offers WSN for climate control in the Netherlands and has only realized a few projects in the last years (Octalix 2011). It is necessary to come with new application of WSN, therefore a close look was needed into possible additional functionality of WSN in regards to human behaviour.

Arens (Arens et al. 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 infrared sensors. In the proposed concept user behaviour was taken into account by an occupancy sensor. 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; this was where the comfort information resided. To best assess the occupants' comfort level, a portable node was developed which senses the local temperature, humidity, light level, and inertial activity level of the user. It also the system interface had three buttons on the side, which allowed the user to input current comfort state (one button each for hot, cold, and neutral). The actuation of the various heating and cooling systems was achieved via control nodes. Energy savings of up to 24% over the standard HVAC control system were achieved during experiments on MIT University (Arens et al. 2005).

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. Low-budget wireless sensor networks with portable nodes show high potential for real-time localization and monitoring of building occupants (Feldmeier and Paradiso 2010). Therefore static wireless sensor nodes were mounted on the floor and communicate 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 Fig. 4.

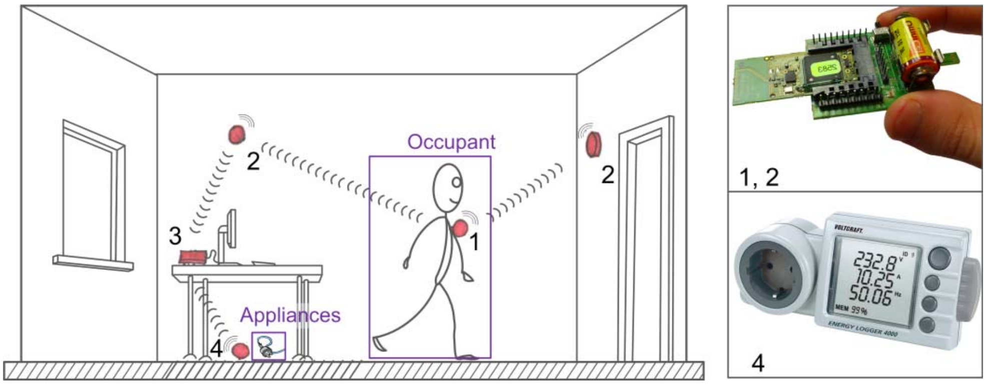


Figure 4 A wireless sensor network (2) tracks the mobile node (1) of the occupant and the energy use of appliances (4) and uses the real-time data for the building system control (3)

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. Fig. 5 shows that there was a more refined grid around the workplaces than, for example, in the corridors. In every zone one power logger was installed, for measuring the energy use and to get an estimation of the heat production.

Figure 5. 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 orange line

RESULTS

Determination user comfort and energy saving potential

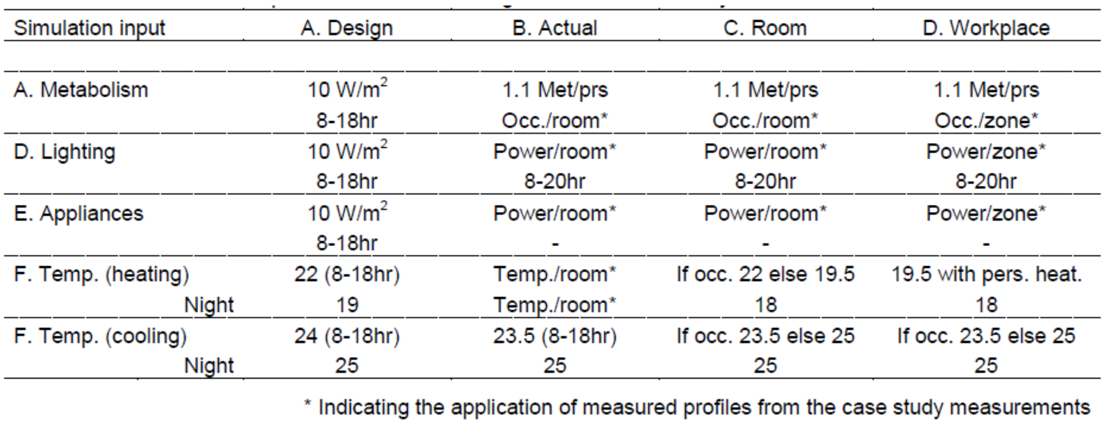
A model was built to determine the primary heating and cooling energy demand for four different cases: energy demand as designed (A), actual energy demand (B) and when taking the 'Human-in-the-loop' on room (C) and workplace level (D). The simulation was performed using a whole building model programmed in the Simulink HAMBase environment. In contrary to earlier research by (Zhang et al. 2009), this study takes into account the real occupancy profiles, the appliances use, lighting profiles and the energy needed for personalized conditioning of the occupants.

In the four cases the building parameters were the same, only there was a change in the user profiles. These user profiles input variables are explained in more detail.

A. Design input

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

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 8-18hr	1.1 Met/prs Occ./room*	1.1 Met/prs Occ./room*	1.1 Met/prs Occ./zone*
D. Lighting	10 W/m^2 8-18hr	Power/room* 8-20hr	Power/room* 8-20hr	Power/zone* 8-20hr
E. Appliances	10 W/m^2 8-18hr	Power/room* -	Power/room* -	Power/zone* -
F. Temp. (heating) Night	22 (8-18hr) 19	Temp./room* Temp./room*	If occ. 22 else 19.5 18	19.5 with pers. heat. 18
F. Temp. (cooling) Night	24 (8-18hr) 25	23.5 (8-18hr) 25	If occ. 23.5 else 25 25	If occ. 23.5 else 25 25

* Indicating the application of measured profiles from the case study measurements

B. 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 1.1met (1met=58.2W/m2, Ad=1.8m2), which is standard for office activities such as typing. For the heating the measured temperature profiles were used as temperature set point. In the winter a temperature set point of 23.5 °C during working time was assumed.

C. 'Human-in-the-loop' – room level

Here only the temperature set point was changed compared to 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 Fig. 9, 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 equaled 80%. For the appliances, the total heat load is presented in Fig. 6. Remarkable to mention is that even when the occupancy strongly decreases (e.g. during the lunch break at 12.00h), the heat load by appliances did not significantly change.

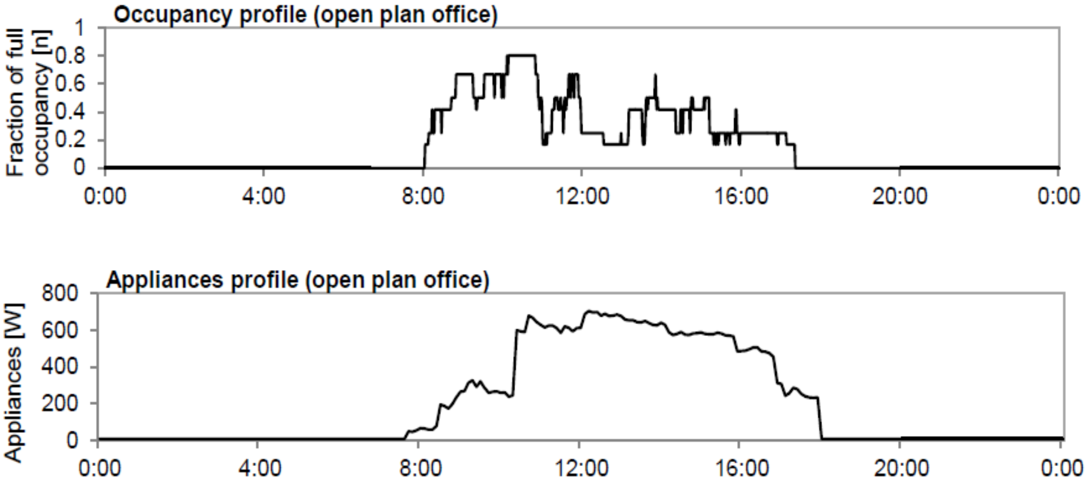


Figure 6 Measured profiles for occupancy and appliances for a typical winter day

D. '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, while an indoor air temperature of 19.5ºC was applied. Therefore hand heaters with a power with a total power of 98W were applied. Since no obvious results could be found for personal cooling, a comfortable temperature set point of 23.5 °C is assumed when a zone is occupied. The change of set point was only applied on the workplaces, e.g. no hand heaters were applied in the toilet or nearby the location of the printer or coffee machine.

Simulation model

A simplified sketch of the simulation model in Simulink is shown in Fig. 7, in this 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.

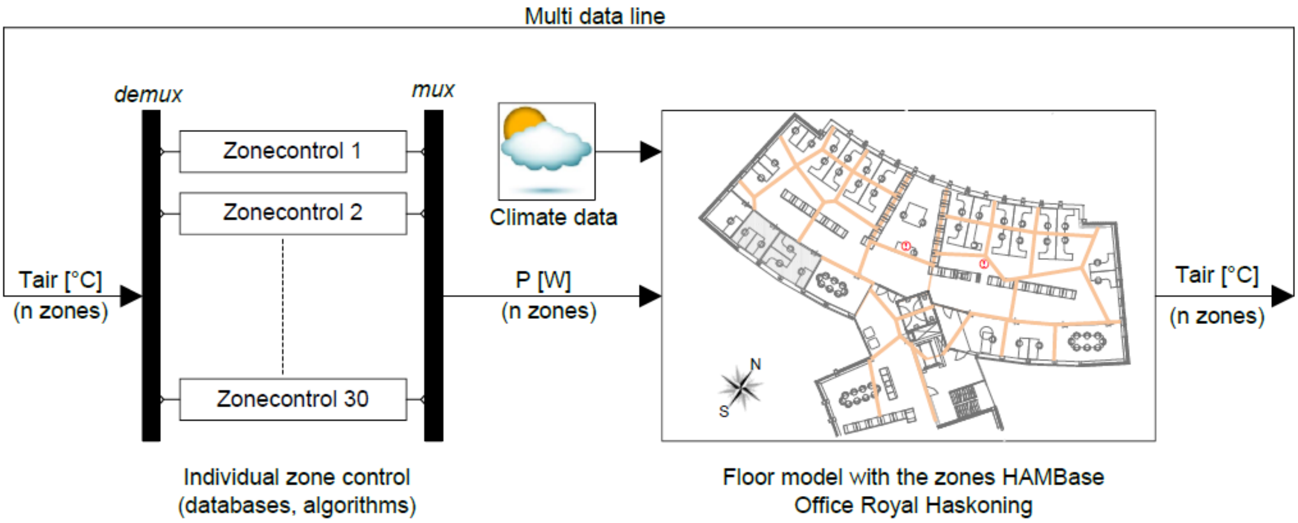


Figure 7 Simplified sketch of the simulation model in Matlab/Simulink. The air temperature was used as feedback control signal for the individual zone models.

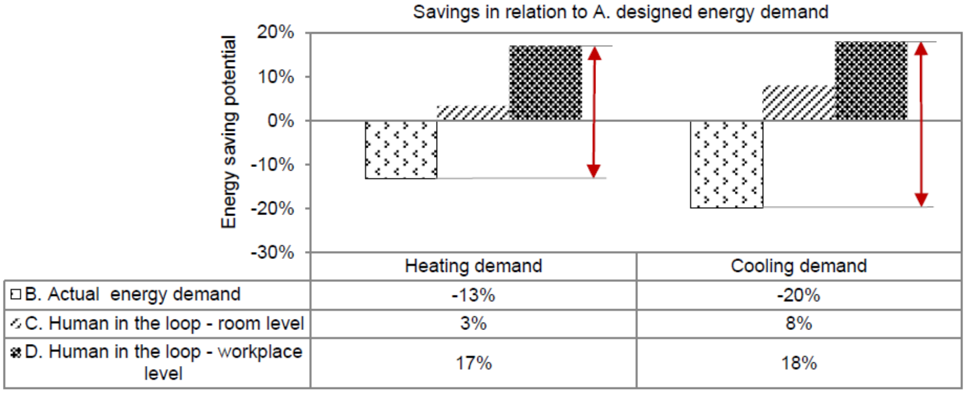
Climate data of the measured 6-week winter period was coupled to the whole-building model. The indoor air temperature of the zones was the output of the whole-building model. This information was used as feedback signal for the control algorithms of the individual zones. A demultiplexer (demux) was used for selecting the data-output from this feedback signal. A multiplexer (mux) was used for combining several data lines into one single signal line. About the simulation model the following can be said:

- Each zone has its own control loop for regulating the indoor air temperature (Fig. 7).
- For the basic room heating (Pbasic) a proportional control algorithm is applied;
- In the cased C and D only control of the temperature is changed, meaning that ventilation rates are not changed according to the occupancy. It is highly potential 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 Fig. 8.

$$\text{energy saving} = 1 - \frac{\left(Q_{\text{basic}} + \left(\sum Q_{\text{local}}\right)\right)_{case}}{\left(Q_{\text{design}}\right)_{@22ºC}} \qquad (1)$$



	Heating demand	Cooling demand
☐ B. Actual energy demand	-13%	-20%
▨ C. Human in the loop - room level	3%	8%
▩ D. Human in the loop - workplace level	17%	18%

Figure 8 Energy saving potential for heating and cooling calculated for a 6-week period, compared with the designed energy use. The energy saving potential of the people-oriented energy control on workplace level compared to the actual energy demand is indicated with the red arrows.

From this figure it was concluded that an increase occurs in energy demand for both the heating (13%) and cooling (20%) in the actual situation. When applying people oriented control on room level, energy savings could be obtained compared to the design reference situation. A higher energy reduction was obtained when the temperature was controlled on workplace level applying personal heating and cooling. Compared to the actual energy demand an energy saving close to 30% for heating and up to 45% for heating could be obtained.

Comfort

Occupant comfort for the cases B. actual situation and C. control on room level were compared with the designed thermal comfort based on the PMV value. Since there was no model available looking at the individual comfort, the well-known PMV index was used. From the measurements the temperatures were available, the averaged radiant temperature and relative humidity were calculated by the building simulation. For the purpose of this evaluation, all other PMV values were considered to have the fixed values shown in Table 2.

Table 2 Fixed parameter values for PMV calculations

Parameter	Clothing (Clo)	Air velocity	Metabolic rate	External work
Value	1	0.1 m/s	1.2 [W/m^2]	0 [W/m^2]

The PMV values were calculated for the third week in January 2012. The applied indoor temperature, radiant temperature and relative humidity parameters for the PMV of the actual situation are shown in Figure 9. The room temperature fluctuated during the day around three degrees Celsius and the radiant temperature circa two degrees Celsius. The relative humidity was between 40% and 50% during this working week. The results of the PMV calculations are shown in Figure 10. The green area presents the designed values between which the PMV should be. In the actual situation, the PMV value did not meet the designed value for 25% of the time. This could be explained by a wrong operation time of the HVAC system, where the building was not yet at its desired temperature at 8 AM. For case C the room temperature set point was 19.5°C when no one is present in the room. The PMV values were only counted for when someone was present. It was clearly visible that the PMV value was lower, where 50% of the values were below the comfort boundary. However, this PMV did not take into account the time it took (5 - 10 minutes) before a building user perceived the change in temperature in slightly cool environments (Wang et al., 2007).

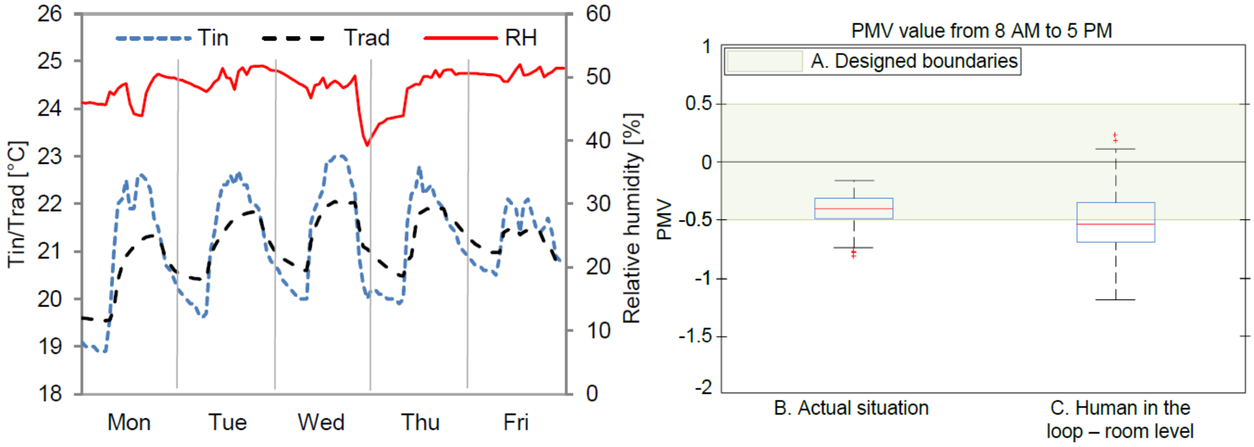


Figure 9 Applied room temperature, radiation temperature and relative humidity to the PMV model, from the third week in January 2012 and Figure 10 PMV designed boundaries compared to PMV result of: B. actual situation and C. applying energy on room level where the values are based the simulation results. Calculated for one winter week between 8 AM and 5 PM

In his research Vissers (Vissers, 2012) showed that it was possible to feed-forward respond to user thermal preferences (i.e. before cool discomfort occurred), while the basic room air temperature was 19.5 °C. By conditioning the hands with a radiation panel the local- and overall thermal sensation of tested subjects were maintained neutral or slightly higher level. Therefore it was assumed that the PMV was between the boundaries when applying local heating. The application of local heating and cooling shows high potential, especially when combining it with the possibilities of indoor localization. The (primary) energy saving potential for heating was calculated according to equation 2. The energy needed for the case was divided by the energy needed for the reference design situation. The results are presented in Figure 11.

$$\text{energy saving} = 1 - \frac{(\mathrm{Q_{basic}} + \sum \mathrm{Q_{local}})_{case}}{(\mathrm{Q_{basic}})_{@22^{\circ}C}} \qquad (2)$$

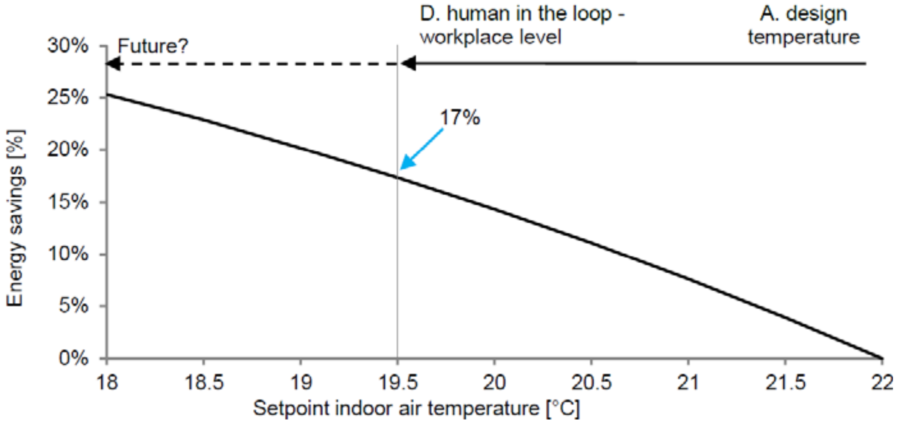


Figure 11 Energy saving potential for heating energy calculated for a 6-week winter period, by decreasing the indoor air temperature set-points and applying local heating per occupant. In the reference case the indoor temperature is controlled at 22ºC without local heating.

The energy saving potential for heating is 17%, as shown in the previous section, when lowering the set point of the indoor air temperature from 22ºC to 19.5ºC and taking into account personalized heating of 98W per occupant (Vissers 2012)

DISCUSSION

Simulation results compared to literature

It was important to verify our simulation results. Zhang also reported the potential energy savings, obtained by a numerical study, for different climate zones in the United States, by expanding the dead-band of the process control setting in which the room temperature is controlled (Zhang et al. 2010). The energy use of a necessary local task-ambient conditioning (TAC) system to still make it comfortable for the occupants was not taken into account by Zhang. Therefore the energy savings, as found in our research, are less high compared to those of Zhang for a similar climate zone, around 23% (Zhang et al. 2009). In addition Van Oeffelen simulated the energy potential for a typical winter situation in the Netherlands. They calculated an energy saving potential of about 25% for heating by decreasing the room temperature set point from 22ºC to 20ºC (Oeffelen et al. 2010), which is about 8% higher as found in this research. However, our research considered real occupancy profiles and real energy use for individual local heating, which makes the results more realistic.

One of the limitations of the current research is the focus on individual workplace, were as in practice there are often shared workplaces. The problem of shared spaces is inherently very tough 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.

The use of electrical appliances is the most influencing variable on building performance, see Fig. 3. In 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 et al. 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 by Fig. 12 with the occupancy and appliance use for two reference days. Connections were visible, but the appliance use did not correlate with the occupancy.

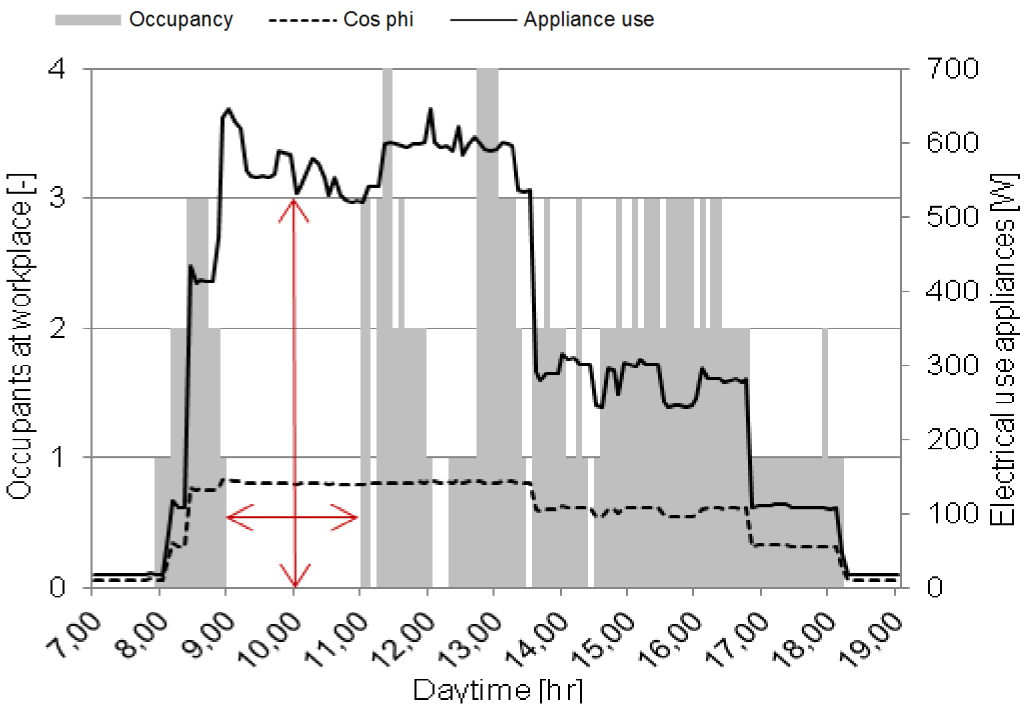


Figure 12 Occupancy for 4 workplaces and total energy demand for those places for a reference day, time step = 5 minutes. The red arrows indicate that energy demand can be reduced when the occupants are not at their workplace.

‘Human-in-the-loop’

This ‘Human-in-the-loop’ approach 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 study by Hoes (Hoes et al., 2009) showed, the ability for a person to control his environment has a significant impact on occupant satisfaction. This asks 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.

Measurements

The measurements on the case study floor only took place for a period of six weeks in winter period. Firstly this means that the obtained results may only be accounted to this measurement period and secondly they are only valid for this case study floor. Mahdavi (Mahdavi et al., 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. Therefore it is plausible that an error in the results consists since the appliances of all the users are measured. Since almost 80% of the floor users wore a node the error might be kept at a minimal.

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 energy performances, the influence of the occupant becomes significant and should be looked into. In the used 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 needed by localizing the building occupant and anticipating on its influences. From measurements of 20 employees during 6 weeks on an office floor it is clear that individual occupancy can be distinguished. A strong correlation between the occupancy and the most important human influence on building performances, use of electrical appliances, was shown on floor level. However, on workplace level a relation between occuoancy and use of electrical appliances is not clear. Further research towards possibilities and advantages is needed.

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