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Human centered energy control: taking the occupancy in the control loop of building systems

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Abstract

The energy use in the built environment accounts for nearly 40% of the total energy use in the Netherlands. Most of the used energy in the built environment (nearly 87% for non-residential) is used for building systems with the goal of providing comfort for the building occupants. In practice the intended energy efficiency as well as comfort level of the HVAC systems is not achieved, resulting in more sickness absence, lower productivity and higher energy costs.

Traditional comfort control focusses on indoor temperature regulation with a uniform thermal environment. Due to individual differences it is not possible to provide an optimal perceived comfort level to all office workers. In response of discomfort, the building user performs actions to restore his individual comfort. An undesired effect of these actions is that the energy use of the building comfort systems often increases. We present a new HVAC control strategy based on the actual demand and indoor localization of the individual building user. In this way we supply energy for comfort only to those positions where needed. With critical performance indicators we looked for the most important parameter (e.g. human actions and building parameters) on building comfort and energy performances. The objective of this critical performance indicator process control strategy is to reduce the energy demand, while maintaining thermal comfort of the individual building occupant. With our new approach nearly 30% energy savings can be achieved on heating demand and up to 38% energy savings on cooling demand compared with current energy demand.

Introduction

During the 1970s and 1980s there became awareness that available energy (e.g. oil, coal) on our planet is limited, but also that the environment needs to be protected because the use of fossil energy sources causes undesirable greenhouse gases. This awareness resulted in a demand for energy savings in buildings. In the last decades the energy performance of buildings improved by better insulation of buildings, more efficient comfort installations and local production of sustainable energy. Still the energy use in the built environment accounts for nearly 40% of the total energy use in the Netherlands. Most of the used energy in the built environment (nearly 87% for non-residential) is used for building systems with the goal of providing comfort for the building occupants [Opstelten et al., 2007]. This emphasizes the importance of reducing the energy use for comfort systems. The EU Directive Energy Performance of Buildings

(EPBD) concerns the use of energy in buildings and urges member nations of the EU to set stricter regulations regarding the efficient use of energy in buildings. Energy performance of buildings is key to achieve the EPBD objectives, namely the reduction of a 20% of the greenhouse gases emissions by 2020 and a 20% energy savings by 2020 compared to 1990 level, and even an energy neutral environment by the year 2050 [EC, 2012].

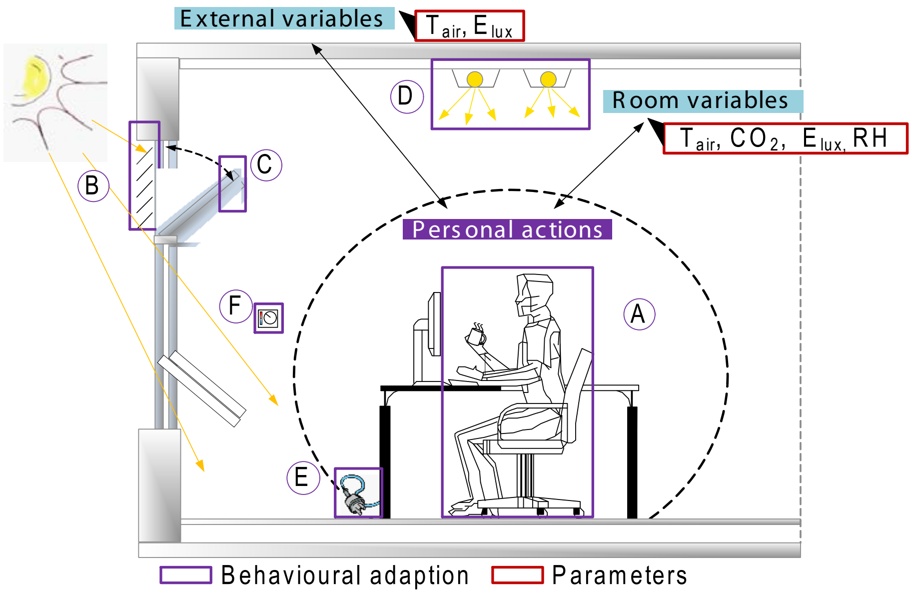


Figure 1. Parameters for human comfort (red box), with the user actions to influence the environment, B. blind control, C. window opening, D. lighting – and F. thermostat control (purple box) and user influence influencing indoor environment, A. user presence and E. use of appliances (green box).

The satisfaction of the occupants with their thermal environment mainly determines the success of the application of HVAC systems. However, in practice the intended energy efficiency as well as comfort level of these HVAC systems is not achieved, resulting in more sickness absence, lower productivity and higher energy costs. To meet the demand for both a more comfortable indoor environment and building energy savings, it is necessary to implement knowledge of the building user in the building comfort control strategy. This section gives an introduction on the energy performances in the built environment, the building user with his or her need for comfort, and the proposed human in the loop approach.

With our current way of thinking and designing those future EPBD objectives will not be achieved. The urgency to bring all measures for improvement of the energy performance into action, and thereby connecting national and international policies, increases [Opstelten et al., 2007]. Therefore steps need to be made to increase the building energy performances which could be done by looking in more detail into the human comfort, the main goal of the energy consumption.

Methodology: Comfort performance leading

Traditional comfort control of the indoor environment has been focused on temperature regulation. This control objective often fails in achieving the primary goal of HVAC systems: a thermally comfortable perceived environment. The main reason is that the body thermal state not only depends on indoor air temperature, but also on other environmental variables (e.g. mean radiant temperature, air velocity, relative humidity) and personal factors such as clothing resistance and activity level.

This means that current building systems which rely on code defined occupant comfort ranges [Klein et al., 2012] are inefficient in their energy usage for maintaining occupant comfort as they operate according to fixed schedules and maximum design occupancy assumptions.

In response to discomfort, the building user performs actions in an attempt to restore his individual comfort [Haldi et al., 2010]. These actions are diverse and can be divided into actions that change the occupants' environment (e.g. opening of windows) and so called personal actions (e.g. get a cup of tea). An undesired effect of these actions is that the energy use of the HVAC system often increases, especially in more energy efficient buildings [Hoes et al., 2011].

To avoid energy wasting behaviour it is needed to deploy energy effectively for comfort on those spots where needed. To achieve this conveniently it is necessary that the HVAC systems automatically adapts to the actual individual needs. This requires a method where the user with his individual needs is included in the control loop of building comfort systems. Within this research this method is called the 'human in the loop approach'.

A control strategy for HVAC control based on the actual demand by the individual users is proposed. It is necessary to look at what locations in the building there are momentary demands for individual comfort and related energy demand of appliances in an office building. Therefore this research looks at the needed energy flows from individual to floor level.

Literature shows that workplaces in office buildings are unoccupied for a large percentage of time, and differ between buildings [Mahdavi et al., 2011]. The coming and going of office workers is deterministic, varying from day to day and from time to time. In modern building an attempt is made to reduce the energy demand by occupant detection. Parys et al. 2011 divided the research towards user behavioural into six fields, shown in **Figure 1**. Occupancy (A) can be considered as one of the research fields in user behaviour. Because being present within the building is clearly a necessary condition to interact with it, this is an important factor in the field of user behaviour [Madavi et al. 2010]. The other research fields are the control of solar shading (B), window deployment (C), control of the lighting (D), the use of electrical appliances (E) and the control of the thermal environment (F) by the occupant. This list is not exhaustive as it is restricted to actions that change the environment and thus influence the building's energy demands [Madavi et al. 2010]. Other adaptive actions like adjusting clothing, having a drink or changing the activity level, better known as personal or intermediate actions, are not included. The interactions with the buildings' environmental systems are difficult or even impossible to predict at the level of an individual person.

As previously described, the user performs actions which negatively influence the buildings energy demand. Studies towards building energy performance defined those actions which directly influence the building energy demand, as shown in **Figure 1**. Blind deployment, light operation and thermostat control are directly driven by discomforting stimuli. The metabolism of the user present and use of electrical appliances do influence the indoor environment [Parys et al., 2011].

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 use their building and if commonly used occupancy spots can be recognized. RFID technology is proposed for building user indoor locating system, because of its accuracy for location estimation and possibilities for identification of the user [Li et al., 2012].

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 is needed into possible additional functionality of WSN in regards to human behaviour.

Arens [Arens et al 2005] proposes a distributed sensor network which might be found in an office in near future. At room scale, the control and actuation could take place within the room itself by a kind of remote controller. The person's thermal state [comfort stat] could be predicted from measured skin temperatures sensed through contact or remotely by infrared sensors. In the proposed concept user behaviour is only 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 is the building occupant; this is where the comfort information resides. To best assess the occupant's comfort level, a portable node was developed which senses the local temperature, humidity, light level, and inertial activity level of the user. It also has three buttons on the side, which allow the user to input current comfort state [one button each for hot, cold, and neutral]. The actuation of the various heating and cooling systems is achieved via control nodes. Energy savings of up to 24% over the standard HVAC control system were achieved during experiments on MIT University.

The human in the loop approach

The studied recent developments regarding thermal comfort and occupant behaviour in the built environment lead to our human in the loop approach. In this approach the human is taken as the leading factor in the design and control of HVAC systems. Nowadays the user is not central in the design as building systems are mainly controlled on building level with (limited) possibilities for adjustment of the indoor conditions on floor and room level. As a result the considerable differences between individuals are not included in the HVAC control [Fanger 1972]..Our bottom-up approach is strictly focused on the well-being of the individual and the energy demand for optimal comfort of the individual. To enhance this bottom-up approach a new control strategy is introduced where the human is put into the control loop of the building services systems to enhance a more direct and better interaction between technological systems and the human being.

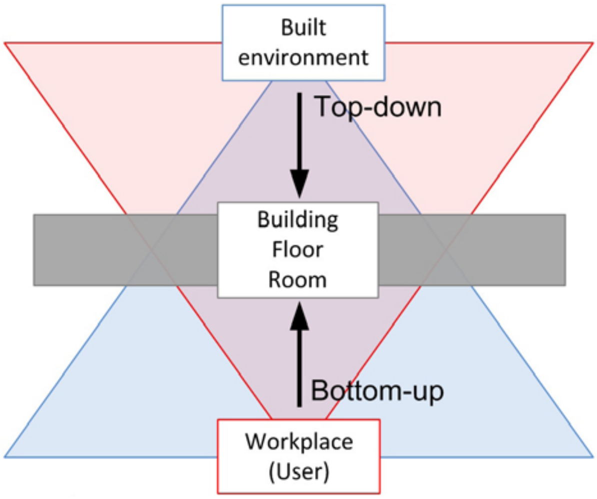


Figure 2. Traditional top-down approach for building system design and new introduced bottom-up approach with the human as leading factor.

Objective

The aim was to assess the energy saving potential when anticipating on the human influences by sending energy only to those spots where energy is needed to change the thermal conditions. Therefore the building occupant needs to be included in the control loop of building services. Non-occupied spots of the building can have low demands regarding the indoor climate and can be conditioned at a minimum level. It is needed to look at the possibilities to localize the occupant, with minimal or no hinder for the building occupant. The proposed principal is presented in **Figure 3**.This figure shows how the building occupant could be leading in the system control, applying the individual preferences by measuring the occupant position and behaviour. In order to control the operation of building systems an intelligent supervisor coordinates the system [Dounis et al. 2009]. The intelligent coordinator makes its decision and sends acknowledge signals to the individual building systems. Intelligent control systems are required to implement the actual dynamic changing individual comfort needs and the behaviour of individual building occupants. This results in intelligent control strategies for building services systems to achieve the highest comfort level and biggest energy savings.

Building analysis

This research used a real building and user's behaviour: measurements were performed on the fourth floor of Royal Haskoning, an international engineering consulting company in The Netherlands, Rotterdam (**Figure 4**).

An analysis was made to look for the most influencing building parameters and user actions on the building performances. Via a walkthrough survey, consisting of interviews and measurements during a week, the band-

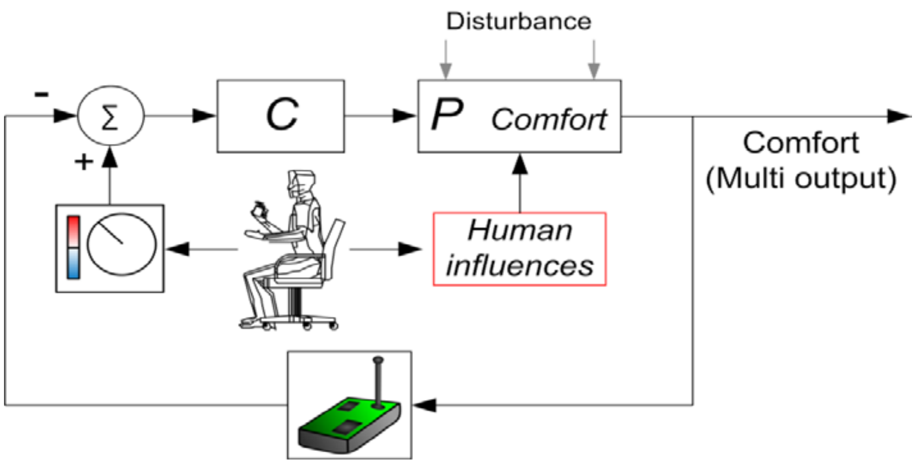
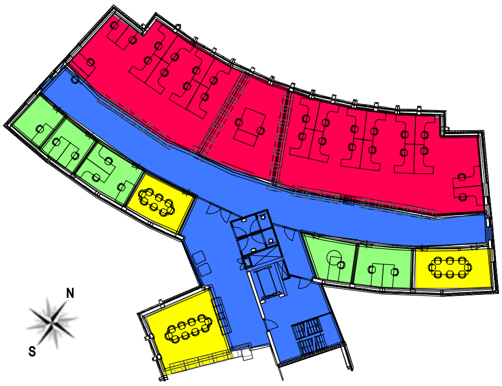


Figure 3. Proposed block diagram of the controlled system with the intelligent coordinator to take the human influences in the loop of building systems via feed forward control.



Properties	
meeting room	(yellow)
open-plan office	(red)
corridor/staircase	(blue)
cell office	(green)
Year of completion	2006
Floor surface	ca. 500 m²
Employees	ca. 35 persons
Type w orkplace	flexible office space
Type of w ork	computer / desk w ork, design, calculation
HVAC system	district heating, cooling machine
room conditioning	induction unit
HVAC control	room level

Figure 4. Floor plan of the case study floor (A) with the important properties of the floor (B) and a picture of the building from the outside (C).

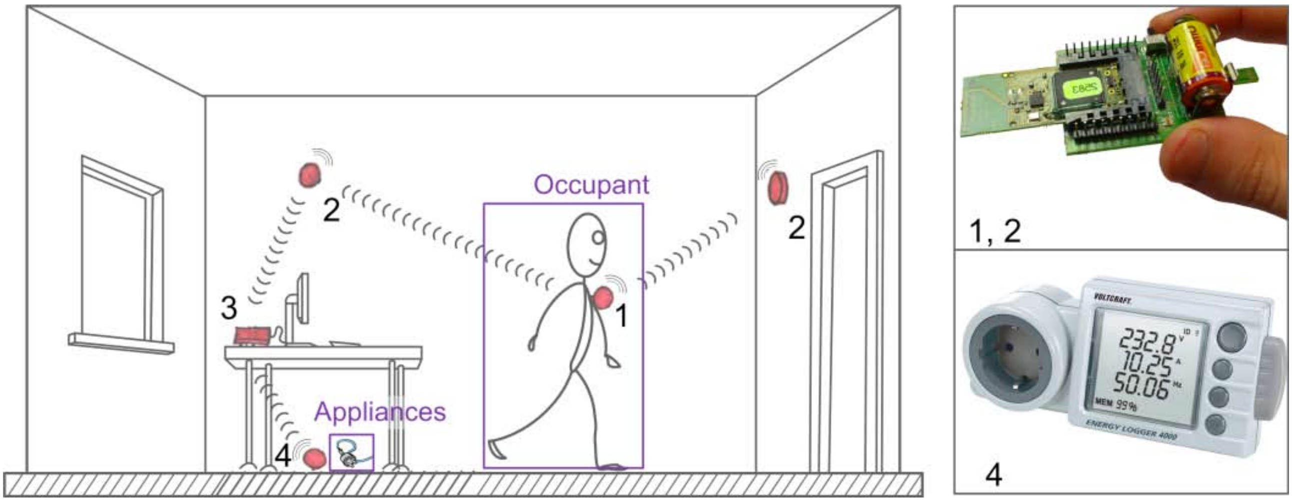


Figure 5. A wireless sensor network (2) tracks the mobile node (1) of the occupant and the energy use of appliances (4) and uses the real-time data for the building system control (3).

width of the different user actions were determined. The observed data was converted to yearly data, using VABI Elements, the most common Dutch software tool for building energy performance analysis. The building parameters and user actions were varied within a predetermined bandwidth based on this analysis. The magnitude of human influences is on average 3-5 times higher than the building parameters, clearly underlining the importance of user behaviour.

Measurements

Applying the bottom-up approach, with the human in the control loop of building services systems, can only be achieved if users can 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 smartphones) carried by the occupant to determine the position of the occupant on workplace level. The measurement set-up is schematically shown in **Figure 5**.

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 oc-

Figure 6. 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.

Figure 7. Occupancy intensity as percentage of the most occupied workplace, showing two hotspots and increased activity around the toilet, coffee machine and printer.

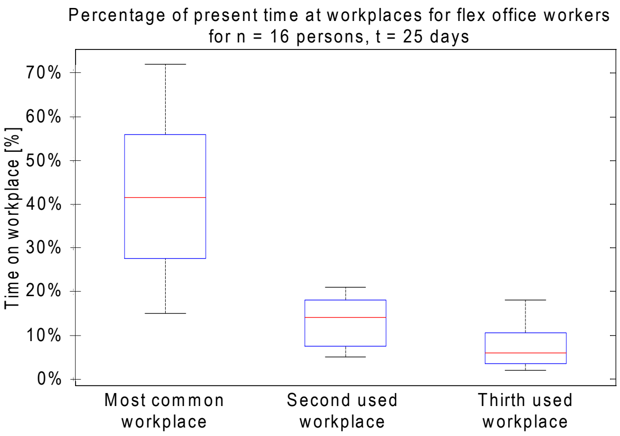


Figure 8. Percentage of time office workers are at their most common workplace and less preferred workplaces.

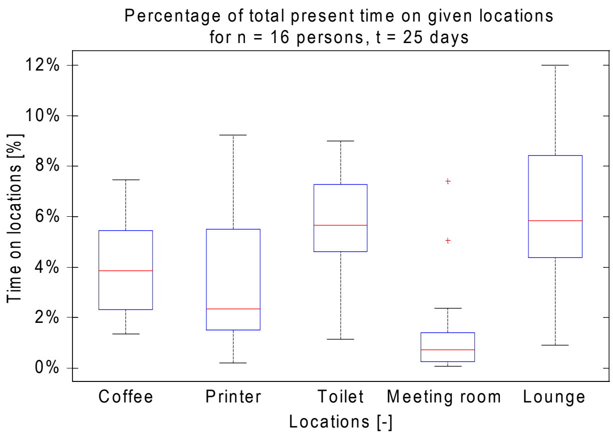


Figure 9. Percentage of time office workers are at a specified location on the floor.

cupant is. With the nodes a mesh is created consisting of 30 zones. **Figure 6** shows that there is 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.

Results

The measurement results were obtained for six weeks during winter period. During this period most of the occupants of the floor (20 employees) wore a node for localization. The average occupancy of the employees was approximately 40%. Occupancy hotspots can be distinguished as shown in **Figure** 7. The amount of time of occupants being present in a zone is summed over the whole period. There are obvious favourite workplaces and higher occupancy intensities around the coffee machine, toilet and printer.

To get an estimation of the people flows inside the building, the occupants' position is closer looked into. In **Figure 8** it is shown that although there are flex workplaces, the employees have a strong preference for a most common workplace, where the second used workplace is occupied for on average 15% of the total present time on. **Figure 9** shows that the buildings users are a significant part of the time on other locations in the building (e.g. coffee machine, toilet).

Appliances

The use of electrical appliances is the most influencing variable on building performance. 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 proved by **Figure 10** with the occupancy and appliance use for two reference days. Connections are visible, but the appliance use does not correlate with the occupancy.

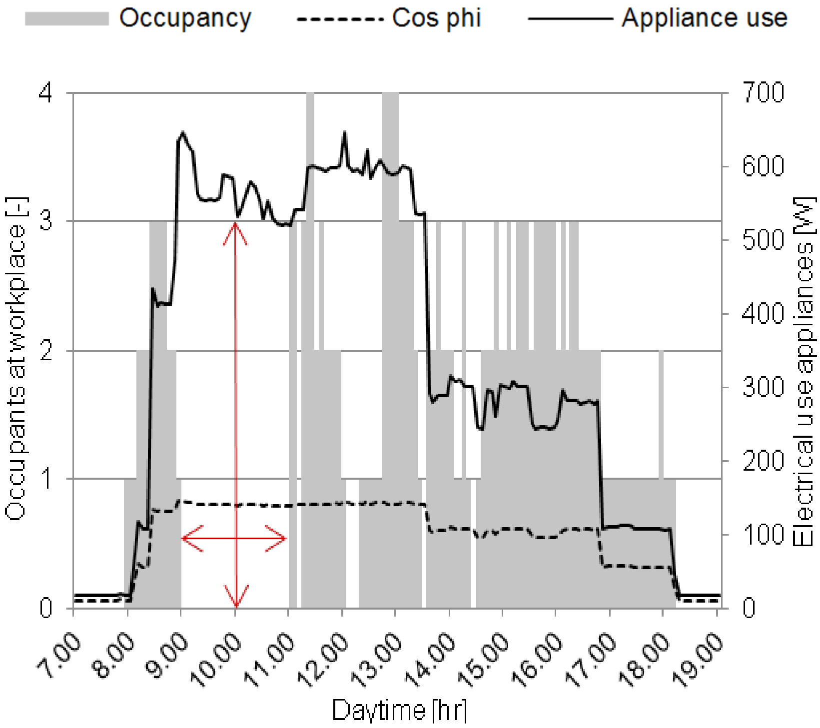
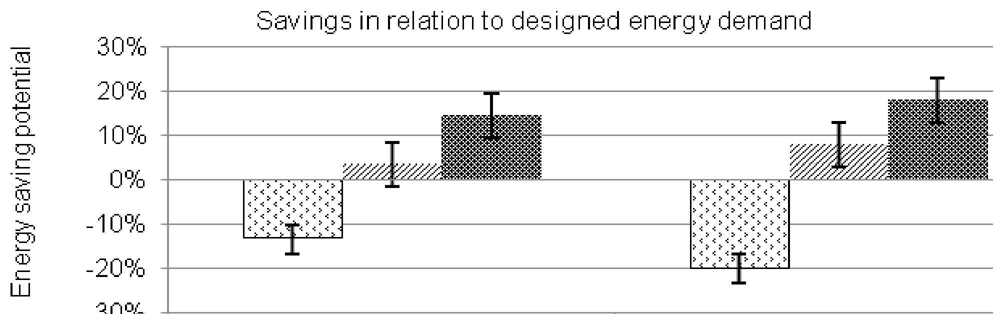


Figure 10. Occupancy for 4 workplaces and total energy demand for those places for a reference day, time step = 5 minutes. The red arrows indicate that energy demand can be reduced when the occupants are not at their workplace.

Energy saving potential

Data of the measurements are applied in a simulation to determine the energy savings potential compared to the designed energy demand. Three variations can be distinguished, B. the actual energy demand, C. send energy to spots only when needed (human in the loop) on room level and D. human in the loop on workplace level with individual climate control. The obtained energy saving potential by the profiles for the three situations is shown in **Figure 11**. The measurements were during the winter, when there was only a heating demand. The acquired profiles for electrical appliances use and occupancy patterns are also applied in the summer situation. A sensitivity analysis is established by applying the standard deviation of the different profiles to the model, to ground the reliability of the results.



	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	14%	18%

Figure 11. Energy savings compared to designed energy demand for actual energy demand (B), energy control on room level (C) and sending energy to the individual on workplace level (D).

Conclusion

Big steps need to be made to reach future targets regarding energy consumption and comfort level in the built environment. 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 occupancy hotspots can be distinguished.

A strong correlation between the occupancy and the most important human influence on building performances, use of electrical appliances, is shown on floor level. However, on workplace level a relation can be noticed, but lets a lot of space for decrease of the energy demand / internal heat gains. Further research towards possibilities and advantages is needed.

With the human in the loop approach more than 20% energy savings can be achieved on heating demand and up to 40% energy savings on cooling demand compared with the actual energy demand. 3E

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