INDOOR AIR QUALITY AND THERMAL COMFORT STRATEGIES: THE HUMAN-IN-THE-LOOP APPROACH

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ABSTRACT

Global warming caused by CO_2 emissions as a result of energy consumption, shows its growing effects on the average temperatures worldwide. Office buildings are responsible for a major share of the 40% of the energy consumption of the built environment. We look at a way to minimize the environmental load of office buildings and at the same moment improve indoor air quality and comfort for the occupants of offices. Therefore the end-users behavior of building occupants needs to be taken into account. New design approaches are needed to implement the behavior of occupants of buildings. Improvement of the energy consumption is made possible by agent-based systems for energy management in buildings. Human-in-the-loop Technology: a technology to implement user behavior is developed. By starting from the human perspective and use available and new technology, the outcome was focused on the ability to provide improved individual comfort for the end user. As the end-users become more important within energy infrastructure of buildings, the focus is on the occupant and therefore a bottom-up design approach has been developed. In the final article an example on the level of workplace will be presented.

INTRODUCTION

Recent research has shown a technical saving potential of 170PJ primary energy and an emission reduction of 11Mton even in a small country as the Netherlands (Opstelten et al 2007). Currently the energy management within buildings is far from optimal, improved control could save up to € 600 billion worldwide (Webb 2008).
The potential savings of energy due to better use of ICT technology is well documented by Røpke et al 2010, however, in most of the research focusing on improved ICT often overlooks the role of user in reducing the energy conservation. Optimised process control is a necessity for the improvement energy performance of buildings (Yu et al 2007). Overall the role of the occupant in relation to the energy consumption has found to be important (Haas et al 1998, De Groot et al 2008). With smart energy efficient buildings the relation between behaviour and energy consumption has become significant, and should be looked into (Pauw et al 2009).

Often the potential benefits of new technologies are reduced by so called human rebound effects. With new and more intelligent control strategies one must take in to 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 et al. 2008).

METHODOLOGY

In former research on predictive environmental-adaptive and user adaptive energy management systems, the application of multi agent software was introduced. In the SMART (Smart Multi Agent inteRnet Technology) (Kamphuis et al 2002) and IIGO (Intelligent Internet mediated control in the built environment) projects, field experiments in several offices were set up. (Jelsma et al 2003, Hommelberg 2005, Kamphuis et al 2005). The field tests showed the potential Multi Agents layer on top of the Building Energy Management systems. In IIGO project a short-term weather prediction was implement in combination with a predictive room temperature control strategy. Based on individual comfort adjustments, and a prediction of the energy cost a optimal set point for the central AHU was estimated.

Within the EU-FP5 project EBOB (Energy Efficient Behaviour in Office Buildings) (Claeson-Jonsson 2005, Opstelten et al 2007) the aspects of personalizing comfort control and presenting the consequences of choices as feedback to the users. Traditionally the control strategy is based on a simplified approach were a general set point is taken as comfort control for a whole room. This leads often to dissatisfaction of occupants and avoidable additional energy consumption.
With today smart technology it is possible to take all individual setting of each occupant into account an find better solutions that can reach an optimal combination of efficient supply optimized comfort. The human behaviour can influence the energy consumption by more than 100% (Brohus et al 2010, Parys et al 2010), so therefore it is necessary to incorporate the human needs better in the control strategies. Sensing, monitoring and actuating systems in relation to the user perception and preferences play the key role in reducing overall energy consumptions in buildings.

Within the Flexergy project the University of Technology Eindhoven, Kropman, ECN and Installect Building Services Consultants worked on a design methodology for structuring and combining different energy flows within a building. The project focused on the integral optimization of energy flows within the built environment when fitting in decentralized sustainable energy concepts. This design methodology should lead to solutions that offer more flexibility to the energy infrastructure; Flex(ible)en)ergy. However in the Flexergy project the user was still represented by a comfort level day profile based on the room temperature setting. Field tests were held at the Kropman office in Utrecht. Based on the experiences with multi-agent system projects and a literature review on the latest developments concerning human comfort we want to derive a new concept for the optimization of individual comfort and energy consumption.

THE HUMAN IN THE LOOP

A comfortable indoor environment for all the people in a building is difficult to reach because of individual differences between persons (for instance metabolism and clothing resistance) it is impossible to provide one uniform indoor temperature that satisfies all people. Nowadays the Fanger comfort model (Fanger 1970) is mainly used to determine the (thermal) comfort inside office buildings. Individual preferences are not taken into account in this model. The satisfaction can be improved by providing an personal workplace climate (microclimate). A large part of the (global) energy consumption is used for creating a comfortable indoor environment (heating, cooling and ventilation) in buildings. Because of the climate change and the limitations of the available energy sources, it is of great importance that energy is used efficiently. Therefore the indoor climate should be optimized with minimizing the energy consumption; the ultimate goal is 'Near Zero Impact Buildings'.

The objective of this article is to describe a design process for the creation of sustainable microclimates, which give individual adjustable thermal comfort and a reduction of the global energy consumption. Based on literature it may be concluded that individual differences, including: age, fat, metabolism and clothing resistance, are of importance for the individual experienced thermal comfort. The preferences of a building occupant concerning: thermal comfort, ventilation and their individual control of it, are incorporated in the design method. 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 (Zhang 2003, Arens 2006). 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 1.
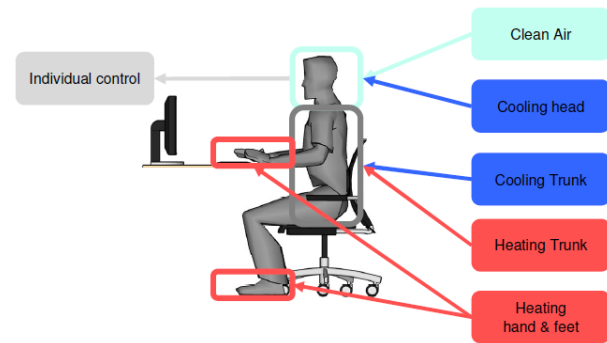

Figure 1. Set up for individual Thermal & Ventilation control.

HUMAN COMFORT AND COMFORT CONTROL

The most recent research on human comfort looks at local sensations of individual body parts (Zhang et al. 2010) and thermoregulation with skin temperature predictions (Munir et al 2009). The interaction between indoor environment and skin is for normal office conditions largely determined by the 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 conservations of up to 25% are possible (van Oeffelen et al 2010). Measuring the radiating temperatures by a low cost Infra Red 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 and Sabbatini 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 (ICS) with different local heating/cooling options (Filippini 2009, Wanatabe et al. 2010). Our intention is to design and built an experimental workplace with an individual controlled heating/cooling panel above the workplace to test our specific approach to comfort and energy management. The implementation of such detailed dynamic approach to individual comfort control is new.

It is necessary to look more closely to the individuals on working space and personal level. So we do not look only to room temperatures and thermostat settings of hot water taps but really look into the dynamic parameters related to the individual thermal comfort, the actual occupancy, and the actual parameters of the building services installations and use of appliances.
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 (Neudecker 2010, Gameiro Da Silva et al 2010). If so, then energy demand and energy supply could become more balanced and less energy wasted. A promising technology to achieve the necessary dynamic process control is by using Multi Agent System technology (Akkermans 2002, Qiao et al. 2006, Dounis and Caraiscos 2009, Lee 2010).

Software agents can act as virtual representatives of the different tasks, within a building. Such multi-agent systems (MAS) can for a potentially powerful framework for the implementation of distributed and delocalized control architectures for the coordination of monitoring and actuation devices in a buildings energy systems (Ponci 2010). The agent representation makes a decentralized control possible in an in-home sensor grid, while due to information exchange between agents external information from the environment can be used to enhance performance.

Agent technology in combination with low cost sensor networks can be implemented at different levels of building automation. Individual agents for individual climate control for each user of the building in combination with feedback on the energy consumption (costs/ sustainability) leads to better acceptance of the individual comfort and a reduction of the energy consumption (Jelsma et al 2003, Kamphuis et al 2005). The central research question is, given the different human behaviour and other individual differences, how should, such an intelligent agent controlled building grid look like and which functionalities are needed to manage demand, human comfort, and (renewable) (decentralized) energy supply.

HUMAN BEHAVIOUR

Reduction of or optimizing of energy use is often done without really taking in to account the goal of the 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)

As until now in practice user behavior has not been part of the building comfort system control strategy in offices, the energy consequences of the user behavior 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 behavior 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 demonstrate energy reduction from occupancy behavioral patterns that have been determined because there was no formal connection to the building energy management systems of these buildings (Dong and Andrews 2009). Behaviour of the occupants is influenced by re bound, being the way improved efficiencies are compensated by increased spending (Hens et al 2010). Therefore we prefer predictive user adaptive process control. To further optimize the performance of these systems, further research is needed into the possibilities and use of systems for individual comfort control on workplace level. The problem of shared spaces is inherently very tough to solve, because all individual preferences and differences cannot be matched. An analysis of occupant behaviour on the energy consumption (Brahme et al 2009),shows that conservation oriented behaviour can reduce energy consumption by one-third (Fig. 2), while in more efficient buildings, by nearly half (Fig. 3).
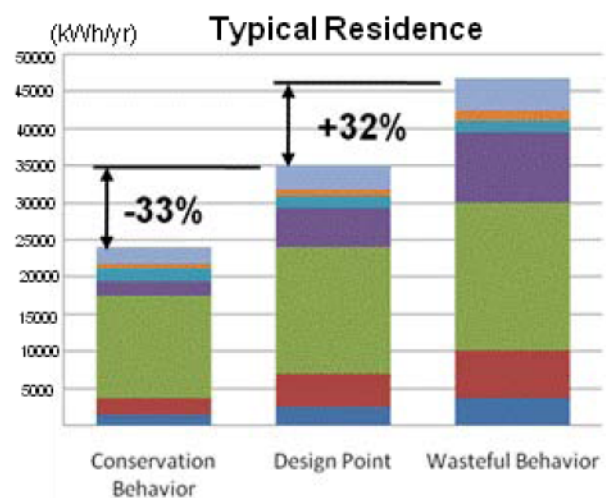

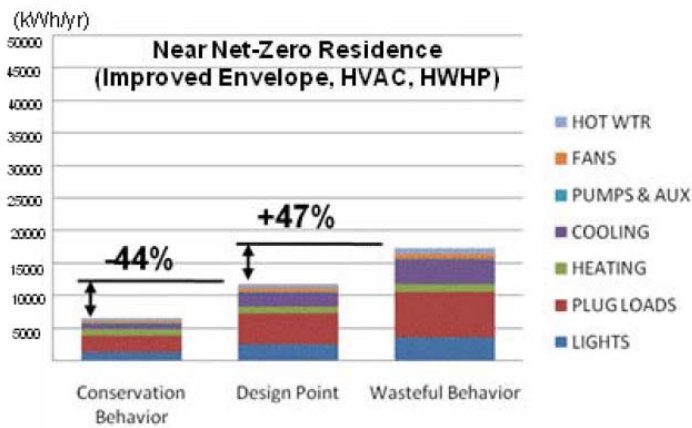Figure 2. Behaviour impact on typical residence (Brahme et al 2009)

Figure 3. Behaviour impact on high efficiency residence {Brahme et al 2009)

Feedback to the user is therefore very important and will be incorporated within our multi agent comfort energy management system.

The recent developments regarding thermal comfort and occupant behaviour in the built environment are discussed from the bottom-up approach. The bottom-up approach focuses on the wellbeing of the individual building occupant instead of the traditional building related top-down approach (see Fig. 4). Seen from this bottom-up approach the user has to be the leading factor in the design of the building and systems.
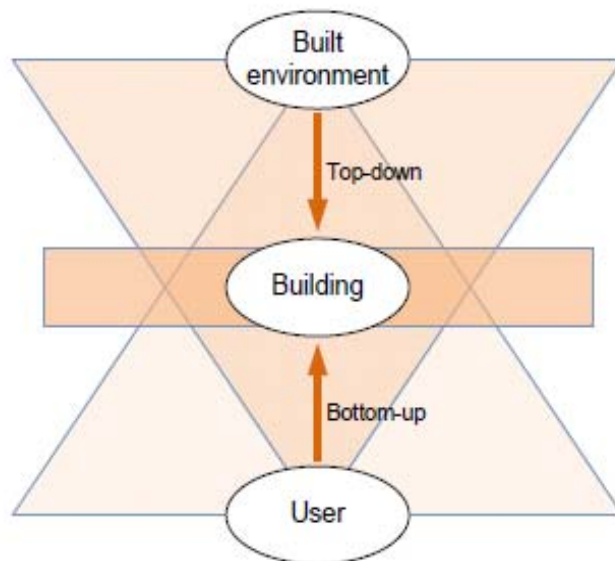

Figure 4. The traditional top-down approach and the relatively new bottom-up approach for building design.

The better we built our buildings, the greater the influence of user behaviour on the building performance. 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).

The main research fields of user behaviour in office buildings are 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 be applied, because they are 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.

INTENDED RESULTS

A good ventilation system should have the following properties: sufficient clean air in the breathing zone, high ventilation effectiveness no draft and individually adjustable. Personal Ventilation (PV) systems can fulfill all these requirements (Melikov 2006). Last but not least, it is clear that occupants want individual control over their environmental conditions at their workplace. To develop the required model for design support, a model, Methodical Design, from the domain of mechanical engineering was adapted for this purpose. The goal and intended result is to design, build and test an intelligent energy grid within buildings with the actual individual human need as leading principle. Therefore, the first step is to apply an appropriate design approach. A hierarchical functional decomposition approach is used to structure the energy infrastructure of a building.

In order to survey and select solutions, engineers classify them according to various properties. These classifications provide the means for decomposing a complex design tasks into problems of better manageable size. Decomposition is based on three main functions (accumulation, transformation and transportation) which of all have to be fulfilled including the substance on which the functions are based (matter, energy and information). This functional decomposition is carried out hierarchically so that the structure is partitioned into sets of functional subsystems and these subsystems in sub-subsystem etc. The decomposition is continued until only simple building components remain (Fig. 5).
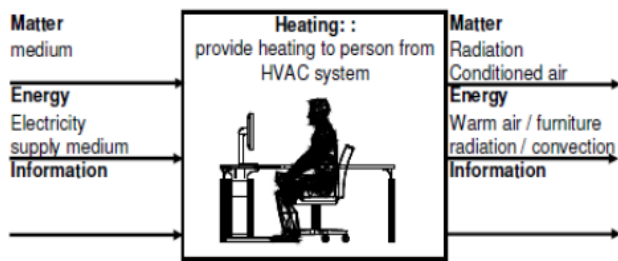
Figure 5. Functional decomposition by using a black box approach

A hierarchical functional decomposition approach is used to structure the energy infrastructure of a building (Zeiler & Quanjel 2007). This method approach makes it possible to study the energy flows connected to heating, cooling, ventilation, lighting, and power demand, within a building on the different levels of hierarchical functional abstraction, see Fig.6. Compared the common approaches our approach offers the possibility to focus on the level of workplace and the level of the individual. This enables us to look more closely on the comfort and energy demands of individuals and to build a more detailed process representation. The individual user has become leading in the whole process to optimize the necessary use of energy to supply the occupants with their own preferred comfort environment and energy for their activated appliances.
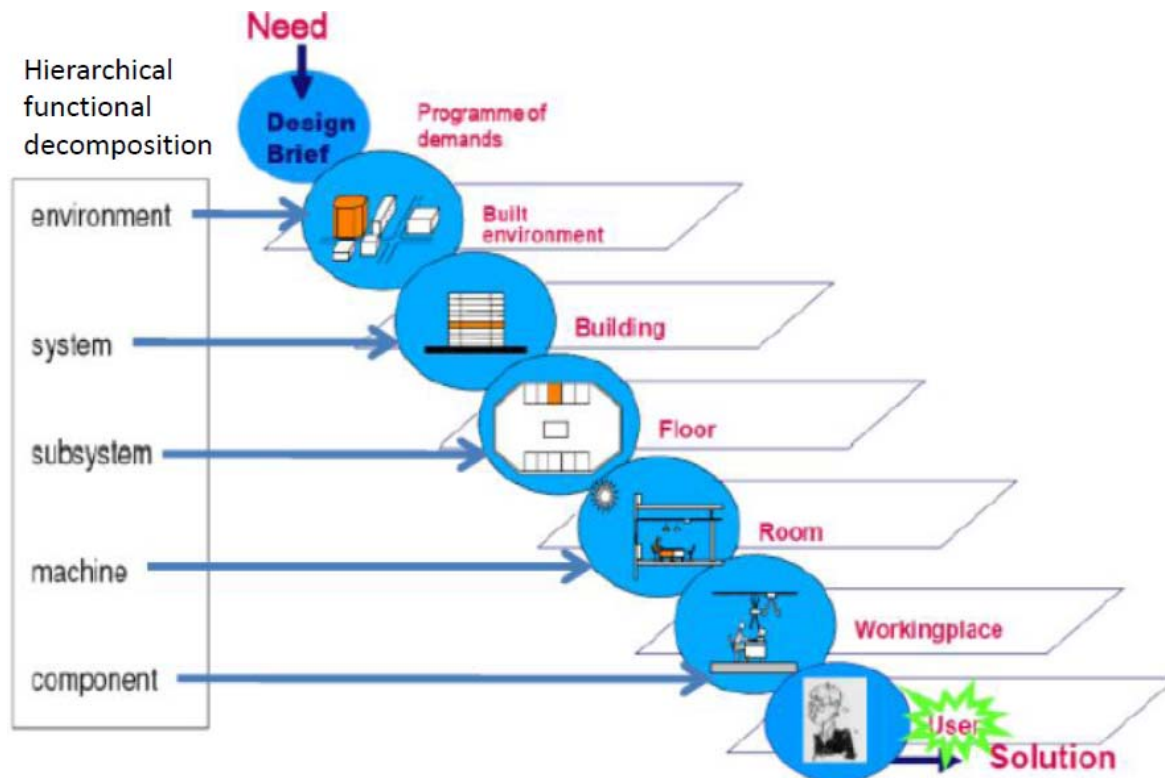

Figure 6. Hierarchical functional decomposition of the built environment.

On different levels abstraction a functional representation of the building and its occupants will be made. This method approach makes it possible to study the energy flows connected to heating, cooling, ventilation, lighting, and power demand, within a building on the different levels of hierarchical functional abstraction. Compared the common approaches our approach offers the possibility to focus on the level of workplace and the level of the individual. This enables us to look more closely on the comfort and energy demands of individuals and to build a more detailed process representation. The individual user has become leading in the whole process to optimize the necessary use of energy to supply the occupants with their own preferred comfort environment and energy for their activated appliances. On different levels abstraction a functional representation of the building and its occupants will be made. First simple representations of the process will be made to look into the interrelations between the different levels within a building system, see Fig. 7: building level (possible energy supply from the grid and renewable energy generation within the building related to the weather forecast and current weather conditions), room level (energy exchange depending on the outside environmental conditions and internal heat load), workplace level (workplace conditions and energy need from appliances) and human level (defining the different comfort needs of individuals and the resulting energy demands). On each level of abstraction solutions can be generated, in this case of individual microclimate the levels: room; workplace and individual needs are relevant (Fig. 7).
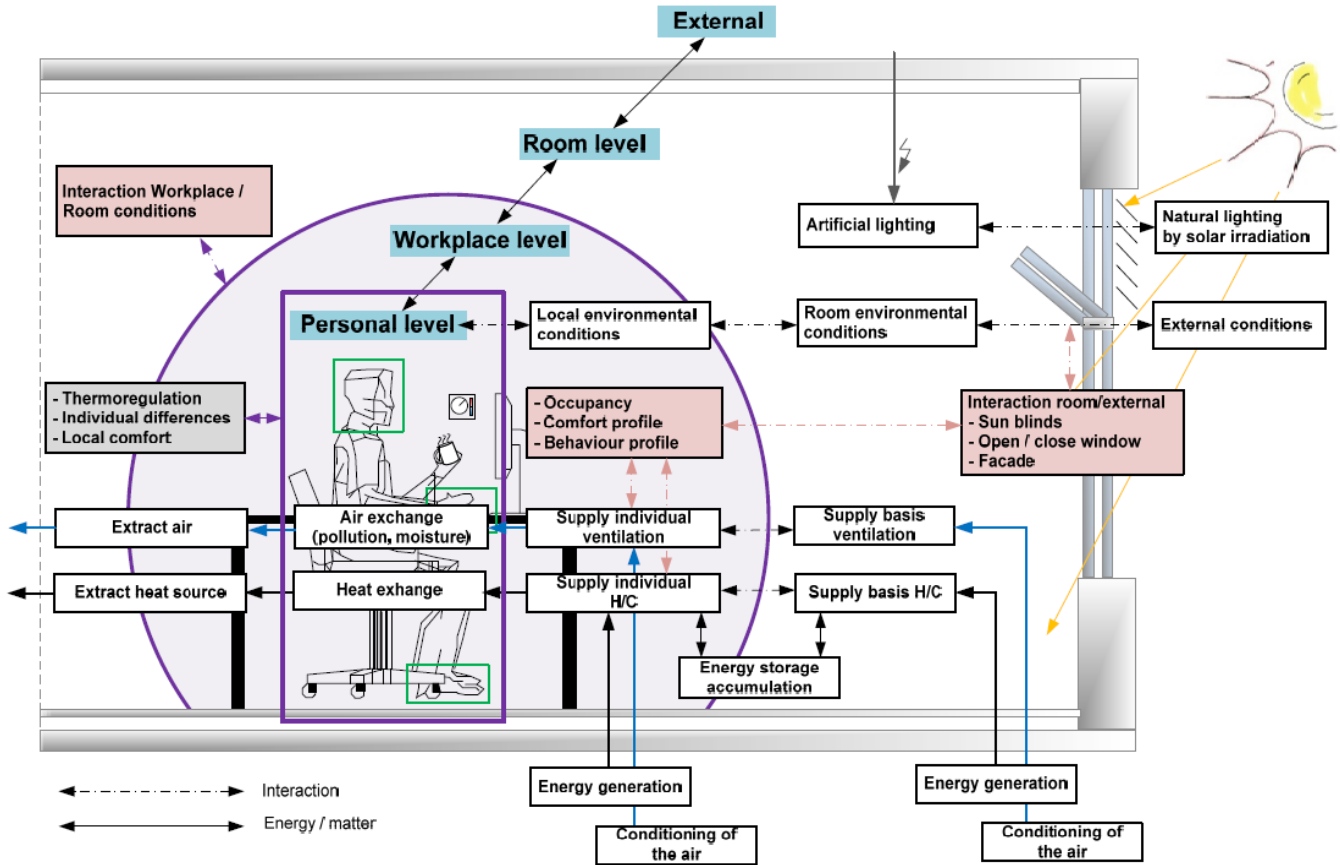
Figure 7. The overall result of the function decomposition on the level of room, workplace and individual

Principle of Micro- and Basic-climate system

The principle of the microclimate system is given in Fig. 8. In the room a global basic climate is created (A). This basic-climate is based on a minimum level for comfort and ventilation. In order to save on overall energy consumption this holds that the temperature of the basic climate is as high as possible under summer conditions and as low as possible under winter conditions. The indoor air quality can also be lower then the quality around the breathing zone. The basic and personal ventilation system and the chilled and heated water for the radiant panel are integrated into a flexible floor-system (B) and realize optimal personal air quality and thermal comfort. The microclimate system consists of the radiant panel under the desktop (C) and a personal ventilation system (D). With this microclimate system the user can directly control the temperature and the ventilation rate at the workplace.
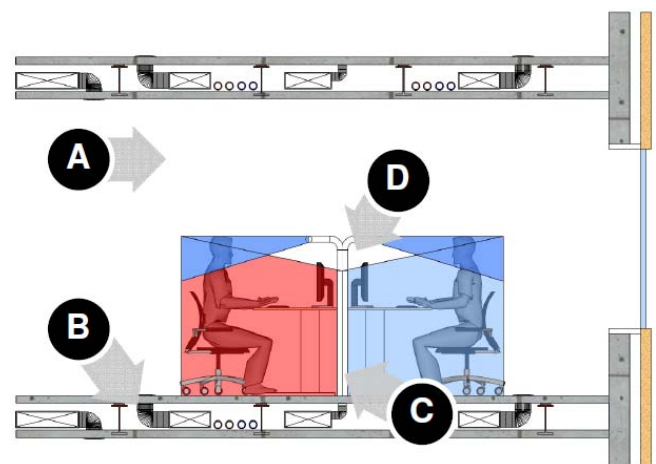

Figure 8. Principe microclimate system

Experiment

A prototype of an office desk with integrated radiant panel was build and use in the experimental setup (Fig. 9). The personal ventilation system was not yet included. Based on the results for heating it can be concluded that

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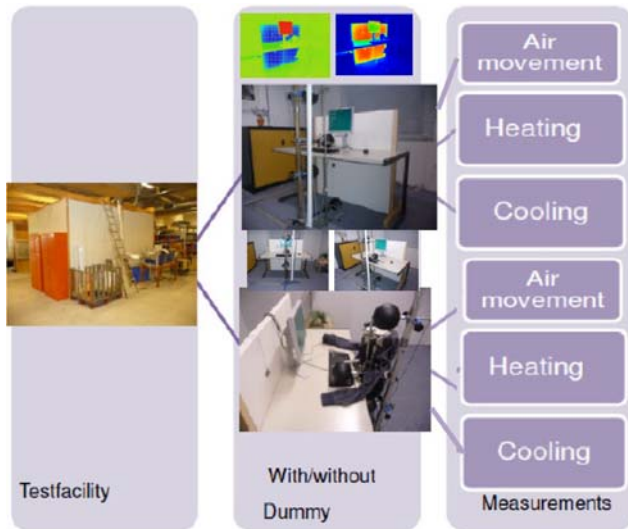heating of the hands and feet is effective (Filippini 2009).

Figure 9. Overview of themo microcroclimate experiment (Filippini 2009).

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This matches with the results from other research in literature (Arens et al 2006). The results of experiments, where hands and feet are cooled show the highest reduction of temperature at the level of the feet and the least near the position of the head (Filippini 2009). This doesn't agree with the comfort theory. Probably the addition of a personal ventilation system could be used for additional cooling of the upper body and the head. This is subject of further research.

Based on indicative calculations, where only the influences of the radiant panel has been implemented, it is concluded that there an energy consumption reduction.
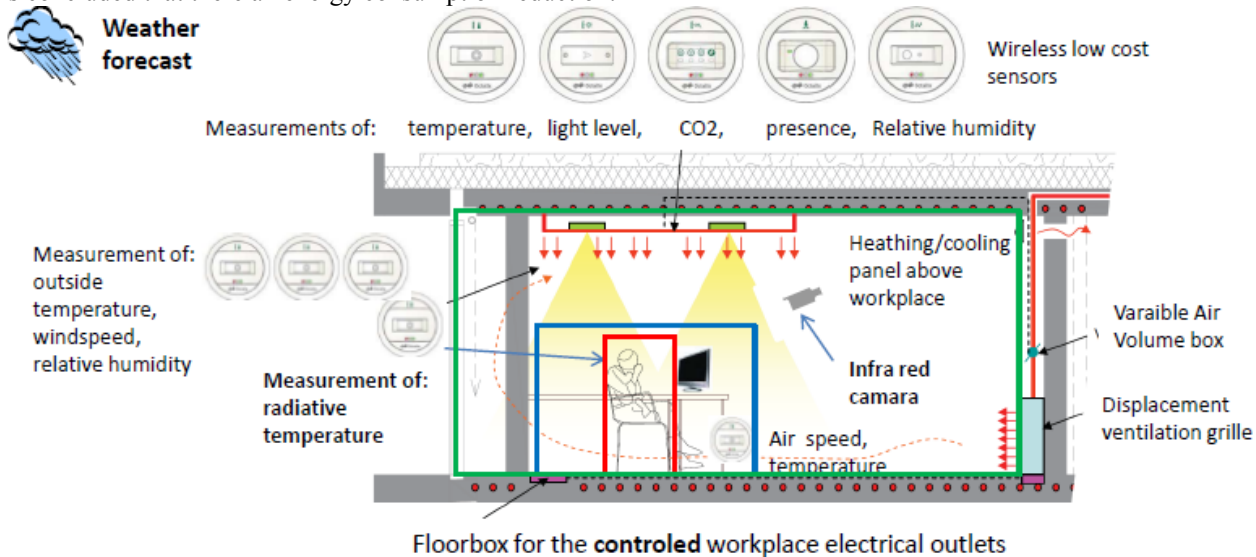
This mainly due to the less strict requirements basic-climate can be increased. As a first estimate a reduction of at least 14% seems possible when a deviation of +1 K in summer and -2K in winter is allowed (Filippini 2009). It is expected that the savings will increase further when the energy reduction due to the PV system is added to the set-up. A good control scheme in order to match the microclimate optimally to the overall climate is a challenge. An intelligent control scheme based is subject of further research.

Based on the abstract representation of occupant, workplace and room, the influences of different characteristic parameters for comfort and energy consumption will be measured. In a rapid prototyping approach, process representations of some of the different levels will be built. This will form the basis of defining different agents within the multi agent process control system. Using data from an existing building and its users it is possible to fit the model immediately with a real live situation. By making a coupling with the Building Management system of the building all the necessary data will be made available to fit and to investigate the behavior of the model compared to real historical data of before the intervention. The expected use of instrumentation is based on a concept for the placing and use of different wireless sensors and infra red camera is shown in Fig. 10. Such a grid of low cost sensors would make it possible to control and manage the individual comfort and the necessary energy for it. Fig. 10 shows how the actual experimental setting of the Smart Energy Building grid could look like based on a recent design.

Figure 10. The concept for the placing and use of different wireless sensors and infra red camera for the smart energy building grid

DISCUSSION AND CONCLUSIONS

Individual Control System (Fig.11) for optimal design of those in practice (Watanabe et al 2010). The

experimental setting of the Individually Controlled System (ICS) consisted of a convection-heated chair (HC), an under-desk radiant heating panel (UD RHP), a floor radiant heating panel (FL RHP), an under-desk air

terminal device (UD ATD) and a round movable panel air terminal device (RMP) (Watanabe et al 2010).
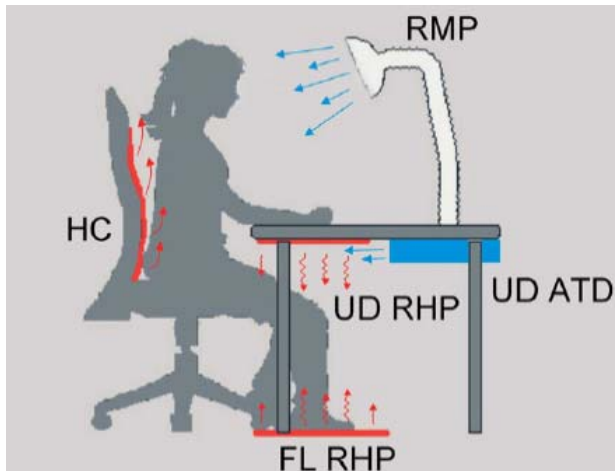

Figure 11. Individually Controlled System (ICS) (Watanabe et al 2010).

The results of thermal manikinexperiments were compared to existing subjective human response data. In general, the analysis of the results of the human subject experiments identified:

Dissatisfaction with the thermal environment was mostly caused by insufficient heating capacity and longer response time of radiant heating panels as well as improper control of ICS.

Thus better design of ICS, including system components with short response time and higher capacity, which can cope with the existing large individual differences between people in regard to preferred thermal environment, needs to be developed.

If occupants have access to an individual control system (ICS), the acceptable ambient temperature range can be further extended, to as much as 18-30ºC1 (Zhang 2003, Zhang et al 2010). Expanding a dead-band produces energy savings in two ways: it reduces the temperature difference between the set points and the building's floating temperature, and it reduces the number of hours per year needed for mechanical conditioning (Zhang et al 2010). By targeting specific body parts, individual control systems (ICS) produce equivalent or higher comfort (Fig. 11) using much less energy to condition the entire ambient space. The energy use of the TAC system can be compared to a conventional HVAC system for different climate zones. The assumed conventional HVAC system consists of variable air volume (VAV) with reheat, and a central boiler and chiller to provide respectively heat and cold.

The energy use for a conventional HVAC system is the energy to keep indoor air temperature within the 21.5 to 24ºC bandwidth. The energy use of the TAC plus HVAC consists of two parts: one to keep the indoor air temperature between the dead-band (e.g. 20-28ºC) and

second the energy needed for the task-ambient conditioning systems itself. When the air-temperature is within 21.5 to 24ºC no TAC is applied. The annual energy savings for widened air temperature set points relative to conventional set points are shown in Fig. 12 (Zhang et al 2009).
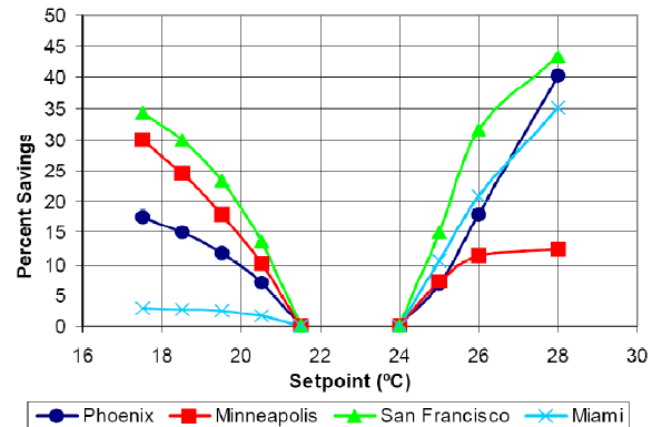

Figure 12. Percent energy savings for widened air temperature set points relative to conventional set point range for different climate zones in the United States (Zhang et al 2009).

The energy use of local task conditioning system for heating and cooling itself is not taken into account. Therefore the energy savings are less high compared to the graph. For the TAC systems the annual energy savings are approximately 40% for the wider 18-30ºC ambient dead-band, and 30% for the narrower 20-28ºC (Zhang et al 2010). Van Oeffelen et al. have shown that energy savings of approximately 25% can be reached by decreasing the room set point temperature in winter situation to 18ºC or even 20ºC (Oeffelen et al 2010).

It appears that the system proposed is very complicated, but the user is not bothered with the technology. Just like par example with an I-pod, the technology is highly complex still they are easy to use and have an enormous added value for their users. Human behaviour is an important factor to consider in the thermal exchanges between a building and its surroundings and the resulting energy consumption (Palme et al 2006). The ability for occupants to make their own choices and control the environment is critical to the satisfaction of users (Isalque et al 2006). This leads to the need to optimize and control the comfort demand and the energy needed to provide it. This research will focus on the application of a smart grid, existing of wireless low cost sensors and actuators for energy management in office buildings.

Especially the application of such a smart grid combined with multi agent technology in a real setting of an office building with its own building management system for process control will show the relevance of the

anticipated applications for comfort and energy management.

The radiant panel of the developed microclimate system meets the theory of the sensitive body parts in the winter, not in the summer. Possibly the PV system could improve the functioning of the system in the summer due to cooling of the head. The developed microclimate system could improve the comfort (thermal and ventilation) and reduce the energy use as been set in this thesis objective. The calculated energy reduction of 14% is based on our measurements and relates to the energy reduction of 25 to 32% as determined by (van Oeffelen et al 2010) based on simulations. However as shown by Schiavon and Melikov (2009) energy saving with personalized ventilation and conditioning is complex. It must par example made clear that the individual systems do not work towards each other and as a result increase the energy consumption. There should be sufficient distance between each microclimate and a supervisory control strategy is needed to realize the optimal performance.

Improvement of the energy consumption is made possible by enhancing individual comfort of occupants and incorporation of their behaviour. A new generation products is being developed for ventilations, cooling and heating on the level of the individual workplace. By starting from the human perspective and use available and new technology, the outcome will be more focussed on the ability to understand the critical aspects of the comfort of the end users. Based on this project new developments will be initiated and new concepts will be tested.

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